Geology of Saipan Mariana Islands

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Part 1. General Geology

GEOLOGICAL SURVEY PROFESSIONAL PAPER 280-A

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U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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Part 1. General Geology

By PRESTON E. CLOUD, Jr., ROBERT GEORGE SCHMIDT, *and*
HAROLD W. BURKE

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A study of the nature, field relations, and origin of the rock succession on this small but complex western Pacific island, and of its regional setting and geologic history since Eocene time

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 280

Geology of Saipan, Mariana Islands

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  A. General Geology
    By PRESTON E. CLOUD, JR., ROBERT GEORGE SCHMIDT, *and* HAROLD W. BURKE

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GEOLOGY OF SAIPAN, MARIANA ISLANDS

GENERAL GEOLOGY

By Preston E. Cloud, Jr., Robert George Schmidt, and Harold W. Burke

ABSTRACT

Saipan, situated about 15° N. and 146° E., is one of the larger and more southerly of the Mariana Islands. The 15 small islands of this chain are strung along an eastwardly convex ridge for more than 400 miles north to south, midway between Honshu and New Guinea and about 1,200 miles east of the Philippines. Paralleling this ridge 60 to 100 miles further east is a deep submarine trench, beyond which lies the Pacific Basin proper. To the west is the Philippine Sea, generally deeper than 2,000 fathoms. The trench coincides with a zone of negative gravity anomalies, earthquake foci occur at increasing depths westward from it, and silica- and alumina-rich volcanic rocks characterize the emergent island chain itself. The contrast between these features and those of the Pacific Basin proper to the east is held to favor the conclusion that the Mariana island arc and trench define the structural and petrographic front of Asia.

Magellan touched at the Marianas in 1521. After him came adventurers, traders, and priests. They found the temperature warm and little varied, rainfall seasonal, and resources modest. Saipan was occupied in 1564, and the name Mariana Islands was applied to the chain by Sanvitores in 1668. In the late 18th and early 19th centuries the Marianas were visited by the scientific exploring expeditions of Malaspina, von Kotzebue, de Freycinet, and Dumont d'Urville. Primarily geologic studies began at the turn of the 20th century, and there has been an increasing number of publications on the geology of the region since 1935.

Although second in size among the Mariana Islands, Saipan has a land area of only 48 square miles. It consists of a volcanic core enveloped by younger limestones. From axial uplands that rise to a maximum altitude of 1,555 feet, the slopes of the north-south elongated island step down to the sea in a succession of mainly erosional terraces that become conspicuous away from a strongly dissected central volcanic area. The lowest bench and the western coastal plain, however, are in large part of constructional origin.

The oldest rocks are andesitic inclusions in dacite, but the island began its decipherable geologic record with the subaerial accumulation of dacitic pyroclastic and flow rocks known as the Sankakuyama formation. The Sankakuyama is dated as Eocene (?) on the basis of late Eocene fossils in overlying strata, and the presence within it of tridymite and cristobalite—metastable forms of silica that are yet unknown from pre-Cenozoic rocks.

Over and around the Sankakuyama formation were deposited the andesitic pyroclastic and greatly subordinate flow rocks of the Hagman formation, and both andesites and exposed dacites were extensively reworked in bordering tropical seas to form the Densinyama formation. This consists mostly of conglomerate and sandstone. The reworked volcanic sediments of the Densinyama grade laterally and upward into a 500-foot succession of warm-water bank limestones known as the Matansa limestone. All three of these units (Hagman, Densinyama, and Matansa) have yielded camerinid and discocyclinid Foraminifera distinctive of the upper Eocene (Tertiary *b*); this indicates relatively short time span and partial lateral equivalence for them.

The Mariana geanticline presumably originated in early Tertiary time, before or during Eocene volcanism. Its growth is believed to have been closely related to the construction of a central volcanic core, which, on Saipan, presumably continued into or through Oligocene time.

Rocks believed to be of Oligocene age are the interlayered andesite flows and marine tuffs of the Fina-sisu formation. These contain smaller Foraminifera considered indicative of moderately deep tropical seas. Included also are planktonic species that imply approximate correlation with the upper Oligocene *Globigerinatella insueta* zone of the Caribbean region.

The 4,600 feet or so of Eocene and Oligocene rocks of mainly volcanic nature that form the core of Saipan are succeeded by 1,500 feet of bioclastic limestones and some coral-algal limestones and unconsolidated sediments of Miocene, possibly Pliocene, and Pleistocene to Recent age. The limestones generally contain Foraminifera and abundant coralline algae of both articulate and crustose types. Locally they also display reef-building corals, *Halimeda* and other calcareous green algae, mollusks, echinoids, and other fossils. Complicated facies relationships are characteristic.

The early Miocene Tagpochau limestone, like the late Eocene Matansa limestone, includes mostly bank-type deposits that accumulated in a tropical sea of shallow to moderate depth. The general scarcity of significant coral masses suggests depths mainly a little too great for vigorous reef growth, although within the zone of photosynthesis and in warm water. At deeper levels, downslope from the Tagpochau bank deposits, reworked tuffaceous sediments accumulated to form the Donni sandstone member of the Tagpochau. Orbitoid, miogypsinid, and other larger Foraminifera indicate a Tertiary *e* age for these beds and possible approximate equivalence to the Aquitanian of Europe. Smaller Foraminifera and mollusks indicate early Miocene in a broad way, without sure ties to specific sections. Two faunal zones are recognizable on the basis of larger Foraminifera, with an intermediate interval of mixing. The lower zone, characterized by *Heterostegina borneensis* van der Vlerk, is referred to the lower part of the Tertiary *e* beds. The upper zone, characterized by *Miogypsinoides dehaartii* van der Vlerk and *Miogypsina* s. s. denotes the upper part of Tertiary *e*. Neither the *Heterostegina borneensis* zone nor the *Miogypsinoides*

dehaartii zone appears to be related to sedimentary facies as mapped.

The Pliocene may be represented by terrace deposits on benches that truncate Miocene strata at levels above the highest probable Pleistocene limestones. However, no fossils are known from these thin terrace sands and gravels.

Younger still than these possible Pliocene terrace deposits is the Mariana limestone of supposed older Pleistocene age, reaching to 500 feet above present sea level, and the Tanapag limestone of late Pleistocene age, restricted to elevations below 100 feet. The Mariana limestone consists of lithified reef-complex and bank-type or lagoonal deposits; whereas the Tanapag is an elevated fringing reef complex. Both contain dominantly modern types of algae, Foraminifera, corals, and mollusks.

Only two new stratigraphic names are introduced for the succession outlined, the presumably Oligocene Fina-sisu formation and the lower Miocene Machegit conglomerate member of the Tagpochau limestone.

Miocene deposits overtopped the volcanic core, and subsequent fluctuating relationships between land and sea led to the formation of somewhere between 12 and 25 marine bench surfaces. Three principal sets of terraces are recognized, according to elevation and intervals of terrace formation: an upper, late Pliocene(?) set with surfaces above 500 feet; an intermediate, middle(?) Pleistocene set between 100 and 500 feet; and a lower, late Pleistocene set below 100 feet. The rock benches below 100 feet tend to be veneered by, or are parts of, the elevated late Pleistocene fringing reef complex. The higher terraces were cut in preexisting rocks by marine erosion. Some are veneered by stratified Pliocene(?) and Pleistocene nonmarine terrace sands. The limesands of the western coastal plain seem mostly to veneer a recently down-faulted part or parts of the lowest constructional bench.

A solution notch at 5 to 8 feet above present sea level gives further evidence of the now widely recognized 6-foot eustatic stand of the sea that may correlate with a late subpeak of the postglacial thermal maximum The fall from this eustatic level was interrupted by a stillstand at about 2 feet Evidence of other possible eustatic levels is found at 12 to 15, 40, and about 100 feet above present sea level and probably below it. If the 100 foot level is eustatic it may correlate with the last major interglacial or interstadial epoch, and deposition of the Tanapag reef limestone would seem to have been in progress during some part or parts of the last Pleistocene glacial advance.

Parallel to the long axis of Saipan are steep, north-northeast to northeast-trending, west-dipping faults, along which dip-slip movement has been relatively down on the west. A few cross faults add to the complexity of this pattern, and minor local folding has taken place. The basic fault pattern may well have originated in Oligocene time, but the oldest clearly datable offsets are post-early Miocene and pre-late Pliocene. Thereafter four intervals of recurrent fault movement can be recognized and closely dated in the local sequence: post-upper terrace formation, or late Pliocene(?); post-Mariana limestone deposition, or early middle(?) Pleistocene; post-intermediate terrace formation, or late middle(?) Pleistocene; and post-Tanapag limestone deposition but before the retreat of the sea from the 6-foot eustatic level, latest Pleistocene or early Recent. The general shape and location of the island are probably in significant degree fault-controlled.

Emphasis is placed on the ecologic implications and age significance of the fossils, and on the origin and historical analysis of the rock succession and geomorphic features

Descriptions of stratigraphic sections and economic geology are appended to the report.

INTRODUCTION

BASIS AND SCOPE OF THE REPORT

Following World War II the U. S. Geological Survey has been engaged in a program of areal studies in the western north Pacific Ocean under financial sponsorship of the Corps of Engineers, U. S. Army. As a part of this program, geological, soils, and ecologic field work was carried out on and around Saipan (figs. 1, 2; pls. 1, 2) from late September 1948 to mid-July 1949 by the authors, soils scientists Ralph J. McCracken and Ray L. Zarza, and briefly by Allen H. Nicol and Jarvis H. O'Mara. These investigations were supplemented by the laboratory studies of paleontologists Milton N. Bramlette, W. Storrs Cole, C. Wythe Cooke, Julia Gardner, J. Harlan Johnson, William Riedel, Ruth Todd, and John W. Wells.

Because studies basic to the evaluation of military problems yielded much purely scientific information, it was decided to publish separately that information and the interpretations that are based on it. This chapter of the resulting report relates to the general geology of Saipan. It is planned that subsequent chapters will deal with soils, petrology of the volcanic rocks, petrography of selected limestones, discoasters and related objects, the larger calcareous algae, Radiolaria, Foraminifera, echinoids, and submarine topography and shoal-water ecology. The mollusks are being reserved for inclusion in a proposed general study of Cenozoic mollusks of the Pacific islands by H. S. Ladd.

For this chapter, "General geology," Burke provided the first draft of descriptions of the Matansa limestone; the equigranular, inequigranular, and tuffaceous facies of the Tagpochau limestone; and the Tanke cliffs stratigraphic section. This was done in the field in mid-1949 and Burke is not responsible for subsequent variations from his original descriptions or for interpretive sections. Schmidt is responsible for basic description of the Sankakuyama, Hagman, and Densinyama formations; the Machegit conglomerate member of the Tagpochau limestone; the rubbly facies of and thick residual clays over the Mariana limestone; all terrace and slump deposits; stratigraphic sections at Machegit cliffs, Talofofo ridge, and Mount Achugau; and the petrology and classification of the volcanic rocks. He shares responsibility for descriptions of the Fina-sisu formation, for the Donni sandstone member and transitional facies of the Tagpochau limestone, and for the thick residual clays over the Tagpochau limestone. Schmidt and Cloud prepared the Appendix on economic geology together. Cloud is responsible for general coordination, for descriptions of geologic units not attributed to Schmidt or Burke, and for microscopic and paleoecologic studies of the limestones in all unit descriptions. The writing of all general sections of this chapter was also by Cloud, with Schmidt's extensive help in general organization, the writing of paragraphs relating specifically to volcanic rocks, and in preparation of illustrations. Responsibility for mapping is indicated on the maps themselves.

Although Saipan includes an area of only 48 square miles, it displays a varied and complicated succession of rocks, and reconnaissance of other islands in the Marianas suggests that it may provide good exposures of some rocks not elsewhere well displayed. This stratigraphy is described in detail, both because it illustrates well some of the complexities of "high island" stratigraphy and because such a study has not previously been published for any similar island nearby.

The reader should not be lulled into a sense of finality, however, by the attempt here made to provide as complete coverage as possible. In spite of intensive efforts in the field over a period of 9 months, and the laboratory studies that have been made since then, much could still profitably be done, both in the field and in the laboratory. There is need for further study of rock weathering and solution. Larger megafaunas could be obtained with intensive collecting—localities in north Saipan that we had intended to revisit for collecting were closed because of fire in an ammunition dump during the latter part of our field work. Offshore and beach zone studies were incidental to the main project ashore, and thus incomplete. Even the stratigraphic succession and subdivision of the rocks have their points of uncertainty and many of the facies contacts mapped are highly generalized. Mapping in the thickly vegetated and precipitous terrain was slow, interpretation of the complexly intergradational rock units is difficult, and some possible lines of investigation had to be foregone or abbreviated for lack of time or means to follow them up. As for geomorphology, it is not feasible to go much beyond the incidental observational data. What is needed here is a unified regional study of the Mariana Islands as a whole, carried out under the continuous field leadership of one person.

In fact, topical studies in the western Pacific, are now needed more than ever— not only of geomorphology, but also of stratigraphic correlation, paleoecology, structure, the volcanic rocks, and geophysical patterns. In the hope of bringing Saipan into better focus and of encouraging further investigation, an effort will be made in later parts of this report to summarize the present state of knowledge in some of these fields. It is inevitable that time and new evidence will modify or invalidate some or many of the opinions to be expressed.

ACKNOWLEDGMENTS

We are indebted to so many for help and encouragement with the preparation of this report and the fieldwork on which it is based that to attempt to thank all would be to run the risk of inadvertent omission. Of course we are sincerely grateful to everyone who aided this study in any way, but we can specifically acknowledge only help of an especially extensive or significant nature.

Without the support of Col.[1] B. C. Snow, then staff engineer, Marianas-Bonins Command, and Sherman K. Neuschel, in charge of the Geological Survey's Pacific program, the fieldwork could not have been accomplished.

Rear Adm. C. A. Pownall, then Commander Naval Forces Marianas, and the personnel under his command on Guam and Saipan, made it possible for the field party to supplement its investigations ashore with a program of marine studies. The success of this operation was assured by outstandingly fine support from Capt. G. L. Compo, then Island Commander of Saipan, his executive officer, Comdr. William Dickey, and Chief Boatswain Francis X. Jozwick.

Col. H. P. Detwiler, commanding officer of the Army Garrison Forces on Saipan when the geologic work was begun there, and Lt. Col. J. P. Davis, first as executive officer to Col. Detwiler and later himself in command, provided living and working quarters, vehicles, and other facilities on Saipan. Mrs. Davis significantly aided the work of the field party by volunteer service as collector and compilation draftswoman.

Comdr. F. L. Sheffield, civil administrator on Saipan during the later geological field work there, arranged for R. G. Schmidt to visit and study Alamagan, Pagan, and Agrihan, in the northern Marianas.

Drs. Shoshiro Hanzawa, Kotora Hatai, and the late Risaburo Tayama helped to clarify controversial matters relating to Saipan geology at a 2-day conference with Cloud and Burke in Sendai, Japan, in July 1949. Also of help was Dr. Ruiji Endo, who prepared for our use in the field "A lexicon of geologic names of Saipan Island," giving translations and page citations of Tayama's original descriptions.

Temporary members of the mapping party not included among authors of reports resulting from this field work are Ray L. Zarza and Jarvis H. O'Mara. Buenusto Reyes of Saipan also assisted with the field work.

GENERAL HISTORY OF THE REGION

Midway between Honshu and New Guinea, and about 1,200 miles east of the Philippines, the convex eastern margin of the Philippine Sea is festooned by 15 widely separated islands that define a remarkably symmetrical arc more than 400 miles long. These are the Mariana Islands (figs. 1 and 2).

They were first seen by people of European descent

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[1] All military ranks here mentioned refer to those held at time of fieldwork.

on March 6, 1521, when the desperate little squadron of Fernan de Magalhaes (Magellan), sailing the 13th parallel westward in the neighborhood of 146° E., "discovered in the northwest a small island, and afterwards two others in the southwest" (Pigafetta, as translated by Pinkerton, 1812). According to a translation from the original logbook of navigator Francisco Albo (Stanley, 1874, p. 223), "On the 6th [March, 1521] * * * we saw land, and went to it, and there were two islands, which were not very large; and when we came between them, we turned to the S. W., and left one to the N. W. * * * and there I took the sun, and one of these islands is in 12⅔°, and the other in 13° and more [north latitude]."

Historians have generally agreed that the island at which Magellan landed and spent three days (Albo, *in* Stanley 1874, p. 223–224) was probably Guam, and some have even pinpointed his stopping place as Umatac Bay (southwest Guam). In fact, however, the original accounts are ambiguous, and Tinian, rather than Guam, may have been the site of Magellan's landing. Even Rota is a possibility, as one of Magellan's sailors was found living there in 1526 (Pinkerton, 1812, p. 324). Recorded latitude and distance between islands seem to favor Guam, however, even though the point cannot be settled conclusively. In any event, Magellan did sight two or three of the Mariana Islands, landed at one of them, and opened a route of travel that was followed by Eltano in 1524, Loaisa in 1526, and many others in later years.

Magellan found the Marianas inhabited by Micronesian people of presumed Indo-Malayan derivation, with a distinct language and distinctive physical characteristics. Pigafetta, who wrote the history of Magellan's voyage, observed that some of the men had "black hair, tied over the forehead, and hanging down to the girdle," and that these "wore small hats made of palm." They would have been according to Mr. Elias Sablan of Saipan, the Chamorri, or nobility, a term that was extended by later explorers to all natives of the Mariana group (see also Safford, 1903, vol. 5, p. 291; 1905b, p. 104; Prowazek, 1913, p. 29; Joseph and Murray, 1951, p. 18).

Chamorro discovery of the Marianas is buried in legend and disputed as to approximate date. The age indicated by carbon-14 activity of a shell associated with pottery 1.5 feet below the surface of the sandy coastal plain at Chalan Piao in southwestern Saipan was originally given as 3,479 ± 200 years (Libby, 1952, p. 680), but recent studies of organically precipitated calcium carbonate suggest a negative correction of 1,500 to 2,000 years on this date (J. L. Kulp, letter of January 15, 1953, to Cloud). In this same excavation Alexander Spoehr found pottery to a depth of 6 feet, about at present sea level. Thus it appears that man already had a history of residence in the Mariana Islands more than 1,500 and perhaps more than 3,500 years ago—long before Magellan arrived.

The first definitely recorded European occupancy of Saipan occurred in November 1564 when Adm. Miguel Lopez de Legaspi landed there and proclaimed Spanish sovereignty over the Mariana Island group. The islands, which had been called Islas de los Ladrones by Magellan, were at this time renamed Las Islas de las Velas Latinas. It was not until 1668 that the Jesuit, Diego Luis de Sanvitores, fulfilling a long ambition to establish a mission in these islands, gave them their present name in honor of Maria Ana of Austria, Queen of Spain, widow of Philip IV, and patroness of the Jesuit order.

The Spanish occupation of the Mariana Islands lasted more than 200 years (until 1899) and greatly influenced the language, habits, religious beliefs, and racial composition of the inhabitants. Government was difficult, and although there were enlightened and thoughtful men among the succession of Spanish governors, the accounts of historians indicate that their efforts were nullified by those who thought that display of force would insure obedience. Punitive expeditions against unruly natives, famine, disease, and mass evacuations reduced the population from an estimated 70,000 to 100,000 in 1668 to fewer than 4,000 natives at the time of the first census in 1710. In the next 50 years or so the population fell to fewer than 2,000. Recovery from this point of near extinction was steady, however. By 1816 the Chamorro population for the Marianas was back up to 2,559 in a total of 5,389, (Prowazek, 1913, p. 24); and by 1898 the total population had increased to about 10,000. By this time, however, pure-blooded Chamorros had all but disappeared (Joseph and Murray, 1951, p. 23), and the present much more numerous inhabitants of the Marianas are mainly descendants of mixed blood from this small group. Caroline Islanders, Japanese, Koreans, and Okinawans were later numerous in Saipan, Tinian, and Rota where they apparently rarely interbred with the Chamorros and are minority strains today.

Throughout Spanish and later times Saipan itself underwent even more drastic population shifts than the Marianas as a whole. In 1694 the Spanish governor of the Marianas, Don Jose de Quiroga y Lossada, had subjugated the natives of Saipan in a series of bloody skirmishes from which, it is said by local elders, several of the present geographic names on Saipan are derived (*Matansa*, for massacre, and *Kalabera*, for skeleton). In 1698 the entire remaining population was removed to Guam where it could be kept under close surveillance, and Saipan remained supposedly uninhabited for more

than 100 years. An abortive effort at colonization was made by Americans and Hawaiians in 1810, a more successful attempt by Caroline Islanders in 1815, and the Chamorros finally began their return in 1816 (Joseph and Murray, 1951, p. 23). Emigration from the Caroline Islands to Saipan became active about 1842 (Marche, 1887; 1898, p. 60; Seidel, 1904a, p. 280). Marche (1898, p. 60) reports that in 1887 two-thirds of Saipan's small population was Carolinian and the other third mostly Chamorros not visibly different from those of Guam. By 1937 the balance between Chamorro and Carolinian has swung in the other direction, the native population of Saipan then being said to include 2,170 Chamorros (as the term is now used) and 796 Carolinians. In addition, however, the island was occupied by 20,696 Japanese, Koreans, and Okinawans (U. S. Navy, 1944, p. 35). Finally, in September 1948, the total native population of 4,962 persons included 3,890 Chamorros and 1,072 Carolinians (Bowers *in* Freeman, 1951, p. 227). Nearly half of these were under 16 years of age (Joseph and Murray, 1951, p. 81).

During the Spanish rule of the Marianas, Guam was the capital and its Umatac Bay was a world-reknowned port for exploring expeditions and trading galleons plying between Mexico and the Philippines. Like the masters of the galleons, the English privateers and pirates who preyed on them also stopped here on occasion with their Spanish prizes and prisoners. Among these were Eaton and Cowley in 1685, William Dampier in 1686, and Woodes Rogers in 1710. Other early visitors to the Marianas included the crews of Anson in 1742, Byron in 1765, Wallis in 1767, Crozet in 1772, La Perouse from 1785 to 1788, Malaspina in 1792, von Kotzebue in 1817, de Freycinet in 1819, and d'Urville in 1828.

Spanish rule of the Mariana Islands ended in 1898–99. Guam was occupied by American forces in 1898 and later purchased from Spain by the United States. In 1899 the remaining Mariana Islands were sold to Germany by the Spanish. During the brief German occupation of the Marianas (1899–1914) the copra industry was considerably expanded, food and stock farming was encouraged, a few schools were established, and Capuchin priests were substituted for Augustinians and Jesuits; but otherwise the handful of German officials seem to have left things essentially as they had been under Spanish rule.

Japan seized the Mariana Islands (except Guam) from Germany in October 1914, and Japanese mandate over these islands was approved by the League of Nations in 1920. Headquarters for the Japanese mandated Marianas were on Saipan. Under Japanese rule an important sugar cane industry was developed in the Marianas, phosphate and manganese were mined, and trade with other mandated islands and Japan was encouraged. Okinawan and Korean laborers were imported to work the sugar fields. The Japanese segregated the Chamorros and restricted their holdings but apparently did not interfere with their religious activities or social customs.

On June 15, 1944, American troops landed on the southwestern beaches of Saipan, and within 2 months the 30-year Japanese occupation of the Marianas was ended (for an account of the campaign see Hoffman, 1950). Guam, which had been taken by the Japanese on December 9, 1941, was retaken by American troops, and the United States trusteeship of the remaining islands, including Saipan, was approved by the Security Council of the United Nations on April 2, 1947, and accepted by the U. S. Government on July 18, 1947.[2]

GEOGRAPHIC TERMINOLOGY

The geographic names used in this report are those approved by the U. S. Board of Geographic Names as recommended in a "Preliminary gazetteer of geographic names for Saipan" (Cloud, 1949). The specific parts of the Chamorro names are adhered to throughout; but, in the text itself, the generic parts at most places are translated to English in the interests of smoother reading—thus Ogso Tagpochau is written Mount Tagpochau and Ogso Talofofo is Talofofo ridge. At irregular intervals bracketed Chamorro translations follow the names of geographic features as a form of translation aid. The maps give the entire approved name in Chamorro only, together with a translating key to generic parts.

Translation of Chamorro specific terms is given in the reference mentioned, and other information may be found in a Chamorro grammar by W. E. Safford (1903–1905a, see also Safford 1905b, p. 113–116) and a dictionary by the Capuchin Father Callistus (1910). Safford also refers to a small Spanish-Chamorro dictionary by Father Ibañez del Carmen, published in 1865.

One matter needs to be clarified. The Chamorro words for the cardinal directions somehow became confused between Guam and Saipan (perhaps at the time of the repopulation of Saipan during the middle and late 1800's). On Saipan north is *katan*, south is *luchan* (*san lichan*, toward the south; *gi lichan*, south of, south from, on the south of), east is *haya* (pronounced hä'zȧ), and west is *lagu* (sometimes given as *lago*). On Guam *lagu* (or *lago*) means north, *haya* south, *katan* east, and *luchan* west. This seem incredible—but the usage for directions on Saipan was verified at every opportunity and is surely correct for that island; the

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[2] Most of the foregoing information was obtained from references cited. A fuller and more recent account of Marianas history is given by Reed (1952).

usage for Guam is given on the authority of Safford (1903–1905a, v. 7, p. 315), and Father Callistus (1910, p. 50, 52, 67, 81) substantiates the double usage. Moreover, Albo's log of Magellan's voyage (Stanley, 1874, p. 223), as quoted on an earlier page, bears out Safford's contention (1903, v. 5, p. 291, 307) that the Spaniards were called *gi lago*, and their language *Finolago*, because they first appeared to the natives coming from a northerly direction.

CLIMATE

Japanese climatic records for Saipan have been summarized in compilations by the U. S. Navy (1944, p. 3–8) and the U. S. Geological Survey (1944, p. 46–47). Temperature and rainfall data from the latter reference are further condensed in table 1.

Saipan is characterized by a tropical oceanic climate. Recorded mean annual temperature ranges from 78° F at an altitude of about 676 feet on the central ridge east of Tanapag to about 85° F in the southwest lowlands. Recorded deviations from the mean are as low as 67° on the central ridge and as high as 102° in the southwest lowlands. The mean annual relative humidity is about 82 percent, with a monthly average between 79 and 86 percent (U. S. Navy, 1944, p. 5). The axial uplands and east slope of the island, being exposed to the easterly trade-winds, are cooler and generally less humid than is its western slope and coastal area.

Average annual rainfall, according to Japanese records, varies from 81.0 inches in the southwestern lowlands to 90.7 inches at an altitude of 676 feet on the central ridge. Mount Tagpochau, which rises to a peak of about 1,555 feet, would doubtless show a higher rainfall still, and a maximum annual precipitation of 130 inches has been recorded at an unidentified locality (U. S. Navy, 1944, p. 5). Records kept at the Tanapag Naval Air Base from September 1948 to August 1949 show only 51.44 inches of rain. This is the minimum yearly rainfall so far recorded for Saipan, but it is conceivable that rainfall in this lee area would average less even than that in the southwestern lowlands. Less than 1 inch of rain has been recorded in some years for the months of February, March, April, and May, but as much as 18.4 inches has fallen in January. September is the wettest month, with averages at two stations of 13.6 and 15.7 inches, and maximums of 25.7 and 27.0 inches. However, in the 1948 to 1949 period noted, July was the wettest month, having 12.81 inches.

TABLE 1.—*Temperature and rainfall data for Saipan (averaged from 9 years of Japanese records)*

	Temperature (Fahrenheit)			*Rainfall (inches)*					
					Maximum monthly				
Station	*Mean annual*	*Maximum*	*Minimum*	*Mean annual*	*Mean*	*Absolute*	*Months with <1 in*	*Rainiest months*	*Less rainy months*
Axial ridge (altitude 686± ft)	78°	89° (Sept.)	67° (Jan.)	90. 7	15. 7 (Sept.)	27± (Sept)	Apr.	July–Oct.	Nov.–June
Southwest lowlands (altitude 10 to 200± ft).	85°	102° (Sept.)	68° (Jan.)	81. 0	13. 6 (Sept.)	25. 7 (Sept.)	Feb., Mar , Apr.	July–Nov.	Dec –June

The table shows that one may recognize a rainy season and a dry season. Some rain falls on a majority of the days in all months of the year; but rains are heaviest and rainy days are most frequent from July through October on the axial uplands and from July through November on the low ground in the southwest. The dry season extends from November or December through June. This is the time of generally continuous easterly trade winds and pleasantest weather. The rainy season is the time of shifting winds and typhoons. During this season the wind comes most frequently from the southeast to east, but it may blow from other quarters, particularly from the south and southwest. Typhoons come generally from the south or southwest, most frequently toward the latter part of the rainy season. During typhoons the wind may rise to very high velocities and do great damage, and the combination of high wind and heavy rainfall almost always does some damage.

A high degree of cloudiness prevails over Saipan, as it does over all the Mariana Islands, which usually can be located from far away by the banks of clouds above them. Over an 8-year period of observations, the mean annual cloudiness averaged 6.7 on a scale that ranges from 0 for cloudless to 10 for completely overcast (U. S. Navy, 1944, p. 6). However, about 59 percent of the hours between 6 a. m. and 6 p. m. are hours of sunshine. Cloudiness is greatest from July to September and least in April. Days with clear skies occur most frequently in February.

WATER RESOURCES

About 73 billion gallons of rain falls on Saipan in an average year. If the rainfall were uniformly distributed in time, which it is not, this would amount to about 200 million gallons per day. The ultimate problem of water supply on Saipan relates to how much of this rainfall can be recovered in usable form.

Sources of potable water on Saipan before American occupation were Donni springs (Bobo I Denni, flowing

80,000 to 400,000 gallons per day), about a dozen smaller springs (such as Talofofo springs, Nicholson spring, Achugau springs), cisterns for catchment of rainfall, a few drilled wells, and several hundred dug wells. Slightly brackish water for industrial purposes was obtained from the starch factory spring, or salt spring, near Tanapag. This spring normally flows from 100,000 to 130,000 gallons daily, and has a chloride content of 480 to 1,200 ppm. Hagoi Susupe, a slightly brackish and generally contaminated lake, furnished water for operation of the Japanese sugar mill at Chalan Kanoa. Dug wells in the low coastal plain along the west coast provided generally brackish water. A few drilled wells in the southern fourth of the island produced fairly large quantities of water of good potability at a fairly consistent flow. Cisterns provided most of the water for individual dwellings away from the villages.

After the American landing many wells were drilled, and a large proportion produced potable water. One Maui-type infiltration tunnel (U. S. Maui No. 1) was extended from the base of a 100-foot shaft near the center of the south quarter of the island. Another Maui-type tunnel was extended from the base of a 200-foot shaft driven down from the 200-foot terrace surface near the center of the west side of the island (U. S. Maui No. 4). Other proposed Maui-type wells were abandoned before completion, but the two mentioned have continued to produce a large part of the potable water used on Saipan since their completion, giving trouble only when the water drops below the level of withdrawal owing to unusually low tides.

The only reasonable possibility for obtaining additional water from surface sources on Saipan consists of utilizing the two small perennial streams and several small springs of the Talofofo grasslands (Sabanan Talofofo) in the east-central part. Small artificial catchment reservoirs might prove feasible; but in the absence of data on runoff and silt carriage, it also seems probable that silting behind a dam or dams in the Talofofo drainage area might easily occur too rapidly to warrant such a venture.

All possible sources considered, development on Saipan of a regular daily supply of almost 5 million gallons of potable water at the source points seems practicable. It should be emphasized, however, that prevention of excessive loss of water enroute to points of demand requires excellent pumping and piping facilities and proper maintenance of them. Deterioration of such facilities in the tropics is rapid but their maintenance is at least of equal importance with the development of original supply and is a commoner source of difficulty in the larger islands.

LAND CLASSIFICATION

The soils and areas of little or no soil on Saipan are grouped into five major land classes. As summarized from the chapter on soils by R. J. McCracken these are:

1. Arable land on gentle slopes originally covered 4,960 acres or about 16 percent of the total land area on Saipan. Between 10 and 20 percent of these arable lands have been rendered indefinitely unfit for agricultural use as a result of military construction during World War II.

2. Marginal land suitable for limited crops or grazing land formerly comprised 12,620 acres or about 41 percent of the total land area. Between 10 and 15 percent of this land is estimated to have been indefinitely withdrawn from use owing to military construction.

3. Nonarable land usable as grazing land or for limited forest growth underlies about 12,660 acres or a little over 41 percent of Saipan. This land is largely rough, stony land, mainly barren of soil, or with thin or very patchy development of relatively infertile soil. It also includes marshland.

4. Low-quality land suitable for grazing but not for crops or forest growth covers 250 acres of north central Saipan. This is essentially an area of outcrop of dacitic breccia and flow rock, comprising slightly less than 1 percent of the total island area.

5. Quarries and the lake known as Hagoi Susupe together account for 230 acres, or less than 1 percent of Saipan's surface.

The uses to which the natural land classes may be put are, of course, further limited by the necessity of replacing large parts of the present plant cover with appropriate new types—for instance, areas of swordgrass would need to be replaced with suitable forage stock before they were actually usable as grazing land.

PLANTS AND ANIMALS

The vegetation of Saipan has been so altered by cultivation, burning, and importation of foreign species that it is difficult for any but the skilled botanist to know what plants are indigenous and which introduced. S. J. M. von Prowazek (1913, p. 104–121) listed the flora, discussed floral communities and relationships, and cited important previous publications. According to the U. S. Navy's "Civil affairs handbook" (1944, p. 16), Sigeki Kawagoe in 1915 recorded a presumably inclusive flora of 107 species grouped in 51 genera. Of these the grasses and legumes include the largest number, with 10 species each. Safford's book on "The useful plants of Guam" describes with care and discusses a flora similar to that of Saipan. We have not attempted to go beyond the sources cited and are not here concerned with inclusiveness or distinction between endemic and introduced.

In the past the coconut palm was of leading importance in the native economy. However, as a result of blights, an extensive but now defunct Japanese sugarcane industry, and war, the coconut is no longer abundant. Bananas, taro, tapioca, yams, and sweet potatoes are extensively raised, and the breadfruit, pandanus, and soursop are important food sources. Mangoes, papayas, and pineapples are grown locally, and coffee, citrus fruit, cotton, tobacco, and kapok trees were introduced and raised in varying quantities in times past. Ifilwood (*Intsia bijuga*[3]) and daog (*Calophyllum inophyllum*) are potentially important timber species.

In terms of broad vegetation patterns, dense and varied jungle growth characterizes the immediate vicinity of the limestone cliffs, whereas the pliant but vicious sharp-edged swordgrass (*Miscanthus floridula* or *M. sinensis*) is the characteristic plant inhabitant of the volcanic areas or areas of highly tuffaceous or argillaceous limestone. Under Baron Mitsui and the South Seas Development Company (Nanyo Kohatsu Kaisha), the Japanese developed an extensive sugarcane industry, and second growth cane occurs over much of the island. The casuarina tree (*Casuarina* cf. *C. equisetifolia*, Australian pine, ironwood) grows extensively along the beaches, and locally it and the xerophytic fern *Gleichenia* compete with swordgrass for living space on the volcanic soils and weathered volcanic rocks. *Casuarina* has also been planted in windbreaks. To the foot-traveler the deceptively smooth-looking areas of thick growth of swordgrass are the most nearly impassable vegetation; second and third in order of difficulty are jungle and second-growth cane.

Leguminous trees and shrubs are among the commonest and most varied on the island, and, of these, the introduced scrub "acacia" *Leucaena glauca* is the commonest and most widely distributed. In fact it is rapidly becoming another serious impediment to cross-country foot travel. Another common leguminous tree, the Formosan koa (*Acacia confusa*), was widely introduced by the Japanese as a windbreak, woodlot, and shade tree. The locally extensive patches of this low tree constitute the pleasantest woodland on Saipan, their dense shrubbery so completely shutting out the sunlight as to inhibit the growth of all underbrush and provide free, if cramped, passage beneath their canopy.

Excepting insects, there is little variety among the land animals of Saipan, and much of what is known of this is summarized in the "Civil affairs handbook" for the Marianas (U. S. Navy, 1944, p. 18–20). The only native mammals are two species of bat, of which the larger, known as the fruit bat or flying fox (*Pteropus kerandreni*), is eaten by the Chamorros, who call it "fanihi." The other species of bat is the common, small, night-flying bat (*Emballonura semicaudata*) Rats are abundant and are generally considered to have been introduced. A few deer (*Cervus mariannus*) were seen in the volcanic terrain of north central Saipan. Pigs, cattle, and chickens are fairly common domesticated animals, but more could easily be kept. Oxen, carabao, and horses are rare. Feral goats were observed in the isolated bluffy area south of north Laulau Point (Puntan Laulau Katan).

Only one land snake is known from Saipan. This is a harmless, small, slender, black, burrowing snake, rather resembling an earthworm—a species (*Typhlops braminus*) which has attained an almost world-wide distribution through artificial means. Marine snakes that are occasionally seen in the shallow water about the island are generally poisonous, but are not aggressive and ordinarily refuse to bite even with provocation. A large monitor lizard (*Varanus indicus*), sometimes erroneously referred to as the iguana, is apparently common but is seldom seen because of its secretive habits. It attains a maximum length of about 4 feet, is dark with yellow spots, and occasionally makes a nuisance of itself by feeding on young chickens. The monitor lizards also eat rats, however. A small blue tailed skink (*Emoia cyanura*) and several species of chirping geckos are common throughout the island.

The house fly is an abundant pest, and mosquitoes are locally a nuisance. Several species of wasps and bees occur on Saipan. One small wasp with an unforgettable sting and a belligerent disposition locates its small nests at shoulder height or lower positions through brush and along walls of buildings and rock faces. Ants are common and some can inflict painful bites. Centipedes, as much as 10 inches long, and small, broadbacked scorpions are probably abundant but are seldom seen. Ticks are reported. Beetles, butterflies, dragonflies, spiders, moths, locusts, termites, fleas, and grasshoppers are common.

A variety of sea and shore birds, as well as a few native land birds, were observed. Apparently most of the native jungle birds recorded by earlier visitors have been exterminated.

Fish and eels of great variety occur in the shallow water around the island, and at least one species of fresh-water eel (*Anguilla marmorata* Quoy and Gaimard) and a small basslike fish [*Kuhlia rupestris* (Lacapède)] occur in Talofofo stream (Sadog Talofofo), in east central Saipan. A small, wide-clawed, edible crayfish [*Macrobranchium lar* (Fabricius)][4] also occurs in Talofofo stream, and shellfish of various sorts are abundant in the coastal waters. As would be expected, the marine fauna is far more abundant and varied than the fauna of the island itself. This, however, is discussed and tabulated in part 4, chapter K, under shoal-water ecology."

The imported African land-snail (*Achatina fulica*) is a familiar pest. It attains lengths exceeding 4 inches, and is extremely abundant in some parts of the island, particularly in areas underlain by limestone. It seems to feed on almost any vegetation, and efforts to eradicate it have so far failed.

MINERAL RESOURCES

The mineral resources of Saipan are both metallic and nonmetallic. The metallic ores include manganese oxides, ocher, and iron oxides. Previous reports of bauxite, however, have not been authenticated. Tayama (1938, translation) reports traces of gold and silver in grains of pyrite and sphalerite in quartz boulders of the Densinyama formation. Nonmetallic resources include phosphate, sand and a little gravel, clay, building and decorative stone, and sources of riprap.

These commodities will probably never be of much importance. Phosphate deposits in northern Saipan were fairly well exhausted by the Japanese, and attempts to develop the manganese resources of the island seem to have been disappointing. It is possible that, with careful exploration and intensive development, somewhere between 12,000 and 160,000 tons of high grade manganese oxide might yet be recovered from Saipan, but it is unlikely that the volume would be significant in terms of world markets beyond Japan.

A more comprehensive survey of the commodities mentioned is given in an appendix to this chapter.

PREVIOUS STUDIES

Excluding an abstract by ourselves (1951), we know of only seven published reports that deal exclusively or primarily with the geology of Saipan (Seidel, 1940b; Tada, 1926; Tayama, 1938; Asano, 1939a; Imaizumi, 1939; Yabe and Sugiyama, 1935; Cole and Bridge, 1953). Geologic and geographic reports that make reference to Saipan, however, are scattered through the published and unpublished record. Moreover, in the following summary, reports on the larger Marianas other than Saipan and on the western Pacific structural province as a whole are considered to be of coordinate importance for understanding the geology of Saipan.

Although a complete survey of the published record has not been attempted, references noted were traced to original sources. It is thus probable that the bibliography includes most papers that are either significant to the immediate problems or of special interest as related to the development of geologic thought about the region. In the rare instances where the original text or a translation of a paper listed has not been seen, reference is made to the actual reporting source. Citations of Japanese-language papers in the bibliography are accompanied by indication of place of availability of an English translation or abstract. Omission of page reference in citation indicates either that the entire reference is pertinent or that we worked from a translation that did not indicate original pages.

In the following review special attention is given to papers that are primarily of historical interest and to those not specifically utilized or discussed in other parts of the report.

EARLIEST SCIENTIFIC EXPLORATIONS, 1792–1839

The earliest expedition to visit the Marianas with scientific exploration as its primary objective was that of Alessandro Malaspina. Malaspina touched at Guam in February 1792, in the service of Carlos IV of Spain. With him as naturalists were Antonio Pineda, Thadeus Haenke, and Luis Née. Pineda, who studied the geology and zoology, died soon afterwards in the Philippines, Haenke never returned to Europe, and full accounts of the observations of Née and Malaspina have never been published (Safford, 1905b, p. 25–28).

Otto von Kotzebue, accompanied by the talented and many-named man who most of the time called himself Adelbert von Chamisso, sailed the ship *Rurik* past Rota and laid over for 6 days at Guam in late November of 1817 (Kotzebue and Chamisso, 1821, Band 2, p. 126–135, Band 3, p. 77–84; Chamisso, 1883, Teil 1, p. 238–244, Teil 2, p. 89). Chamisso and Kotzebue recorded that the Mariana Islands were a volcanic chain, with young volcanoes in the north of the chain, noted the occurrence of raised coralliferous limestone on Guam and the recent reef at Apra harbor there, and described the general topography of Guam. They show Guam and some unrecognizable islands to the north on a chart of "Der Carolinen Inseln" (1821, Band 3, facing p. 85).

On March 17, 1819, Louis de Freycinet reached Guam aboard the French corvette *Uranie* and had to lay over for several months because of illness among the crew. During this interval side trips were also made to Rota and Tinian. With de Freycinet were the zoologists J. R. C. Quoy and J. P. Gaimard, and the botanist Charles Gaudichaud-Beaupré. Gaudichaud (1826, p. 64–87) described the botany and general appearance

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[3] Founders' names are omitted from species names that are merely quoted from previously published records or based on field determinations and not reconfirmed by specialists for this study. The original data are mainly in U. S. Navy (1944) and von Prowazek (1913).

[4] The fish and eel were identified by Leonard Schultz and associates in the U. S. National Museum, the crayfish by Lipke B. Holthius of the Leiden Museum.

of Guam, Rota, and Tinian and recognized the general difference between volcanic and limestone terrains and their floras. He began a stubborn botanical legend when he attributed the barrenness in vegetation of certain volcanic soils to "destruction des hommes." Quoy and Gaimard (1824, p. 32–36, 592–601, 658–671) describe the Marianas with special reference to Guam, discuss the coral fauna and importance of corals as rock builders, and describe the limestone terraces of Guam and Rota. They report, on Guam, thousands of the little axis deer, presumably introduced earlier from the Philippines and Sulu (Smith, 1925, p. 41), as well as hordes of rats. Quoy and Gaimard had a good idea of the geology for their time, and, like Gaudichaud, recognized a general correlation between vegetation and terrain. Like him, also, they thought the latter due to extraneous factors: "Les montagnes, qui ont toutes subi l'action du feu, son arides et peu boiseés. Les forêts recouvrent le calcaire et forment une demiceinture a l'île" (p. 32). Quoy and Gaimard held basically modern views about the formation and growth control factors of living reefs (p. 660–661).

After the *Uranie* came the *Astrolabe*, under command of J. S. C. Dumont d'Urville who brought a large scientific staff. They anchored at Umatac Bay on May 2, 1828 and remained on Guam 28 days to rest and repair equipage. Quoy and Gaimard were back again, as zoologists with d'Urville, but their accounts were purely zoological this time. In the great series of reports on the results of investigations by this expedition the only comment on the geology of the Marianas seems to be a remark by d'Urville (1830, tome 1, p. xciii) that Guam, with its feldspathic lavas, reminds him of the environs of Carteret, New Ireland. He gives an account of his arrival and stay at Guam in volume 5 of the narrative (1833, p. 251–286), and atlas 3 has some interesting pictures of Umatac and vicinity. This atlas also contains a map of part of the Pacific Ocean by d'Urville and Lottin that shows Guam, Rota, and Tinian, but not Saipan. D'Urville paid a second, but cursory, visit to Guam on January 1, 1839 (Safford, 1905b, p. 32).

MOSTLY DORMANT INTERVAL, 1840–1900

Little scientific interest was shown in the Mariana Islands between 1840 and 1880, but there was a renewal of attention to the area between 1880 and 1900. J. D. Dana, who never visited the area, quoted some of the observations made by Quoy and Gaimard on Mariana geology in his book on "Corals and coral islands" (1872, p. 306–307, 344–345). He also (1885) discussed Guam as an example of an island where volcanism may have been concomitant with subsidence of the sea floor. J. A. Guerra wrote a general account of the Marianas which we have not seen, but which was summarized by Ferdinand Blumentritt in 1883. Blumentritt's summary briefly mentions features of the reefs, channels, and islands and comments on Apra harbor (Guam), but it is too generalized to be of present value.

The only accounts that appear to be of interest for the period 1840 to 1900 are those of Alfred Marche who traveled extensively in the Marianas from April 1887 to March or May 1889. He visited most of the islands, spent more than 2 months on Saipan, and took particular interest in archaeological ruins, water supply, topography, and geology. A letter from Marche, published in the Société de Géographie in 1887 gives a brief account of his first impressions and is followed by a curiously inaccurate statement from Instructions nautique (Hydrographie française) No. 584 to the effect that Mount Tagpochau (Ogso Tagpochau) and Mount Achugau (Ogso Achugau) are extinct volcanic cones. Marche himself later climbed Mount Tagpochau and clearly recognized that it was of limestone from base to top (Marche, 1890, p. 25; 1898, p. 65–69). His longer account (1898) in particular treats of the history of exploration of the Marianas, discusses the natives and their past, and gives measurements of and shrewd observations about the archaeological ruins on Tinian, Rota, and elsewhere. Marche also correctly recognized the northern Marianas as young volcanic islands and the southern Marianas as mainly elevated limestone islands. His accounts of the harbor facilities and water supply for Guam especially, but also for other islands visited, are excellent for their time and would until very recently have been considered useful sources of such information. At the time of Marche's visit the town of Garapan (then known as San Isidore de Garapan) was the largest town on Saipan, and second in size only to the colonial capital of Agaña on Guam.

The 10-day visit of an official German party to the Marianas during November 1899 (von Bennigsen, 1900, p. 108–111) is of interest only because one member of the party, the botanist Volkens, was later cited (Seidel, 1904b, p. 219) as of the opinion that Mount Tagpochau was a volcano. In his own account of the trip Volkens (1902, p. 414–422) merely comments briefly on the vegetation and general geography of the Marianas.

INTERVAL 1900–1920

In 1902 S. Yoshiwara published the first paper relating to the outer margin of the Philippine Sea that presents results sufficiently advanced to be, in themselves, of interest in a present-day report. He announced the presence in the Bonin Islands of Eocene camerinids associated with andesitic pyroclastic rocks and overlain by limestone with Miocene orbitoids—both

new stratigraphic records for the open Pacific. He concluded (1902, p. 301) that "the submarine volcanic eruption of the Ogasawara group [Bonins] began in the Eocene epoch, and had already ceased before the Miocene." Yoshiwara also noted the occurrence of felsic volcanics in the Bonins, and discussed the recent and historic volcanic activity of the Volcano and Nanpo Shoto Islands. He directed attention to a report by Susuki in 1885, of serpentine from Kurose in Ototo Jima (one of the Bonins) but does not confirm this report. In an English translation of Susuki's paper, on file in the U. S. Geological Survey, however, the only mention of serpentine in the Bonin Islands is that it in places forms an alteration product of hypersthene in the andesitic rocks.

Also at the turn of the century, G. Fritz, the German district commissioner on Saipan, wrote general accounts of Tinian (1901a), Rota (1901b), and a trip to the northern Marianas (1902). Fritz described the anchorage at Tinian, observed that the island's surface was of coralliferous limestone and deep-red clays, and noted the presence of potable ground water. He also remarked on the vegetation, fauna, topography, archaeology, and history of Tinian and made a few brief comparisons with Saipan. Concerning Rota, Fritz observed that the terraced limestones enclosed a volcanic core which he supposed might be intrusive, commented on the perennial steams of the south and east coasts, mentioned the useful plants and animals, described the early history and archaeological ruins, and presented a sketch of the island and its anchorage. He spent 20 days on a cruise of the northern Marianas aboard a Japanese ship in May 1901, and made many careful observations on their general shape and topography, vegetation, fauna, general rock types, mineral products, water resources, and archaeology. Fritz observed that the Marianas are sharply divisible into two groups of islands (Fritz, 1902, p. 96). Although all were recognized as basically volcanic in origin, those from Medinilla south were seen to have their highest peaks surmounted with limestone, while those to the north were recognized as wholly volcanic. He also notes that even sparse growths of coral are rare in the northern volcanic islands and records that he saw no elevated coral limestone there.

The earliest petrographic investigations of volcanic rocks from the Mariana Islands were made by Kaiser (1903, p. 114–120), who described and published chemical analyses of single specimens of andesite from Pajaros and Saipan. These samples were collected by G. Fritz, who sent them to Kaiser for study at Leipzig. According to Kaiser, however, the specimen of andesite from Saipan was obtained from an ancient ruin at Magpi, in the northern part of the island, and may not have come from Saipan. The composition of the rock does not agree with analyses of andesite known to be from Saipan.

Alexander Agassiz (1903, 365–378, 392) reported the results of a brief visit to Guam and a passage near Rota on the U. S. Fish Commission steamer *Albatross* in February 1900. He took four deep bottom-samples in the general neighborhood of Guam—notable for the presence of manganese, red clay, pumice, and fine volcanic sand. He noted the "distinct coralliferous limestone terraces, marking the position of former sea level and indicating the periods of rest during the elevation of Guam," and he counted not fewer than seven such terraces on Rota. He also observed lines of caverns in vertical limestone faces and accurately described the irregularly pinnacled surface of the weathered limestone. He mentioned records of a destructive earthquake in 1849. Like Gaudichaud and Quoy and Gaimard before him, Agassiz recognized the association of thick jungle vegetation with limestone terrain and barren slopes with volcanic rocks, and he observed the general distribution of volcanic rocks and limestones. He states that Saipan, Tinian, and Aguijan, like Rota and Guam, are partly volcanic and partly limestone, and that there are 12 young volcanoes in the northern islands. Agassiz did not, however, appreciate that the blanketing limestones over the volcanic cores of the southern islands originated through normal sedimentary overlap. He referred at several places (p. 365–367, 371–372) to "volcanic outbursts" that have "burst through the coralliferous limestone," citing photographs purported to show such pnenomena, describing supposed contact metamorphism of the limestones, and even concluding as he steamed past the north end of Rota "that the slope of the northwestern point, as well as * * * the vegetation, indicated a volcanic outburst."

In 1904 L. M. Cox, an engineer in the U. S. Navy, published an account of Guam in the Bulletin of the American Geographical Society. He correctly concluded that the volcanic rocks were the older and that they were overlapped by younger limestones—a conclusion strongly implied but not specifically stated in Marche's reports of 1890 and 1898. He also describes some effects of the destructive earthquake of September 22, 1902, gives an account of the general natural history, and provides a land classification map.[5]

H. Seidel (1904b) summarized geological information available on Saipan at the beginning of the 20th century in his brief paper "Der geologische Aufbau der deutschen Marianen-Insel Saipan" and, even more briefly, in a general paper on Saipan published in the same year

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[5] The "college" of which Cox writes was the Colegio de San Juan de Letran, endowed by Queen Maria Ana for the teaching of Catholicism and elementary practical crafts (*see* Safford, 1905b, p. 21–22, 127–128).

(1904a). His sources of information included the already referred to accounts of G. Fritz, Alfred Marche, and de Freycinet, as well as oral accounts by Hermann Costenoble and his own observations. He recognized the presence to the very summit of Saipan of upraised and terraced limestones and rejects an opinion attributed to a letter from the botanist G. Volkens that Mount Tagpochau is volcanic. Seidel also describes the notched shore line of Saipan; gives data on the history, fauna and flora, earthquakes, topography, drainage, and water supply; records his belief that the natives had known the use of fire before the arrival of Magellan; and recognizes the twofold subdivision of the Marianas into young volcanic islands and older islands with eruptive cores capped by limestone. Later Seidel also published general accounts of Rota (1914a) and Tinian (1914b). He describes briefly the general geography and natural history, reiterates the twofold subdivision of the Marianas, takes note of the well-defined terraces on both Tinian and Rota, and remarks on Anson's stay at Tinian. A contemporary of Seidel, H. Hofer (1912), also wrote briefly of Tinian, but we did not see his report, which is not known to be available in the United States. Reference to another brief account of the Marianas by G. Volkens (1901) is made by Utinomi (1944, p. 98) but we have not seen Volkens' account either.

H. H. L. W. Costenoble, a Thuringian emigrant to Saipan in 1903, apparently lived there with his family for some time and traveled among the other German Marianas and to Guam. He gives a good general account of the Marianas for his time (1905). Like most of his predecessors, Costenoble recognized the northern islands as volcanoes and the southern islands as composite structures of volcanic rocks and limestone, but, as did Agassiz, he wrongly concluded that the volcanics were at least partly intrusive into the limestones: "Nur an wenigsten Stellen ist der Kalküberzug durch vulkanische Ausbruchsmassen unterbrochen" (p. 5). He tells of the 1902 earthquake on Guam, how at Agaña "das heute noch die halbzerstörte Kirche und zahlreiche Hausruinen an jenes Ereignis gemahnen" (p. 5). Costenoble, like others, was impressed by the terraces. With reference to Saipan, he correctly described the configuration of the slopes and terraces of Mount Tagpochau and their "coral" limestone nature. He also gives a brief account of water resources, notes flowing streams, and describes two 'Brachwasserlagunen" (presumably Lake Susupe and a subsequently filled lake or swamp in the horn of land at Muchot Point). The occurrence of eels and fresh-water fish in the running streams of Saipan is noted. Costenoble makes some cogent observations on the native inhabitants, their history, and the effects of European occupation, and remarks prophetically about the utilization of natural resources and the economic future of the Marianas.

In 1905 W. E. Safford gave a general account of the natural history of Guam under the title "The useful plants of Guam." While serving as assistant governor of Guam from August 1899 to August 1900 he pored through the archives and added to his notes from wide reading and travel to produce an excellent general account of the geography, climate, hydrography, vegetation, fauna, history, and people of Guam, with many original observations. Safford's ideas of the geology (1905b, p. 46–52) were apparently derived mainly from Agassiz, and he unfortunately perpetuates the latter's misconception of the relationships between limestone and volcanic rocks: "All of the mountain peaks of Guam are undoubtedly of volcanic origin. In some of them the outlines of the craters may still be traced" (p. 51). He records some of the severe earthquakes of the historical period on Guam, cites one not mentioned by other writers (April 14, 1885), and gives a good account of that of September 22, 1902, which allegedly did $22,100 worth of damage on Guam and strongly affected the region at least as far north as Saipan.

Eduard Suess, in his monumental "Das Antlitz der Erde" (1909, especially p. 336–339), described the Mariana Islands on the basis mainly of the calier accounts by Fritz and Agassiz. It is interesting to note that Suess, without having seen Guam, was correctly skeptical of Agassiz' conclusion that the volcanic rocks were intrusive. Suess also was the first to express in writing the opinion that the Marianas and related island arcs were structurally allied to Asia.

S. J. M. von Prowazek in 1913 wrote the fullest account to date of the general geography, history, and natural history of the Marianas. Prowazek accompanied a Prof. Leber to Saipan, Tinian, Rota, and Guam, but he did not visit the northern islands and gets his information on them from Fritz (1902). He made large natural history collections whose species were identified for him by specialists in Germany. Prowazek's book summarizes geographic data for all the Mariana Islands (p. 3–5); discusses their discovery, exploration, history, ethnology, and archaeology (p. 6–73); discusses their geology, water resources, and climate (p. 74–81); describes in particular the scenery and topography of Saipan, Tinian, and Rota (p. 82–86); gives a remarkably complete faunal summary with special reference to terrestrial forms (p. 87–103); lists the flora and describes floral communities and relationships (p. 104–121); and provides a bibliography of 76 pertinent and varied titles (p. 122–125). He describes Anson's visit to Tinian in 1742, as well as many other early explorations, expresses the unorthodox and probably incorrect view that the Chamorros were of Japanese derivation, and records data on the causes and history of depopulation of the Marianas during early Spanish occupation. He provides a sketch of the former lake at Muchot Point in western Saipan. Prowazek also gives a record of 22 earthquakes for 1901 to 1903, notes damage to the archaeological "Houses of Taga" on Tinian and the church at Garapan by a strong earthquake in 1902, and records a severe quake in 1849. Prowazek (p. 74), like Suess, held that the Marianas, Yap, and Palau were structurally a part of Asia.

In a provocative paper R. A. Daly (1916) called attention to the work to be done in Pacific geology and recorded andesites and felsic volcanic rocks from the Mariana and Bonin Islands. Soon afterwards, W. Koert and L. Finckh (1920) stated that the Marianas from Anatahan to Pajaros are dominantly andesitic and reported serpentine on Tinian and Agrihan. Schmidt, however, found random samples from Pagan and Agrihan to be dominantly basalt, and andesite dominant only in samples from Alamagen, Sarigan, and Anatahan. The reports by Koert and Finckh of serpentine from Tinian and Agrihan have never been confirmed and are highly doubtful unless reference is made to spot alteration of mineral grains.

SINCE 1920

W. H. Hobbs made cruises to the Bonin, Volcano (or Sulphur), Mariana, Caroline, and Palau Islands in 1921 and 1923. He stopped at several of the islands (apparently including Saipan), observed their regional arrangement, and published a paper on "The Asiatic arcs" (1923). Hobbs recognized that the Mariana Islands are not arrayed in a simple line, with the young volcanic islands on the north and older, more complex islands on the south. He believed that there were three lines of islands in the Marianas (see his figs. 2 and 3): (1) an easterly belt of elevated reef-terrace islands (Medinilla and Rota, alined with Santa Rosa reef south of Guam), (2) a middle belt of old volcanic and limestone islands (Saipan, Tinian, Aguijan, Guam), and (3) a westerly belt of recent volcanoes (islands north from Anatahan, alined with Esmerelda shoal west of Saipan). The old volcanic core of Rota, however, indicates that his first and second belts should be combined. Hobbs shows several profiles through Saipan and other islands and (his fig. 2) labels what from the profile given can be only Mount Tagpochau as "Volcano (Extinct)." This perpetuated an error that dates to at least 1887 and is still a popular legend. Twenty-one years later Hobbs (1944), in an expanded version of his 1923 paper, again labeled Mount Tagpochau as a volcano (map 18, p. 242).

In a broadly conceived paper dealing with the distribution of the land snail *Partula* in the Marianas, H. E. Crampton (1925, p. 5–8) makes reference to the geology of the larger Mariana islands. He presents, without indicating his source of information, the erroneous view earlier expressed by Agassiz that the volcanic rocks are intruded into the overlying limestones. Contrary to fact, he states that through the northern plateau of Guam "volcanic masses have broken their way, as attested by the metamorphosis of the contiguous rock," asserts that "Barrigada [a Cenozoic limestone hill] is such an intruded mass" (Crampton, 1925, p. 6).

In 1926 Fumio Tada visited Saipan and Yap for "no more than 4 days" (each?), and his paper on "Abrasion terraces of the South Sea Islands" appeared in the same year. In it he discusses the terraces, with special attention to those of Saipan. He presents evidence favoring origin of most of these terraces by marine erosion, describes the reefs and offshore bank west of Saipan, considers that the swamps of the west coast are the sites of old lagoon depressions, and concludes that the west coast is sinking and the east rising. He recognized that the terraces of Saipan are difficult to correlate within the island and suggested that cliffs were best developed on the east side of the island because of "irregularity of the wave force." Tada also makes reference to a paper by Tsujimura (1917) in which the latter is quoted as describing on Iwo Jima 6 to 10 terrace benches and a top plateau with "remains of elevated coral reef." Insofar as they overlap, Tada's findings are in essential accord with conclusions expressed in the present report.

From Hydrographic Office charts, W. M. Davis in 1928 (p. 243) concluded that there were two and only two lines of islands in the Marianas—a conclusion substantiated by the present studies. He describes the conical form of the northern young volcanic islands, and, on the basis of previously published accounts, gives brief descriptions of all the larger islands (Davis, 1928, p. 243, 391, 420).

In 1928 P. J. Searles wrote a popular account of the geology of Guam, which was later reprinted in the Guam Recorder; and he followed this with a similar account of the "Geology of the Marianas Islands" (1936). Because Searles spent some time in the area, and because his accounts appear to have been widely circulated, it seems necessary to refer to errors contained in them. These include references to a probable volcanic origin for "all the mountain peaks" and to nonexistent volcanic craters, assignment of the Marianas to the Sunda Arc (Indonesia), and interpretation of the volcanic rocks as intruded into overlying limestone.

The Guam Recorder also provides other popular notes on the local geology by Norah D. Stearns (1937a, 1937b, 1938) and a very good account of the "Seismicity of the island of Guam" by the Jesuit W. C. Repetti (1936), then chief of the Seismic and Magnetic Division of the Manila Observatory. Repetti states that during 12 years between 1915 and 1930 (for 3 years the seismograph was inoperative), 900 earthquakes were recorded on Guam, and 130 of these were felt. However, destructive or semidestructive earthquakes are known only for the years 1825, 1834, 1849, 1862, 1863, 1870, and 1902. According to Repetti, the majority of the earthquakes that affect Guam originate in the Nero deep. In 1939 he published a list of earthquakes felt in Guam.

In the decade 1931 through 1941 came a series of Japanese publications on the Marianas and other islands of the southwestern north Pacific. Early in this decade appeared B. Koto's important paper on "The Rocky Mountain arcs in eastern Asia" (1931), of which plate 4 is a reproduction of Japanese Hydrographic chart 6080 (also in Hobbs, 1944, map 7, p. 231). This chart extends from Kamchatka to New Guinea and Formosa to the Marshall Islands. It shows in crude form most of the submarine structural features that later appeared on U. S. Hydrographic Office chart 5485 (see Hess, 1948).

Then came papers by Tsuboya (1932), Yoshii (1935), Tayama (1936a, b, 1937, 1938, 1939a, b), Tayama and Ota (1940), Otuka (1938), Asano (1939a, b), Motizuki (1940), Tanakadate (1940), and four papers in the two Jubilee volumes commemorating Prof. Hisakatsu Yabe's 60th birthday (Asano, 1939b; Imaizumi, 1939; Kodaira, 1941; and Sugawara, 1941). The titles of these papers as listed in the bibliography give a fair idea of their contents, and they will subsequently be referred to as appropriate. The Sixth Pacific Science Congress was the occasion for a brief but important summary paper by Yabe, Hatai, and Nomura (1939) on "The Tertiary stratigraphy of Japan," which gives correlation data for Saipan, the Ryukyus, Formosa, and Korea, as well as Japan proper. At almost the same time there appeared Cole's important paper on Miocene "Large Foraminifera from Guam" (1939), and a record of the key echinoid *Sismondia* from the Miocene *Eulepidina* beds of the Bonin Islands (Nisiyama, 1937). These last reports, together with Imaizumi's description (1939) of a new decapod from the Tagpochau limestone, and that by Yabe and Sugiyama (1935) of *Saipania tayamai* from a "boulder" in the Densinyama beds, constitute the total previous descriptive paleontology of the Mariana and Bonin Islands available during our field work. Other papers of the Japanese decade are listed by Tayama (1938, 1952) and in other references cited.

During and following the decade of accelerated Japanese activity H. T. Stearns was a heavy contributor to the published and unpublished record of the geology of the Mariana Islands. Since World War II, A. M. Piper, R. W. Sundstrom, Josiah Bridge, the present writers, and others have also visited and described parts of the region in unpublished reports or reports of very limited distribution, and one rather extensive published report by Cole and Bridge (1953).

Various strategic reports issued by the U. S. Army and Navy contain compilations of geologic and related data available at the beginning of the World War II campaign in the Marianas, but they are of limited accessibility and specialized treatment and are mainly not cited or listed.

Most recently N. M. Bowers has summarized the geography of the Mariana Islands (*in* Freeman, 1951, p. 205–229); Tayama (1952) has published his large and profusely illustrated volume on "Coral reefs in the South Seas," with scattered references to and a number of photographs and maps of the rocks and terrain features of Saipan; and W. S. Cole and Josiah Bridge (1953) have prepared a summary of the geology and larger Foraminifera of Saipan, based mainly on information and collections available before the beginning of our field studies. Also of interest is an excellent summary by John Rodgers (1948) of the phosphate deposits of the former Japanese mandated islands; as well as papers by Krauskopf (1948), Macdonald (1948), and Swenson (1948) which deal with the geology, petrography, and ground water of Iwo Jima and confirm the bench system and high reef remnants reported by Tada (1926). A recent paper by Ma (1953) suggests fluctuations in the latitude of Saipan, which, incidentally, are not confirmed by paleoecological data in the present report. Cloud and Cole (1953) recorded an Eocene foraminiferal fauna from Guam and questioned the occurrence of significant post-Eocene volcanism in the southern Marianas. Since then, however, Todd, Cloud, Low, and Schmidt (1954) have shown that primary volcanic rocks of late Oligocene age occur on Saipan, and that volcanism in the Marianas probably recurred through Cenozoic time.

GENERAL COMMENTS

The views of the Japanese geologists and the results of immediate postwar reconnaissance as related to Saipan are extensively summarized by Bridge (Cole and Bridge, 1953). Here we need only to note that, excepting the Fina-sisu formation and the Machegit conglomerate member of the Tagpochau limestone, all names here used for stratigraphic units of Saipan are attributed to Tayama (1938). Our descriptions of the stratigraphy, however, are based entirely on original data and our interpretations differ in a number of particulars from Tayama's. Such differences are understandable, not only because of time limitations on Tayama's field work, but also in view of the really complex stratigraphic relations.

On a regional scale H. H. Hess (1948) has provided the major synthesis and summary of facts and interpretations for the western north Pacific. The Mariana arc, however, has been mentioned by nearly everyone who has written about island arcs or the western north Pacific, notably by J. H. T. Umbgrove (1945, p. 207–208; 1947, p. 171–177, 188–189, 202–205, 210, 211; and 1949, p. 47). Some other papers that contain material related to problems of regional structure are by R. N. von Drasche (1879), W. J. Sollas (1903), Eduard Suess (1909), W. H. Hobbs (1914, 1923, 1944), Patrick Marshall (1924), J. W. Gregory (1930), B. Koto (1931), F. A. Vening Meinesz (1931, 1948), Philip Lake (1931), A. Born (1932), A. C. Lawson (1932), L. J. Chubb (1934), Gutenberg and Richter (1939, 1941, 1949), Otto Jessen (1943), H. M. Schuppli (1946), J. Bridge (1948a), G. A. Macdonald (1949), P. H. Kuenen (1950), J. T. Wilson (1950), and the several brief papers of a colloquium on plastic flow and deformation within the earth, published under the general editorship of Beno Gutenberg (1951).

As concerns insular water-supply problems in general, in addition to unpublished reports by Piper, Stearns, and Sundstrom, papers by C. K. Wentworth (1942, 1947, 1948b) are of special interest in presenting controlling principles clearly and graphically.

The larger Foraminifera proved to be especially helpful in field studies, and a paper by van der Vlerk and Dickerson (1927) was a useful summary reference. Much help was obtained from the summaries of larger Foraminifera by T. W. Vaughan and W. S. Cole (*in* Cushman, 1948) and by M. F. Glaessner (1947).

Other papers listed in the bibliography are of interest mainly in relation to specific problems and will be referred to at appropriate places. The reader desiring further references to Micronesian geology or general natural history is referred to bibliographies by Prowazek (1913, p. 122–125), Reid (1939), and Utinomi (1944). The "Selected bibliography of Micronesia" prepared for the U. S. Navy in 1946, was seen by us in carbon copy form only, and the annotated list of references prepared by the U. S. Navy (1948) in connection with a summary of the geology of Guam is of very limited distribution and essentially unavailable.

REGIONAL GEOLOGY

In 1879 Richard N. von Drasche concluded that the island arcs and seas adjacent to the Asiatic mainland had been continental in distant geologic periods. His evidence was petrographic, continental affiliation being indicated by metamorphic and plutonic rocks. He extended his continental boundary southward from Kamchatka, and oceanward from Japan, the Philippines, New Guinea, New Caledonia, and New Zealand. Eduard Suess (1909, p. 336) subsequently affirmed that the true eastern boundary of Asia really lay still farther seaward, that it is, in fact, defined by the deep sea trenches east of the island arcs that enclose the Philippine Sea. Stille (1944) supports the views of Suess and argues that the Philippine Sea is actually a former continental area. Hess (1948) and Gutenberg and Richter (1949, p. 26) also indicate a close relationship of the Philippine Sea and its outer arcs to Asia, and several other recent writers have implicity supported this view (Born, 1932, fig. 306; Bridge, 1948, fig. 3; Ladd, 1934, fig. 6).

In contrast to the views of Suess, Stille, and others, however, several recent writers have favored exclusion of the Philippine Sea from the Asiatic block. Lawson expressed this view in 1932, Umbgrove has expounded it in several papers (for example, 1947, p. 204, 211), and Irving (1952, p. 445) adheres to the same opinion.

There is, it seems, little dispute with the broad thesis that the western Pacific borderlands, together with Asia proper, can be referred to an Asiatic structural block, separable on the basis of geological and geophysical data from the Pacific Basin proper to the east, and from the Australian structural block to the southeast (fig. 1). It is, however, a subject of lively discussion whether the Philippine Sea and the Mariana arc may properly be regarded as parts of this same Asiatic block, whose eastern boundary would then be approximately defined by the south to north Palau-Yap-Mariana-Japan trench system. In the following pages the evidence in support of this conclusion is summarized and the origin of island arc and trench systems is briefly discussed.

ISLAND ARCS OF THE PHILIPPINE SEA MARGINS

Vening Meinesz (1948) found that the Mariana and Yap trenches (figs. 1, 2) coincide with marked local negative gravity anomalies and less marked regional anomalies, separating the Pacific realm of oceanic basalts on the east from a region characterized by andesites and silicic volcanic rocks with continental affinities on the west. Matuyama (1936; see also Hess, 1948, fig. 9) showed that a belt of negative anomalies is eccentrically situated to the west of the axis of the southern Japan trench (fig. 1), perhaps because of eastward migration of the topographic trench axis caused by sedimentary filling from the west. The trench system that borders the Philippine Sea at the

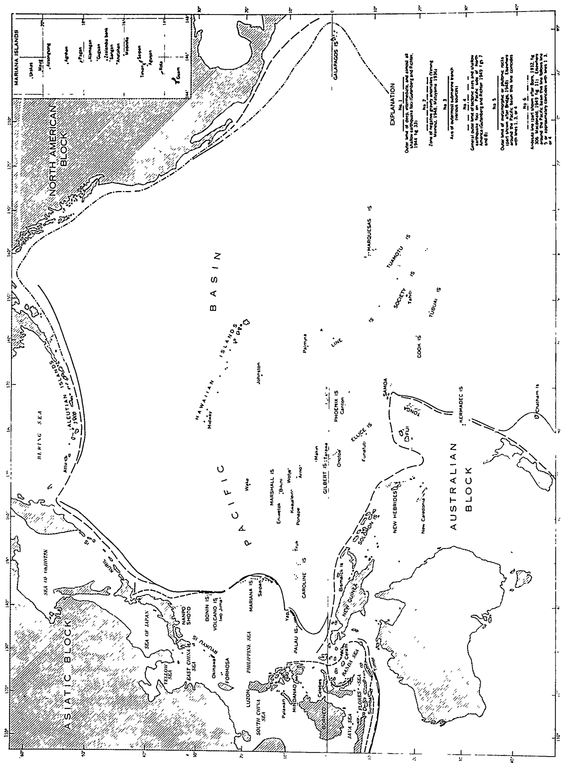

FIGURE 1.—Major structural elements of the Pacific Ocean area.

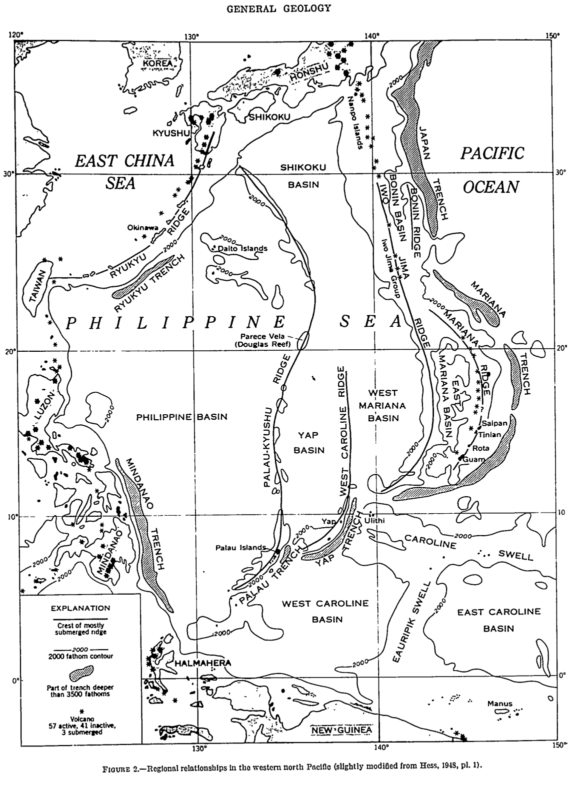

FIGURE 2.—Regional relationships in the western north Pacific (slightly modified from Hess, 1948, pl. 1).

east thus approximately coincides with marked negative gravity anomalies at at least three places, and probably coincides with a negative anomaly belt.

This contrasts with Indonesia,[6] where the negative anomaly belt is expressed as an outer island arc or submarine ridge bordered oceanward by a trench (fig. 1). Significant similarity, however, is found between the Mariana and Indonesian arcs in the distribution of earthquake foci. The locations and depths of earthquake foci given by Gutenberg and Richter (1949, figs. 16, 17; Hess, 1948, fig. 6) indicate that a zone of weakness dips about 45° westward beneath the Philippine Sea from the trench system on its east. This zone is broadly divisible into a moderately dipping part in the outer layers of the crust and a part that dips 45° or more toward the continent at depth. A similar pattern of earthquake foci dips beneath the Indonesian arc and seas from the trench system on their oceanic side.

The Mariana arc has been regarded as a simple arc consisting of a single line of islands and contrasting with the so-called double arcs of Indonesia and the arcuate Ryukyu chain of islands at the western edge of the Philippine Sea. Its double arc structure has been shown by Hess (1948), however, and stratigraphic, petrographic, and geographic evidence suggests broad comparison between this and the Cenozoic parts of the Ryukyu arc.

Reference to the inset map on figure 1 will show that a line drawn to connect all islands of the Marianas would make a sharp bend between Medinilla and Anatahan. A generalized connecting line would miss these and immediately adjacent islands. Yet, if an arcuate line connecting the young andesitic and basaltic volcanoes from Anatahan northward is continued to the south on the same radius, it intersects an intermittent sulfur boil about 25 miles west of Saipan and a submerged peak having the shape of a volcanic cone that lies to the west of Guam. In addition, all of the Mariana Islands that have a core of older Tertiary volcanic rocks mantled by younger Cenozoic limestones are arrayed along a similarly curving line that parallels the very young volcanic line 25 or 30 miles to the east. These older volcanic-limestone islands show high-angle normal faulting parallel to their long axes (north-south), and on Guam folding and west-to-east thrust faulting.[7]

In the Ryukyus, as in the Marianas, an eastern belt of mainly Eocene and younger Cenozoic sediments is paralleled about 30 miles to the west by a belt of very young volcanoes. A major difference is that the core of the Ryukyu arc contains upper Paleozoic rocks almost from end to end, as well as granitic intrusions of late Paleozoic or Mesozoic age (Hanzawa, 1935, p. 11, 17). The Ryukyu arc thus appears to represent an older and more complex structural feature than the Mariana arc, but not so complex as the Indonesian arc.

Their broad morphologic and stratigraphic similarities and their relatively simple structure imply that the Ryukyu and Mariana arcs, if not basically homologous, are at least more similar to one another than either is to the very complex Indonesian arc. Coincidence of the outer Ryukyu Islands with a zone of negative gravity anomalies, in the manner of Indonesia, is rendered improbable by the absence of a trench between the two belts of Ryukyu Islands. Moreover, soundings have revealed no submarine ridge between the Ryukyu arc and the trench east of it that could form the homologue of the Indonesian outer arc. When gravity surveys are made of the Ryukyu arc, therefore, the odds favor the likelihood that the Ryukyu Islands will turn out to be sites of maximal gravity values, while the Ryukyu trench, like the Mariana trench, should approximately coincide with a belt of local negative anomalies or minimal values of gravity. Such a belt may well lie to the west of the trench axis because of heavy sedimentation, and may show partial regional compensation owing to relatively great age.

All observers have noted the striking parallelism and curving patterns of the island arc systems, and the continuity of some of them with folded mountain chains of the continents. This suggests relationship between the two and a continental type of structure for island arcs.

AFFINITIES OF WESTERN PACIFIC BORDERLANDS WITH ASIA

Umbgrove (1947) and others have concluded that the Indonesian seas are eugeosynclines of relatively recent origin, and that the Indonesian lands and seas are properly part of Asia. Actual recent geographic continuity with the land mass of Asia is strongly indicated for at least the western half of this region and probably all of it. The Philippines, as Irving (1952, p. 445) shows, are structurally homogeneous with Indonesia, and the Sulu and Celebes seas belong to the same pattern. Cutoff and offset of Tertiary folded belts along the abrupt north shore of Borneo indicates that the deep Sulu Sea, like the Java Sea and probably the South China Sea, has recently foundered (Reinhard and Wenk, 1951, p. 15).

The granitic massifs and intrusive rocks of Indonesia, the Philippines, and the Ryukyus (van Bemmelen, 1949, p. 236–242, 254, 371–372, fig. 73; Reinhard and Wenk, 1951, p. 14; Suzuki, 1937; Hanzawa, 1935, p. 11) are strong indication of continental affiliation.

Moreover, Warren Smith (1925, p. 39–44) long ago called attention to the Indomalaysian biotic affinities of the Philippines, and Von Koenigswald (1953) recently reported the occurrence of probable Pleistocene rhinoceros and elephants on Luzon and a *Stegodon* on Mindanao. The Asiatic biotic affinities of Indonesia are summarized by van Bemmelen (1949, p. 4–5, fig. 5) on the basis of the work of Wallace, Weber, Mayr, and others. *Rhinoceros* and *Stegodon* roamed from Asia proper to Formosa in the Pleistocene (Yabe, Hatai, and Nomura, 1939, p. 470). Rhinocerotids, gomphotheres, an equid, and other land mammals traveled from the mainland to Japan during the Miocene (Takai, 1939). The distribution of poisonous snakes and wild boars in the Ryukyus (Hanzawa, 1935, p. 56–59), as well as the occurrence of fossil elephants and deer (D. E. Flint, oral communication), indicates a post-Oligocene connection of the Ryukyus with Asia proper.

Indonesia, the Philippine archipelago, Formosa, Japan, and the seas behind them each, thus, in some place or places appears to have been continuous with the Asiatic land mass during some of Cenozoic time. Apart from independent evidence to the same effect, it is merely corollary to this to consider that the Ryukyus and the mostly very shallow East China Sea also are properly a part of the geographic continent of Asia. The question naturally arises as to whether the Philippine Sea and the island arcs at its eastern border should be associated with or excluded from the Asiatic continental block.

The petrographic, structural, and geophysical affinities of the area in question with the Asiatic block have been mentioned. There is, however, a recurrent idea to the effect that the Philippine Sea is too deep to be continental; and it is true that this is a very deep sea. Perhaps 20 percent of its floor is more than 3,000 fathoms deep, and it attains profound depths. Nevertheless, the supposedly once dry Banda Sea attains a depth of more than 4,000 fathoms, and 5 percent or more of its bottom exceeds 3,000 fathoms. The floor of the recently foundered Sulu Sea reaches more than 2,700 fathoms at places, and several large basins that lie within the granite-intruded island chains of the Australian structural block exceed 2,000 fathoms (Glaessner, 1950, figs. 1–3).

Thus it is seen that, while the Philippine Sea does attain greater depths than do the seas of Indonesia, and more of it lies at great depths, parts of both are very deep. Moreover, the scale of the differences indicated casts serious doubt on the validity of depth as a criterion for determining continental or oceanic affinities. Topographically the Philippine Sea and arcs suggest no important structural differences from the Indonesian seas and arcs. Nor is there basis for regarding those parts of the Philippine Sea that lie below, say, 3,000 fathoms as having broadly different geologic affinities from those that are shallower than 3,000 fathoms. Gravity data suggest that the Mindanao trench is a structural depression. The Palau-Kyushu ridge and similar parallel ridges in the Philippine Sea may well be geanticlinal.

The possibility that most or all of the Philippine Sea was land in the past cannot be either confirmed or conclusively eliminated on the basis of present knowledge. The absence of continentally derived sediments or biotic links in the islands of its eastern arcs weakens the likelihood that any of it was connected to Asia proper at any time after late Eocene. But the distribution of subaerial and submarine volcanics in the Mariana Islands suggests more extensive land to the west of the present islands during Eocene time, and the amphibolite schists and gneisses of Yap may be considered suggestive of a once large tract of parent sediments or volcanic rocks in that area.

The conclusion that the boundary between the Asiatic structural block and the true Pacific Basin is nearly located by the Palau-Yap-Mariana–Japan trench system is favored by (1) the seeming coincidence of the trench system with a belt of negative gravity anomalies; (2) the distribution of earthquake foci beneath and at increasing depths westward from the trench system; (3) the abundance of silica- and alumina-rich rocks of the andesite suite in, but not beyond, the outer island arcs; (4) the similar restriction of metamorphic, plutonic, and highly silicic rocks; (5) the apparent limitation of elevated Tertiary sediments to the area west of the trench system; and (6) submarine topography. In the Pacific Basin proper, approximate gravimetric compensation prevails; seismic inactivity is the rule; oceanic olivine-, picrite-, and nepheline-basalts are abundant and andesites rare; plutonic, metamorphic, and most highly silicic rocks are unknown; Tertiary sediments are known only from the subsurface; and the narrow trenches and ridges that are known lack the arcuate curvature and alinement with known continental structures that is shown by the ridges and basins of the Philippine Sea.

The Philippine Sea is, for these reasons, here regarded as structurally allied to Asia, and in this sense a deep epicontinental sea. Whether this area has long been a part of Asia, or whether it is only in the process of being added to a growing continental block (Wilson, 1950) is a moot problem. The origin of the negative anomaly belts and island arcs is also disputed. The negative gravity anomalies indicate downward extending wedges of light material, such as convection-current-induced sial roots, crustal rocks that have been overidden along a deep-reaching thrust zone, or sedimentary filling of

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[6] In this report Indonesia is the geographic area sometimes called the East Indies.

[7] The Bonin Islands to the north, and the Yap and Palau islands to the south, also include old Cenozoic rocks but do not show the very young volcanic rocks.

a gigantic structural depression. Even though the exact nature of these wedges is not understood, the trenches with which they coincide appear to reflect profound subcrustal phenomena.

ORIGIN OF THE ISLAND ARCS

The essence of the island arc problem involves reconciliation of the gravity data with other geophysical and geological evidence. Hypotheses of origin so far advanced come mainly under the three general categories of contraction, convection, and geochemical differentiation.

The explanation for the peripheral negative anomaly belts, an essential part of any hypothesis of origin, was until very recently considered by most who have dealt with the problem to be the downward protrusion of sial roots. However, the recent discovery of probable great thicknesses of sediments in the Puerto Rico trench (Ewing, 1952) has suggested to some that the negative anomaly belts may reflect sedimentary phenomena, an explanation that evades the question of trench origin. The already noted asymmetric relationship between the topographic axis of the southern Japan trench and the linear trend of its negative gravity anomalies bears on the significance of this point for arc structure, as will seismic and gravity surveys of trenches remote from sites of heavy Tertiary sedimentation, such as the Mariana and Tonga trenches.

Assuming the existence of sial roots, there is great disagreement as to whether such structures are best explained as a result of compressional elastic downbuckling (Umbgrove, 1947, p. 173, 177–178), compressional plastic downbulging (Vening Meinesz, *in* Gutenberg and others, 1951), plastic downdragging by convection currents (Hess, Griggs, *in* Gutenberg and others, 1951), geochemical differentiation (van Bemmelen, 1949, p. 281–295), or by downward dragging beneath overriding thrust blocks (Wilson, 1950, p. 96). Moreover, the distribution of earthquake foci is more irregular than was once thought, and analysis of stress patterns by Benioff (Wilson, 1950, p. 95) indicates downward movement on the upper side of the supposed seismic shear zone at depth—the reverse being true above about 70 kilometers.

Stratigraphic data indicate the Mariana arc to have been emergent through most of Cenozoic time and suggest that present structure reflects an early Tertiary arc and trench pattern. The absence of a folded ridge or island arc above the negative anomaly belt and the general prevalence of normal faulting suggests that the region has not undergone strong compressive deformation—perhaps the principal difference between it and the Indonesian arc. In this connection Hess, among others, has recognized (*in* Gutenberg and others, 1951, p. 529–530) that it helps greatly to explain persistence of a sial root without mountains above it if one assumes the existence of convection currents.

On the other hand, Francis Birch (*in* Gutenberg and others 1951, p. 533–534) has confronted the convection hypothesis with serious irregularities in the elastic properties of the earth's mantle. The zone between 200 and 800 kilometers has irregular elastic properties, as opposed to relative uniformity at depths between 900 kilometers and the base of the mantle, and general uniformity in the uppermost 200 kilometers. These irregularities do not eliminate the possibility of convection currents, but they require a special explanation for differences of elasticity, such as change of phase. The possibility of having separate convection systems within zones of similar and uniform elastic properties above 200 and below 900 kilometers has also been advanced, although the adequacy of shallow convection cells to account for sial roots of the dimensions necessary is open to question.

Some of the mechanical difficulties in accounting for peculiarities noted have been considered by J. Tuzo Wilson (1950) to be resolved by calling upon a contracting earth to produce normal faulting between 70 and 700 kilometers, with thrust faulting above a level of no strain at about 70 kilometers. The distribution of earthquake foci and relative movements determined by Benioff are consistent with this interpretation, and variations in the shapes of arcs may be accounted for by variation in the locally determined stress pattern above 70 kilometers. This needs to be considered, however, in context with the thermodynamic problems presented by a contracting and radioactive earth.

The origin of island arcs remains a problem. It appears that no explanation yet advanced is both comprehensive and consistent with all important facts and probabilities. A useful interim working model, however, might include oceanward creep of the continental blocks along deep reaching shear zones, combined with convection currents to explain persistent trenches coincident with negative anomaly belts.

GEOMORPHOLOGY

INTRODUCTION AND SYNOPSIS

Although it is the second largest of the Mariana Islands, Saipan is only 13 miles long north to south, and it averages less than 4 miles wide. Its 48 square miles are about 12 percent of the roughly 400 square miles in the Mariana Islands. It is less than one-fourth as large as Guam and only a little larger than Tinian, its neighbor to the immediate south.[8] The principal geomorphic subdivisions of Saipan, exclusive of the offshore features, are shown in figure 3 as summarized below.

This small and conspicuously terraced island juts above the sea to maximum heights of 1,555 feet at Mount Tagpochau (Ogso Tagpochau) a little south of center, and 835 feet in the Matuis area, toward the north end. From these highland centers a succession of limestone benches, separated by scarps, falls away stepwise to the sea. Toward the midlength of the island they also descend to an intricately dissected volcanic ridge that marks a part of the island crest between the limestone uplands. A second group of volcanic hills, centering about the Laulau area, abuts the southeastern corner of the Tagpochau area. These areas, together constituting the axial uplands, will later be described as the terraced limestone uplands, the central volcanic ridge and slopes, and the Laulau volcanic area.

The axial uplands are bordered by a set of low terraced benches and limestone platforms that carry the terrace pattern downward. The low limestone platforms are conspicuous, broad, subequidimensional areas at the south, southeast-central, and north margins of the axial uplands. The low terraced benches fit around and between them. A belt of clay hills along the middle eastern margin of the island and two isolated fault ridges along the southeastern coast complicate the geomorphic pattern. The northern margin of the southern limestone platform is also complicated by two spurs of low hills separated by a conspicuous shallow depression. Volcanic rocks occur in the western member of this pair (Fina-sisu hills).

The eastern, southern, and northern coasts of the island are backed by high to low cliffs which are mainly of limestone, but which locally include deposits of volcanic origin. The west coast, however, is bordered by a narrow coastal plain of limesand (calcium carbonate sand) and volcanic outwash. Toward the south end of this coastal plain is a small brackish lake, surrounded by a rather extensive marshy area. A former lake at Muchot point has been filled in. Other small depressions are wet mainly after rains.

Westward from the west coast is a shallow lagoon bordered by a barrier reef. Toward its north and south ends the barrier reef approaches shore and changes to a fringing reef. A wide pass interrupts the barrier reef at midlength, and a small limesand islet lies just inside the reef at the north side of this pass. Westward beyond the southern half of the reef is a broad submarine platform, 15 to 30 fathoms deep, indented at its north and south edges by deep valleylike reentrants.

Saipan, however, is considerably more complex geomorphically than this brief description indicates. This diversity results from a variety of mainly destructional processes acting upon an intergrading succession of volcanic and calcareous rocks and sediments, over a period of time that extends from the present day through the Pleistocene and probably into the Pliocene.

MATERIAL AND STRUCTURAL FOUNDATIONS

The fabric from which the geomorphic features of Saipan have been evolved consists of dacitic and andesitic pyroclastic rocks and flows, marine sands of volcanic composition, and a variety of limestones and calcium carbonate sediments. The dacitic and andesitic materials together represent less than one-sixth of the total land area of Saipan; limestone and associated sediments comprise more than two-thirds of the island; and the rest consists of various unconsolidated materials, marsh, and lake.

Table 2 summarizes the areal representation of the outcropping rocks and unconsolidated mantling deposits of Saipan:

TABLE 2.—*Acreage of outcropping rocks and unconsolidated mantling deposits*

Rock type or covering element	*Area (acres)*
Andesitic rocks:	
Breccia, conglomerate, and associated finer sediments	1,915
Tuffs	480
Flow rocks	80
	2,475
Dacitic rocks:	
Breccia	240
Aphanitic flow rock	200
Tuff and mixed pyroclastics	15
	455
Marine sandstone and conglomerate of volcanic composition	840
Limestone:	
Mainly compact	10,845
Generally porous	6,580
Marly and tuffaceous	1,795
Rubbly and conglomeratic	1,875
Unclassified but mainly impure	600
	21,695
Alluvium, clay wash, and clay over impure limestone	1,350
Terrace sands and gravels of volcanic source materials	577
Emerged limesand and calcareous gravel	2,717
Marsh and lake deposits	600
Landslide and slump deposits	11
	5,255
	30,720

In addition to the limitations imposed by the material foundation itself, however, the processes that produced present land forms have operated under certain structural controls. The shape of the island itself and the general north-northeasterly trend of ridges and long terraces is related to fault pattern and orientation of the probably geanticlinal submarine ridge from which the island rises. Some terrace benches at the north end of the island have been tilted to the west by cross faulting. Minor folds along northwest-trending axes

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[8] Excessive estimates of area sometimes given for Saipan probably result from inclusion of the barrier reef and shallow lagoon along its west coast, and the fringing reefs along other parts of the shore.

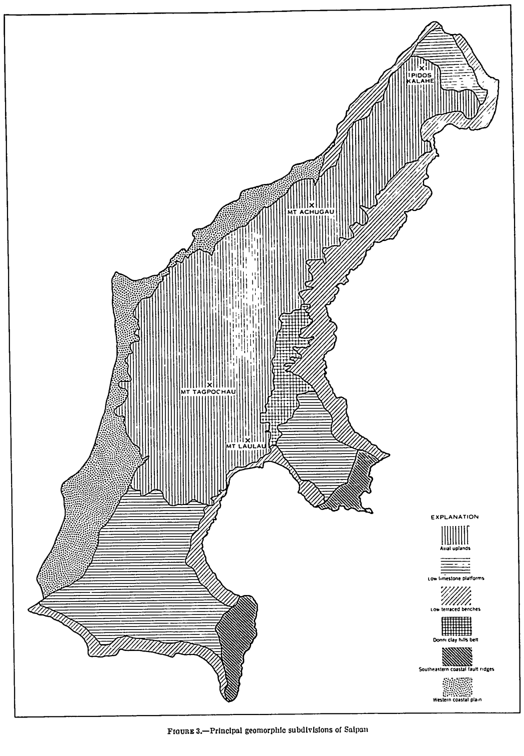

FIGURE 3.—Principal geomorphic subdivisions of Saipan

affect tuffaceous sediments in the lower east slopes of the island. The broadly horizontal position of much of the limestone has perhaps contributed to the general evenness of some of the well-defined terraces. Steep dips on the dacitic rocks have influenced the form of the prominent strike ridge known as Ogso Achugau in the north-central part of the island.

PREVAILING GENETIC PROCESSES AND CHARACTERISTIC RESULTS

FORMATION AND MORPHOLOGY OF BENCHES AND SCARPS

The terraces that dominate the terrain pattern of Saipan consist of nearly horizontal or slightly sloping benches, separated by seaward-facing scarps or steeply sloping surfaces (pls. 20–23). At places the change from one bench level to another is accomplished by a relatively broad, moderate to gentle slope that is more aptly termed a ramp than a scarp. The processes that are effective in producing these features are marine erosion, faulting, subaerial erosion, and, to a minor degree, construction.

That the bench surfaces are for the most part of marine origin is evident from their generally horizontal attitude or gentle seaward slope, their concentric arrangement, and the inadequacy of available terrestrial processes to do the job. That they are mainly erosional is shown by their habit of cutting across rock types, the clastic nature of most of the underlying limestone, and the evidence that much of the foundation limestone was formed as bank deposits at depths averaging about 10 to 50 fathoms. Some of the bench surfaces, especially in or near areas of volcanic rocks, are locally mantled with bedded sands and gravels which have not yielded fossils and which may be confluent fluviatile deposits formed behind a retreating sea in low-level outwash areas. Parts of the lowest benches mostly less than 80 feet above sea level but locally as much as 100 feet, appear to be constructional in the sense that they represent emerged fringing reefs only slightly modified by subaerial erosion.

It appears that at various times in the Quaternary history of Saipan marine erosion produced flat or seaward-sloping benches near sea level, through solution, abrasion, and biologic action in the intertidal zone. Although at any given time these processes were active only through a relatively narrow vertical zone, erosion also served to produce scarps at the backs of benches through undermining and collapse and through the quarrying action of wave-confined water and air. The slope of marine erosion benches may reflect the rate of rise or fall of sea level. Chemical solution and biologic destruction acting for a sufficiently long time at one level would produce a nearly flat bench, but if the sea rose or fell quickly a seaward-sloping bench would presumably result. A bench due primarily to mechanical abrasion should also slope seaward.

The ability of warm marine waters to dissolve calcium carbonate is believed to relate primarily to diurnal variations in the carbonic acid equilibria of intertidal waters, due to photosynthetic activities of marine plants. Physicochemical solution is, presumably, most marked on unprotected rock surfaces where such plants are abundant. Also of importance is organic solution, as well as disintegration and abrasion, by algae and animals that penetrate or cling to rock surfaces (Otter, 1937). It is believed that the present-day sea-level notch, as well as the 6-foot notch above it, result from a complex of factors in which solution plays a leading part. Intertidal marine waters are probably slightly solvent during the later night hours, because changes in ionic equilibria due to night time buildup of carbon dioxide (Orr, 1933, p. 52–53; Manton, 1935, p. 281–298; Emery, 1946; Cloud, 1952*b*, p. 34–41) temporarily increase the relative capacity of the water to hold calcium carbonate in solution.

The benches below 100 feet are probably attributable to shifts of sea level, caused by melting and accretion of Pleistocene ice. The many changes in the relative position of land and sea that resulted in bench cutting at higher elevations may be tectonic effects, or even in part actual sea-level changes due to factors other than glacial. A complicated pattern of incomplete terraces has resulted from the fact that all intervals of bench erosion tended to destroy or interrupt surfaces at higher levels, and that subsequent erosion and tectonic movement add difficulty to the correlation of bench remnants.

The most recent extensive rock surfaces include partly constructional and partly destructional benches between about 12 and 100 feet above sea level. The most conspicuous of these surfaces is between 20 and 40 feet. They appear to be parts of the surface of a former fringing reef complex that descends from a maximum elevation of around 100 feet. Organic growth associated with this reef formed a nearly continuous to spotty veneer on an emerging surface that was simultaneously affected by marine abrasion and solution. Where not artificially leveled, such surfaces tend to be conspicuously irregular, both from subaerial solution effects and from residual features.

Both the dominant erosion terraces and the low, partly or largely constructional terraces are modified by subaerial erosion, mainly solution. The occurrence of ramps instead of scarps between benches may be due to subaerial effects or to vagaries of marine erosion.

The results produced by the foregoing factors were locally influenced by faulting. Erosional scarps tend to find preexisting faults. Later faults or renewed movement on old faults have themselves produced scarps that resemble wave-eroded scarps in most respects except their more conspicuous straightness. Where such faults have tilted or plainly offset recognizable bench surfaces they present no difficulty in interpretation. At places, however, benches believed to be former parts of the same surface displaced by faulting may in reality be genetically separate surfaces.

At the lowest level of all, 5 to about 20 feet above sea level, is the western coastal plain of Saipan—a constructional mantle of limesand on a rock surface that rises inland from somewhat below present sea level near the coast. This underlying rock bench may for the most part have dropped to its present position by relatively recent faulting.

TERRACE SUCCESSION

The number and succession of recognizable rock terraces vary locally, and a very detailed study would doubtless show an extensive succession of minor and partly overlapping steps. From a short distance at sea, or in a low-angle oblique view from the air, one gets the impression that all benches above the western coastal plain could be grouped into 10 to 12 major terrace units. Tayama (1952, p. 196, fig. 15) suggests 14 and presents a map showing 13 surfaces. Our attempts to correlate probable bench remnants shown on a 20-foot contour-interval topographic map of Saipan suggest somewhere between 12 and 25 surfaces; but time did not permit the running of precise level lines and terrace profiles. To settle on a definite number of terraces, if such can be settled upon, would call for much more precise and detailed data than are presently available, and for special attention to elevations at the backs of terraces. These "maximum" elevations are probably the only ones that will have a wide significance in marking stands of the sea as opposed to onlap or offlap intervals. Special significance is also attached to coincidence of such levels with former sea level notches and flat-floored sea caves.

Future studies may solve the problem, but on the basis of the inadequate data at hand it seems safe to conclude only that bench remnants exist at many levels between the sea and the island crest. Those nearer sea level and those nearer the island crest appear to be more clearly defined than those at intermediate levels. By way of illustration, the following list gives elevations or ranges of elevation at which probable or possible bench remnants were noted. Overlapping ranges represent separate areas. In terms of time of cutting and gross elevation only, these terraces are divisible into three groups: an upper set, mainly above 500 feet, of late Pliocene (?) age; an intermediate set, between 100 and 500 feet, of middle (?) Pleistocene age; and a lower set of late Pleistocene age, below 100 feet and perhaps in part reflecting older surfaces that once belonged to the intermediate set.

Elevations of bench remnants on Saipan, in feet above sea level

1. 5–6 [1]
2. 12–15
3. 20–40 [1] (40 [1])
4. 40–60
5. 50–80 [1]
6. 80–120 (100 [2])
7. 120–180 [1] (140 [2])
8. 180–230 (200 [2])
9. 210–280 [1] (240 [2])
10. 310–350 [1]
11. 400–430 [2]
12. 450–470
13. 520–580
14. 600–620
15. 640–700 [1]
16. 680–740 [2]
17. 740–780 [1]
18. 800–830 [2]
19. 840–860
20. 900–950 [2]
21. 1,080–1,140 [1]
22. 1,180–1,220 [2]
23. 1,330–1,350 [1]
24. 1,440–1,480 [1]
25. 1,510–1,550 [1]

[1] Seemingly best defined levels.

[2] Better defined or more consistent general levels or intervals, none instrumentally determined.

TERRESTRIAL SOLUTION AND SOLUTION FEATURES

GENERAL CONSIDERATIONS

Leaving aside the broader features described above, it is a fair generalization to say that the limestone terrain on Saipan owes its natural surface details almost entirely to the effects of terrestrial solution. Nearly everywhere the surfaces of the purer limestones are pitted, pinnacled, creviced, and ridged from the action of rain water, aided by organic acids from the dense vegetation. Caves and sinks are formed from still solvent ground waters.

The rain that falls upon the generally porous and pervious Mariana and Tanapag limestones probably for the most part moves almost directly downward, either to underlying impervious rocks, or to a water table which is in hydrostatic balance with the sea in accord with the principles of the Ghyben-Herzberg lens. For this reason few or no valleys or surface runoff features of any sort are developed on the broader expanses of these limestones. Where any limestone occurs in narrow concentric belts, however, valleys may develop in relation to impervious rocks that underlie and extend inland and upward from beneath such belts of limestone. Such valleys result from collapse of linear cavern roofs above underground streams, and examples may be seen in various stages of development inland from the central part of Laulau Bay (Bahia Laulau).

The mainly compact limestones of Miocene and Eocene age, which are more homogeneous, less porous, and at higher elevations than the younger limestones, have developed a system of generally steep and slotlike valleys. This may result from runoff and solution being concentrated in initially low areas or seeking out vertical zones of shattering or relatively high permeability in the rocks. The purer limestones in their natural condition have highly irregular solution surfaces with many pinnacles and crevices—typical karrenfeld. The impure limestones develop a thicker blanket of soil and rounded surfaces marked by more nearly "normal" runoff patterns.

SOLUTION RAMPARTS

At the seaward margins of several limestone benches are narrow knife-edged ramparts as much as 20 to 30 feet high that slope steeply landward to the bench behind them and are almost vertical at their seaward sides (pl. 5*C*). Such rims have been interpreted as emerged reefs, but, with one possible partial exception, all known to us are solution features. Two major explanations of such solution ramparts have been made.

According to one of these explanations (Hoffmeister and Ladd, 1945), when rain falls on any inclined limestone surface, some of it will run down the inclined surface dissolving the limestone on its way. Only those drops of rain that fall on the rim can dissolve the rim, but the downslope areas are affected both by the rain that falls on them and that which runs inward from the margin. It is held that over a period of time solution can thus etch out the peripheral ramparts. This explanation is theoretically applicable to surfaces that originally inclined or were later tilted landward from their scarp fronts. However, it does not satisfactorily account for the ramparts on flat surfaces, or those that originally inclined toward sea-facing scarps, as most of those in question do to some degree.

A probably more generally applicable explanation of the rampart structures described has been formulated by Delos E. Flint and Raymond A. Saplis (Flint, 1949; Saplis and Flint, 1949). They contend that surficial cementation of the scarp-face accompanies or precedes the development of rampart-rimmed scarps. The rampart is then held to result from differential solution which favors preservation of the relatively well-indurated scarp face rather than the more porous limestone beneath the terrace surface behind it. This process is especially favored along wave-cut or stream-cut scarps, where constant or frequent contact with waters saturated with calcium carbonate leads to interstitial precipitation of calcium carbonate in a zone extending inward from the scarp face.

CAVES AND SINKHOLES

The caves of Saipan give some idea of the amount of underground solution that has occurred and warn of sinkhole formation yet to come through collapse of cavern roofs. Small caves are numerous but only two large ones are known. One of the big ones, known as Liyang As Teo, lies at the base of the lowest of the three South Kalabera cliffs (Laderan Kalaberan Lichan), near its midlength. Here, at an altitude of 320 feet, a 10-foot opening leads to a vaulted cavern about 75 feet in diameter and 80 or 90 feet high. At the far end of this cavern, a natural shaft about 70 by 50 feet across extends straight upward about 100 feet and vertically downward 114 feet to a pile of collapse debris about 13 feet high. Two long passages lead from the base of this shaft. One extends for 600 feet S. 60° W. and has an average height near 6 feet and a width near 20 feet. It has many constrictions and several small roomlike expansions. The other passage extends about 200 feet N. 20° W. It begins as an opening about 12 feet wide and 15 feet high but narrows rapidly and averages about 8 by 8 feet. It is nearly filled with a clutter of large blocks of limestone which, from the comparative thinness of the dust layer on them, are assumed to have collapsed to their present positions fairly recently. This passage is very straight and may follow a joint. The cavern of Liyang As Teo with all its extensions is entirely within the inequigranular facies of the Miocene Tagpochau limestone. It probably continues by smaller and impenetrable channels to sea level or to impervious rocks beneath. However, no standing water was found anywhere within it.

The other larger cavern visited is the underground stream channel known as Liyang Falingun Hanum, in southern Kalabera where the ravine called As Failan goes underground into a pair of narrow and tortuous channels. The longest of these channels extends about 900 feet southeastward toward the sea before it becomes too small for human passage. Here also no standing water was found.

Because it is probably fairly typical of the sort of cavern that may be expected almost anywhere within the Mariana limestone, a small cave not quite a mile west-northwest from Dandan point was observed and measured. This small cave opens from the west side of the quarry numbered S–26, and its top is 32 feet below the outcrop surface of the Mariana limestone at that point. It is 65 feet long and averages 17½ feet wide. It is 17 feet high for the first half of its length, abruptly constricts at midlength, and pinches out westward.

Many sinkholes were observed on Saipan and are indicated by the symbol for depression lines on the detailed geologic map. Two of these are of special interest because of their precipitous nature, their considerable depth, and the fact that they communicate with the sea. The material in their bottoms indicates that they are the result of the collapse of cavern roofs. Each is about 100 feet in diameter and 80 to 100 feet deep. One is known to the natives as I Madog, meaning "The Hole." It lies just inshore from Madog point (Puntan Madog), in the northeast part of the island, and is commonly referred to by Americans as "Marpi Cavern." The other and similarly collapsed cavern lies just north of and above Hasngot beach (Unai I Hasngot) at about the midlength of the east coast.

LATERITIC WEATHERING

The uniformly warm but not excessive temperatures and high but not excessive humidity and rainfall that prevail on Saipan are those of the humid tropics, ameliorated by an oceanic environment and a fringe position on the equatorial typhoon belt. Long rainy periods, accompanied by a high rate of oxidation and high bacterial activity, are effective in converting the iron- and alumina-rich andesitic rocks and sediments to iron and aluminum sesquioxides: clay, soft saprolites, and lateritic soils. The soil so formed is infertile, impervious, and thinly vegetated, rarely supporting elements other than swordgrass, xerophytic ferns, and casuarina. The weathering of limestones, of course, is primarily by solution as has been stated. However, solution of tuffaceous or marly limestones may produce soils resembling those derived from weathering of the andesitic rocks, and at this stage they come under the influence of similar weathering and erosional processes. The dacitic rocks are almost unweathered.

RUNOFF

Runoff erodes the surfaces of weathered volcanic rocks and impure limestones by rill erosion and sheet-wash. On the deeply rotted andesitic pyroclastic rocks and marine sandstones of andesitic composition this has resulted in an intricate dendritic system of narrow, steep-walled ravines separated by short, steep spurs. In the area of dacite outcrop the effect of runoff has been more to wash away intermixed tuffaceous or loosely consolidated materials and leave behind prominent, rugged, steep-sided, and thinly vegetated small hills of flow breccia or linear ridges of aphanitic flow rock. In areas of impure limestone that yield a deep residual clay to weathering, runoff produces an intricate pattern of gullies. In one elongate area of impure and loosely consolidated limestone and reworked volcanic rocks, it appears to have washed much of this material out from behind seaward-lying, broad, ridgelike terrace remnants of firmly indurated rock so as to leave interior depressions with outlets through narrow defiles that transect the defending terrace remnants. At two places adjacent to andesitic sandstone, runoff has worked beneath an overlapping limestone fringe to produce subterranean passageways.

STAGE OF DEVELOPMENT

The fresh scarps and terrace surfaces, and the steep-walled valleys of the volcanic areas indicate that the recently emerged land area of Saipan is in a youthful stage of erosion. Assuming no change in sea level, solution should eventually produce large cavern collapses, extensive sinks, and highly discontinuous terrace surfaces; and lateritic weathering and runoff should reduce the areas of outcropping volcanic rocks to low, rounded, mature hills. The east, north, and south coasts should be cut back by marine action, but the west coast will erode slowly or even advance seaward because of the protective outlying reef.

SYSTEMATIC GEOMORPHOLOGY

The prevailing genetic processes, acting on the described material and structural foundation of Saipan for the time that has been available to them, produced a complex set of small-scale geomorphic subdivisions. Apart from coastal and offshore features, these include 25 distinct parcels of terrain grouped in 6 larger terrain divisions (fig. 3; pl. 3), most of which are of destructional origin. Geomorphic features of mainly constructional origin include only the western coastal plain, parts of the low terraced benches below an altitude of 100 feet, and parts of the shore.

Of the 6 principal geomorphic divisions recognized, the axial uplands cover by far the greatest area. The low limestone platforms and the western coastal plain, however, have an importance beyond their smaller areal extent as level areas suitable for large-scale construction and farming. The low terraced benches include nearly level areas like the limestone platforms, but these are narrow strips of flat land rather than broad platforms. They are of interest as passageways from one platform to another, for small-scale construction, and for agriculture. The Donni clay hills belt and the southeastern coastal fault ridges are still smaller selfdescriptive terrain units of coordinate rank with those named above.

The geomorphic subdivisions recognized, with reference to plate and figure numbers of photographs which illustrate them, are as follows (pl. 3 and fig. 3):

- 1 Axial uplands (pls. 16, 17, 20, 21*B*, 22*A*, 23, 24)
  - 1A Terraced limestone uplands (pls. 16, 17, 20, 22*A*, 23, 24)
    - 1Aa Tagpochau uplands (pls. 20, 22*A*, 23, 24)
      - 1Aa1 Central terraced uplands (pls. 20*A*, 23)
      - 1Aa2 Terraced eastern slope (pl. 20*A*)
      - 1Aa3 Terraced western slope (pls. 22*A*, 23, 24)
      - 1Aa4 Southern and southwestern spurs (pls. 20*B*, 22*A*)
    - 1Ab Matuis uplands (pls. 16, 17*A*, 24*A*)
      - 1Ab1 Matuis uplands proper (pls. 16, 17*A*, 24*A*)
      - 1Ab2 Southwestern spur
      - 1Ab3 Madog spur (pls. 5*C*, 16*B*)

  - 1B Volcanic uplands (pls. 17, 19, 20, 21*B*, 22*A*, 24)
    - 1Ba Central volcanic ridge and slopes (pls. 17, 19, 20*A*, 24)
    - 1Bb Laulau volcanic area (pls. 20*B*, 21*B*, 22*A*)
- 2 Low limestone platforms (pls. 16, 20*B*, 21*A*, 22, 23*A*)
  - 2A Southern platform (pls. 20*B*, 22)
    - 2Aa Eastern platform segment (pl. 22*B*)
    - 2Ab Western platform segment (pl. 22)
    - 2Ac Fina-sisu hills (pls. 20*B*, 22*A*)
    - 2Ad Dago depression (pls. 20*B*)
    - 2Ae Dandan spur (pls. 20*B*, 22*B*)
  - 2B Eastern platform (pls. 20*B*, 21*A*, 23*A*)
  - 2C Northern platform (pl. 16)
- 3 Low terraced benches (pls. 16*B*, 17, 20*A*, 22)
  - 3A Magpi benches (pl. 24*A*)
  - 3B East coast benches (pls. 16*B*, 17, 20*A*)
  - 3C Laulau benches (pl. 21*A*)
  - 3D South coast bench and scarp (pl. 22)
- 4 Donni clay hills belt (pl. 20*A*)
- 5 Southeastern coastal fault ridges (pls. 20*B*, 21*A*, 22*B*, 23*A*)
  - 5A Hagman ridge (pls. 20*B*, 21*A*, 22*B*, 23*A*)
  - 5B Naftan ridge (pl. 22*B*)
- 6 Western coastal plain (pls. 20*B*, 22, 23, 24)
  - 6A Coastal plain proper and low hinterland slopes (pls. 20*B*, 22, 23, 24)
  - 6B Susupe marshland and lake (pls. 20*B*, 22*A*)
- 7 Coastline, beaches, and offshore features (pls. 16–24)

Descriptions of these subdivisions follow, beginning with the highest and largest and extending downward and seaward to generally smaller terrain units. Brief mention of special coastline, beach, and offshore features will conclude the section on geomorphology. Levels of bench surfaces are taken from the topographic map.

AXIAL UPLANDS

Plates 16, 17, 20, 21*B*, 22*A*, 23, 24

The axial upland area that extends through the northern three-fourths of Saipan consists of northern and southern terraced limestone uplands that are separated by a central volcanic ridge and are abutted at the southeast by a patch of high volcanic hills.

The axial uplands as a unit culminate near their south-central part at an elevation of 1,555 feet, in Mount Tagpochau (Ogso Tagpochau). Encircling and descending from this peak is a stairlike succession of nearly flat benches and vertical scarps of limestone that merges northward into a narrow-crested ridge composed mostly of volcanic rocks. Northward from the highest point of this central volcanic ridge at Mount Achugau (Ogso Achugau, 767 feet) the axial uplands again consist of flat benches and scarps of limestone, terminating, in the majestic Bañadero cliffs (Laderan Bañadero pls. 11*C*, 16*A*) that rise more than 600 feet above the 170-foot platform at their base to a peak of 835 feet at Pidos Kalahe in the section known as Matuis. Most of these limestone benches approach horizontally, but a few are tilted.

The slopes of the central volcanic ridge are intricately dissected into steep hills and short, rugged valleys that were cut deeply into the impervious clays and saprolites of the weathered volcanic foundation rocks in consequence of original slopes and by headward sapping. The northern and southern thirds are marked by steep-walled, slotlike valleys that incise a terrain of Miocene and Eocene limestones. Such valleys have resulted from a complex of factors that include (1) solution and collapse of linear cavern roofs; (2) solution and abrasion along zones of shattering, faulting, or sedimentary weakness; and (3) headward cutting and cliff-sapping at the heads of intermittent streams localized in underlying volcanic rocks or more easily eroded and less permeable facies of the limestone succession.

From the axial uplands, the valleys slope generally east or west with conspicuous exceptions. The longest valleys and the two perennial streams are on the eastern slope in the volcanic terrain near the midlength of the island. In general the western slope is more precipitous than the eastern slope.

Most of Saipan above an altitude of 300 feet belongs in the axial uplands province, but its foothill spurs at places reach below 100 feet.

TERRACED LIMESTONE UPLANDS

Plates 16, 17 20, 22*A*, 23, 24

The terraced limestone uplands include parts of the axial uplands that lie south and north from the central volcanic ridge and slopes. The two principal units of this subdivision are named from the fact that they center on the land divisions known as Tagpochau and Matuis. Characteristically they include the succession of nearly flat benches and vertical scarps of limestone that rises above the roughly 200-foot bench level. They are underlain almost exclusively by Miocene limestone but also include much smaller areas of Eocene limestone and patches of other rocks.

TAGPOCHAU UPLANDS

PLATES 20, 22*A*, 23, 24

The southern unit of the terraced limestone uplands, the Tagpochau uplands, center on Mount Tagpochau and comprises the topographically dominant and areally largest of the well-defined terrain units on Saipan. For descriptive purposes it is further divided into four subunits.

1. The central terraced uplands (pls. 20*A*, 23) include the uppermost terraces that generally surround Mount Tagpochau above a level of about 1,000 feet. A northern prong takes in the ridge slope that descends northward to a 680- to 700-foot terrace level, at the center of the island, where the central volcanic ridge begins. Four general bench levels above 1,000 feet are recognizable in this area: a capping bench at 1,500 to 1,550 feet, a second at 1,440 to 1,460 feet, a third at 1,180 to 1,220 feet, and a fourth bench at roughly 1,080 to 1,160 feet. The area is entirely underlain by a pure, massive, and well-indurated facies of the Miocene Tagpochau limestone, and solution effects have complicated the topography. Bench surfaces are irregular and not at consistent levels. They are separated by prominent scarps or steep ramps. The conspicuous though areally small 1,440- to 1,460-foot bench is surrounded by a 10- to 20-foot high peripheral solution rampart that gives it a dished-out appearance—a shallow, bowllike depression with a well-developed subsurface drainage through solution crevices beneath. Except for cultivated clearings or construction the area is mainly covered with a dense growth of jungle vegetation. The limestones beneath the southern and southeastern slopes are sufficiently impure to have yielded a residue of altered tuffaceous contaminants that provides a rather poorly drained, infertile clay soil over impure limestone. In consequence, a mat of high serrate-edged swordgrass supplants jungle vegetation here.

2. The terraced eastern slope (pl. 20*A*) takes in the area between the lower margin of the upper terraced uplands at 680 to 1,000 feet and the upper margin of the Donni clay-hills belt at 300 to 400 feet above sea level. The more westerly parts of the eastern slope rise steeply toward the Tagpochau cliffs (Laderan Tagpochau) and the eastern margin is defined by the abrupt Machegit and Adelug cliffs. It is dissected by steep-walled east-trending ravines. The middle part, below I Agag cliffs, is an obscurely defined and irregular north-south depression that lies behind a broad, discontinuous, and generally flat-topped frontal limestone ridge that surmounts and extends south from the Machegit and Adelug cliffs. It is presumably washed out by lateral erosion on the marly to tuffaceous and indurated limestones and reworked volcanic sediments that underlie the area behind the well-indurated frontal ridge. This ridge seems to be a composite of remnants of four bench surfaces, at present elevations of about 520–560, 620–640, 680–700, and 740–770 feet above sea level. Other flat-topped hills and presumed bench remnants in the area are generally accordant with the same four approximate levels. It is possible that the middle depression itself was partly or mainly prepared by marine scour on relatively nonresistant beds during bench cutting and only accentuated by lateral subaerial drainage. Young marine deposits that would serve to substantiate such an interpretation have not been found, however. The bluffs and steep slopes of this area are thickly wooded, but large parts of the gentle slopes were cleared for farming woodlots, or construction. In areas of reworked volcanic deposits and deeply weathered impure limestone, gully patterns have developed on poorly drained clay surfaces.

3. The terraced western slope (pls. 22*A*, 23, 24) of the Tagpochau uplands is an area of generally steep slopes broken by scattered bench and scarp remnants of a formerly well defined terrace system. It extends downward from the lower margin of the upper terraced uplands at 680 to 1,000 feet to the upper edge of the western coastal plain and adjacent slopes at elevations as low as only 20 feet or so above sea level. It is underlain mostly by tuffaceous parts of the Miocene Tagpochau limestone. Slopes are generally steep. Except where cleared for cultivation or construction, this area supports a vegetation of jungle growth and, over the more highly tuffaceous sediments, occasional large patches of swordgrass. The area generally is cut by a system of gullies and ravines. Terrace remnants are thus, for the most part, difficult to recognize except for a few broad surfaces that occur mostly at the lowest levels. Differential erosion of the bedded sediments produces stepped slopes and variation in ravine walls from steep to near vertical. The terrain as a whole is more markedly dissected and has fewer continuous nearly level surfaces than the eastern slope. Matching of roughly accordant bench remnants suggests the former existence of possibly 8 bench surfaces at present distances above sea level of 80–120, 140–160, 200–220, 320–360, 520–580, 600–680, 780, and 840–860 feet.

4. The southern and southwestern spurs (pls. 20*B*, 22*A*) of the Tagpochau uplands extend southward and southwestward from the upper terraced uplands as a series of mainly flat-topped or gently sloping spurs and hills separated by deep ravines and extending to less than 50 feet above sea level. This terrain unit is divisible into a southern or Dandan spur, a middle or Gallego spur, and a southwestern or Tipo Pale spur. The bedrock is mainly impure Miocene limestone that weathers to sporadic concentrations of soil, separated by stepped slopes of limestone ledges. Swordgrass, with scattered casuarina, thrives on the flat surfaces and gentler slopes where the poorly drained clay soils accumulate, and jungle vegetation envelopes the cliffed ravine sides and steep slopes. Except in the broader ravine bottoms and the southern parts and gentle lower slopes of the Dandan and Gallego spurs this area is little used for cultivation or construction. In combination with the terraced western slopes, which it in part resembles, this is the most cut up and least developed part of the Tagpochau uplands. Nevertheless 11 different bench surfaces are suggested by seeming bench remnants at present distances above sea level of about 80–120, 140–160, 190–210, 250–280, 400–420, 450–470, 540–560, 600–640, 660–680, 740–780, and 920–940 feet.

MATUIS UPLANDS

Plates 16, 17*A*, 24*A*

The northern unit of the terraced limestone uplands, the Matuis uplands, centers on the area of Matuis and includes the conspicuous westward-tilted terraces of the north prong of the island. It is underlain almost entirely by relatively pure and compact facies of the Tagpochau and Matansa limestones. The terrace remnants are clearly defined and well preserved, but the slope of the bench surfaces makes correlation with benches outside this area difficult. Westward tilting of these terrace surfaces by probably as much as 15° occurred before planation of adjacent younger terrace surfaces below 200 to 300 feet, for the latter are not tilted. The Matuis uplands are divided into the Matuis uplands proper, the southwestern spur, and the Madog spur.

1. The Matuis uplands proper (pls. 16, 17*A*, 24*A*) descend from an elevation of 948 feet at the peak of the uppermost of the three prominent terraces that compose south Kalabera cliffs to somewhat less than 100 feet above sea level. The area is one of prominent west-tilted limestone benches in part separated by conspicuous bluffs and generally irregular from solution effects. The benches were mostly cleared and planted in sugarcane by the Japanese, whereas the bluff areas support a dense growth of jungle vegetation. A prominent rampart 20 to 30 feet high rims a part of the 800-foot surface that surrounds the peak of Pidos Kalahe (pls. 16*A*, 24*A*) at the north point of the area, and less conspicuous ramparts mark parts of the eastern rims of some of the other benches (pl. 5*C*). Four prominent tilted benches (pl. 16) occur at 400–430, 680–740, 800–830, and 900–950 feet. Matching of flat and sloping surfaces shown on the topographic map suggests remnants of other benches at 300–320, 340–360, 380–460, 580–620, and 760–780 feet.

2. The southwestern spur is a long, narrow projection from the Matuis highlands proper; both are generally similar but are separated by the deep fault-ravine of Kanat Papua. The spur borders the central volcanic ridge, slopes to the west, and shows bench remnants at 180–200, 220–240, and 260–280 feet.

3. The Madog spur (pls. 5*C*, 16*B*) extends eastward from the north end of the Matuis uplands proper and includes a prominent limestone bench remnant at 180 to 220 feet. This surface is rimmed at the top of its seaward cliff boundary with a rampart about 10 to 20 feet high (pl. 5*C*). Other margins are steep slopes down to lower surfaces and up to the Matuis uplands proper.

VOLCANIC UPLANDS

Plates 17, 19, 20, 21*B*, 22*A*, 24

The volcanic uplands include the principal areas of outcropping volcanic rocks and sediments outside the Fina-sisu hills area (Ogso Fina-sisu). This terrain unit includes the central volcanic ridge and slopes that lie between the terraced limestone uplands of Matuis and Tagpochau. It also takes in the Laulau volcanic area at the southeastern margin of the Tagpochau uplands.

CENTRAL VOLCANIC RIDGE AND SLOPES

Plates 17, 19, 20*A*, 24

The area included in the central volcanic ridge and slopes rises from about 40 feet above sea level on the east and west to about 740 feet at Mount Achugau in the northern part. The area is underlain principally by andesitic and dacitic flows and pyroclastic rocks of the Sankakuyama, Hagman, and Densinyama formations. The southern part of this area, Talofofo ridge (pls. 17*B*, 20*A*, 24), is narrow and nearly flat on top. It seemingly represents a terrace surface or intergrading surfaces at elevations from 600 to 680 feet. Away from the summit of the central ridge the terrain is cut up by deep, steep-walled ravines and narrow intervening spurs generally oriented east and west. The northern part of the area, centered around the Achugau grasslands (Sabanan Achugau), is chiefly underlain by dacitic rocks. Here the topography is more subdued and consists of small rounded hills and narrow ridges which to some extent are probably related to primary volcanic structures. Mount Achugau (pls. 5*D*, 17, 24) is a narrow ridge of steeply dipping flows and pyroclastic rocks that may represent a remnant of a volcanic cone. Dips are perhaps accentuated by later eastward tilting.

The weathered rocks and derived soils of the central volcanic ridge and slopes are largely impervious, and the topography owes its nature to the resulting heavy runoff. Drainage east and west from the central ridge controls the orientation of the ravines and side spurs. The principal ravines are as long as a mile and on the eastern side of the island cut across the narrow limestone fringe that forms the eastern terraced corridor.

LAULAU VOLCANIC AREA

Plates 20*B*, 21*B*, 22*A*

The Laulau volcanic area is a short ridge of volcanic rocks adjoining the lower southeastern slopes of the Tagpochau uplands. It rises from a few feet above sea level, along the shore of Laulau bay, to an elevation of about 660 feet. The area is mostly underlain by upper Eocene andesitic breccias, but the ridges along the southeastern slope are capped by lower Miocene limestone. The relatively impervious weathered products of the volcanic rocks have been incised by surface runoff into narrow, steep ravines which drain to the southeast, away from the ridge summit, and are separated by steep narrow spurs.

LOW LIMESTONE PLATFORMS

Plates 16, 20*B*, 21*A*, 22, 23*A*

The low limestone platforms include conspicuous broad benches at the northern, southern, and eastern extremities of Saipan. The northern and eastern platforms are underlain entirely by the porous Pleistocene Mariana limestone. The southern platform is mostly of the same rock unit but includes also areas of volcanic rocks and Miocene Tagpochau limestone. Because of their broad and relatively even nature, the soil-covered limestone surfaces of these platforms were largely planted in sugarcane during Japanese occupation.

SOUTHERN PLATFORM

Plates 20*B*, 22

The southern platform proper consists of principal segments at roughly 120 feet and 200 feet. The north-northeasterly trending scarp that separates the lower western segment from the higher eastern segment may be of fault origin, separating former parts of a single broad platform. But it might equally well be partly of fault origin and partly due to fault-controlled erosion at the lower bench level. Northward extensions from the platform segments are the largely volcanic Fina-sisu hills on the west, and the mainly limestone Dandan spur on the east. Between the upper or northern ends of these features lies the Dago depression, a relatively broad area of internal drainage mostly surfaced with late Quaternary clay wash.

EASTERN PLATFORM SEGMENT

Plate 22*B*

The western three-fourths of the eastern platform segment is a nearly horizontal limestone surface that lies generally about 200 feet above sea level but descends to elevations as low as 80 feet. It rises eastward from a low, clay-bordered, north-south ramp to a slightly higher bench remnant at 230 to 250 feet, and from this to the western border of the Naftan ridge at 280 feet. The clay strip between the two bench remnants is a fairly thick layer over a limestone substratum. Shallow gullies ramify its surface, as they do similar gently sloping clay surfaces elsewhere on Saipan.

WESTERN PLATFORM SEGMENT

Plate 22

The western segment of the southern platform is a slightly irregular limestone surface about 120 feet above sea level. Its western and southern scarp margins descend to near sea level and it rises northwestward toward the Fina-sisu hills. Two broad, shallow sinks and a small, deep sink are bunched together at the lower end of a panhandlelike northern extension.

FINA-SISU HILLS

Plates 20*B*, 22*A*

The Fina-sisu hills extend pronglike north-northeastward from the western side of the western platform segment to the beginning of the Tagpochau uplands. This area is mainly of deeply weathered andesitic tuff and flow-rock of probable Oligocene age at the south, and impure lower Miocene limestone at the north. Elevations range from about 20 feet above sea level to 280 feet. The volcanic hills are gently rounded and have maximum elevation barely exceeding 200 feet. The deeply clay-blanketed gentle eastern slope of the main ridge is cut by shallow gullies and is generally cultivated. A similar, small eastward extension of these hills is separated from the main ridge by a narrow strip of limestone along which sinks are concentrated. The steeper western front of the volcanic part of the Fina-sisu hills is mostly underlain by an andesitic lava flow 80 to 100 feet thick and generally wooded with Formosan koa or scrub acacia. The impure limestones of the northern part of the area display a relatively thin soil cover and irregularly stepped slopes. The steep western slope leading down to the Susupe marshlands is rough and has thick copses of brush above and nearly continuous brush below.

DAGO DEPRESSION

Plate 20*B*

The Dago depression extends from the northern end of the Dandan spur westward to a line of sinks along an inferred fault zone at the lower edge of the Fina-sisu hills. The floor of this shallow, internally drained depression is of clay wash which retards subsurface drainage. During much of the rainy season the principal sink area of its southeastern quadrant contains standing water below the 130-foot contour level.

DANDAN SPUR

Plates 20*B*, 22*B*

The Dandan spur is an elongate northward extension from the eastern platform segment that consists mainly of cavernous, permeable Pleistocene limestone at a bench level of 250 to 280 feet above sea level. Westward it is bounded by a fault scarp that drops the adjacent ground about 80 feet. Eastward it descends to the coastal Laulau benches. Its northern part includes a fairly large outcrop area of Miocene tuffaceous

sandstones that produce rounded gullied hills. Sinklike depressions form where valleys on these volcanic sediments run beneath the overlapping younger limestone. The area was principally planted in sugarcane during the Japanese occupation.

EASTERN PLATFORM

Plates 20*B*, 21*A*, 23*A*

The eastern platform coincides essentially with the area known as Chacha, on the Hagman peninsula, the eastern extremity of Saipan, north of Laulau bay. It is a nearly horizontal surface of porous Pleistocene limestone at elevations mostly of 200 to 250 feet, and averaging near 240 feet. However, it descends to 100 feet or less at its northeastern and southwestern margins. The area is mainly cleared for cultivation and construction.

NORTHERN PLATFORM

Plate 16

The northern platform is mainly a horizontal surface similar to the eastern platform and underlain by similar rocks. It is only about half as large as the eastern platform, however. It ranges from 80 to 180 feet in elevation, its principal bench surface lying at 160 to 180 feet and averaging near 170 feet. Like the eastern and southern platforms it is mainly cleared for cultivation and construction.

LOW TERRACED BENCHES

Plates 16*B*, 17, 20*A*, 22

The areas of low terraced benches include narrow elongate limestone benches and scarps between or at lower levels than the low limestone platforms and between the northern platform and the western coastal plain.

MAGPI BENCHES

Plate 24*A*

The Magpi benches include a narrow belt of mainly porous Pleistocene (?) limestone that extends from the northern platform to the northern end of the western coastal plain at the northwest end of Saipan. This area is bounded by the sea on the west, and eastward by the bluffs at the western border of the Matuis uplands and the northern platform. It preserves bench remnants at general elevations near 30, 50, 70, and 150 feet and is mainly cleared for agriculture or construction except for the lower seaward part. The latter is a very narrow belt pinnacled by solution and matted with grass and low brush.

EAST COAST BENCHES

Plates 16*B*, 17, 20*A*

The belt of east coast benches and scarps extends from the northern platform south along the coast to the eastern platform. It is a narrow to broad, elongate, terraced belt mainly underlain by the porous Pleistocene Mariana and Tanapag limestones. At places it is surfaced with thin patches of quartz-rich terrace sands and gravels. It is bounded by the sea on the east, and on the west by the northern platform, the Matuis uplands, the central volcanic uplands, and the Donni clay-hills belt. At the south end it swings eastward and extends along the north side of the eastern platform. It rises from sea level inland to an elevation of about 300 feet at points adjacent to the central volcanic uplands. Bench surfaces occur roughly at 12–15, 20–40, 40–60, 50–80, 80–120, 120–240, and 180–300 feet. This belt of benches is most prominently developed in the vicinity of the Kalabera district of northeast Saipan, where it consists mainly of a slightly seaward-sloping bench as much as three-quarters of a mile wide. The east coast benches are mainly cleared for agriculture and construction, except for dense jungle scrub where they abut the Matuis uplands, and for extensive windbreaks of casuarina along the seaward bluffs. The surfaces of low benches along the seaward margin are typical irregular limestone solution surfaces covered with a thick growth of brush. The lowest coastal bench, in most places from about 12 to about 40 feet above sea level, in large part probably represents an elevated former fringing reef surface modified by solution effects. This surface corresponds with the elevated reef surfaces of the Laulau and south coast benches. Along its central and southern stretch, adjacent to the central volcanic uplands and the Donni clay hills belt, the belt of east coast benches is interrupted by several narrow, steep-walled, slotlike, east-west ravines.

LAULAU BENCHES

Plate 21*A*

The Laulau belt of benches loops around Laulau bay, connecting the eastern and southern low limestone platforms across the foot of the Tagpochau uplands. It is underlain by porous Pleistocene limestones with minor patches of massive Miocene limestone and gravelly alluvium. It rises 200 feet above sea level from the coast and includes bench remnants at roughly 20–30, 40–50, 60–80, 110, 150, and 170 feet. The northeastern segment below the eastern low limestone platform, as well as the narrow stretch of mainly elevated limesands along the beach that borders the broad northern reef area, includes cleared or cultivated patches interspersed with thickly wooded spurs and cliff zones. Somewhat more than the southern half of the area, however, is overgrown with a dense growth of scrub pandanus, *Scaevola*, and other jungle brush.

SOUTH COAST BENCH AND SCARP

Plate 22

The south coast bench skirts the southern seaward margin of the southern low limestone platform from which it is separated by a prominent low terrace face. It is mainly floored with the porous Pleistocene Tanapag limestone and probably represents an elevated former fringing reef surface somewhat modified by post-emergence solution effects. The same fault that separates the eastern and western segments of the southern low limestone platform offsets this bench slightly, dividing it into an eastern segment that slopes from 40 to 80 feet and a western segment that lies mainly between 12 and 50 feet. It is nearly flat, though seaward sloping, and is mainly cleared except for a dense growth of remnant jungle scrub along the scarp above it and planted casuarina windbreaks along parts of the seaward bluffs.

DONNI CLAY HILLS BELT

Plate 20A

The Donni clay hills belt extends northward from the Laulau volcanic area as an irregularly narrow strip about 3 miles long and ⅛ to ¾ mile wide. It is bounded on the west by the lower eastern slopes of the Tagpochau uplands and on the east by the eastern platform and the east coast corridor. This area is underlain mainly by the deeply weathered Donni sandstone member of the Tagpochau limestone, but impure limestones and andesitic conglomerates and sandstones are locally included in this geomorphic unit. Elevations range from about 110 feet to 520 feet. The hills consist of short, rounded and flat-summitted ridges generally oriented east and west and separated by short, steep-sided ravines. The eastern part of the belt, where underlain by the Donni sandstone member, appears to be an exhumed surface. The short east-west ridges generally coincide with "anticlines" whose axes trend east-west and plunge 5°–10° to the east. Tongues of the overlapping Mariana limestone extend westward up the intervening "synclinal" valleys. The northern and southern parts of the area are mostly cleared for farming; the central part of the belt is covered with large stands of the introduced Formosan koa and scrub acacia.

SOUTHEASTERN COASTAL FAULT RIDGES

Plates 20B, 21A, 22B, 23A

Two small faulted ridge areas along the southeastern coast of Saipan stand in contrast to the bordering low limestone platforms and terraced corridors in their rough and precipitous topography, generally thick vegetation, and isolated nature. These are the Hagman ridge and the Naftan ridge, which probably in large part owe their general similarity as well as some of their most distinctive features to the movement along the same fault, subsequent to terrace planation.

HAGMAN RIDGE

Plates 20B, 21A, 22B, 23A

Hagman ridge lies at the eastern extremity of Saipan. It rises from the sea, along its eastern margin, to a maximum elevation of about 485 feet, and then slopes steeply westward to the eastern limestone platform. For the northern three-fourths of its length, the summit of the ridge is flat and slopes gently northward to the southern end of the belt of east coast benches. In this area it is underlain by the highly porous Mariana limestone. On the east the northward extension of the ridge falls away in a series of steep scarps and rough-surfaced benches. The lower eastern slopes are covered by a chaotic maze of large limestone blocks that have separated only slightly and are creeping slowly seaward over underlying volcanic sediments. The southern and southeastern part of the ridge area consists of highly dissected andesitic volcanic rocks, with sea cliffs as high as 300 feet. At the south and southeast borders of the area the porous limestone narrowly overlaps the volcanic sediments in seaward-sloping terraces whose surfaces are about 75–100 and 125–200 feet wide. Except for a cleared area of about 15 acres at the summit the northern part of the ridge is covered by thick jungle vegetation over a karsted surface. The volcanic slopes at the south support only thin stands of casuarina and patches of sword grass.

NAFTAN RIDGE

Plate 22B

Naftan ridge is the most southeasterly part of Saipan. It rises abruptly from the sea to a maximum elevation of about 407 feet and then descends westward by a series of low scarps and ramps to the eastern segment of the southern low limestone platform. It is mainly of the highly porous Mariana limestone, and is a series of uncertainly defined and seaward sloping benches. The mainly vertical or near-vertical bluffs along the coast can be descended to the sea only at the more gradually sloping north end or along a small and precipitous volcanic reentrant near its midlength. The latter is a chaos of volcanic rocks and slumped limestone masses that can be entered or left unaided only from the south end. All along the coast a constant mist of salt spray even to heights of nearly 200 feet keeps coastal vegetation down to low scrub or grass that at many places mats over a very rough solution-pinnacled undersurface. Elsewhere jungle growth thrives except for broader-than-usual cleared surfaces.

WESTERN COASTAL PLAIN

Plates 20B, 22, 23, 24

The western coastal plain extends the full length of the west border of Saipan south from the Magpi benches. It is mainly floored by loose and recently deposited calcium carbonate sands south from the Tanapag area and by similar limesands, low lying terrace deposits of reworked volcanic materials, and clay wash toward the north end. Its surface rises gradually inland to heights generally not more than about 20 feet, but at places to as much as 100 feet where the transition to bedrock is over a rising surface of clay outwash or soils derived from deep weathering. Within the area are rare pinnacles of outlying limestone and occasional depressions. The soil on it is loose, well-drained, and easily worked, especially in the limesand areas. The ground is almost everywhere cleared and cultivated except for local brushy areas or woodlots that commonly coincide with patches of limestone outcrop.

Part of the western coastal plain is marshy. The largest area of marshland surrounds the shallow brackish lake called Hagoi Susupe and is separated from the coastal plain proper (pls. 20B, 22, 23, 24). This area is called the Susupe marshland and lake (pls. 20B, 22A). It is nearly everywhere marshy during the rainy season and in part marshy all year round. Its sticky blue clays at many places support a thick growth of tall tough jointed bamboo grass, or cane.

COASTLINE, BEACHES, AND OFFSHORE FEATURES

Plates 16–24

The west shore of Saipan south from the Magpi benches is an almost continuous limesand beach, backed at only a few places toward the north by low limestone ledges (pls. 22–24). At one place near midlength it is interrupted by a small wedge of mangrove swamp extending up a short tidal inlet. Seaward from this long west-coast beach is a shallow lagoon (pls. 17B, 20B, 23, 24), which is walled off from the Philippine Sea beyond by a barrier reef (pls. 17, 24) that lies about 2 miles offshore at the harbor entrance but approaches the shore and grades into a fringing reef at its north and south ends (pls. 22B, 24A). Just north of the harbor entrance is the small round islet of Mañagaha (pls. 17, 24C), consisting of loose limesand that extends to only 8 or 10 feet above high tide level. Small lagoonal reef patches are locally abundant south of Mañagaha islet (pl. 24C).

Most of the rest of the island rises abruptly above a narrow fringing reef (pls. 5C, 16B, 18A, 19B, 20, 21, 22) or fronts the sea in precipitous bluffs that range from only 10 or 15 feet high to more than 100 feet. At a few places the sea cliffs even surpass heights of 200 feet. The parts of the shoreline which are shown on available hydrographic charts as fringing reefs appear to be mainly erosional sea level benches with the merest film of algae and other living organic matter. At the south end of the island (pls. 22B, 24A), however, are fringing reefs with depressed reef flats (moats) that support more vigorous organic growth. Some of the so-called fringing reefs are actually sea-level benches in volcanic materials (pl. 21A) with an appreciable organic component only at the permanently submerged front. Where these fringing benches front precipitous bluffs, they locally support massive collapse blocks at their landward margins. Organic growth and entrapment of physico-chemically precipitated calcium carbonate at the basal margins of such blocks weld them firmly to the bench on which they rest, so that they come to resemble sea stacks.

Along the zone of fringing reefs, sand or gravelly beaches are found at only a few places along the south shore (pl. 22), behind the broader reef area at the northern end of Laulau bay (pl. 21), back of two well-developed stretches of fringing reef toward the south end of the east coast corridor (pls. 19B, 20A), in Fañunchuluyan bay (pls. 5C, 18A), and at a few valley mouths and other protected stretches of coast (pls. 17B, 18B, 19A).

A natural pass through the barrier reef near the center of the west coast leads eastward into a dredged channel about a mile long and 30 feet deep. This, in turn, extends farther eastward into a protected anchorage about three-fourths of a mile in diameter and of depths generally greater than 30 feet—the deepest part of the lagoon (pl. 24). This area has been dredged in part, and its general contour and the location of shoal waters within it are shown in detail on Hydrographic Office Chart No. 6062 (scale 1:12,000; see also Hydrographic Office Chart No. 6060, scale 1:72,950). An extensive bank area off the southwest coast of Saipan offers anchorage for larger ships. It is generally shallower than 20 fathoms. Laulau bay (pls. 20B, 22B, 23A) on the east coast offers some shelter from storms but is too deep and has too steeply sloping a bottom for good anchorage.

GEOLOGIC SUCCESSION

INTRODUCTION AND SYNOPSIS

About two-thirds of the composite geologic column and most of the central core of Saipan consist of the mainly volcanic Sankakuyama, Hagman, Densinyama, and Fina-sisu formations. These are exposed over an area of about 4½ square miles, or less than 10 percent of the land surface. The primarily limestone units—

Matansa, Tagpochau, Mariana, and Tanapag limestones—underlie about 36 of the island's 48 square miles; and various unconsolidated or marginal deposits underlie the remaining 7½ square miles.

In its simplest terms, and with estimated maximum thicknesses in feet, this geologic succession is:

1. Elevated limesands (Recent)	<30
2. Alluvium and clay wash (Pleistocene and Recent)	<30
3. Younger terrace deposits (Pleistocene and Recent)	20±
4. Tanapag limestone (younger Pleistocene)	<50
5. Post-Mariana terrace deposits (Pleistocene)	<10
6. Mariana limestone (older Pleistocene)	500±
7. Older terrace deposits (Pliocene?)	10±
8. Tagpochau limestone (older Miocene)	1,000±
9. Fina-sisu formation (younger Oligocene)	400+
10. Matansa limestone (younger Eocene)	500±
11. Densinyama formation (younger Eocene)	800±
12. Hagman formation (younger Eocene)	1,100±
13. Sankakuyama formation (Eocene?)	1,800+
	6,250 [9]

[9] This is necessarily not the true maximum, as it piles up measurements of laterally equivalent beds and because maximum thicknesses are not superposed.

The principal subdivisions, including the eight named formations, are summarized and compared with standard faunal and stage zonation in table 3 (in pocket).

For purposes of discussion and mapping, the principal stratigraphic subdivisions of Saipan are further broken up into a number of minor units. Two of these subordinate rock units are given member names because of their physical distinctness and general lateral continuity, but the others are designated simply as facies of named formations, or as unnamed subdivisions of surficial units. The various facies (and members) mapped represent local expressions of the general continuum of sedimentary or volcanic processes that produced the formation to which they are referred. Where it has been possible to follow their contacts, they generally appear to grade into other facies and to recur at different localities and different levels in the stratigraphic succession. This is a reflection of the depositional history of the rocks of Saipan. The original materials were deposited against, around, and over older rocks and sediments, and under fluctuating environmental conditions that resulted in complexly interfingering relationships among contemporaneous deposits of various sorts. Approximation of thicknesses for such generally overlapping and veneering deposits, some without known bases, is, of course, subject to obvious difficulties and uncertainties. The sorts of relationships envisaged are shown diagrammatically in the columnar section on plate 1.

By way of more inclusive summation and comparison, and for use in connection with the detailed geologic map, a chart, "Descriptive summary of the geologic units of Saipan," is in pocket. Diagrammatic illustrations and local stratigraphic ranges of some distinctive and stratigraphically significant genera of larger Foraminifera and algae, given in figures 4 and 5, present partial basis for subdivisions and correlations made. Partial lists of fossils at appropriate places in the stratigraphic discussion give further data. Nearly all fossil determinations given are attributable to W. Storrs Cole (larger Foraminifera), Ruth Todd (smaller Foraminifera), or to other specialists. Following chapters by these specialists will complete the documentation for conclusions expressed on age, correlation, and paleoecology.

The basis for paleontologic subdivision and correlation in the western Pacific has recently been extensively discussed by van Bemmelen (1949, p. 79–103) and by R. M. Kleinpell and others (in Corby and others, 1951–53, p. 229–297). It is thus unnecessary here to review these matters beyond emphasizing that standard age designations of post-Eocene units in the western Pacific are generally problematical. There is, to be sure, great hope that continued study of planktonic and pelagic organisms (Radiolaria, silicoflagellates, diatoms, coccoliths, discoasters, planktonic Foraminifera, cetaceans) will eventually solve these problems and permit reasonably accurate correlation with the standard European section. Until this objective is achieved, however, the reader should bear in mind that a question mark is understood after age designations of Indo-Pacific Tertiary units in terms of European standards. Correlation with the Indonesian Tertiary letter zones is believed to be on a sounder basis, especially below the Pliocene (see references above, and van der Vlerk, 1948), but even here the probability of incompletely understood faunal facies and extension of supposed ranges is too great to warrant positive conclusions regarding the presence or absence of particular units.

In the detailed descriptions to follow discussion of petrographic terminology and locality citation, the individual geologic units are taken up in approximate succession from oldest to youngest. Description of the unconsolidated units is generalized, but the named formations and their subordinate parts are described more or less in a pattern. Some repetition is unavoidable in this organization of information into different categories but we have tried to hold it to the useful minimum.

The stratigraphic sections graphically summarized in figure 6 provide an impression of variations in rock type.

PETROGRAPHIC TERMINOLOGY

It is our aim, in discussing the geologic units of Saipan, to say in purely descriptive terms what the characteristics of a particular unit are before considering what these features mean genetically. There follows a brief

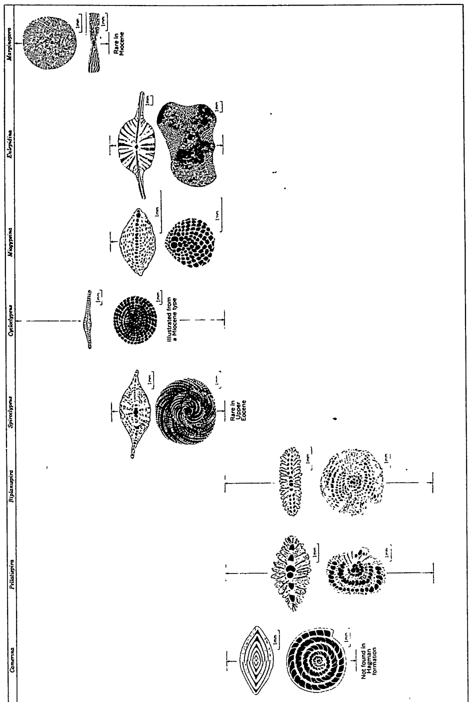

FIGURE 4.—Illustrations and local stratigraphic ranges of some distinctive genera of larger Foraminifera.

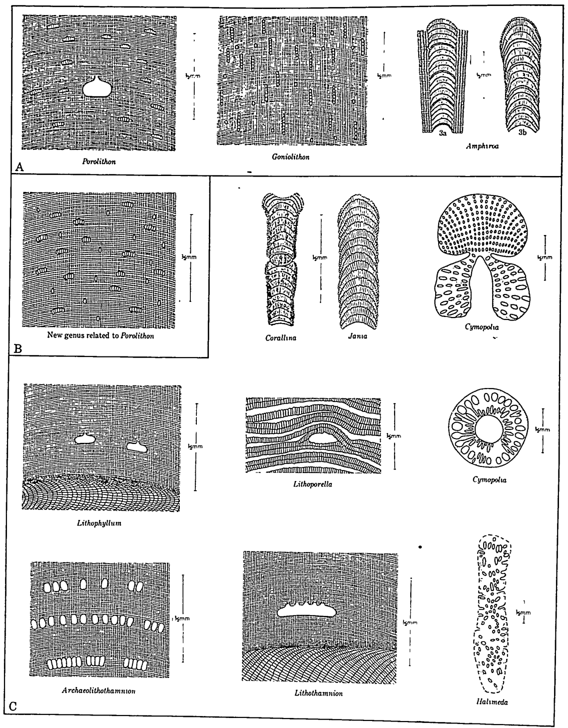

FIGURE 5.—Illustrations and local stratigraphic ranges of some distinctive genera of calcareous algae. A, Pleistocene and Recent; B, Miocene, Tertiary *e*; C, upper Eocene to Recent.

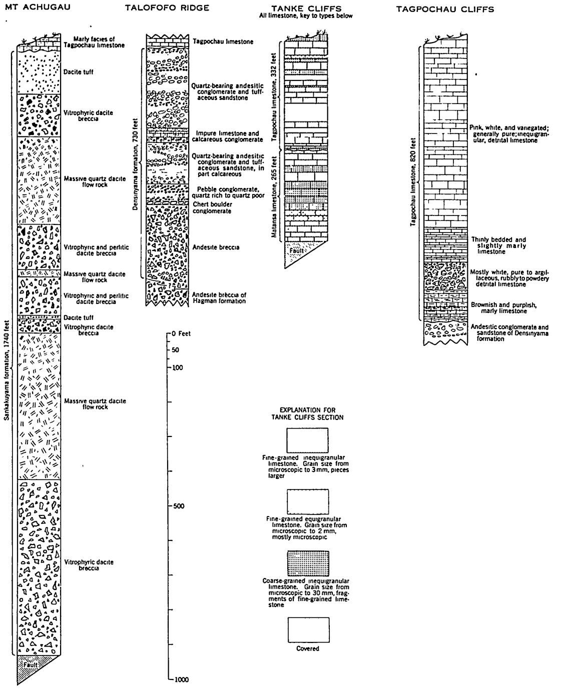

FIGURE 6.—Graphic summary of selected stratigraphic sections.

explanation of the terminology to be used in the description of the rocks and sediments under consideration.

PRIMARY VOLCANIC ROCK TYPES

Two principal types of effusive rock occur on Saipan. Both are characterized by a relatively high content of silica, high content of alumina in relation to the sum of the alkalies and lime, low potash content, and low content of femic minerals. These rocks do not readily fit into a classification based upon modal feldspar composition. It thus proves convenient to classify them primarily on the basis of the sum of their femic minerals, and secondarily on the average composition of their modal feldspar (predominantly plagioclase). On this basis we call them simply dacite and andesite. This terminology is consistent with that followed by Kuno (1950, p. 958–959) and other Japanese petrographers for similar rocks in Japan and is also believed to afford the most consistent expression of chemical affiliations.

The rocks herein called dacite (dacite, hornblende-bearing quartz dacite porphyry, dacite vitrophyre, dacite perlite) are leucocratic, glassy rocks that contain less that 5 percent by volume of femic minerals (hornblende, biotite, magnetite, hematite). Their modal feldspar is oligoclase, having an average composition ranging from An_{12} to An_{15}. They have an unusually high silica content. All contain tridymite, cristobalite, or chalcedony in addition to quartz. They are low in alumina, iron, magnesia, lime, and potash content compared to the average composition of dacite given by Daly (1933, table 1, p. 15). Under the system of classification proposed by Shand (1946, p. 225–245) the Saipan dacites are soda rhyolites, but under Johannsen's classification (1939, p. 155–156) they are leucodacites.

The andesites of Saipan, of which augite-hypersthene andesite is the commonest variety, are leucocratic, mainly crystalline rocks that contain between 10 and 30 percent femic minerals (pyroxene, magnetite, ilmenite). Their modal feldspar is predominantly labradorite, with an average composition ranging from An_{55} to An_{70}. All contain a relatively large amount of normative quartz, which can be correlated with the presence of tridymite and cristobalite in the groundmass of the rocks. The modal silica minerals and the normative quartz are disregarded in the classification. A small amount of potash-rich feldspar, possibly anorthoclase, is also present in the groundmass, but is not considered in the classification. The andesites have a relatively high content of alumina and lime and a low content of potash compared to the average composition of andesite as given by Daly (1933, table 1, p. 16). According to Shand's classification the Saipan andesites are lime andesites, but under Johannsen's system they are quartz basalts.

The chemical analyses and normative mineral compositions given in table 4 will amplify the basis for the terminology used, but full discussion is deferred to a later chapter on the petrology of the volcanic rocks.

TABLE 4.—*Average chemical and normative mineral composition of 3 samples of dacite and 7 of andesite from Saipan*

Analyses
(*Percent by weight*)

	Dacite	Andesite
SiO_2	78.20	57.45
TiO_2	.17	.60
Al_2O_3	10.58	17.84
Fe_2O_3	.66	3.01
FeO	.75	3.60
MnO	.04	.10
MgO	.22	3.02
CaO	1.28	8.02
Na_2O	3.54	2.79
K_2O	1.69	.66
H_2O-	.28	1.02
H_2O+	2.72	1.07
P_2O_5	.12	.15
	100.25	99.99

Norms
(*Percent by weight*)

		Dacite	Andesite
	Q	47.52	17.10
	or	10.01	3.89
	ab	29.87	23.58
	an	6.12	34.10
di	wo	------	2.32
	en	------	1.60
	fs	------	.53
hy	en	------	5.90
	fs	.53	2.11
	mt	.03	5.34
	il	.30	1.22
	hm	------	---------
	ap	tr	tr
	sm[1]	.32	---------
	co[2]	1.43	---------

Normative plagioclase
(*Percent by molecular weight*)

	Dacite	Andesite
or	21	6
ab	66	40
an	13	54

[1] Sillimanite. [2] Cordierite.

ROCKS AND SEDIMENTS AS FIELD ASSOCIATIONS

The dacitic and andesitic rock elements of Saipan occur most abundantly as flow rocks and subaerially deposited pyroclastic rocks. They are also found, mixed in large or small proportions with calcium carbonate, as marine pyroclastic deposits, as reworked pseudovolcanic deposits, as terrace deposits, and as contaminating elements in limestones. The greater part of the island, however, is underlain by relatively pure limestone.

In order to avoid prejudicing interpretation, the same terms are used to describe similar characteristics of rocks and sediments regardless of origin. Thus *breccia*, *conglomerate*, *gravel*, *sandstone*, and *sand* apply as descriptive terms whether the material in question is mainly calcium carbonate or mainly of volcanic composition, and regardless of whether it is a subaerial or submarine pyroclastic deposit or consists of reworked materials. *Agglomerate* is avoided. *Tuff* is applied only to demonstrably pyroclastic deposits, but *tuffaceous* is used in a purely descriptive sense to indicate the presence of sand-sized particles of initially volcanic origin in a sediment whether reworked or primary. Terms for bedding and grain size, of course, are the same for all rocks and sediments.

REFERENCE TO LOCALITIES

Field localities to which reference is made in the stratigraphic and paleontologic sections of this report are shown on a special locality-finding map (pl. 4). Locality numbers, arranged in numerical order at the lower right corner of this map, may be found by reference to grid coordinates. The letter prefix of these numbers indicates the collector—B for Burke, C for Cloud, S for Schmidt. To avoid possible future confusion, it should be noted that the original field numbers were all further preceded by MS, standing for "Marianas, Saipan," and Schmidt's were mostly followed by the letter "f" to indicate a fossil locality. All of our field records are in terms of the full original numbers. Thus S618 of the published report equals MSS–618f of the field records. By including all essential locality data on plate 4 it has been possible to dispense with the publication of detailed locality descriptions.

The original field locality numbers are used throughout the text in place of or in addition to permanent locality numbers, because the latter vary according to biologic groupings. A single field number may be represented by several numbers in the permanent files and in chapters to follow, and cross-reference to a standard register is needed. This register, will also accompany parts 2 and 3. This locality finding map is intended to be used in connection with the generalized geologic map (pl. 2) at the same scale.

THICKNESS ESTIMATES

Like many other islands, Saipan is an area of complex sedimentary overlap and abrupt lateral variation of volcanic rock units. The estimation of thicknesses at such places presents special problems and involves a large element of subjectivity. Is it proper to assume that a marine rock unit that crops out intermittently from sea level to an elevation of 1,000 feet is at some place 1,000 feet or more thick if not stepped up by faulting? Or shall we say that its maximum continuous or observed thickness of, say, 150 feet is nearer the truth? The choice depends on total relationships of the rock unit which may or may not be known, and it may be neither extreme.

A kindred problem is involved in computing the thickness of a succession of moderately or even steeply dipping beds which may approximate a shingle like arrangement of initially dipping strata within a broad stratal unit that as a whole is believed to dip gently. Is it better to follow the limited evidence of the eye or to make allowance for the interpretation? That would seem to depend on how good the evidence for the interpretation was and in which direction the person called upon to name a figure chose to be bold.

Shall the thickness of a volcanic unit be taken as measured in its marginal exposures, or should allowances be made for probability of increase or decrease in thickness toward the source? This would seem to depend on the kind of volcanics and where their source was.

Allowances made and conclusions reached will vary with the individual, the area, the particular facts and interpretations, and perhaps even from one time to another for the same individual. In the pages that follow each case is considered individually on the basis of whatever limited evidence was available for it, and without adhering rigidly to any fixed set of routine manipulations. Where it is not accomplished by conventional methods, the manner of "guessing" any particular thickness is given. The general trend of reasoning by which we have arrived at rounded-off thickness figures involves first making computation allowances consistently in the direction of a low to moderate estimate for the maximum exposed thickness of individual units. Such figures have then been roughed off to the next higher figure in the range of tens or hundreds, according to the inferred degree of accuracy, and on the assumption that it is improbable that we would actually have found the thickest existing sequence of any unit in an insular area of such complex genetic history and discontinuous exposures.

SUPPOSED EOCENE

SANKAKUYAMA FORMATION

Plates 5, 6*C*, 16*B*, 17, 18*A*, 19*A*

DESCRIPTION OF THE FORMATION

General characteristics.—The Sankakuyama formation consists of dacitic flows and pyroclastic rocks of several textural varieties. For the most part, however, these rocks are glassy and extremely silicic. In many places they are traversed by narrow seams of yellow, white, and gray chalcedony and cryptocrystalline quartz. Thin veinlets of manganese oxide are ordinarily found with the silica minerals. The rocks are in part conspicuously laminated. They are little affected by weathering. The formation lacks fossils and underlies the oldest dated rocks of late Eocene age. It is referred to the Tertiary because it contains abundant primary tridymite and cristobalite—minerals that are unknown in pre-Tertiary volcanic rocks.

It includes four principal facies of varied relations and known to be repeated in the general succession: massive dacite flow rocks; vitrophyric and perlitic dacite breccias; dacitic tuffs; and mixed dacitic pyroclastics.

Thickness.—The maximum thickness of the Sankakuyama formation is not known, but an incomplete section calculated to be 1,800 feet thick is exposed at

Mount Achugau and the actual thickness is probably of the order of a few thousand feet.

Areal distribution and typical occurrences.—The main body of the Sankakuyama formation underlies about two-thirds of a square mile of intricately dissected terrain in the Achugau district of north central Saipan. In addition to this, dacite-vitrophyre and perlite breccia and banded dacite flows occupy about 25 acres immediately north of the eastern section of the Talofofo road. Mixed dacitic pyroclastic rocks form the islet of Maigo Fahang in Fañunchuluyan bay and are exposed for about one-fourth mile in sea cliffs nearby on the main island.

A small exposure of dacite ("liparite") is reported by R. Tayama (1938) to be at the foot of the cliffs at Bañadero. However, the outcrop could not be found by the writers and subsequent discussion with Tayama brought out that it was probably beneath a present area of road fill at the east of Bañadero cliffs and that it might have been a boulder.

Type section.—The Sankakuyama formation was named by R. Tayama (1938, p. 31) and its type site given by him as Mount Achugau (pls. 5*D* and 17). Nowhere on Saipan is a complete stratigraphic succession of the Sankakuyama formation exposed, but the best partial succession begins in the cliffs that form the northern flank of Mount Achugau and continues through its south flank. That sequence is here designated the type section. It is summarized in figure 6 and described in appendix A.

Weathering.—Weathering and secondary alteration have affected the rocks of the Sankakuyama formation differentially. The flow rocks and breccias are, for the most part, little affected by weathering, and in areas underlain by these rocks the soil is ordinarily thin and stony. Foliated, brecciated, and highly vesicular parts of these rocks are more prone to alteration by surface weathering, and the ground-mass of such rocks is in places altered to a light-brown, pink, or reddish-purple aggregate of kaolinitic clay, quartz, and minor hematite. Rocks that contain veinlets of chalcedony, cryptocrystalline quartz, and manganese oxides are commonly altered to a soft, pale-pink and orange-pink claylike material. In some part this alteration may be related to a secondary, hydrothermal mineralization accompanied by the introduction of the silica and manganese oxides, for the rocks are much more extensively altered where heavily veined by these minerals.

The vitric dacitic tuffs of the Sankakuyama formation are commonly deeply weathered to an unctuous, white to light-brown, kaolinitic clay aggregate.

Terrain and vegetation.—Mount Achugau (pls. 5*D*, 17, 24*C*), near the center of the dacitic outcrop area, rises to an altitude of 767 feet, and has a maximum local relief of about 600 feet. The average relief in the area underlain by the Sankakuyama formation is perhaps 200 feet. The area is incised by deep, generally V-shaped ravines, the longest about one-half mile in length. The sides of the ravines are steep to nearly vertical. In headwater areas the drainage channels are broader and more open, and local relief in such areas is low.

The higher parts are generally covered with sword-grass or the xerophytic fern *Gleichenia*, but are devoid of trees except for local scant growth of introduced casuarina and acacia. Many ravine bottoms and cliffs support a dense jungle vegetation.

Age and correlation.—The dacitic rocks of the Sankakuyama formation are the oldest outcropping on Saipan. Although lacking fossils, they are disconformably overlain by andesitic tuffs and flows of the Hagman formation, by beds of the Densinyama formation, and by the Matansa limestone, all of which contain Foraminifera of late Eocene age. The Sankakuyama rocks are therefore Eocene or pre-Eocene in age.

Indirect evidence for the assignment of the Sankakuyama formation to the Tertiary rather than to the pre-Tertiary is the presence of tridymite and cristobalite in the groundmass of these rocks. It is believed that these minerals invert to quartz with time, and E. S. Larsen, Jr., has stated (oral communication) that tridymite and cristobalite are rare in pre-Miocene rocks that he has examined and are unknown in rocks of pre-Tertiary age.

Guam is the only other island in the Marianas on which dacitic rocks of composition similar to those of the Sankakuyama formation have been found. Risaburo Tayama (written communication to Cloud, July 13, 1949) reports a small inclusion of dacite in andesitic conglomerate in Talofofo Valley on Guam, and the writers collected a cobble of porphyritic quartz dacite in a bed of andesite conglomerate at Mount Santa Rosa. The source from which these silicic rocks came has not been found, but it is probably Eocene or older.

Origin.—The rocks of the Sankakuyama formation mostly represent consolidated accumulations of erupted ash, lapilli, blocks, and lava flows of presumed subaerial origin. However, at one place in the bluffs at Fañunchuluyan Bay, they include mixed dacitic pyroclastic rocks that may have been produced by subaqueous reworking of these primary volcanic materials.

At and southward from Mount Achugau, tabular, south-dipping flows and interlayered beds of breccia and tuff form a homoclinal sequence. These rocks represent flows and pyroclastic breccias and tuffs derived by surficial extrusion of lavas and explosive eruption and accumulation of dacitic blocks and ash. Several large, thick (as much as 200 feet) bodies of gently inclined and uniformly layered masses of dacite and flow breccia at the south end of this homocline may represent stubby steep-walled flows (coulees). Strongly foliated and steeply inclined massive dacite and dacite-breccias in the northern part of the main area of dacitic outcrop may be parts of viscous domal protrusions (the exogenous and endogenous domes of Williams, 1932, fig. 37, p. 145).

Unless they are in part represented by the plugs described in the next paragraph, the vents out of which the mapped dacitic rocks were erupted are not clearly identifiable and may lie mainly beyond the outcrop area. However, rocks that are thought to belong to volcanic domes may cover large vents; and Mount Achugau itself probably is a remnant of a volcanic cone the center of which was not far north of the present peak. At and eastward from Mount Achugau (pls. 5*D*, 17, 24*C*) the dacitic rocks have a monoclinal southerly and south-southeasterly inclination except around probable remnants of volcanic domes (pl. 2). The crest of Mount Achugau is composed of a layered sequence of dacitic flow rocks and breccias that dip between 40° and 50° to the south, only about 10° to 15° greater than the angle of repose of volcanic debris on the slopes of presently active andesitic and basaltic cinder cones. The south slope of the peak is a dip slope, while the north side falls away in a steep series of nearly vertical cliffs. The structure resembles a part of the flank of a stratovolcano which has been deeply eroded and perhaps slightly tilted toward the south.

Related volcanic plugs.—Two small subcylindrical bodies of rock about 15 feet in diameter, presumed to be volcanic plugs, are surrounded and apparently overlain by the breccia-tuff facies of the Hagman formation at Mount Laulau and in a quarry about one-half mile due east of Point Flores (Puntan Flores) in west-central Saipan. These plugs are composed of well-indurated volcanic breccia containing angular blocks of hornblende-bearing dacite porphyry, quartz-bearing augite-hypersthene andesite porphyry, and several types of silicified rocks containing finely granular pyrite and other sulfide minerals. The hornblende-bearing dacite porphyry contains abundant quartz phenocrysts as much as 1 cm in diameter. They are apparently older than the rocks of the Hagman formation, and probably in some way are related to the dacite succession, perhaps representing the differentially eroded upper part of plugs that fill buried source vents of a part of the Sankakuyama formation not exposed to view.

SUPPLEMENTARY DESCRIPTIONS OF MAPPED FACIES

MASSIVE DACITE FLOW ROCK

Plates 5*A*,*B*, 6*C*, 16*B*, 18*A*

Lithology and field relations.—The massive flow rocks of the Sankakuyama formation consist of finely porphyritic dacite in tabular, lens shaped, and irregular bodies. The tops of individual flows are commonly massive and opaline. The middle and basal parts of the flows are generally minutely vesicular and pumiceous. The flow rock unit also includes texturally distinct rocks of similar composition that are believed to be parts of protrusive domes.

The groundmass is mainly of dacite glass, silica minerals (quartz, tridymite, cristobalite, opal, chalcedony), oligoclase microlites, microscopic grains of magnetite and biotite, and flecks of hematite. In some of the flow rocks the groundmass glass is mostly recrystallized and the rock is essentially cryptocrystalline. All of these rocks contain small, rounded to subhedral phenocrysts of quartz and oligoclase, with an average diameter of less than 1 mm and scarce microphenocrysts of magnetite generally less than 0.5 mm in diameter. The phenocrysts and microphenocrysts form about 3 to 8 percent of the rock by volume.

These flow rocks possess a well-developed layered flow structure which is commonly highly contorted, dislocated, and wraps around isolated blocks of dacite in brecciated portions of flows. The layering gives the rocks a banded appearance and is the result of variation in color and texture between layers, and the streaking out of these layers by internal movement during flow. Layers of light-gray, extremely porous, vesicular rock from about 1 mm to perhaps 2 or 3 cm thick alternate with layers of dark grayish-red or light-red, massive, glassy rock to give the flows their foliate structure. Small vesicles are elongated parallel to the direction of flow. Foliation due to flow structure in the massive dacite flow at Fañunchuluyan beach is shown in plate 5*B*.

Over an area of about 40 acres in the Sabanan Achugau district unbrecciated bodies of dacite of remarkably uniform texture and composition are thinly layered (layers are 0.1 to 10 mm thick) and the layering is horizontal to gently inclined and not contorted. The rock is of paler tones of red, pink, orange, and gray than are the typical flow rocks previously described. It is generally massive though somewhat vesicular and porous, and is resistant to weathering and erosion. Ordinarily these rocks display parting surfaces parallel to the foliation, and, at one locality on the south flank of Mount Achugau, they show columnar jointing (pl. 6*C*).

Another variant of the flow-rock unit, also found in the Sabanan Achugau district, includes bodies of coarsely foliated, in places brecciated, massive to minutely vesicular dacite that are intercalated with irregular masses of chaotically foliated flow breccia. The layering in these rocks is highly contorted, dislocated, ordinarily steeply inclined (50° to 90°), at many places vertical, and nowhere uniformly oriented for more than a few tens of feet.

The larger bodies of flow rock show a pronounced parting parallel to the flow structure of the rocks. Jointing, invariably at a high angle to the plane of foliation, is also well-developed in many of the flow rocks. In part, at least, the jointing is probably due to contraction of the rocks upon cooling, and the flows are locally brecciated where movement continued during the cooling process and displaced blocks bounded by joint surfaces. The brecciated flows are similar in origin to the dacite vitrophyre and perlite flow breccias described below, but they differ from these rocks in that they are composed of porphyritic dacite, are not so glassy, and do not possess the extreme fragmental structure of the flow breccias.

Mineralization.—Some of the flow rocks are veined by thin seams of yellow, white, and gray chalcedony and cryptocrystalline quartz, and microscopic seams in the flow rock are commonly filled with partially recrystallized opal and with chalcedony. In some flows microscopic mineral and rock fragments are embedded in the opal and chalcedony filling, and the seams form microscopic breccia veins. The seams of chalcedony and cryptocrystalline quartz are from a fraction of a millimeter to nearly a centimeter wide.

Fibrous crystalline manganese oxides, in part or perhaps dominantly pyrolusite, also form veins and fill former open spaces in the dacite flow rocks. Commonly the manganese oxides are found along with cryptocrystalline quartz and chalcedony, in places intimately mixed. Seemingly compact veins of manganese oxides, as wide as 1½ to 2 inches, contain microscopic stringers of cryptocrystalline silica. In some instances manganese oxides, cryptocrystalline quartz, and chalcedony fill narrow, closely spaced fractures and form a sheeted-zone type of mineral deposit; in other places they fill open spaces in brecciated flow rock and form a stockwork type of deposit. Deposits of this type, as well as single veins, were mined by the Japanese during World War II.

Thickness, areal distribution, and typical occurrences.—Flow rocks are common within the area of dacite outcrops. The largest body forms the middle 450 feet or so of the section at Mount Achugau and extends laterally for one-fourth mile. The crest of Mount Achugau is a steeply dipping (45°–50°) flow that can be traced east or west along its strike for about one-fourth mile. It is 10 to 20 feet thick. In the Sabanan Achugau region several massive, irregularly shaped bodies of porphyritic dacite are exposed over an area of 40 acres and are as much as 200 feet thick. The lens-shaped dacite flow that is interbedded with dacite vitrophyre breccia in the sea cliffs above the southern part of Fañunchuluyan beach can be traced for one-fourth mile, swelling in this distance from a few feet to a maximum thickness of 60 feet (pl. 5*B*, 18*A*).

Origin.—The tabular and lens-shaped bodies of porphyritic dacite of the Sankakuyama formation, which are interlayered with beds of vitrophyric and perlitic breccia and tuff, have the usual characteristics of surface flows. The limited lateral extent of these flows (none was observed to be more than one-fourth mile long), their generally lenticular form, the contorted flow-banding, and the small size of vesicles—all indicate that they were mostly of high viscosity. Yet, some are only 10 to 20 feet thick and maintain a fairly uniform thickness through distances as great as one-fourth mile. In order for such unbrecciated silicic lavas to have been extruded and spread out over the surface, they must have acquired a relatively low viscosity through a high content of volatiles, and this is indicated by the extreme vesicularity of the rocks, some of which are pumiceous. The tops of many flows have a massive, flintlike texture where vesicles are completely filled with silica minerals. This feature may be the result of the rise and escape of volatiles at the top and surface of the flows, the volatiles carrying dissolved silica and depositing chalcedony, opal, tridymite, and cristobalite in greater amount at the top than in the base or middle parts of the flows. Following their extrusion, the dacite flows evidently congealed very rapidly, for the groundmass of the rock is largely glass, spherulites are extremely small, and the phenocrysts show only slight resorption effects against the groundmass.

Those bodies of brecciated and foliated rock in which the flow structure is ordinarily steeply inclined (40°–80°) to vertical and commonly contorted may have originated as viscous, glassy, and in part autobrecciating lavas protruded within or extruded from a small volcanic dome or domes. The structure of these rocks bears a close resemblance to that of several of the dacitic and rhyolitic domes described by Williams (1932, p. 51–146), a type of volcanic structure commonly developed in craters or on the flanks of dacitic and rhyolitic volcanoes. Similar structures of Quaternary age and demonstrably protrusive origin along the eastern shore of Lake Taupo in New Zealand were shown to Cloud by James Healy in 1949.

The thinly layered, mostly flat-lying or gently inclined (5°–20°), unbrecciated bodies of minutely vesicular porphyritic dacite, which occur in the southern part of the area of dacitic outcrop, and which have such a remarkably uniform texture and composition, also may represent thick, viscous flows extruded within a volcanic dome which overlapped previously extruded breccias. Some of the thick masses of foliated flow

breccia associated with these rocks may have formed as steep-sided flows or coulees, which moved slowly outward and away from the domal eruptive center. The foliation in these rocks is the result of slight textural and mineralogical variation between layers only a few millimeters in thickness, rather than a streaking produced by marked outward movement, as in the surface flows. Internal movement in some of these rocks, however, was at least enough to displace vesicles and feldspar microlites around the larger phenocrysts. The texture of the rocks is characteristic of a coherent body of congealed lava, which was perhaps not so rich in volatiles as the surface flows, for these thick but thinly laminated dacite masses are not so highly vesicular and the vesicles are minute and mostly microscopic. This may simply indicate however, that water in these lavas escaped less violently than in the surface flows, leaving less evidence of its presence.

VITROPHYRIC AND PERLITIC DACITE BRECCIA

Plates 5*B*, 18*A*, 19*A*

Lithology and field relations.—The breccia facies of the Sankakuyama formation includes explosively ejected breccias and foliated, autoclastic flow breccias or domal breccias of similar composition. These consist mainly of angular to subrounded fragments of dacite vitrophyre and perlite, commonly enclosed in a glassy tuffaceous matrix. They form tabular beds and irregular masses of rock which range from a few feet to 400 feet thick. Thin, tabular and lens-shaped flows of massive vitrophyre are commonly present within the flow breccias

The groundmass of the vitrophyre and perlite fragments is a transparent dacite glass that contains small microlites and crystallites of oligoclase feldspar. The perlite is a variety of vitrophyre with a groundmass made up of small concentrically structured spherules of transparent dacite glass. Both the vitrophyre and perlite contain small, rounded to subhedral phenocrysts of oligoclase and quartz, with a mean diameter of slightly less than 1 mm, and microphenocrysts of magnetite generally less than 0.5 mm in diameter. The phenocrysts form between about 2 and 8 percent of the rocks by volume. The fragments of dacite vitrophyre and perlite range in size from a fraction of an inch to about a foot in diameter, have an average diameter of about 3 inches, and constitute from about 60 to 100 percent of the breccia. Vitrophyre and perlite are almost invariably associated in the breccias.

In many of the pyroclastic breccias and even in some of the foliated flow breccias the larger fragments are enclosed in a light-gray to white tuff matrix composed of angular fragments of dacite vitrophyre and pointed shards of dacitic glass as long as a few millimeters. The matrix constitutes between about 10 to 40 percent of the rock. In places, especially in the pyroclastic breccias, the matrix is porous and poorly consolidated and probably represents fine-grained dacitic ash. The porous matrix is sometimes weathered to a soft, white, siliceous claylike material.

Near the surface, the fragments of vitrophyre and perlite in the dacitic breccias are generally surrounded by a narrow selvage of white claylike material a few millimeters thick. This is of secondary origin and represents an alteration along the boundary of the fragments where open space permits easy access to ground-water solutions.

The widely occurring autoclastic flow breccias have a well-developed foliation due to flow structure. Commonly, however, the well-defined swirling flow planes are contorted, dislocated, and steeply inclined. A foliated and fragmental internal structure is characteristic, and in some of the breccias fragments of vitrophyre and perlite appear to be welded in a glassy tuff matrix, forming a massive rock with the characteristics of a solidified brecciated flow. The flow breccias generally contain thin tabular and lens-shaped layers of massive, unbrecciated, banded vitrophyre from about 1 to 10 feet thick. The attitude of these layers ranges from steeply inclined to nearly horizontal and is parallel to the flow structure of the breccias with which they are associated. These layers represent thin flows of massive vitrophyre which are continuous over only short distances.

The typical pyroclastic breccias form thin tabular and thick irregular masses composed of a jumble of unsorted fragments of vitrophyre, perlite, and scarce porphyritic dacite surrounded by a glassy tuffaceous matrix. These rocks have a typically nonfoliated clastic structure or are only indistinctly foliated, are commonly without any visible layering, and are intercalated with beds of dacitic tuff.

Andesitic inclusions.—At one locality, in the upper part of north Fahang ravine (Kanat Fahang Katan), a bed of vitrophyre breccia contains rare rounded pebbles and cobbles of light brownish-gray quartz-bearing augite-hypersthene andesite as much as 8 inches in diameter. These inclusions are significant because, together with accessory inclusions of augite andesite in mixed dacitic pyroclastic beds at Fañunchuluyan beach, they represent the oldest known rocks in the volcanic basement of Saipan and have presumably been derived from bodies of andesite underlying the dacitic rocks of the Sankakuyama formation.

Thickness, areal distribution, and typical occurrences.—Dacite vitrophyre and perlite breccias account for 40 to 50 percent of the area underlain by rocks of the Sankakuyama formation. Tabular layers of breccia interbedded with tabular flows of unbrecciated dacite are found in the type section of the formation at Mount Achugau (Ogso Achugau), the basal breccia layer there being 400 feet or more thick. An upper layer high in the same section has a maximum thickness of 100 feet, though the minimum thickness is much less because the bed thins laterally. Several large irregular bodies of breccia and flow breccia in the Sabanan Achugau district are interlayered with dacite flow rock and beds of dacitic tuff, the latter with a composition much like that of the matrix of the pyroclastic breccias. Breccia lies above and below the lens-shaped body of dacite flow rock in the cliffs at Fañunchuluyan beach, and is well-exposed in the road cut along the East Coast Highway west of here. The eastern part of the body of vitrophyre flow breccia in the Nanasu Grasslands (Sabanan Nanasu) has a minimum calculated thickness of 340 feet; and in the western part of the same mass a thickness of 240 feet is exposed in the cliffs on the north side of the upper part of Nanasu ravine (Kanat Nanasu).

Origin.—Interpretation of origin of the dacite vitrophyre and perlite breccia is limited by the facts that they have been deeply eroded and displaced by faulting and are only imperfectly exposed. Their origin was probably complex, and unequivocal explanation for parts of the breccia facies is difficult.

Vitrophyric and perlite breccias associated with banded and steeply inclined flow rocks in the northern part of the dacitic terrain may have originated in part as thick viscous masses of self-brecciating lava extruded without extensive flowage at the surface from a volcanic dome or domes. The typical breccia of this area has a chaotically dislocated and steeply inclined (40°–90°) contorted flow banding, and some outcrops show thin, steeply inclined layers of massive, unbrecciated foliated vitrophyre. The presence locally in the breccias of what appear to be typical pyroclastic materials may be explained by the falling-in of airborne debris or by local incorporation of preexisting pyroclastic materials. Some of the more indistinctly foliated, structurally heterogeneous, and nearly flat-lying masses of breccia within the Sankakuyama formation are as thick as 200 feet and are associated with highly foliated breccias. These possibly formed as viscous, glassy, steep-sided flows or coulees, which moved slowly outward and away from a domal protrusion or other vent source and became brecciated by reason of movement during and following solidification. Other breccias may have originated as the product of hot avalanche or talus breccias, accumulating around domes or cones.

In the vicinity of Mount Achugau and in the central and southern parts of the area of dacitic outcrop, breccia beds are interlayed with thin beds of vitric dacitic tuff and surface lava flows. These lack flow structure or other visible layering. They are without reasonable doubt the product of explosive eruption.

The extreme vesicularity of many of the glassy breccia fragments, the fragmental and banded nature of the breccias, and the explosive origin of many of these rocks suggest that the lavas which gave rise to the breccias were viscous and gas-rich.

DACITIC TUFFS

Lithology and field relations.—The dacitic tuffs of the Sankakuyama formation include well-stratified, medium- to coarse-grained, light-gray to white, glassy tuff and minor beds of lapilli tuff. They form tabular beds and lenses intercalated with nonfoliated vitrophyric and perlitic pyroclastic breccias. The pyroclastic texture and predominantly small grain size of these tuffs serves to distinguish them from other facies of the formation.

Typical dacitic tuffs consist of small interlocking shards of dacite glass, small fragments of dacite vitrophyre and perlite, and generally broken angular grains of oligoclase, quartz, and small crystals of accessory magnetite. The beds of medium-grained tuff in the type section of the formation at Mount Achugau are almost entirely of elongate and somewhat flattened shards of glass and small angular grains of quartz and oligoclase (average composition about An_{20}). The glass shards are as long as 1 cm. They are flat, elongate, and oriented roughly parallel to the bedding. The quartz, oligoclase, and magnetite grains generally form less than 5 percent of the rock by volume. The mineral grains are less than 2 mm in diameter. The vitric tuffs are similar in composition and texture to the fine- and medium-grained tuff matrix of the pyroclastic breccias.

The approximate composition of glassy dacitic tuff from the type section at Mount Achugau is 65–75 percent glass shards, 20–30 percent dacite vitrophyre and perlite fragments, 2–4 percent oligoclase and quartz, and less than 1 percent magnetite.

The glassy dacitic tuffs are mostly well-bedded and commonly thinly bedded. Ordinarily they are well-indurated, massive, and unjointed; but in many places the bedding is cut and even offset by jointing and by internal movement of small magnitude along joint surfaces. They are evidently quite porous, for weathering commonly reduces them to a white, punky clay.

The other principal group of dacitic tuffs, the lapilli tuffs, are formed of an aggregate of coarse angular fragments of dacite vitrophyre, perlite, and porphyritic dacite surrounded by a finer-grained matrix of glass shards, rock fragments, and small grains of quartz, plagioclase feldspar, and magnetite. The matrix is lithically identical to the fine-grained glassy tuffs. It is commonly light gray or white, powdery, and, because of weathering, soft at the surface. Like the fine-grained glassy tuffs, the lapilli tuffs are well bedded and the foliation is commonly broken along myriads of closely spaced vertical joints. The characteristic color of the coarse tuffs is pale red to light gray and white.

In the cliff section on the south side of Nanasu ravine (Kanat Nanasu), fine-grained glassy tuffs and lapilli tuffs are interbedded with thin layers of compact, well-indurated, grayish-red tuff which has a marked platy parting parallel to the bedding. The platy parting is coupled with a closely spaced vertical jointing. The layers are thus intensely fractured and broken so as to resemble thin beds of breccia.

Thickness, areal distribution, and typical occurrences.—The dacitic tuffs form a minor part of the Sankakuyama formation and are found at widely separated intervals throughout it. They underlie an area of only a few acres within the main area of dacitic outcrop. Typical outcrops are the thin tuff bed (about 10 feet thick) in the upper part of the type section at Mount Achugau and the tuff sequence that crops out in the south wall of the upper part of Nanasu ravine (Kanat Nanasu). The latter has a calculated thickness of about 400 feet, and the maximum thickness of the tuffs here is probably somewhat greater. A small body of glassy tuff in the upper part of north Fahang ravine (Kanat Fahang Katan) is about 60 feet thick. The minimum thickness is probably much less, for the tuff beds appear to grade or lens out into the breccia facies.

Origin.—The dacitic tuffs presumably represent consolidated beds of explosively erupted volcanic ash and lapilli. There is no evidence to suggest that they are other than typical subaerially deposited pyroclastic rocks.

MIXED DACITIC PYROCLASTICS

Plates 5*A*,*C*, 18*A*

Lithology and field relations.—The mixed dacitic pyroclastics comprise interlayered breccias and coarse tuffs, mainly aggregates of the several textural types of dacite. They are well bedded and crossbedded.

The tuffs are medium- to coarse-grained, bedded tuffs and lapilli tuffs. They consist of angular fragments of dacite vitrophyre and perlite, porphyritic dacite (rare), inclusions of augite andesite, glass shards, and broken grains of quartz, feldspar, and magnetite. In some instances they are almost entirely of vitrophyre fragments. Grain size ranges from a fraction of a millimeter to about 3 cm. The tuff beds are fairly well consolidated, porous, a few inches to tens of feet thick, and interbedded with layers of breccia. Cross lamination is common, but ripple marks, swash marks, and rounded particles were not observed.

The breccias are of two fairly distinct types. The commonest (pl. 5*A*) are tuff-breccias composed of angular fragments of dacite vitrophyre and perlite and scarce to abundant accessory inclusions of dark grayish-brown, massive, aphanitic augite andesite. In some beds these mafic inclusions constitute about 10 percent by volume of the breccia. The rock fragments are enclosed in a matrix of finer-grained material made up of small fragments of dacite vitrophyre, glass shards, and small grains of quartz and oligoclase feldspar. The larger rock fragments range in size from a fraction of an inch to about 1 foot across, while the inclusions of augite andesite are mostly less than 5 inches across. The average diameter of the rock fragments is about 3 or 4 inches. The breccias are well bedded, though not in so distinct a manner as the tuffs. They form tabular beds and layers from a foot or so to tens of feet thick. The principal difference between the breccias and tuffs is in grain size.

A second type of breccia crops out near the base of the pyroclastic rocks in the islet of Maigo Fahang and at the foot of the cliffs above Fañunchuluyan beach. The breccia is composed of elongate, tabular blocks of light-gray to white, fine-grained, glassy tuff and angular, roughly equant fragments of banded dacite vitrophyre. The flattened, crudely rectangular-shaped blocks of tuff have an average length of about 6 or 8 inches and a maximum length of about 2 feet. They are well indurated but porous, and are composed of small glass shards and grains of quartz and oligoclase feldspar. Many of the blocks are rectangular or trapezohedral in outline, and their long axes are alined roughly parallel to the general lamination of the pyroclastic sequence as a whole (see pl. 5*A*). The structure is locally so pronounced that it resembles the face of a brick wall. The matrix or "mortar" between the tabular blocks comprises about one-fourth to one-half the volume of the breccia. The matrix is a fine- to medium-grained tuffaceous material composed of angular fragments of dacite vitrophyre, glass shards, and small angular grains of quartz and oligoclase feldspar. The structure of the beds suggests an intraformational breccia.

Thickness, areal distribution, and typical occurrences.—The mixed dacitic pyroclastic rocks form the small islet of Maigo Fahang (pls. 5*C*, 18*A*) just offshore from Fañunchuluyan beach and are exposed along a distance of one-fourth mile in the sea cliffs above the southern part of Fañunchuluyan beach to the west of Maigo Fahang. This, the only outcrop of such rocks on Saipan, exposes an incomplete thickness of about 160 feet of beds.

Origin.—The well-developed low-angle crossbedding and unusual brecciated structure suggest that the mixed pyroclastic rocks were deposited in shallow water, rather than subaerially, in contrast to most of the Sankakuyama formation. Field relationships, in turn, suggest that these beds represent a seaward facies of some part of the Sankakuyama formation.

EOCENE

HAGMAN FORMATION

Plates 6, 7, 10*A*, 12*D*,*E*, 13*A*, 18*B*, 21

DESCRIPTION OF THE FORMATION

General characteristics.—The Hagman formation includes andesitic pyroclastic rocks, lava flows, and water-laid volcanic sediments, some of which contain late Eocene fossils. Its three principal facies comprise occurrences of andesite flow rock 30 feet or more thick, breccias and tuffs, and conglomerate and tuffaceous sandstone.

The Hagman differs from the Sankakuyama formation below in being dominantly andesitic, and from the Densinyama formation (mainly above) in generally lacking quartz and quartz-bearing rocks.

Some of the tuffaceous sandstones of the Hagman formation closely resemble parts of the Fina-sisu formation (late Oligocene) and the Donni sandstone member of the Tagpochau limestone (Miocene), and isolated outcrops belonging to these three units are at places separable mainly on the basis of stratigraphic association and fossils. Similarly, parts of the conglomerate-sandstone facies are indistinguishable from local non-quartz-bearing parts of the corresponding facies of the Densinyama formation except on the basis of stratigraphic association. Confusion with the Densinyama may be aggravated by the atypical presence of occasional pebbles of quartz porphyry in the conglomerate-sandstone facies of the Hagman formation, and of quartz grains and fragments of dacite in the basal Hagman beds at and near their overlapping contact with the Sankakuyama formation.

Thickness.—The thickness of the Hagman formation is taken as 1,100 feet—roughly the same as the cumulative thickness of its facies. The true maximum thickness of the formation could well be greater. To add the thicknesses of partially equivalent parts is admittedly a crude and inaccurate means of approximating the whole, which we cannot measure; yet this seems a reasonable thing to do. For one thing, estimated facies thicknesses are probably not true maximum thicknesses, and some allowance should be made for submarine and subsurface extensions. Indeed, it seems entirely possible that subsurface thicknesses in central parts of the outcrop area may exceed those of some of the marginal locations where measurements and computations are necessarily made. On the other hand, some facies may be in part repeated stratigraphically. A realistic estimate of total thickness, therefore, is believed likely to fall toward the maximum cumulative figure.

Areal distribution and typical occurrences.—The Hagman formation underlies a considerable part of eastern and west-central Saipan, in the hilly grasslands known as Sabanan As Akina and Sabanan Talofofo. Smaller areas of outcrop are at Mount Laulau and the Sabanan Hagman area, in the southeast center, and in the Achugau district of the north-central part of the island. The combined area underlain by rocks of the Hagman formation is about 1¼ square miles.

Typical occurrences of the three facies of the Hagman formation are as follows: (1) andesitic flow rock is exposed in the lower part of Talofofo creek, in the bottom of the northern branch of south Fahang ravine (Kanat Fahang Lichan), and in As Agaton creek (Sadog As Agaton); (2) the breccia-tuff facies is best developed in the Talofofo grasslands (Sabanan Talofofo) and at Mount Laulau; and (3) the conglomerate-sandstone facies is best exposed in the sea cliffs at Hagman beach (Unai Hagman), the type locality of the formation.

Type section.—The name "Hagman andesite" was proposed as a formation name by Tayama (1938, p. 31) without designation of a specific type section, although Point Hagman (Puntan Hagman) was cited as the type site. At this locality the conglomerate-sandstone facies of the Hagman formation is well exposed (pls. 6*E*, 7*A–B*), but other facies are missing. However, this outcrop represents the best exposure of any part of the Hagman formation on Saipan and is therefore here adopted as the type section.

Terrain, vegetation, and weathering.—The terrain underlain by rocks of the Hagman formation is generally one of sharp local relief (pls. 17, 18*B*, 20*A*). Intermittent runoff has produced a dendritic drainage pattern of steep-sided, V-shaped ravines that are locally more than 100 feet deep and as long as three-fourths of a mile. The two perennial streams on the island, Talofofo creek (Sadog Talofofo) and the northern branch of I Hasngot ravine (Kanat I Hasngot), flow across rocks of the Hagman formation and have their source in springs issuing from the contact between the breccia facies and the overlying Tagpochau limestone.

A dense growth of swordgrass flourishes on the Hagman terrain, and there are also thin stands of casuarina on many of the ridge crests.

These rocks are readily susceptible to prevailing weathering processes. The intensity of alteration and decay depends both on topographic location and on the texture and degree of consolidation of the rocks.

Fossils, age, and correlation.—All fossils found in the Hagman formation are from the conglomerate-sandstone facies. Included in mainly fine-grained calcareous tuffaceous sandstones are the distinctive larger Foraminifera *Biplanispira, Discocyclina,* and *Pellatispira;* about 175 species of smaller Foraminifera from 19 localities; small fragments of coral; echinoid spines and plate fragments; rare bits of mollusks such as *Conus* and *Mytilus;* fragmentary articulate and crustose coralline algae; and rare pieces of the green algae *Halimeda* and *Cymopolia.*

Rocks resembling the Hagman formation and probably correlative with it are found on Tinian, Rota, and Guam.

Comparison is made in table 5 of selected significant fossils known from the Hagman and other formations of Eocene age on Saipan.

In the present study principal reliance in pre-Pliocene age determination is placed on the larger Foraminifera because of their wide distribution across facies and because their age relations appear to be fairly well established in Indonesia. On this basis, and as is discussed in more detail in the chapter on "Larger Foraminifera," the Hagman formation, Densinyama formation, and the Matansa limestone all appear to be of late Eocene age. Field relationships, although concordant with partial equivalence, indicate also a general upward succession from oldest to youngest in the order named. The adjacent diagram indicates that the generic distribution of the larger Foraminifera on Saipan is at least consistent with this succession and could be construed to substantiate it. As there is also a strong correlation between faunal variety and number and preservation of samples, the apparent faunal restrictions

TABLE 5.—*Partial list of fossils from the Eocene rocks of Saipan*

	Hagman formation[1]	Densinyama formation[2]		Matansa limestone		
	Facies					
	Conglomerate-sandstone	Conglomerate-sandstone	Limestone-conglomerate	Transitional	Pink	White
LARGER FORAMINIFERA						
(Identified by W. Storrs Cole)						
Asterocyclina sp	×	×	×	×	×	×
Biplanispira fulgeria (Whipple)	----	×	×	×	×	×
mirabilis (Umbgrove)	----	×	×	×	×	×
hoffmeisteri (Whipple)	×	×	×	----	----	----
Camerina saipanensis Cole	----	×	×	×	×	×
Discocyclina (*Discocyclina*) *amphala* (Fritsch)	×	×	×	×	×	×
Fabiania saipanensis Cole	×	×	×	×	×	×
Heterostegina saipanensis Cole	×	×	×	×	×	----
Pellatispira orbitoidea (Prorale)	×	×	×	×	×	----
Spiroclypeus vermicularis Tan	----	----	×	×	×	×
SMALLER FORAMINIFERA						
(Identified by Ruth Todd)						
Benthonic:						
Angulogerina vicksburgensis Cushman	×	----	----	----	----	----
Asterigerina sp	×	----	----	×	----	----
Bulimina semicostata Nuttall	×	----	----	----	----	----
Cibicides cocoaensis (Cushman)	×	----	----	----	----	----
Dentalina cooperensis Cushman	×	×	----	×	----	----
Gaudryina (*Siphogaudryina*) *rugulosa* Cushman	----	----	×	----	----	----
Nonion micrum Cole	×	----	----	----	----	----
planatum Cushman and Thomas	×	----	----	----	----	----
Robulus alato-limbatus (Gömbel)	×	×	----	×	----	----
Siphonodosaria cocoaensis (Cushman)	×	----	----	----	----	----
Planktonic:						
Globorotalia centralis Cushman and Bermudez	×	×	----	----	----	----
Hantkenina sp	×	×	----	----	----	----
ALGAE						
Articulate corallines	×	×	×	×	×	×
Crustose corallines	×	×	×	×	×	×
Codiacean green, *Halimeda* sp	×	----	×	×	----	×
Dasycladacean green, *Cymopolia* sp	----	----	×	----	----	×

TABLE 5.—*Partial list of fossils from the Eocene rocks of Saipan*—Continued

[1] No fossils were found in the flow rocks and breccia-tuff facies.

[2] No fossils were found in the breccia facies.

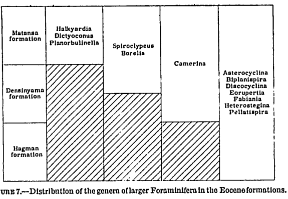

FIGURE 7.—Distribution of the genera of larger Foraminifera in the Eocene formations.

could be artificial and cannot be considered significant unless similar ranges are repeated in other areas.

Origin.—The Hagman formation includes subaerially deposited pyroclastic rocks, lava flows, and penecontemporaneously reworked marine volcanic sediments. The late Eocene volcanic activity which produced these rocks presumably followed a period of erosion and nondeposition, for rocks assigned to the conglomerate-sandstone facies of the Hagman formation unconformably overlie Sankakuyama dacites in the northeast-central part of Saipan.

The breccia-tuff facies and the conglomerate-sandstone facies of the Hagman formation are closely interrelated. The breccia-tuff facies is interpreted as a landward, subaerial, pyroclastic deposit that grades eastward (seaward) into the largely marine conglomerate-sandstone facies. The source material for the latter was washed and wasted into the sea along the margin of a primarily volcanic landmass and was probably also in part erupted directly into the sea. Much the same general relation between contemporaneous subaerial and water-laid facies of andesitic and basaltic pyroclastic rocks exists today along the margins of the young volcanic islands of the northern Marianas.

The rock fillings of the vents from which the rocks of the Hagman formation were erupted either do not outcrop or were not recognized. They may be buried beneath younger deposits or perhaps were located wholly to the west of the present island. The eastward-dipping, homoclinal arrangement of the Hagman formation and the general absence of a water-laid conglomerate-sandstone fringe along the western side of Saipan suggest that the major source of the eruptive products lay to the west of the present land area. The Hagman formation thus probably represents the preserved eastern margin of a formerly more extensive mass of dominantly pyroclastic deposits whose eruptive centers lay farther west in a once larger island mass.

SUPPLEMENTARY DESCRIPTIONS OF MAPPED FACIES

ANDESITE FLOW ROCK

Lithology and field relations.—The flow rocks of the Hagman formation include tabular bodies, 30 to 80 feet thick, of augite andesite and augite-hypersthene andesite. They are interlayered with the fragmental rocks and do not form a continuous unit.

A 40-foot-thick flow that is associated with andesitic tuffs north of the eastern end of Talofofo road is light to dark olive-gray, vesicular, finely porphyritic augite andesite. Small acicular phenocrysts of labradorite are set in a microcrystalline groundmass composed of lath-shaped crystals of labradorite and fewer grains of augite, magnetite, and ilmenite(?). The top of the flow is highly vesicular; the vesicles are as much as 5 mm in diameter, commonly flattened oval, and in places lined with zeolites. The base and middle of the flow are minutely vesicular, and many of the vesicles are lined with zeolites. This flow overlies dacite vitrophyre breccia of the Sankakuyama formation. The flow itself is overlain by siliceous, radiolarian-bearing tuffaceous sandstones and calcareous tuffaceous sandstones, some of which contain abundant smaller Foraminifera.

The other flow rocks of the Hagman formation are light to dark greenish-gray to light purplish-gray, medium-grained, massive, porphyritic augite-hypersthene andesite. They contain abundant equidimensional phenocrysts of labradorite and fewer of hypersthene and augite. The groundmass is microcrystalline and contains microlites of plagioclase; small grains of monoclinic pyroxene, magnetite, and ilmenite(?); tabular crystals of tridymite and needles of cristobalite(?); and small isolated prisms and irregular forms of anorthoclase(?). Hypersthene and augite phenocrysts and groundmass pyroxenes in some of the flows possess narrow to broad reaction rims of finely granular hematite, magnetite, and monoclinic pyroxene. The augite-hypersthene andesite flows are characteristically homogeneous and lack flow banding and vesicularity.

Like other flow rocks on Saipan, those of the Hagman formation lack pillow structure. Unlike those of the Fina-sisu formation they also lack columnar jointing. The Hagman flows in Talofofo ravine, however, are traversed by a widely spaced, platy parting subparallel to their top and bottom surfaces.

Thickness, areal distribution, and typical occurrences.—Andesite flow rocks form a minor part of the Hagman rock succession, the total outcrop area of the 5 known occurrences being only about 10 acres.

The already mentioned flow north of the eastern end of Talofofo road crops out in the bottom of the northern branch of south Fahang ravine (Kanat Fahang Lichan). This flow has a maximum thickness of about 40 feet and is of small lateral extent. A massive flow of augite-hypersthene andesite about 80 feet thick is exposed in the bottom of Talofofo creek (Sadog Talofofo) and another of unknown thickness in the bottom of As Agaton ravine (Kanat As Agaton) in northwest Saipan. A flow about 30 feet thick occurs in the first ravine south of Talofofo creek, and a small irregular body of this rock (not shown on the geologic map) is associated with water-laid conglomerate and sandstone in the upper part of Halaihai ravine (Kanat Halaihai).

Weathering, terrain, and vegetation.—Exposures of the flow rocks are very small, not intensively weathered, and not characterized by any special terrain or vegetation features.

Origin.—The flow of vesicular augite andesite that is interlayered with marine tuffs of the conglomerate-sandstone facies presumably originated by the quiet outwelling and spreading out beneath the sea of fairly fluid lava. The vesicularity, to be sure, might be interpreted to suggest a subaerial origin, but the probable depth of deposition of the marine beds above and below casts doubt on the abrupt fluctuations of sea level that would be necessary to account for a subaerial flow within these beds.

The characteristically nonvesicular and poryphyritic augite-hypersthene andesite flows associated with the breccia-tuff and conglomerate-sandstone facies were probably somewhat more viscous upon eruption than the flow of augite andesite. The flows associated with the breccia-tuff facies were erupted subaerially if our inference as to the subaerial origin of this facies is correct.

The tabular, concordant body of augite-hypersthene andesite that is interlayered with beds of calcareous andesitic conglomerate and sandstone, along the lower part of Talofofo creek, may represent either a flow or a shallow sill. The lower contact with the sediments appears to be very regular and sharp, but there is no indication of an upper chilled margin that might suggest an intrusive origin. Like the flows associated with breccia of the Hagman formation, this flow (or sill) is massive and nonvesicular, is devoid of pillow structure, and does not exhibit columnar jointing. Because it is interlayered with marine volcanic sediments it is inferred to be a submarine flow.

BRECCIA-TUFF FACIES

Plates 6*A*,*B*, 10*A*, 12*D*,*E*, 21*B*

Lithology and field relations.—The breccia-tuff facies is made up of irregular, poorly consolidated, and largely unstratified andesite breccias which contain minor irregular beds and lenses of tuff-breccia, lapilli-tuff, and medium- to coarse-grained tuff.

The unaltered breccia is a coarse, heterogeneous aggregate of generally coarsely porphyritic fragments of many textural varieties of andesite surrounded by a medium- to coarse-grained matrix of lithic tuff. Augite-hypersthene andesite, quartz-bearing augite-hypersthene andesite, augite andesite, and hypersthene andesite are the common rock types. The fragments range in size from lapilli that are a fraction of an inch in diameter to blocks having a diameter of 6 feet. The average diameter of the blocks is perhaps 1 foot or slightly less, and they form 70 to 90 percent of the volume of the breccia. At a few places the breccias grade to tuff-breccias, whose composition is of more tuff matrix than larger fragments. In fresh exposures the breccia fragments range from angular to rounded, but angular and subangular fragments predominate. The chief megascopic characteristic of the breccia fragments is their mineralogic and textural heterogeneity. Their colors, when fresh, are light and dark gray, light to dark greenish-gray, brownish-gray, and pale red.

A generally medium- to coarse-grained tuff matrix forms about 10 to 30 percent of the typical andesite breccia and as much as 60 percent of the tuff-breccia. It is identical in texture and composition to the andesitic tuff and lapilli tuffs which form thin beds and lenses within the breccia-tuff facies. It includes angular to subrounded ash- and lapilli-sized fragments identical to the rock types that comprise the larger breccia fragments, as well as fewer grains of plagioclase (labradorite), augite, hypersthene, and magnetite. The labradorite grains are generally subhedral to anhedral, have a maximum length of about 5 mm, and average 1 or 2 mm in greatest diameter. Augite and hypersthene grains are generally euhedral to subhedral and broken. They have a maximum diameter of 8 mm and an average diameter of 1 mm. Magnetite grains are subhedral and anhedral and are generally less than 0.5 mm in diameter.

The thin irregular beds and lenses of medium- to coarse-grained tuff and lapilli tuff of the breccia-tuff facies are from about 1 foot to 10 or more feet in thickness, are poorly stratified, and are composed of angular fragments of andesite and fewer grains of labradorite, augite, hypersthene, and magnetite. Rock fragments are predominant. The tuff beds are discontinuous, commonly lens-shaped, and can rarely be traced far. In general they are moderately consolidated.

Along the eastern side of the island the breccia grades into and interfingers with a marginal marine facies of calcareous andesitic conglomerate and tuffaceous sandstone.

Thickness, areal distribution, and typical occurrences.—The largest areas of outcrop of the breccia-tuff facies are in the southern part of the Talofofo grasslands (Sabanan Talofofo), where the thickness is at least 400 feet and may exceed 600 feet; in the northwestern part of the As Akina grasslands (Sabanan As Akina); at Mount Laulau (Ogso Laulau), where roughly 600 feet of section is exposed; and at the water tank hill in the I Lisong district. Although this facies underlies an area of only 0.8 square mile, it is the most widely exposed unit of the Hagman formation.

Typical outcrops of the breccia-tuff facies are at so-called "Water Tank Hill," in an abandoned railroad cut along the south side of Mount Laulau, in the andesite quarry adjacent to the West Coast Highway about one-half mile due east of Point Flores (Puntan Flores), and in the headwater area of Talofofo ravine.

Weathering.—The rocks of the breccia-tuff facies are intensely weathered at the surface, and the alteration extends tens of feet downward. At and near the surface the mainly porphyritic breccia fragments are generally altered to red, green, lavender, gray, brown, yellow, and white clay materials; to ferric oxides (hematite, goethite, limonite); and to serpentine and chlorite minerals. At the same time, these fragments retain their original grain shapes and textures as a result of contrast between the weathering products of groundmass and phenocrysts. This relict texture is a characteristic feature of the weathered breccia boulders.

Thin tuff beds, and the tuff matrix of breccias within the breccia-tuff facies, are commonly in a more advanced state of decay than the larger rock fragments. Relict texture is indistinct, and the concentration of ferric oxides is much greater in the tuffs than in the decayed andesite blocks.

In the upper part of the weathered zone of the breccia-tuff facies, the larger andesite blocks at some places have a core of fresh rock surrounded by concentric mantles of decayed rock. The fresh cores of these boulders work loose from the breccia through erosion and removal of the weathered mantle. They then scatter over the surface, giving a false impression of the intensity of alteration and the true degree of angularity of the breccia fragments.

The soil developed on the breccia-tuff facies is dark red to reddish brown and is commonly slightly mottled at depth. The soils are ordinarily not more than 1 or 2 feet thick and have a pH of 6.0 or lower. Because of deep dissection in areas underlain by the facies, a soil mantle has little chance to develop except on gently sloping ridge crests.

Origin.—The breccia-tuff facies of the andesitic Hagman formation is interpreted as a landward, subaerially deposited accumulation of volcanic debris that grades eastward (seaward) into a largely marine conglomerate-sandstone facies. The variety of the breccia fragments probably indicates that they mostly represent accessory volcanic debris, derived from preexisting andesitic rocks of earlier eruptions. Cognate blocks, derived from coexisting magmas and lavas during eruption of the breccia, are scarce or nonexistent. Only a few breccia fragments are similar enough in composition and texture to breccia-associated flows to pass for cognate material.

The breccias, and the thin tuff beds which are interlayered with the breccias, are devoid of interstitial calcium carbonate, fossils, and sedimentary structures that would indicate a water-laid origin.

CONGLOMERATE-SANDSTONE FACIES

Plates 6*D*,*E*, 7*A*–*C*, 13*A*, 21*A*

Lithology and field relations.—The conglomerate-sandstone facies includes intergrading beds of well-to poorly stratified, partly calcareous, water-laid andesitic conglomerate and tuffaceous sandstone. The beds form irregular, lens-shaped layers which pinch and swell along the bedding and are commonly of limited lateral extent. They lie mainly along the east-central margin of Saipan and grade westward to the breccia-tuff facies of the Hagman formation.

The conglomerate-sandstone facies differs from the breccia-tuff facies in its generally better bedding, its larger proportion of tuffaceous materials, its content of marine microfossils, and in the more generally rounded nature of its larger fragments. It differs from the otherwise similar conglomerate-sandstone facies of the Densinyama formation in generally lacking quartz or quartz-bearing rock fragments.

The conglomerates of this facies consist mostly of rounded to subangular fragments of andesite. Locally they also contain rare fragments of dacite porphyry and occasional pebbles and cobbles of gray to brown limestone having Eocene Foraminifera. The variety of andesite rock types is the same as that of the breccia facies—augite-hypersthene andesite, quartz-bearing augite-hypersthene andesite, and augite andesite are the commonest varieties. The fragments range in size from pebbles less than ½ inch in diameter to boulders 15 feet long—a common size is 1 to 2 feet across. Bedding in the thick boulder conglomerate beds is poorly developed.

The sandstones are mostly thinly bedded and cross laminated. Some are calcareous but others are noncalcareous. Locally, in exposures north of the Talofofo road, a few beds of fine-grained tuffaceous sandstone are siliceous and contain Radiolaria, and still other beds contain pebbles and smaller fragments of dacitic rocks. Such sandstones are found at and near the basal contact of the Hagman strata with the underlying dacitic rocks of the Sankakuyama formation. Table 6 gives the estimated range in mineral composition of the typical sandstones in the facies.

TABLE 6.—*Estimated composition of typical sandstones in the conglomerate-sandstone facies, in percent by volume*

	Noncalcareous sandstones	*Calcareous sandstones*	*Radiolarian-bearing sandstones*
Andesite fragments	10–30	5–30	10–20
Plagioclase (labradorite)	50–60	40–60	40–60
Augite	5–10	1–5	5–10
Hypersthene	5–10	1–5	2–5
Magnetite	1–4	1–2	1–2
Calcium carbonate (includes Foraminifera)	--------	5–40	--------
Radiolaria	--------	--------	1–5
Clay minerals	0–10	0–10	0–15

Noncalcareous sandstones are common in the coastal outcrops at Hagman and I Naftan and in exposures north of the Talofofo road. The typical rock is a light greenish-gray, light-gray, or yellowish-brown, compact, even-textured, crystal-lithic tuffaceous sediment. It consists of small angular fragments of andesite and angular and broken grains of labradorite (An_{50-65}), augite, hypersthene, and smaller grains of magnetite. Fragments of light- to dark-brown andesitic glass, with included plagioclase and pyroxene microlites, are common in some of the sandstones. The rock is mostly medium- to coarse-grained and fairly well sorted. Grain size generally ranges between 0.1 and 1.5 mm, with a mean grain diameter of slightly less than 1 mm. Some beds, however, contain rock fragments as much as 2 cm in diameter.

Calcareous sandstones locally characterize the conglomerate-sandstone facies along the coast at Hagman but are most common in eastern Talofofo and in the northernmost outcrops of the facies. They contain interstitial calcium carbonate, Foraminifera, and occasional fragments of calcareous algae, altogether totalling 5 to 40 percent of the rock volume. The unweathered rock is light greenish gray to nearly white, more rarely yellowish brown and brownish gray, and compact. It consists of angular fragments of andesite, reworked fragments of fine-grained tuff, and angular grains of labradorite (An_{50-65}), hypersthene, augite, and small grains of magnetite. These sandstones are moderately well sorted and medium to coarse grained. Grain size ranges between 0.1 and 1.2 mm in a typical sample, and occasional fragments are 2 or 3 cm.

Thickness, areal distribution, and typical occurrences.—The conglomerate-sandstone facies is exposed over an area of about 270 acres and toward the east coast it largely underlies younger limestones. It crops out at several places in the Talofofo and Hagman grasslands, and in the coastal bluffs at the east of Naftan peninsula, and north of Talofofo road. The largest and best exposed area of outcrop is in the type section of the formation at Hagman (pls. 7*A*,*B*, 21*A*).

The computed minimum thickness of the facies in the bluffs above Hagman beach is 400 feet, and the maximum thickness may well be several hundred feet greater. The thickness in a dissimilar succession north of the eastern end of Talofofo Road is computed to be about 390 feet. The actual thickness cannot reasonably be approximated because a complete section is nowhere exposed, and the attitude of the beds at most localities is erratic or obscure.

Weathering.—The conglomerate-sandstone facies and associated flows of augite-hypersthene andesite are relatively fresh at the surface. This is due only in part to the well-consolidated nature of these rocks. The short length of time that the observed outcrops have been exposed to weathering is probably a more significant reason for the relatively fresh condition of the conglomerate and sandstone, in particular. This facies lies seaward of the breccia-tuff facies and its principal occurrences are in relatively new exposures along or near the shore. Where exposed in cliff faces and capped by younger limestones the conglomerate and sandstone beds are quite unweathered (pls. 7*A*,*B*).

Origin.—The conglomerate-sandstone facies is interpreted to be the result of the reworking of volcanic source materials, derived mainly from the penecontemporaneous breccia-tuff facies, in a nearshore marine environment.

DENSINYAMA FORMATION

Plates 7*D*, 8*A*, 17*A*, 18*B*, 20*A*

DESCRIPTION OF THE FORMATION

General characteristics.—The Densinyama formation comprises andesitic conglomerates, noncalcareous and calcareous andesitic tuffaceous sandstones, quartzose conglomerates and sandstones, tuffaceous limestones, and conglomerates that consist of andesite and limestone pebbles and cobbles. An andesite breccia that occurs locally at the base of the formation may represent a direct pyroclastic accumulation. The formation is characterized by the almost unfailing presence of quartz and quartz-bearing rocks, and by the fact that it is a generally well-bedded sequence of sandstone and conglomerate with intercalated lenses and beds of impure limestone.

The Densinyama beds are distributed among three principal facies, as follows (roughly from base to top): breccia facies; conglomerate-sandstone facies; and limestone-conglomerate facies. The conglomerate-sandstone facies is further subdivided into quartz-rich and quartz-poor subfacies.

It is difficult to distinguish some parts of the Densinyama formation from the Machegit conglomerate member of the Tagpochau limestone, and from parts of the Hagman formation, and it is entirely possible that parts of these three units have locally been confused in mapping.

Thickness.—The thickness of the formation varies conspicuously from one locality to another. Its aggregate total has been computed as about 730 feet in the type section, but this is an extremely rough computation based on a series of allowances calculated to give a low to moderate figure. The actual thickness probably at places exceeds 800 feet, and the formation thins to disappearance. A round figure of 800 feet is thus rather arbitrarily taken for the approximate maximum thickness of the Densinyama formation.

Areal distribution and typical occurrences.—Densinyama strata underlie an area of about 2 square miles in the north-central and east-central parts of Saipan. The largest areas of outcrop are in the As Akina and Talofofo districts. The breccia facies is exposed on the east and west flanks of Talofofo ridge beneath the conglomerate-sandstone facies. Beds of the conglomerate-sandstone facies also crop out along a discontinuously exposed belt of volcanic rocks in the I Hasngot, I Denni, As Teo, and Papago districts; in the western part of the Papago district in the gently rolling terrain immediately below and east of the Tagpochau cliffs; and at Hagman.

Type section.—The name "Densinyama beds" was proposed as a formation name by Tayama (1938, p. 33) without designation of a type section. He gave as a type locality the ridge called Densinyama (radio hill) by the Japanese, the correct native geographic name of which is Ogso Talofofo, or Talofofo ridge (pls. 17, 20*A*, 24*C*).

The best section of the formation is exposed along Talofofo road, an old track that runs west and east from the crest of Talofofo ridge in north-central Saipan. The succession at this place, here designated the type section, includes about 730 feet of beds of the three main facies of the formation, but the bulk of it is of the conglomerate-sandstone facies. It is summarized in figure 6 and described in appendix A.

Weathering.—The rocks of the breccia and conglomerate-sandstone facies of the Densinyama formation are highly altered at the surface, and their andesitic components are in most instances completely changed from their original composition. Effects of weathering processes extend tens of feet down.

Andesite fragments weather to mixtures of white, brown, green, maroon, and lavender clay and ferric oxides; the plagioclase phenocrysts ordinarily weather to a white kaolinitic clay; the ferromagnesian minerals weather to serpentine and chlorite minerals and eventually to montmorillonite clays and iron oxides; and the groundmass minerals weather to a mixture of clay materials and ferric oxides (principally limonite and hematite). As in the Hagman rocks, relict textures are preserved in weathered andesite boulders, and they tend to weather spheroidally.

The quartz-bearing rocks of the Densinyama formation are much less affected by weathering. The outer surface of silicified pyritic rocks and chert boulders is commonly altered to a brownish limonitic mantle from a fraction of an inch to several inches thick. The common alteration products in the siliceous fragments are kaolin minerals and brown and yellowish-brown geothite and limonite. A few chert boulders contain small flecks of hematite, and silicified pyritic rocks contain small flaky aggregates of alunite.

The limestone-conglomerate facies is not weathered in the same manner as the breccia and conglomerate-sandstone facies. The volcanic fragments in the impure limestone and limestone-volcanic conglomerate weather to clay, but at many places the calcareous cement tends to retard weathering. However, leaching of the calcareous bond from such rocks may completely destroy their identity and leave behind only a clay mass representing the compacted alteration products of the included volcanic materials.

The soils developed from parent rocks of the Densinyama formation are dark brown and brownish red at the surface. The subsoil is red, yellowish red, and gray, locally mottled. The soils developed from noncalcareous rocks are acidic, especially at depth, and have a pH of 6.0 and lower. Soils developed over calcareous beds are slightly acidic or neutral. The deepest soils are developed in areas of tuffaceous sandstone and conglomerate and are largely confined to broad ridgecrests, for the terrain is deeply dissected and the soil is extensively removed by erosion. Little or no soil mantle has developed over much of the exposed breccia facies, for erosion in areas of breccia outcrop has formed steep bare slopes, and any loose decayed rock material is washed away as it forms.

Terrain and vegetation.—The topographic relief in the Densinyama outcrop area along Talofofo ridge (pls. 17*B*, 18*B*) averages nearly 100 to 150 feet. Closely spaced, relatively deep, V-shaped ravines head immediately below the crest of Talofofo ridge and drain northwest and southeast from it. The longest stream is about three-fourths mile.

Swordgrass is the prevalent plant on the Densinyama terrain. Casuarina thrives in some areas, particularly on the crests of ridges. Although jungle growth is largely absent from volcanic terrain, it covers a large area of Densinyama beds on the eastern side of Talofofo ridge. This jungle growth includes pandanus, thorn trees, breadfruit, and many vine plants. Its existence on the volcanic rocks is probably related both to topography and to calcareous content of the underlying strata—leading to moisture retention and production of a soil less acid than that characteristically formed over primary volcanic rocks of this region.

Fossils, age, and correlation.—Fossils of the Densinyama formation are from the quartz-rich part of the conglomerate-sandstone facies and from the limestone-conglomerate facies. Wherever fossils are sufficiently distinctive for their age to be determined, these fossils are late Eocene, Tertiary *b* of the Indonesian faunal succession.

In addition to fossils tabulated under discussion of the age of the Hagman formation, the conglomerate-sandstone facies of the Densinyama formation has yielded other Foraminifera; rare molluscan fragments; ostracods; echinoid fragments; and two small fragments of silicified dicotyledonous wood. The coralline algae from this facies are mostly fragmentary.

The limestone-conglomerate facies contains larger Foraminifera at many localities. Miliolids and other forms represent the smaller Foraminifera. The abundant and mostly fragmentary articulate and crustose coralline algae are represented by genera such as *Lithothamnion*, *Archaeolithothamnion*, and "*Corallina.*" Bits of coral, occasional molluscan fragments, echinoid spines, and fragments of other organisms have been noted in thin sections and found in outcrop at a few places. At localities S150 and S190 the calcareous green alga *Halimeda* is fairly abundant and a dasycladacean alga probably referable to *Cymopolia* was noted in sections from S219.

The Densinyama formation cannot be confidently correlated with any specific stratigraphic unit on any of the other Mariana Islands or elsewhere in the western Pacific. However, a bed of calcareous andesitic sandstone, containing about 5 percent of small quartz grains, and exposed along the west slope of Carolinas hill on Tinian, may be equivalent to part of the Densinyama formation.

Origin.—The basal breccia facies of the Densinyama formation is probably the product of subaerial volcanic eruption, though this is difficult to prove. The breccia does not contain fossils or interstitial calcium carbonate, the included rock fragments are angular to rounded and unsorted, and the structure of the deposit resembles that of a volcanic breccia. The rock fragments that make up the breccia are predominantly andesitic, but fragments of quartz-bearing rock are present in small quantity, and perhaps represent fragments of rock torn loose from within the volcanic vents during eruption of the breccia materials. The fact that some of the fragments are rounded will not be regarded as an objection by those who have observed the common occurrence of rounded constituents in recent volcanic agglomerates. Yet, angularity of a conspicuous fraction of the larger constituents and lack of sorting suggest short transport and little or no reworking.

The sedimentary deposits of the conglomerate-sandstone facies of the Densinyama formation were derived through marine reworking of preexisting volcanic and sedimentary source materials. The presence of marine fossils indicates that deposition took place in a marine environment, and the kinds of benthonic Foraminifera and algae in the rocks indicate accumulation at depths that range from probably less than 10 fathoms to perhaps as much as 100 fathoms or more. The presence of dicotyledonous wood at one locality suggests (but does not prove) the presence of land nearby, and some of the deposits could be intertidal. Associated beds and lenses of impure limestone and calcareous conglomerate are thought of as isolated lenticular masses deposited at various stratigraphic levels within the upper part of the conglomerate-sandstone facies. These calcareous beds are in part laterally equivalent to and gradational with the basal transitional facies of the Matansa limestone.

Fragmentary articulate coralline algae are the most abundant bioclastic element in the limestone-conglomerate facies, but all of this material could be transported. Some of the crustose corallines, however, are found as broad surfaces of pavement-type algae or crusts around large matrix grains and indicate entombment in or very near the place of growth. The presence of *Halimeda* indicates warm water, and the occasional dasycladacean algae indicate not only warm but very shallow water at the site of deposition or in the near vicinity (Cloud, 1952a, p. 2134).

The rocks which make up the breccia facies are believed to be of an accessory nature and derived from preexisting flows and pyroclastic rocks of earlier eruptions, perhaps including material from the Hagman and Sankakuyama formations. The andesitic rocks of the conglomerate-sandstone facies and the limestone-conglomerate facies were probably in large part derived from the Hagman formation and from the breccia facies of the Densinyama formation. Dacite fragments and some of the free quartz grains in these rocks have presumably been derived from the Sankakuyama formation. The limestone fragments in calcareous conglomerate beds are Eocene, and their most likely source is from calcareous deposits in part equivalent to the Mantansa limestone. However, the concentrations of quartz-rich rocks (chert, silicified pyritic rocks, dacite porphyry, and free quartz grains) in parts of the conglomerate-sandstone facies were probably derived from some source outside the present outcrop area of the Matansa, Hagman, and Sankakuyama formations, for the exposed parts of these formations do not contain large masses of chert and other quartz-rich rocks of the type found in the Densinyama formation. The source of these rocks is presumably either buried by other sediments or was situated in the western part of the inferred formerly larger land area.

SUPPLEMENTARY DESCRIPTIONS OF MAPPED FACIES

BRECCIA FACIES

Lithology and field relations.—The breccia facies of the Densinyama formation is a heterogeneous mixture of coarse, angular to rounded fragments of pyroxene andesite and scattered fragments of several types of quartz-bearing rocks in a tuffaceous matrix. The matrix forms from 5 to 50 percent or more of the deposit. The rock fragments are mainly varieties of augite-hypersthene andesite, quartz-bearing augite-hypersthene andesite, and augite andesite. The quartz-bearing rocks include chert, partially to completely silicified pyritic rocks, coarsely porphyritic dacite, and finely porphyritic, glassy dacite.

The andesite fragments of the breccia facies range from a fraction of an inch to 4 feet in diameter, with a mean diameter of about 6 inches. The siliceous fragments have a much smaller average diameter, ranging from less than an inch to perhaps a foot across. However, a wrong impression of smaller size range and predominance of siliceous elements is easily given by the weathering loose of siliceous fragments from the matrix, and their local concentration as gravel blankets a foot or so thick over the surface of the breccia. Fragments of weathered andesite that work out the matrix quickly disintegrate and are removed by rainwash.

Thickness, areal distribution, and typical occurrences.—The breccia facies lies at the base of the Densinyama formation, is overlain by the conglomerate-sandstone facies, and forms a substantial part of the Densinyama succession. It is exposed over a total área of about one-third of a square mile. The largest areas of outcrop are on the east and west flanks of the central and northern part of Talofofo ridge, where it unconformably overlies the andesite breccia and tuff facies of the Hagman formation. It has a maximum thickness of about 240 feet in a section along Talofofo road west from Talofofo ridge. Elsewhere it is between 40 and 100 feet thick, with an average near 60 feet.

CONGLOMERATE-SANDSTONE FACIES

Plate 7*D*

Lithology and field relations.—The conglomerate-sandstone facies constitutes the largest part of the Densinyama formation and consists of intergrading, stratified, locally calcareous, water-laid beds of conglomerate and sandstone. The individual beds are continuous only over short distances, for they represent lenses or intertonguing bodies of rock that grade laterally into one another. The chief sedimentary classes are tuffaceous sandstones, pebble conglomerates, and boulder conglomerates. They consist of subangular to well-rounded fragments of andesite, dacite, chert, silicified pyritic rocks, and free quartz grains. Andesite fragments are the most abundant, but locally there are beds that contain little or no andesite. The most distinctive components are the widely distributed quartz-rich rocks and free quartz grains. Conspicuous boulders of massive, sulfide-bearing, iron-stained chert are abundant in the lower part of the conglomerate-sandstone facies.

The local presence of interstitial calcium carbonate and marine microfossils and an intimate association with the impure limestone and calcareous conglomerate facies, serve to separate the conglomerate-sandstone facies from the breccia facies of the Densinyama formation. There also appears to be a gradual increase of calcareous materials toward the upper part of the facies.

Its quartzose components set it apart from otherwise similar rocks in the Hagman formation. The quartz grains are dominantly angular and some are doubly terminated euhedral crystals. They are as much as 4 mm in diameter and average about 2 mm. On the basis of abundance or essential absence of visible quartz the facies is divided into two subunits: one with much quartz, and the other with little or no quartz.

Extensive outcrops of an andesitic conglomerate that contains little or no visible quartz or fragments of quartz-bearing rock occur in the I Denni district and in the As Teo district immediately east of Adelug cliffs. This quartz-poor conglomerate grades northward into quartz-rich beds of the conglomerate-sandstone facies in the vicinity of the Cross-Island Connecting Highway along the northern boundary of the I Denni district. The quartzose components reach their maximum concentration in outcrops along the western part of Talofofo road. Here the rocks are siliceous conglomerates with rounded fragments of andesite, chert, quartz dacite, and other siliceous rock fragments in a matrix rich in quartz grains and hydrous ferric oxides.

South of the Talofofo road, both east and west from Talofofo ridge, the basal part of the conglomerate-sandstone facies consists of a boulder conglomerate that is almost exclusively of chert fragments. These fragments are well rounded and range from a fraction of an inch to 10 feet across. The chert fragments in the boulder conglomerate and in other conglomerate beds of the Densinyama formation are massive and vuggy; are commonly iron-stained at the surface; and are light to dark reddish brown, yellowish brown, grayish red, pale red, and light gray. A few of the chert boulders are thinly layered or banded.

Nature of the siliceous components.—The chert fragments consist of fine-grained cryptocrystalline silica with a grain size less than 0.01 mm. Finely divided hematite and hydrous ferric oxides (principally birefringent goethite), are present in the cherty rocks in volumes as great as 5 to 10 percent. Sulfide minerals also occur in many of the chert fragments as finely disseminated grains. The grain size of the sulfides is ordinarily less than 0.5 mm. In some of the chert fragments, small irregular vuglike cavities as long as several millimeters are lined with small drusy quartz crystals and thin coatings of sulfide minerals which include pyrite, chalcopyrite, arsenopyrite(?), and bornite(?). Azurite, malachite, and hematite are found lining some of the small vugs and are evidently an alteration product of the copper and iron sulfides. The chief sulfide mineral of the chert fragments is pyrite. Specular hematite(?) is present in some of the rocks as small euhedral crystals less than 0.05 mm long. In thin section it is transparent and deep red. Tayama (1938) even reports traces of gold associated with the sulfides in the pyritic rocks.

The pyritic chert boulders are thought to be mainly of replacement origin, though some of the thinly banded and sulfide-free fragments may be chemically precipitated.

The chert fragments are associated with partly silicified rocks in several stages of replacement. Relict minerals and replacement textures give some clue to the nature of the original parent rock from which they have been derived. Most of the partly silicified rocks are heavily iron-stained and are reddish-brown, pale red, and light grayish red. They contain finely divided hematite, goethite, and limonite. Relict grains of feldspar and quartz as much as 4 mm in diameter are common in these rocks, but the large quartz grains are not invariably present. The feldspar grains are partly altered to a flaky aggregate of alunite and fine-grained quartz and occasionally to a mixture of alunite, kaolinite, and quartz. In many of these rocks the feldspar grains are completely altered, and their former presence is marked only by patches of flaky alunite and fine-grained quartz. In some instances cryptocrystalline silica has replaced the feldspar grains in a manner that has preserved the crystal outline of the feldspar. Remnant feldspar grains are oligoclase-andesine, having a composition between An_{25} and An_{35}.

The groundmass of the silicified rocks generally consists in large part of cryptocrystalline silica, with disseminated hydrous iron oxides, hematite, and scattered sulfide grains (to as much as 3 or 4 percent of the rock volume). Sulfides are common in the alunite-bearing rocks, and in a few rocks pyrite constitutes as much as 40 or 50 percent of the volume. The sulfides are generally very finely divided, small, euhedral to subhedral crystals less than 0.05 mm in diameter. Weathering tends to convert the sulfides to ferric oxides.

Large quartz grains are present in the groundmass of some of the silicified rocks. These quartz grains are angular to rounded and have ragged borders toward the chertified groundmass. The free quartz grains of the sandy component of the conglomerate-sandstone facies are euhedral to subhedral and do not closely resemble the occasional quartz grains of the cherty rocks.

A few of the silicified rocks contain grains of ankerite as much as 0.1 mm in diameter in finely crystalline patches as much as a millimeter across. The ankerite is generally associated with thin stringers of goethite.

Thickness, areal distribution, and typical occurrences.—The conglomerate-sandstone facies crops out over an area of about 1½ square miles in the north- and east-central parts of the island, the largest areas of outcrop being in the Talofofo and As Akina districts. In the type section of the formation along Talofofo road it is calculated to be roughly 500 feet thick. A discontinuous north- to south-trending belt below and east of Adelug and Machegit cliffs has a calculated incomplete thickness of about 240 feet; and a nearly isolated mass of unknown thickness crops out in the western part of the Papago district, below and east of Tagpochau cliffs. An 80-foot conglomerate layer near the top of the steep slopes in the northern part of the Hagman grasslands thins eastward and pinches out beneath overlapping Miocene limestone.

Origin.—The remarkable concentration of the varied quartz-rich rocks in parts of the conglomerate-sandstone facies needs special explanation. The best implication as to probable source for the noncherty siliceous rocks is found in the two small dacitic volcanic plugs already described under the Sankakuyama formation. These plugs are apparently older than the Hagman breccia and are probably related in time of origin to unexposed facies of the Sankakuyama dacite succession. Although in themselves they do not seem a logical or adequate source for all of the noncherty quartzose rocks that have been reworked into the Densinyama beds, they suggest the nature of this source.

The derivation of the large chert boulders in conglomerate beds of the Densinyama formation is also not specifically known but their size suggests a source nearby. Many of the large chert blocks have a clastic texture such as might have been derived from silicification of impure limestone or tuffaceous rocks. The thinly layered, banded, variegated chert boulders could have been derived from beds of marine chert formed by chemical precipitation of silica. Such beds might occur beneath Densinyama ridge or in former source areas to the west, but none are known to crop out.

When all local possibilities have been exhausted, it becomes evident that some additional source outside the presently exposed parts of the Matansa, Hagman, and Sankakuyama formations is needed to account for the presence of such a large concentration of quartz grains and quartz-bearing rocks in the Densinyama formation. Again it is convenient to call upon the formerly greater provenance area that is thought to have extended westward from present-day Saipan in late Eocene time.

The sedimentary nature of the upper part of the Densinyama formation is indicative of a marked change in the geologic processes acting to form the rock succession of Saipan. With the advent of Densinyama time, and shortly following an early phase of volcanic activity that produced the basal breccia facies, volcanic eruption temporarily ceased to be the dominating factor in rock genesis on Saipan, and marine deposition became dominant.

LIMESTONE-CONGLOMERATE FACIES

Lithology and field relations.—The limestone-conglomerate facies forms lens-shaped and irregular beds within the upper part of the conglomerate-sandstone facies. The typical impure limestone of this unit is coarse-grained, thickly to thinly bedded, fragmental, and light brown to yellowish white or pink. It contains many small pebbles, granules, and grains of andesite; chert and silicified pyritic rocks; and small, anhedral to euhedral grains of quartz. In places, impure limestone grades to a relatively pure, compact, inequigranular, detrital limestone. The impure limestones of this facies differ from parts of the basal transitional facies of the Matansa limestone only in being completely included within typical Densinyama beds so far as can be told or inferred from available outcrops.

Thin sections show that the tuffaceous limestones contain from 20 to 80 percent of bioclastic calcite ranging in grain size from 0.2 to 10 mm, with a common range of 0.5 to 1.0 mm, and including mostly fragmentary articulate coralline algae and larger Foraminifera. Miliolids and other smaller Foraminifera are also common locally. The matrix which makes up 20 to 80 percent of the rock, is of tuffaceous material and crystalline calcite, the grains of which are less than 0.1 mm and commonly only a few microns in diameter.

Calcareous conglomerates are generally associated with the impure limestones and the two are laterally and vertically gradational. The mainly subrounded pebbles and cobbles of the calcareous conglomerates are of foraminiferal limestone, andesite, and quartzose rocks surrounded by a medium- to coarse-grained tuffaceous matrix with a calcium carbonate bond. The volcanic fragments are as much as a foot in diameter, but the mean diameter is 1 to 2 inches. In the As Akina district several thin and widely separated patches of conglomerate are devoid of intermixed volcanic material and include only rounded pebbles and cobbles of compact, fossiliferous Eocene limestone.

Thickness, areal distribution, and typical occurrences.—The largest continuous outcrop of the impure limestone and calcareous conglomerate facies is a 13-acre patch that lies immediately below and east of the crest of Talofofo ridge, east of the ridge road and mostly south of the Talofofo road. On the eastern flank of the northern part of Talofofo ridge the facies is about 50 feet thick, but it thins markedly and pinches out north and south along the strike. Small isolated patches of the facies, a few feet to 10 or 20 feet thick, are also found in the As Akina district. The total land area underlain by the facies is only about 30 acres in extent, and it forms a very minor part of the Densinyama formation.

Origin.—The impure limestone and calcareous conglomerate facies is envisioned as isolated lenticular masses or tongues within the upper part of the conglomerate-sandstone facies of the Densinyama formation. These calcareous beds are probably laterally equivalent to and gradational with the basal part of the Matansa limestone, for the basal transitional facies of this limestone is contaminated with volcanic material and interfingers with conglomerate and sandstone beds of the Densinyama formation, and both contain similar assemblages of large Foraminifera. This equivalence is significant. It indicates that at least part of the conglomerate-sandstone facies of the Densinyama formation was formed contemporaneously with massive detrital limestone in closely associated and intergrading marine environments.

MATANSA LIMESTONE

Plates 8*B*, 17*A*

DESCRIPTION OF THE FORMATION

General characteristics.—The Matansa limestone is a pure to impure, inequigranular, clastic limestone containing distinctive upper Eocene Foraminifera. It includes three principal facies: (1) a basal transitional facies of dull yellowish to red-brown, tuffaceous to marly limestone and calcareous conglomerate; (2) pink, highly foraminiferal clastic limestones; and (3) white, sparingly foraminiferal clastic limestones.

These limestones are mostly well indurated and massive to well bedded. They grade from relatively pure calcium carbonate rock to impure or even tuffaceous limestones with increasing proportions of volcanic detritus. This volcanic material is ordinarily andesitic, but the facies also includes a high proportion of quartz grains. Disseminated manganese oxides are common locally and show replacement of microfossils. Colors may be white, pinkish white, pink, dull red, or yellowish to reddish brown.

The range in size of individual grains of the Matansa limestone on megascopic inspection appears to be chiefly from 0.5 to 3.0 mm, and the rock shows an extreme range in grain size from a few microns to 25 mm long. The larger grains are mainly Foraminifera or bits of algae, but the largest of all are angular, of the same composition as the matrix, and commonly coated with a thin film of clear calcite. In a random selection of thin sections studied, particles less than 0.1 mm to about 10 microns in largest dimension make up from 5 to 70 percent and characteristically account for 20 to 50 percent of the rock. Part of this material is considered to be detrital on account of its darkness and the irregular shapes of the grains, but much is clear microcrystalline calcite. The latter is interpreted as the inversion product of interstitial precipitate that probably came down as aragonite.

The basal beds of the formation overlie or grade laterally to the upper beds of the Densinyama formation, and the basal contact may be either transitional or locally unconformable. The beds that succeed the Matansa in the local column are the probably Oligocene volcanic rocks of the Fina-sisu formation, but these have nowhere been recognized in direct contact with the Matansa. In the local succession the Matansa beds are actually overlain by Miocene (Tertiary *e*) or Quaternary deposits.

The white facies of the Matansa limestone has nowhere been seen in the same succession with the other two facies of this formation. However, the transitional facies is gradational upward and laterally to the pink facies, and the white facies is generally a still purer calcium carbonate rock than the pink facies, although approximating its characteristics locally. This, as well as field relationships, suggests that the white and pink facies probably intergrade in the same manner as the pink and transitional facies. The general upward succession appears to be one of increasing purity from transitional through pink to white.

Thickness.—The greatest observed thickness of the Matansa limestone is at Tanke cliffs (Laderan Tanke), in northeastern Saipan, where an incomplete section of the white facies measures about 260 feet thick. A complete section of the white facies would probably be at least 300 feet thick, and the composite thickness of the Matansa formation as a whole is 500 feet or more.

Areal distribution and typical occurrences.—Outcrops of the Matansa limestone as here recognized are restricted to the north-central part of Saipan, between Fañunchuluyan and Talofofo. Altogether they cover less than a square mile.

A typical occurrence of the white facies of the Matansa limestone is in the lower part of Tanke cliffs (see fig. 9, and description of Tanke cliffs section), and the pink facies is well displayed toward the south end of Papua cliffs (Laderan Papua), the type section of the formation. The basal transitional facies occurs at several localities along both sides of Talofofo ridge (Ogso Talofofo). It is especially well displayed just north of Talofofo road, where the local thickness is about 140 feet.

Type section.—Tayama (1938, p. 32) applied the name "Matansya beds" to a part of the rocks that are here called Matansa limestone. He cited as the type locality the "Matansya district," an area known to the Chamorros as Matansa. The unit is now redefined and referred to as the Matansa limestone, an Eocene unit of formational rank.

As Tayama did not select a specific type section for the formation, one is here designated. This is the succession of Eocene strata that extends up the southern part of the west-facing Papua cliffs, in the southeastern part of the Matansa district, about 300 feet south of a small roadside quarry. In this section is exposed about 100 feet of beds belonging to the pink facies of the Matansa limestone. It is almost uniform throughout and corresponds to the mode described for the pink facies.

Weathering, terrain, and vegetation.—The pink and white facies of the Matansa limestone are characterized by a terrain of cultivated benches and wooded scarps and the transitional facies by steep brushy to grassy slopes and ravines. Weathering has produced thin clayey soils, with many residual limestone pinnacles on the purer limestone surfaces.

Fossils, age, and correlation.—All facies of the Matansa limestone are fossiliferous. Articulate and (in lesser amount) crustose coralline algae and larger Foraminifera are the most abundant, and the latter demonstrate a late Eocene, Tertiary *b*, age. Smaller Foraminifera are abundant in some thin sections.

Fossils significant for age and correlation are listed in a table under the discussion of the Hagman formation, and further remarks on faunal content are given in the separate discussions of the several Matansa facies.

Origin.—The larger bioclastic and occasional volcanic particles of the Matansa limestone are imbedded in a microgranular matrix of dark, clastic and clear, crystalline calcite. The clear calcite was probably precipitated interstitially as aragonite and only later altered to calcite. The fossils indicate deposition at shallow to moderate depths in a tropical marine environment.

Evidence that the sediments of the basal transitional facies were laid down on and adjacent to parts of the old volcanic land mass is provided by their great impurity, tuffaceous nature, and stratigraphic relationships. The sediments of the pink facies, being purer calcium carbonate but otherwise similar, were presumably deposited offshore from, as well as generally above, the basal transitional sediments. The white facies, consisting of mainly clean bioclastic debris and interstitial, chemically precipitated calcium carbonate, clearly accumulated in a situation where it could receive little contamination from the volcanic core of the island. This requirement would be satisfied either by deposition offshore from the pink facies or by upward succession to purer deposits. As it seems unlikely that either of these conditions would obtain to the complete exclusion of the other, the white facies is interpreted as generally succeeding but also intergrading with the upper part of the pink facies, even though their actual relationships were not observed.

The generally superior position of the white facies, however, is supported by fossil evidence which suggests it to have been deposited in shallower waters than the pink or transitional facies. The abundant larger Foraminifera of those two facies suggest depths of around 40 to 50 fathoms, and although the accompanying algae probably for the most part lived at shallower depths their generally fragmentary nature suggests transport (observed miliolid Foraminifera were probably also transported from shallower water). Larger Foraminifera, on the other hand, are generally rare in the white facies, while miliolids, *Halimeda*, and the dasycladacean *Cymopolia* are locally abundant. This strongly indicates (Cloud, 1952a, p. 2134) shoal depths for origin of much of the white facies sediments. To be more specific, but less cautious, deposition mostly at 15 fathoms or less seems reasonable, and parts of the facies may have come to rest not far below low tide level.

The evidence summarized is believed to favor the view that the transitional and pink facies accumulated mainly at moderate depths in a tropical or subtropical sea around the volcanic core of Saipan and eventually buried it. The white facies then presumably capped this sequence as a bank deposit which accumulated mainly at shoal depths. That its site of deposition was not affected by strong wave action is suggested by the absence of sedimentary breccias and the fact that the sediments are of so high a degree of purity and fineness.

SUPPLEMENTARY DESCRIPTIONS OF MAPPED FACIES

BASAL TRANSITIONAL FACIES

Lithology and field relations.—The basal transitional facies of the Matansa limestone is characteristically a well-bedded, sparingly quartz-bearing, tuffaceous limestone that grades upward into the pink facies of the same formation. It is compact to poorly indurated, medium- to coarse-grained, and grades laterally and downward to parts of the Densinyama formation. Distinction between it and the impure limestone and calcareous conglomerate facies of the Densinyama formation is based on association; and it is understood that some rocks mapped as Densinyama may be only the areally isolated ends of lobes of impure Matansa limestone.

Impurities from underlying and intergrading volcanic rocks are invariably present in the transitional facies. They include particles of andesite, fragments of siliceous rocks, angular to subrounded quartz and feldspar grains, grains of magnetite and hematite, and clay minerals. Quartz is typically abundant, occurring as angular and subrounded grains with an average diameter of about 2 mm. Calcium carbonate is, of course, the major constituent of the rock; and it is mainly fragmental and inequigranular. Much of the rock is a tuffaceous algal-foraminiferal limestone in which the larger grains are mainly fragments of articulate coralline algae 0.3 to 0.6 mm long, and scattered to abundant large Foraminifera as long as several millimeters. These are imbedded in 15 to 30 percent, by volume, of a matrix that consists of minute grains of tuffaceous material and clear crystalline calcite less than 0.1 mm in diameter. The grain size of the rock as a whole ranges from less than 0.1 to 10 or more mm but is predominantly in the range of 0.5 to 2.0 mm. The color ranges through shades of yellow, red, pink, brown, and gray, depending on the amount and kind of impurities that are present.

The characteristic tuffaceous limestone of this facies locally grades into a conglomerate that contains well-rounded pebbles and cobbles of compact Eocene limestone, andesite, chert, and other siliceous rock types in a tuffaceous matrix. This conglomerate occurs as thin, discontinuous layers that are a few feet thick and are interbedded with layers of sandy limestone. The pebbles and larger rock fragments have a maximum diameter of 8 to 10 inches, the average being about 1 inch.

The immediate contact between the basal transitional facies and the overlying pink facies of the Matansa limestone was not observed. However, it is assumed to be a gradational one, as the lowest exposed part of the pink facies contains much tuffaceous material, and there is a gradual decrease in contamination upward into much purer pink limestone.

Thickness, areal distribution, and typical occurrences.—The transitional facies ranges from more than 140 feet thick to a feather edge where it lenses out into the Densinyama formation. On the northeast slope of

Talofofo ridge (Ogso Talofofo), just northeast of the highest point on Talofofo road, the calculated thickness is 60 feet, assuming an approximate average dip of 10 degrees east-northeast. This is probably near the maximum for that immediate area. The maximum computed thickness of 140 feet is in an incomplete faulted wedge on the west side of Mount Achugau (Ogso Achugau), along Talofofo road.

The combined areal extent of the known (two) and probable (one) mappable occurrences of the transitional facies amounts to only about 30 acres. The largest known area of outcrop is in an irregularly L-shaped area that lies northeast of the highest point of the Talofofo road. The questioned patch adjacent to the western part of Talofofo road is assigned to the Matansa limestone, rather than to the limestone-conglomerate facies of the Densinyama formation, because of its nearness to and possible former continuity with the patch of presumed Matansa transitional beds immediately to the north. The fact that it is overlain by beds of the Densinyama formation is interpreted as an outwedging relationship.

Terrain, weathering, and vegetation.—Slopes in areas underlain by this facies are for the most part fairly steep, and erosion has cut down through the poorly consolidated tuffaceous limestone to form short, narrow, steep-walled ravines.

The tuffaceous limestone and conglomerate constituting the facies weathers to a thin red soil that ranges from only a few inches to perhaps a foot thick. The soil is stony and generally neutral to slightly acidic.

Swordgrass is the commonest plant, but Australian "pine", or casuarina, grows in thick stands at some places. Although the areas underlain by the transitional facies were completely burned over in May of 1949, historical records suggest that revegetation will be by the same floral elements.

Fossils and age.—In addition to the algae and Foraminifera tabulated in the discussion on the age of the Hagman formation, the basal transitional facies of the Matansa limestone contains miliolids and other small Foraminifera, rare bits of mollusk shells, and echinoid spine fragments. The age is late Eocene, Tertiary *b*.

PINK FACIES

Plate 8*B*

Lithology and field relations.—The pink facies of the Matansa limestone is a bioclastic limestone of a distinctive flesh-pink to dull-red (rarely white) color, with abundant camerinid and discocyclinid Foraminifera. It is a relatively pure limestone in comparison with the transitional facies but relatively impure compared with the white facies.

It is inequigranular, well indurated, commonly massive or obscurely bedded, and locally well bedded. The grain size ranges from less than 0.1 mm to fragments 15 mm or more across, but the greater volume of the rock consists of 0.5 to 2.0 mm grains. Much of the rock is an algal-foraminiferal limestone in which fragments of mainly articulate coralline algae 0.2 to 0.7 mm long, and scattered to abundant large Foraminifera as much as several millimeters long, are imbedded in 5 to 60 percent (average 15 to 40 percent) by volume of microgranular clastic and clear crystalline calcite. Areas of equigranular rock are common within the general mass but individually insignificant. The larger fragments are characteristically angular, of the same general texture as the matrix, and commonly with a surrounding film of clear microcrystalline calcite. Some of the rounded fragments have algal crusts. Occasional patches of this facies contain disseminated grains of volcanic origin and local concentrations of argillaceous material.

Although nowhere seen in contact with it, the pink facies of the Matansa limestone probably grades laterally in its upper part to the white facies of the same formation and is eventually displaced and succeeded upward by the white facies. Reasons for this conclusion are given under discussion of origin in the general description of the formation.

Thickness, areal distribution, and typical occurrences.—The pink facies ranges from a feather edge to a maximum known thickness of about 150 feet on the west side of, and south-southeastward from, Mount Achugau. It crops out in small patches through areas of older rock. The aggregate area of outcrop is only about 90 acres.

The most typical occurrence and best displayed section of the pink facies of the Matansa limestone is in the west-facing scarp of Papua cliffs (Laderan Papua) in southeastern Matansa, immediately south of a small roadside quarry. Its thickest development is on the west side of Mount Achugau and to the south-southeast. Other occurrences are similar in nature and of minor areal importance.

Weathering, terrain, and vegetation.—The pink facies weathers to a reddish-brown clayey soil, 2 to 3 feet deep, across a sharply defined surface with smooth-surfaced residual pinnacles projecting 3 to 4 feet above the ground. Its terrain of narrow marine benches and abrupt cliffs mostly supports a dense jungle vegetation.

Fossils and age.—Fossils significant in identifying the pink facies as of late Eocene (Tertiary *b*) age are listed in a table under the description of the Hagman formation. Besides the forms there named, this facies of the Matansa limestone also includes abundant miliolids and other smaller Foraminifera locally, occasional bits of coral, the problematical "coral" *Saipania tayamai* Yabe and Sugiyama (loc. C21), rare fish centra, rare Bryozoa, and species of the molluscan genera *Conus*, *Lithophagus*?, *Mytilus*, and *Turbo*?. Genera of coralline algae recognized include the articulates *Jania* and *Corallina* and the crustose *Lithothamniom*.

WHITE FACIES

Plate 17*A*

Lithology and field relations.—This facies is an equigranular, clastic, limestone; well-indurated, massive to locally well-bedded, generally pure, and characteristically white. The grain size ranges from less than 0.1 to 30 mm, most commonly from 0.2 to 1.0 mm. The larger fragments are generally angular and of the same composition as the matrix. It is mainly an algal or algal-foraminiferal limestone, with many articulate coralline algae 0.2 to 0.5 mm long and at places many miliolids and occasional larger Foraminifera. In thin section the matrix of microgranular calcite accounts for about 20 to 50 percent of the rock. This matrix material is less than 0.1 mm to only a few microns in diameter and is partly dark fine-clastic material and partly clear crystalline calcite of probable physicochemically precipitated origin (as aragonite).

Most of the white facies is essentially free of impurities. However, at the base of the Tanke cliff (Laderan Tanke) section is an interval 40 feet thick in which particles of manganese oxide and hematite make up a large part of the rock and in which manganese oxide has replaced the limestone in irregular patches through intervals as much as 10 feet thick. Also, at a few places angular fragments of relatively pure limestone as long as 30 mm occur in a well-indurated argillaceous matrix.

Although the color of the facies is generally white, the rock is locally black to gray from included manganese oxide, pink from included hematite, or reddish brown from interstitial argillaceous material.

Thickness, areal distribution, and typical occurrences.—The thickness of the white facies is at least 256 feet in the measured section below the inequigranular facies of the Tagpochau limestone at Tanke cliff in northeastern Saipan. As a guess, perhaps another 50 to 100 feet extends below the base of this section, a fault contact with breccia of the Sankakuyama formation. This is also the best displayed occurrence of the white facies, but another large mass occurs northward from As Frailan ravine (Kanat As Frailan) on the east side of the island, and three smaller patches are situated along the central ridge of the island just south of Little Burma road. The combined outcrop area is slightly less than one-third of a square mile.

Terrain, vegetation, and weathering.—The terrain of the white facies in general is one of benches and vertical or near vertical scarps, like that of the purer facies of the Miocene Tagpochau limestone. It also has a similar vegetation of jungle growth in scarp areas and cane fields with property-line trees and woodlots on bench surfaces. The rocks weather to a red clayey soil across a sharply defined surface above which residual limestone pinnacles project. The soil is generally less than 2 feet deep but pinnacles are as high as 4 or 5 feet.

Fossils and age.—Some of the characteristic Tertiary *b* (upper Eocene) fossils of the white facies of the Matansa limestone are listed in a table under the description of the Hagman formation.

The larger Foraminifera are rare in this facies, but a wide variety of algae are recorded, and *Halimeda* and the dasycladacean genus *Cymopolia* are locally abundant. Miliolids (and other smaller Foraminifera) are found in many thin sections; are abundant at localities B56, B83, and B85; and are dominant at localities B65 and B185. The usual echinoid spine and shell fragments, and rare bits of mollusks were also noted.

Among algae, the crustose corallines are represented by *Archaeolithothamniom*, *Dermatolithon*, *Lithophyllum*, and *Lithoporella*, and the articulates by *Corallina* and *Jania*. *Halimeda* is not uncommon and is abundant in thin sections from locality B67. Because the dasycladacean algae are especially significant as indicators of shoal water, it is worth recording that the genus *Cymopolia* was observed in thin sections from localities B22, B53, B67, B75, B80, B85, B199, B272, B274, B289, B329, B330, and C12. It is abundant at localities B67 and B199.

OLIGOCENE

FINA-SISU FORMATION

Plate 8*C,D*

General characteristics.—The Fina-sisu formation (new name) consists of calcareous marine tuffs and interbedded andesite flow rocks, with distinctive planktonic smaller Foraminifera in some of the tuffs. Most of the flows are less than 20 feet thick, but one is 80 to 100 feet thick. The tuffs are well bedded and mostly calcareous. Some closely resemble parts of the Donni sandstone member of the Tagpochau limestone, and both flows and tuffs similar to those of the Fina-sisu occur in the conglomerate-sandstone facies of the Hagman formation. The alternation of flows and tuffs, however, appears to be characteristic of the Fina-sisu formation.

On the geologic map the 80- to 100-foot andesite flow and an areally extensive outcrop of similar flow rock of unknown thickness are shown separately from the rest of the formation.

Thickness, areal distribution, and typical occurrences.—The base of the Fina-sisu formation is nowhere exposed, and the true maximum thickness is unknown. The maximum exposed thickness is computed as about 400 feet in the incomplete type section across the Fina-sisu hills or ridge (Ogso Fina-sisu), south of As Lito village.

Outcrops occur sporadically over a deeply weathered area of about three-fourths of a square mile in southern Saipan. Typical outcrops of the interbedded tuffs and flows may be seen along and near As Perdido road, along tracks running north and south from it, and in and adjacent to As Lito village. Fairly fresh porphyritic augite andesite of the 80- to 100-foot flow has been exposed in tunnels along the south side of two of the deeper ravines between the west-facing spurs of Fina-sisu ridge. A 55-acre patch of deeply weathered augite andesite flow rock of undetermined thickness occurs in northwestern As Lito. A few planktonic smaller Foraminifera at 290 to 295 feet in well No. 7, at Chalan Kiya, may be from a thin interval of Fina-sisu strata between Donni and Densinyama beds.

Type section.—The type section of the formation extends eastward from the conspicuous fault at the west side of Fina-sisu hills up the ravine 300 to 400 feet south of structure section *C—C′* (pls. 1, 2), and south of As Lito village, to the unconformably overlapping *Acropora*-rich facies of the Mariana limestone. It is essentially that shown along structure section *C—C′*.

From the faulted base of this section upward to the next fault east it includes roughly 50 to 70 feet of tuff, 80 to 100 feet of andesite, and 250 feet of tuff with interbedded thin andesite flows. The minimum thickness of the formation is thus about 400 feet. Eastward along section *C—C′*, provided there is negligible displacement along faults, the total incomplete section would be about 800 feet thick and contain two thick flows. However, it is conceivable that the flow rock east of As Lito village is a repetition of the same flow that occurs toward the base of the section, just as the outcrops west of the basal fault are probably repeated from above this flow. We can be reasonably sure only that the section is probably more than 400 feet thick.

Further remarks on lithology and field relations.—The flow rock of the Fina-sisu formation is a light to dark olive-gray and greenish-gray, vesicular, aphanitic to finely porphyritic augite andesite. It contains small acicular phenocrysts of labradorite set in a micro-crystalline groundmass composed of lath-shaped crystals of labradorite; less abundant grains of augite, magnetite, and ilmenite(?); and rare prismatic apatite crystals. The tops of the flows are vesicular. The vesicles are as much as 5 mm in diameter and commonly are flattened oval. In places they are lined or filled with zeolites, and, more rarely, with calcite, to form amygdules, but amygdules are not common. The thick flow exposed along the western side of the Fina-sisu hills has a moderately well developed subvertical columnar jointing. The columns are between 1 and 2 feet wide and are intersected by a second system of joints nearly parallel to the flow surfaces. The two joint sets have broken the flows into more or less equidimensional blocks that average about a foot across and weather spheroidally at and near the surface (pl. 8*C,D*).

The typical tuffs are light gray, light greenish-gray, brownish gray, and yellowish brown; well- to poorly consolidated; and fine- to coarse-grained. They are mostly altered to kaolinitic and montmorillonitic clays, serpentine specks, limonite, and hematite. Montmorillonite is the principal clay mineral.

They are water-laid, crystal-lithic tuffs composed of angular and subangular, altered fragments of augite andesite, and grains of labradorite (An_{50-65}), augite, scarce hypersthene, and magnetite. Rock fragments in some beds are a centimeter or slightly more in diameter, but the mineral grains are generally less than 2 to 3 mm in diameter. Some of the tuffs contain abundant smaller Foraminifera and as much as 30 or 40 percent interstitial calcium carbonate. These strongly resemble the *Globigerina* beds of the Donni sandstone member of the Tagpochau limestone, as well as some beds of the conglomerate-sandstone facies of the Hagman formation. Tuffs in which calcium carbonate and Foraminifera are abundant grade into tuffs in which these elements are lacking. The estimated mode of a typical tuff of the Fina-sisu formation (specimen S527) in volume percent is: plagioclase 25 percent, rock fragments 10 percent, augite 5 percent, magnetite 1 percent, Foraminifera less than 1 percent, and clay materials and limonite 58 percent.

Terrain, vegetation, and weathering.—The terrain is one of gently rolling hills, fronted to the west by truncated west-facing spurs that slope gently eastward to the lowland of As Lito and northern As Gonno. To the south and west these hills are clothed with tough, tangled grasses and occasional small to large copses of exotic woodlot trees such as the Formosan koa (*Acacia confusa*). To the north and east they are extensively cultivated.

The rocks of the Fina-sisu formation are intensely weathered, outcrops are few, and nowhere are fresh rocks naturally exposed. The soil developed on the flows and tuffs is orange-red and reddish brown, averages several feet deep, and is 20 feet or more deep at places along As Perdido road. It is acidic and grades downward into the parent rock through a zone of saprolite that preserves the relict texture of the original rock. The tuffs alter to plastic, iron-stained, kaolinitic and montmorillonitic clays in shades of orange, red, green, brown, and lavender.

Fossils, age, and correlation.—Both Tayama (1938) and the present writers earlier referred the rocks of the Fina-sisu to the Hagman formation. Lithic resemblance between these units is strong, and, inasmuch as detailed mapping demonstrated unconformable overlap of the earlier Miocene Tagpochau limestone completely across the Fina-sisu beds, an upper Eocene age assignment for the Fina-sisu was consistent with all we then knew about the stratigraphy of the Mariana Islands.

Subsequent study of field collections by Ruth Todd, however, revealed in the Fina-sisu formation a unique assemblage of 62 species of smaller Foraminifera. Of this total, 44 species are known on Saipan exclusively in the Fina-sisu, whereas only 19 are shared with Eocene (Hagman) and Miocene (Tagpochau) strata. Comparison with microfaunas of other areas then brought out important similarities between the common planktonic Foraminifera of the Fina-sisu beds and those of upper Oligocene strata in the Antillean-Caribbean region (Todd and others, 1954). On the basis of the smaller Foraminifera alone, it now appears that the Fina-sisu formation is an approximate western Pacific correlative of the *Globigerinatella insueta* zone of the Caribbean region—probably late Oligocene, perhaps Chattian, and presumably equivalent to zone *d* of the Indonesian Tertiary. The only other fossils found in the Fina-sisu beds are sparse discoasters and Radiolaria.

The field evidence of unconformable early Miocene overlap also indicates a pre-Miocene (or earliest Miocene) age for the Fina-sisu formation. It thus to a degree substantiates the late Oligocene age determination based on the general expression of the smaller Foraminifera and the common occurrence in Saipan and Trinidad of the distinctive, supposedly short-ranging planktonic species *Globigerinatella insueta* Cushman and Stainforth, *Globigerinoides bispherica* Todd and *Globigerinoides subquadrata* Bronnimann.

Origin.—Modern representatives of the genera of benthonic Foraminifera that occur in the Fina-sisu beds are said by our associate Ruth Todd to live characteristically at depths of 200 fathoms or more. Some of these are *Cassidulina, Dentalina, Ehrenbergina, Pleurostomella, Pullenia, Trifarina,* and *Uvigerina.* These tuffaceous sandstones, therefore, may have originated through the settling of volcanic debris into a marine environment as deep as 200 fathoms or more—although we do not accept this foraminiferal evidence as proving such depth without reservation. It is not known what proportion of the sediments of this formation might represent volcanic ash erupted directly into the sea and what part may be reworked, but the interbedded lava flows suggest a penecontemporaneous derivation for most of it. It therefore is regarded as a true marine tuff.

The flows of augite andesite that are interlayered with the calcareous tuffs presumably originated by outwelling and fluid spreading of lava that was derived from fissures or other vents to the west of the present outcrop area. The flows were very likely submarine, for they are interlayered with marine tuffs.

MIOCENE

TAGPOCHAU LIMESTONE

Plates 6*E*, 7*C*, 9, 10, 11, 12*A*, *B*, 16, 17*A*, 20, 21, 23

DESCRIPTION OF THE FORMATION

General characteristics.—The Tagpochau limestone is a complex of calcareous clastic rocks that intergrade with one another and are distinguished from other fragmental limestones on Saipan mainly on faunal evidence. Its most widely distributed facies is a compact, generally pure, pink to white, inequigranular limestone that is at most places rich in distinctive larger Foraminifera. However, the formation also includes impure limestone, as well as sandstone and conglomerate of reworked volcanic materials.

In terms of the standard Indonesian biotal succession, the Tagpochau limestone appears approximately to span the Tertiary *e* interval of early Miocene age, as will be discussed later. Studies of the larger Foraminifera by W. Storrs Cole permit a twofold faunal subdivision—lower *e* characterized by a group of Foraminifera which will be referred to as the *Heterostegina borneensis* assemblage, and upper *e*, containing other distinctive elements grouped as the *Miogypsinoides dehaartii* assemblage. These zones appear to overlap and to intergrade with an intermediate assemblage characterized by *Miogypsinoides bantamensis* in the zone of overlap.

Six lithic facies and two members are mapped within the Tagpochau limestone, as follows: (1) Donni sandstone member of calcareous, tuffaceous, sand-sized sediments of which some beds are rich in *Globigerina* and other smaller Foraminifera; (2) Machegit conglomerate member, a new formal unit lithically similar to the conglomerates of the Densinyama formation; (3) transitional facies of calcareous tuff, marl, and calcareous andesitic conglomerate; (4) tuffaceous facies of poorly indurated, very impure limestones; (5) marly limestone facies; (6) rubbly limestone facies; (7) equigranular limestone facies; and (8) the dominant inequigranular limestone facies. In several large areas south from Mount Tagpochau it was not feasible to differentiate these facies.

Description of the several facies and members mentioned is reserved for a following section. It

should be noted here, however, that only a rough order of upward succession is (or can be) indicated by the order of listing of subdivisions, especially as regards units 1 through 3 above. Actually the rocks assigned to the Donni sandstone member appear to occur most commonly toward the middle of the general succession; and the Machegit conglomerate member occurs above the Donni member or the transitional facies, or is laterally equivalent to them. Strata referred to the transitional facies itself although typically intervening between the Donni member and more typical calcareous facies of the Tagpochau, may occur either above or below the Donni beds. Reference to the columnar section and structure section on plates 1 and 2 will indicate this complexity graphically.

The other mapped facies of the Tagpochau limestone grade laterally and vertically into one another in even more erratic patterns. They also recur in different parts of the formational succession. Lenses or tongues of each occur commonly in masses of other facies, and local intraformational unconformities are found. Below the dominating inequigranular facies, however, one commonly finds a downward succession through rubbly, marly, and finally tuffaceous facies before reaching the volcanic core rocks. There are many local exceptions to this general rule of succession, however, and even some apparent reversals of it. All of the facies and members except the Machegit conglomerate appear to occur in both the *Heterostegina borneensis* and the *Miogypsinoides dehaartii* faunal zones.

Thickness.—The Tagpochau limestone ranges from a feather edge to maximum incomplete thicknesses of about 820 feet in the type section east of Mount Tagpochau and 900 feet in northern Saipan (composite of Bañadero cliffs and Tanke cliffs section). It also extends to 1,550 feet above sea level at Mount Tagpochau from a position at sea level to the west (structure section *C—C′*). Approximate maximum thickness thus cannot be estimated with assurance. It probably exceeds 900 feet, however, and 1,000 feet is taken as a convenient round figure (see discussion under Bañadero cliffs section, appendix A).

Areal distribution and typical occurrences.—Tagpochau beds cover nearly half of the 48-square-mile land area of Saipan. They form the principal axial uplands of Saipan except for the volcanic segment which extends for 1½ miles south from Mount Achugau. Sections in northeastern and northern Saipan display well the fauna and the purer limestone facies of the Tagpochau. The tuffaceous and marly facies are best developed on the lower western slopes of Tagpochau cliffs in the west-central part of the island, and in the north-central and southwest-central parts. The best and most continuous development of the rubbly facies is on the lower eastern slopes of Tagpochau cliffs in and adjacent to the lower part of the type section, and entirely within the *Heterostegina borneensis* faunal zone.

A general areal pattern of facies trends is recognized. (1) North of Mount Achugau the Tagpochau limestone is dominantly pure and mainly in the inequigranular facies, both in the *Heterostegina borneensis* and *Miogypsinoides dehaartii* faunal zones. However, it includes also some large bodies of the equigranular facies and a few small interfingering patches of impure material represented by the Donni sandstone member and the tuffaceous facies. (2) In north-central Saipan, south from Mount Achugau, the Tagpochau limestone occurs as isolated patches of various facies overlapping volcanic rocks, and largely in the lower *e* or *H. borneensis* faunal zone. (3) In south-central Saipan the pure facies of the Tagpochau are dominant; but the impure facies are also widely developed. Both principal faunal zones are represented here also. (4) South of Mount Tagpochau large parts of the Tagpochau limestone could not be classified in any recognized facies and are mapped as "undifferentiated Tagpochau." All facies of the formation, however, are represented in the southern part of the island, and most outcrops appear to be in the upper, or *M. dehaartii* zone.

Type section.—The Tagpochau limestone was originally described and named as the "Tappocho limestone" by Tayama (1938, p. 35). He gives the type locality as the summit of "Mount Tappocho," which is Mount Tagpochau (Ogso Tagpochau) of the present report. The spelling of the formational name is here revised to conform with Chamorro usage.

The name Tagpochau limestone as here used has also been revised to include both the "Tappocho" and "Laulau" limestones of Tayama. As Tayama cited no type section, one is now designated. This extends from the base of the Miocene succession at the head of the valley that runs westward from Nicholson spring, upward to the summit of Mount Tagpochau. It is situated immediately to the north of structural cross-section *C—C′* as shown by the line of V's on the detailed geologic map (pl. 1). The marly, rubbly, and inequigranular facies are well exposed in this section, which also includes a good development of both principal foraminiferal assemblages. Other facies and members are well displayed to the east and southeast from here.

This section is graphically summarized in figure 6. It shows roughly the following upward sequence of Tagpochau strata: (1) about 90 feet of thinly bedded yellow marls with occasional corals and other megafossils, constituting the marly facies of the Tagpochau limestone but largely concealed by thick residual clays; (2) about 80 feet of yellowish-white, pure to slightly marly, rubbly to powdery and brecciated limestone without well-defined bedding, comprising the rubbly facies of the Tagpochau limestone; and (3) about 650 feet of limestones referred to the inequigranular facies of the Tagpochau limestone. Of the latter about the lower 100 feet are generally thinly bedded and slightly marly; whereas the upper 550 feet are massive, compact, white and pink or variegated limestones. The incomplete thickness of the Tagpochau limestone in the type section is thus about 820 feet. The lower beds, to somewhere within the lower part of the inequigranular facies, carry the *Heterostegina borneensis* assemblage, and the upper inequigranular limestones are in the *Miogypsinoides dehaartii* zone.

Internal relations.—It has already been hinted, and it is apparent on examination, that there is a sort of general succession upward within the Tagpochau strata from the vicinity of any particular buried volcanic mass. The more impure facies occur low in such a section, and the purer limestone facies are at higher stratigraphic positions. But the tuffaceous and marly facies, although prone to be basal or near basal at any particular place, are perhaps more appropriately designated "marginal" facies than "basal" facies. They occur where, or near where, the Tagpochau succession overlapped some volcanic mass, both against the volcanic rocks as overlapping deposits and away from them as interfingering patches or wedges of sediments. As the volcanic core so buried extended from present sea level to at least 767 feet above (Mount Achugau) and perhaps higher (buried under Mount Tagpochau), a facies that might be in a basal position high on a buried hill could easily be higher stratigraphically than a purer limestone facies that was originally deposited offshore from it.

From the probable relief and topographic complexity of the buried volcanic rocks, it is to be expected that the varied facies would be both intergradational and recurrent; and mapping bears out this expectation. Unfortunately, cover by vegetation and younger deposits and the nature of the terrain have prevented tracing facies contacts in the detail to be desired. We have at many places, therefore, inferred the probable configuration of contacts on the basis of the parts of other contacts actually traced in detail. The unavoidably subjective picture that results has been kept as clear as possible by employing special symbols for inferred or arbitrarily located contacts on the geologic map.

The Donni sandstone member seems to occur more constantly at a particular stratigraphic level than other Tagpochau units. It is believed to be near the middle of the formation, considered in an overall view, although at any given place it may be at the base or near the top of the local Tagpochau succession. It abuts, wedges into, and grades laterally and vertically to other facies of the Tagpochau limestone; and it thins from about 200 feet to the point of disappearance.

Terrain, vegetation, and weathering.—Many of the scarps and benches of the island are in the moderately indurated to well-indurated facies of the Tagpochau limestone. The scarps in the well-indurated material attain maximum heights of 500 to 600 feet. The benches in moderately indurated material are commonly modified to a rolling surface with a linear grain. Slopes of 15° to 20° predominate in the poorly consolidated material. Lenses and patches of impure limestone within masses of pure limestone form topographic lows. Most of the scarps and benches are believed to be due to wave erosion and solution at higher stands of the sea (or submergence); but some are due to faulting, which has developed structural scarps and has caused bench surfaces to be repeated.

The more extensive bench surfaces are nearly everywhere covered with old sugarcane fields, separated by straight rows of scrub trees along former property lines or paths. Scarps, steep slopes, ravines, and very small irregular benches generally support a dense jungle-type vegetation. Woodlots of the so-called Formosan koa (*Acacia confusa*) and windbreaks of this, casuarina, or other trees or brush break the monotony of the cane fields on some bench surfaces.

The more purely calcitic facies of the Tagpochau limestone weather by solution to an alkaline to neutral, red to brown, clayey soil (pl. 11*A–B*) over a sharply defined limestone surface from which numerous smooth-surfaced pinnacles project above the soil mantle. The soil averages 2 to 3 feet in depth; the pinnacles, 4 to 5 feet in height. With an increase in included volcanic material the soil layer becomes thicker, acidic, and mottled, and the contact of soil and rock becomes gradational.

Solution also accounts for the fact that vaulted caverns are common in the purer limestones, and that small irregular caves, crevasses, and sinkholes are abundant. Marginal solution ramparts as high as 30 feet are found along the outer (seaward) rim of some benches in the Tagpochau limestone.

Fossils, age, and correlation.—The Tagpochau limestone has yielded a variety of fossils. Larger Foraminifera are generally present, commonly abundant, and ordinarily distinctive. Because of this, and the ties which they provide with the standard Indonesian Tertiary succession, they are regarded as of special importance for correlation of the Tagpochau limestone. Smaller Foraminifera, fragments of mollusks, and algae also occur here and there throughout the formation. They are commonly abundant and locally are dominant rock-forming components. Concentrations of mostly still unidentified impressions of mollusks and small coral-algal reef masses are known locally. Spines and fragments of echinoids are common, and complete specimens have been found. One fairly well preserved carapace of a crab has been recovered from earthy inequigranular limestone in association with the echinoid *Sismondia*, and occasional impressions of crab claws are known from various facies of the formation.

Table 7 gives a partial list of fossils from the Tagpochau limestone, based on paleontologic studies in progress at the time of its compilation. It is intended here only to give a general idea of fossils present and to set forth the principal evidence for correlation and paleoecologic interpretation (for instance, only 30 of the 170 or so species of smaller Formanifera identified are here listed). Comprehensive fossil lists and systematic descriptions and revisions will be included in the paleontological parts of the report.

When all the qualifications are made, the consensus of available fossil evidence favors an early Miocene age for the Tagpochau limestone, as Miocene is understood in the western Pacific. It appears to span Tertiary *e* on the basis of the orbitoid Foraminifera, with lower and upper faunal zones. It is mainly early Miocene in terms of Indonesian mollusk zonation. The corals and echinoids also favor an early Miocene age. Tertiary *f* elements occur in association with larger Foraminifera ordinarily considered distinctive of Tertiary *e*, but these are so unusual that they are interpreted to represent downward extensions of faunal ranges.

By way of amplification, it may be noted that the algae are more useful in ecologic interpretation than in age determination, because their stratigraphic ranges are not yet well understood. Also several extensions of previously supposed geographic and stratigraphic ranges will be noted by the specialist. For example, the blue alcyonarian coral *Heliopora coerulea* is here recorded in the pre-Pliocene of the Indo-Pacific for the first time, the rock-boring echinoid *Echinostrephus* is recorded as a fossil for the first time, and the range of *Katacycloclypeus* is here first extended below Tertiary *f*.

Despite general agreement of the faunal evidence, however, the precise age limits and exact correlation of the Tagpochau limestone cannot be fixed with finality, and some further discussion of these matters is in order.

On the basis of Shoshiro Hanzawa's studies of the larger Foraminifera, Risaburo Tayama assigned his "Laulau limestone," which is here included with the Tagpochau, to the Aquitanian. Tayama considered the Aquitanian to be Oligocene. However, he referred his "Tappocho (=Tagpochau) limestone" to a position within the Miocene. In a conference with Cloud and

TABLE 7.—*Partial list of fossils from the Tagpochau limestone* [1]

	Donni sandstone member	Transitional facies	Tuffaceous facies	Marly facies	Rubbly facies	Equigranular facies	Inequigranular facies
LARGER FORAMINIFERA							
(Identified by W. Storrs Cole)							
Borelis pygmaeus Hanzawa	----	----	×	×	×	×	×
Cycloclypeus (*Katacycloclypeus*) *transiens* Tan	----	×	----	----	----	----	----
(*Cycloclypeus*) *eidae* Tan	----	×	×	----	×	×	×
Heterostegina borneensis van der Vlerk	----	×	×	×	×	----	×
Lepidocyclina (*Eulepidina*) *ephippioides* Jones and Chapman	----	×	×	×	----	----	×
(*Eulepidina*) *badjirraensis* Crespin	----	----	----	----	----	----	×
(*Nephrolepidina*) *parva* Oppenoorth	----	----	×	×	×	×	×
sumatrensis (Brady)	×	×	×	×	----	×	×
verbeeki Newton and Holland	----	----	×	×	×	----	×
verrucosa Scheffen	----	×	×	×	×	----	×
Miogypsina (*Miogypsina*) *thecidaeformis* (L. Rutten)	----	×	×	×	×	×	×
Miogypsinoides bantamensis Tan	----	----	×	----	----	----	×
dehaartii (van der Vlerk)	×	×	×	×	×	----	×
Sorites martini (Verbeek)	----	----	×	----	×	×	×
Spiroclypeus higginsi Cole	----	----	----	----	×	----	×
tidoenganensis van der Vlerk	----	----	----	×	×	×	×
SMALLER FORAMINIFERA							
(Identified by Ruth Todd)							
Benthonic							
Amphistegina madagascariensis D'Orbigny	----	×	----	×	----	----	×
Anomalinella rostrata (H. B. Brady)	×	----	×	×	----	----	×
Asterigerina carinata D'Orbigny	----	×	----	----	----	----	----
subacuta Cushman	----	×	----	×	----	----	----
Cibicides lobatulus (Walker and Jacob)	----	×	----	----	----	----	----
Clavulina angularis D'Orbigny	----	----	----	----	----	----	×
multicamerata Chapman	----	----	----	----	----	----	×

See footnote at end of table.

TABLE 7.—*Partial list of fossils from the Tagpochau limestone*[1]—Continued

	Donni sandstone member	Transitional facies	Tuffaceous facies	Marly facies	Rubbly facies	Equigranular facies	Inequigranular facies
SMALLER FORAMINIFERA—continued							
Discorbis mira Cushman		×					×
Eponides cf. *E. umbonatus* Rouss	×						
Gaudryina (*Siphogaudryina*) *rugulosa* Cushman		×					
Nonion grateloupi (D'Orbigny)							×
pacificum (Cushman)		×					
Osangularia bengalensis (Schwager)	×						
Planorbulina acervalis H. B. Brady		×					
Reussella glabrata (Cushman)		×					
simplex (Cushman)							×
Streblus byramensis (Cushman)		×					
mexicana (Nuttall)		×	×				
Tubulogenerina tubulifera (Parker and Jones)		×					
Planktonic							
Globigerinoides conglobata (H. B. Brady)	×						
rubra (D'Orbigny)	×						
sacculifera (H. B. Brady)	×	×					
Globorotalia menardii (D'Orbigny)	×						
tumida (H. B. Brady)	×						
Orbulina bilobata (D'Orbigny)	×						
universa D'Orbigny	×						
Sphaeroidinella dehiscens (Parker and Jones)	×						
kochi (Caudri)	×						
seminula (Schwager)	×						
ANTHOZOA							
(Identified by John W. Wells)							
Astreopora sp.							×
Heliopora coerulea (Pallas)							×
Leptoseris floriformis Gerth							×
Trochoseris florescens Felix							×
MOLLUSCA							
(Identified by Julia Gardner)							
Gastropoda							
Bulla reussi Martin			×				
"*Cassis*" sp			×				
Cerithium (*Ptychocerithium*) *progoënse* Martin			×	×			
(*Thericium*) aff. *C. columna* Sowerby				×			
Conus sp			×				
Cypraea sp	×		×	×			
Murex sp				×			
Strombus sp			×	?			×
cf. *S. rembangensis* Martin					×		
Terebra cf. *T.* (*Strioterebrum*) *indica* Martin			×				
Trochus sp							×
Turritella cf. *T. javana* Martin				×			×
sedanensis Martin			×	?			
cf. *T. spolongensis* Martin				×			×
Vermetus sp							×
Xenophora sp		×		×			
Pelecypoda							
Arca (*Acar*) *reticulata* (Gmelin)				×			×
Barbatia (*Barbatia*) sp							×
Cardium (*Fragum*) *javanum* Wanner and Hahn				×			×
Chlamys (*Aequipecten*) *exaratus* (Martin)			×	×			
cf. *C. sedanensis* (Martin)		×		×			
Echinochama sp							×
Ensis sp							×
Lithophagus							×
Parvilucina sp				×			
Spondylus sp							×
Tellina sp			?				×
Tridacna sp			×				
Venus (*Chione*) *listeri* Gray							×
ECHINOIDEA							
(Identified by C. Wythe Cooke)							
Acanthocidaris sp		×					
Clypeaster n. sp		×					
Echinolampas aff. *E. convacus* Hayasaka				×			
Echinostrephus n. sp			×				
Heterocentrotus sp		×					
Parasalenia n. sp							×
Schizaster n. sp							×
Sismondia polymorpha Duncan and Sladen (=*S. convexa* Nisiyama)				×	×		×
ALGAE							
Articulate corallines			×	×	×		×
Crustose corallines			×	×	×		×
Codiacean green, *Halimeda* sp			×				×
Dasycladacean green, *Cymopolia* sp							×

See footnote at end of table.

[1] No fossils were found in the Machegit conglomerate member.

Burke on July 13, 1949, Hanzawa gave as his opinion that the faunas of the Tagpochau limestone examined by him represent only Tertiary *e*, which he considers equivalent to the Aquitanian and refers to the late Oligocene. Exhaustive analysis of field and laboratory data in collaboration with W. Storrs Cole finally resulted in realization that the larger Foraminifera from the Tagpochau limestone comprise a *Heterostegina borneensis* zone of early Tertiary *e* age and a *Miogypsinoides dehaartii* zone of late Tertiary *e* age, all Tertiary *e* being here referred to Miocene. Whether Tertiary *e* is most properly to be regarded as Oligocene or Miocene is, of course, a problem which can be permanently settled only on the basis of comparison with the standard European section, and convincing comparison must await the establishment of standards of correlation based on planktonic or pelagic organisms. Pending this, we feel that the evidence summarized favors considering the fauna in question to be earliest Miocene, or roughly Aquitanian.

It has been suggested (Finlay, 1947; LeRoy, 1948) that a world-wide stratigraphic datum is represented by the lowest occurrence of the planktonic foraminifer *Orbulina* s. s. (*O. universa*), a form which makes its first appearance on Saipan in the Donni sandstone member of the Tagpochau limestone. LeRoy (1948, p. 507, also chart p. 504), in fact, believes that this first appearance of *Orbulina* s. s. may correspond "to the divisional line marking Tertiary *e* and Tertiary *f* of central and south Sumatra." He also states that, in Ecuador and the Caribbean, "*Orbulina* and *Candorbulina* enter the section profusely at the base of the Upper Oligocene," with *Candorbulina* extending into the "upper Middle Oligocene." On this basis he would correlate zone *e* of the East Indies Tertiary section with the middle Oligocene of the Caribbean section, although it would seem that the beds in which *Orbulina universa* first appears there are uppermost Oligocene or basal Miocene (Todd and others, 1954, p. 674, 675).

H. J. Finlay, who refers (1947, p. 352) upper zone *e* and the Aquitanian to the base of the Miocene, as we do, indicates the first appearance of *Orbulina* in New Zealand to be basal zone *f*, or roughly Burdigalian. He also states (1947, p. 338) that the first appearance of *Orbulina* (with which he includes *Candorbulina*) "always seems to be somewhere in the early Miocene." Finlay cites, with expressions of doubt, reported occurrences of *Orbulina* in the Aquitanian of Oregon and French Morocco (p. 337), and in the Oligocene of Cuba and Trinidad (p. 338). He also notes that Cushman had plainly indicated the correlative significance of *Orbulina* as early as 1940 (Cushman and Dorsey, 1940, p. 40–42), and calls attention to other published records of its occurrence.

Although one apparently considers basal Tertiary *f* to be late Oligocene and the other Miocene, both Finlay and LeRoy indicate it as the point of first appearance of *Orbulina* s. s. in Indonesia. On Saipan, as already noted, its first appearance is Miocene, in terms of the Caribbean section, and within Tertiary *e* of the Indonesian sequence. The probable upper Oligocene of Saipan (Fina-sisu formation) occurs unconformably beneath the Tertiary *e* beds, within which the Donni sandstone member is intercalated, lacks *Orbulina* s. s., and contains planktonic Foraminifera distinctive of the Caribbean *Globigerinatella insueta* zone. The seemingly different local times of first appearance of *Orbulina* s. s. are probably conditioned by facies relations. It occurs most characteristically in banded calcareous tuffs that were presumably deposited in offshore areas. Where only pure shoal-water limestones occur, planktonic Foraminifera are likely to be rare.

Rocks correlative with the Tagpochau limestone occur on Tinian, Rota, Guam, and elsewhere in the western Pacific, but the proper nomenclature for these strata is mostly not yet established.

Origin.—The distribution, the gradational characteristics, and the lithic and faunal features of the various facies of the Tagpochau limestone indicate that the formation is the composite product of nearshore sedimentary processes, acting over a considerable range of depth and time. Miocene marine deposits overlapped ancestral Saipan and eventually buried it completely. Because the greater part of the island so buried was composed of volcanic rocks and sediments, the immediately overlapping strata of the Tagpochau beds are likely to be tuffaceous or marly, regardless of actual position in the composite vertical section. Although they accummulated nearshore, these sediments probably did not all come to rest in shallow water. They are also of a far greater variety than even the eight subdivisions mapped would imply. In fact, if the distinctive Donni and Machegit members are excluded, the rest of the formation represents an almost continuously variable sequence, within which the facies mapped merely approximate broad central tendencies.

The Foraminifera and algae found in the Tagpochau limestone and its physical features, indicate that its strictly calcareous parts originated mainly in waters of shallow to moderate depth. On the basis of extrapolation from known depth ranges of algae, species of smaller Foraminifera, and the living larger foraminifer *Cycloclypeus* (Cloud, 1952a, p. 2133–2134, 2144), average depths for these parts were probably 10 to 50 fathoms, with a total range from intertidal to somewhat more than 50 fathoms. The abundance of larger Foraminifera also suggests that the bioclastic sediments accumulated on open banks rather than in reef-ringed lagoons. The tuffaceous and marly facies, which occur at basal positions in various parts of the succession, may have in part accumulated along shore and graded seaward to the clastic bank deposits of the inequigranular, equigranular, and other limestone facies.

The rock-boring echinoid *Echinostrephus*, as well as the echinoid *Sismondia* and crabs, probably inhabited nearshore waters. The dasycladacean alga *Cymopolia* implies very shallow water at its place of growth, and, although only fragments were found at most places, its abundance at locality B107 suggests shoal-water deposition. The benthonic smaller Foraminifera also suggest very shallow waters. Direct evidence of true reef remnants has so far been found in the Miocene of Saipan only as a single small coral-algal mound, but probably other small reefs also rose from the shallower parts of the progressively subsiding bank on which the inequigranular facies is inferred to have accumulated.

The matrix of very fine grained (<0.1 mm) calcium carbonate in which the larger bioclastic fragments of the limestone facies are imbedded amounts to about 20 to 50 percent of total rock volume. It contains much clear calcite that is believed to be largely the alteration product of physicochemically precipitated aragonite. At places this forms thin films of clear calcite around clastic grains, as in beach rock. That any of it could really have been beachrock is doubtful both from association and biota, but it would seem that the amount of interstitial precipitate means that the clastic grains were free to move slightly and not tightly packed, as under load.

The benthonic smaller Foraminifera from the Donni sandstone member suggest its origin at greater depths than the 10 to 50 or so fathoms implied for the bulk of the formation. According to Ruth Todd, they indicate depths of 200 fathoms or more for the accumulation of the Donni sediments. At the same time, the transition and wedging of these sediments into shallower water deposits indicates that their depositional environment at places extended into the 50-fathom zone. In fact, these relations make it difficult for us to accept depths much in excess of 100 fathoms, if as deep as this, for the Donni beds, even though they do appear to have formed farther offshore, and probably at greater depths than equivalent limestone beds.

Presumably the volcanic materials that make up the tuffaceous sandstone of the Donni beds were somehow concentrated in a zone of mainly deeper sedimentation below the bank margins—but the question is, how? Lithic resemblance and distribution pattern suggest that the bulk of the Donni sediments may have been moved along the eastern bank margin from current-swept tuff outcrops of the andesitic Fina-sisu and Hagman formations at a sedimentary level mainly below that at which contemporaneous limestone beds were accumulating. The general absence of Donni beds from the western side of the island, moreover, suggests their close relation to source materials, currents, and depth. Likewise, local thickness variations suggest a linear sedimentary trap or area of concentration parallel to and in from the present eastern shore. Shoreline fluctuations during sedimentation naturally produced complicated relations, and scour by descending currents may have locally provided an uneven bottom topography which was then mantled by depositional "folds."

SUPPLEMENTARY DESCRIPTIONS OF MAPPED SUBDIVISIONS

DONNI SANDSTONE MEMBER

Plates 6*E*, 9*A*,*C*, 20*A*, 21*A*

Lithology.—The Donni sandstone member comprises thinly bedded and well-bedded, soft, tuffaceous,

marine sandstone, siltstone, marl, and shaly beds, and pebble and granule conglomerates. The detrital materials are dominantly reworked volcanic sediments and the bonding material is calcareous and weak. Grain size is very fine (< 0.1 mm) to very coarse (4.0 mm or larger), but mostly about 1.0 mm. The color is characteristically drab. It includes shades of brown, gray, green, and light red, but light and dark brown and yellowish to olive gray are dominant.

The detrital components consist characteristically of grains of andesite, with minor dacite(?), clay minerals, magnetite, and quartz, all loosely bound by calcium carbonate. *Globigerina* and other smaller Foraminifera occur at most places and locally constitute the bulk of some thin layers. At places the sandstone contains scattered fragments or even large blocks of fossiliferous Tertiary *e* limestone, that presumably rolled or slid into it from penecontemporaneous deposits in shallower waters above its place of accumulation. Commonly the basal part of the Donni consists of very coarse-grained rock having an average grain diameter of about 4 mm. Locally it even contains thin layers of pebble conglomerate intercalated with fine- to medium-grained sandstone, but such layers rarely exceed a few feet in thickness, and ordinarily they are much thinner. The pebbles are from about 5 mm to 2 or 3 cm in diameter and consist of rounded fragments of intensively weathered andesite and fine-grained calcareous tufflike material.

The large proportion of clay minerals and the weakly bonded nature of the rock produce the effect of firm softness so that, when wet, the finer-grained layers have somewhat the appearance and feel of soapstone and have been so called.

Joints in the Donni member are commonly filled with crystalline calcite, forming narrow veinlets 1 to 3 mm wide. Upon weathering of the sandstone these veins project above the surface and outline the joint pattern in a distinctive manner.

Field relations.—Although at any given place the Donni member may lie relatively above, below, or within the local Tagpochau succession, its general distribution pattern suggests that it properly occupies a position somewhere near the middle of the formation. Isolated outcrops, of course, probably occur at several stratigraphic levels within this broadly medial position.

In the vicinity of Hagman point the orbitoidal, upper Tertiary *e*, transitional facies of the Tagpochau limestone, deposited at moderate to shallow depths, grades upward into the supposedly deeper water deposits of the Donni. The transitional facies contains layers of calcareous sandstone that are similar in texture and composition to the Donni. These layers become more and more abundant toward the top of the transitional facies so that it passes gradually upward into the Donni sandstone member, presumably as sea level rose or sea bottom sank. In a coastal re-entrant of central I Naftan Donni-like materials are intimately mixed with limestone in upper Tertiary *e* beds belonging to the transitional facies of the Tagpochau limestone. In As Teo the Donni member is also gradational into the transitional facies, and in almost the same manner as at Hagman point. Probably the Donni also grades into or interfingers with the Machegit conglomerate member in this same area, although such a relation was not actually observed.

Although the Donni member appears transitional to other beds at some places and wedges out into presumably equivalent strata at others (as at I Madog), it also seems to abut generally contemporaneous or slightly older strata at other places, and it occurs on the western side of Saipan only in the Chalan Kiya area. How the Donni may have achieved its unusual outwedging or abutting relations and restricted distribution is briefly considered in a preceding discussion of the origin of the Tagpochau limestone.

Areal distribution, typical occurrences, and thickness.—Outcrops of the Donni sandstone occur over an area of about 1.2 square miles, mainly along the east side of the island. In its most continuous belt, from the north shore of Laulau bay northward to I Hasngot ravine, it averages about 100 feet thick and overlaps Eocene volcanic rocks as well as several facies of the Tagpochau limestone. The probable continuation of this same belt in the southern third of Saipan thins markedly southward.

In general the Donni member is thickest at the south-central part of Saipan and thins to the east, north, and south. At the surface, in the vicinity of Chacha wells, in the Hagman area, its calculated thickness is 200 feet, and the drillers' records of the Chacha wells are in essential agreement with this figure.

However, in the cliffs north of Hagman point, east of Chacha wells and in the extreme eastern portion of the island, the Donni member is only 20 to 35 feet thick. In the eastern Achugau grasslands, the thickness is about 60 feet. And at I Madog far to the northeast, and I Naftan, far to the southeast, it is less than 10 feet thick. Small tongues or lenses of Donni-like sandstone also occur in undifferentiated strata of the Tagpochau limestone in and near I Eddot grasslands (Sabanan I Eddot), in the south-central part of the island, but Foraminifera were not obtained from these occurrences.

Cuttings from a drilled well at Chalan Kiya in southwest Saipan provide the only record of Donni beds from western Saipan. This record is given in table 8, with faunal determinations by Ruth Todd. Assuming horizontal beds, it indicates a minimum of 20 feet of the

Donni sandstone member, a probability of 110 feet, and possibly as much as 170 to 190 feet.

TABLE 8.—*Cuttings from a drilled well at Chalan Kiya, Saipan*

Nature of cuttings and fossils	*Depth below surface (feet)*
Powdery limestone containing shallow-water benthonic Foraminifera, with rare Miocene or younger planktonic specimens. Possibly the Mariana limestone, the rubbly facies of the Tagpochau limestone, or both.	55–95
Tuffaceous sandstone with abundant Donni-type planktonic Foraminifera.	125–145
Donni-type planktonic Foraminifera present, possibly as contaminant in lower part.	185–235
Oligocene (Fina-sisu) Foraminifera possibly present. Too poor and few for certain determination, and beds might belong to the Donni.	290–295
Densinyama-type siliceous sediments. Barren or nearly so, with contamination by Miocene globigerinids in lowest sample.	415–481

Type section.—The Donni sandstone member of the Tagpochau limestone was originally described by Tayama (1938, p. 38) as the "Donny beds." He gives the type locality as Donny (same locality as I Denni, from the possessive form of Donni), but designates no type section.

The Donni beds are here considered to be a member of the Tagpochau formation, comparable with other facies of the formation but warranting recognition as a named member because of sharply distinctive lithic nature and paleoecological characteristics, and generally pronounced lateral persistence. The type section of the Donni member is herewith designated as being between I Hasngot ravine and I Pitot ravine (Kanat I Hasngot, Kanat I Pitot). Its base is west of the junction of the Cross-Island Connecting Highway and the East Coast Highway and its top is along the East Coast Highway about 800 feet east-southeast of the junction. This succession is essentially uniform throughout and corresponds to the mode described for the Donni member.

Weathering.—Although the Donni sandstone member is soft and easily weathered, its soil cover is ordinarily shallow. The Donni soils are brown to red, slightly acid to slightly alkaline, iron-bearing clays from a few inches to perhaps 2 or 3 feet thick, and the average soil layer is less than a foot thick. They consist of clay minerals mixed with iron and aluminum sesquioxides and are ordinarily highly plastic. Dark-red plastic clays as thick as 6 or 8 feet are confined to a small area northeast of Donni springs (Bobo I Denni).

On the surface above and east of a small quarry at the north end of Dago cliff (Laderan Dago) a few thin layers of bentonite-like, expanding clays occur as a probable weathering product of the Donni. This material is a light-green to white, highly plastic, hygroscopic mixture of clays, all of which probably belong to the montmorillonite group.

Terrain and vegetation (pl. 20*A*).—The Donni beds are easily gullied, and where the area of outcrop is extensive the characteristic topographic expression is an intricate pattern of narrow ravines.

In the broad belt of outcrop along the eastern side of the island small east-west folds (maximum amplitude, 40 to 50 feet) effect a certain topographic control in that "anticlines" generally coincide with ridges, whereas intervening valleys are "synclinal."

Where undisturbed, the surface of the Donni sandstone member ordinarily supports a dense growth of swordgrass, but jungle growth flourishes in areas where calcareous beds weather to a good moisture-retaining surface. Large stands of the introduced Formosan koa may be seen in the area of outcrop immediately south from Halaihai ravine (Kanat Halaihai). The thin soil layer retained over the larger part of the Donni member seems not to be much favored for agricultural purposes, although sugarcane was successfully cultivated on it by the Japanese at several places.

Fossils, age, and correlation.—The known fauna of the Donni sandstone member of the Tagpochau formation is dominated by small Foraminifera, which are represented by nearly 100 identified species. Species of *Globigerina* are most abundant, but *Orbulina* and many other genera are also present. There is a strong foraminiferal facies difference between the Donni member and other facies of the Tagpochau limestone—only 21 of the 166 species that occur in the whole of the Tagpochau being held in common between the Donni and the rest of the Tagpochau, and 12 of these being blanktonic forms. A very few larger Foraminifera have been found in the Donni member, and these are of types that are common in the calcareous facies of the Tagpochau limestone. Fragments of inequigranular Tagpochau limestone that occur in the Donni beds contain many individuals of *Lepidocyclina*, *Miogypsinoides*, and *Miogypsina*. At locality B186 a limestone ledge reported by Burke to be clearly interbedded in the upper part of a sequence of Donni beds produced large Foraminifera of the upper Tertiary *e Miogypsinoides dehaartii* zone. At the sea cave called I Madog, a little northeast of B186 the Donni sandstone member wedges out into and beneath lower Tertiary *e Heterostegina borneensis* limestones.

On the basis of faunal content as partially listed under the general discussion of the formation, as well as on stratigraphic association, the Donni is considered to be lower Miocene. It appears to include equivalents of both upper and lower Tertiary *e* of the Indonesian section.

Origin.—Among the benthonic small Foraminifera of the Donni sandstone member are genera which in modern seas occur only in relatively deep water, while the most likely source for its noncalcareous lithic components is believed to have been preexisting Oligocene and Eocene volcanic sediments. Its geographic distribution and unusual stratigraphic relationships appear to rule out a primary volcanic origin. Although it was formed penecontemporaneously with other facies of the Tagpochau limestone, it thus, presumably, accumulated at depths below the banks on which the carbonate facies of the Tagpochau were accumulating and derived its clastic components mainly from reworking of older source materials. This interpretation would also explain the presence in the Donni beds of occasional scattered cobbles and rare large angular boulders (as much as 3 feet in diameter) of Tagpochau limestone. Although the depths suggested by the benthonic Foraminifera of the Donni are considered to indicate much deeper water, it seems probable, from its gradational relations to other facies, that the Donni sediments themselves at least locally extended into waters little if any deeper than 50 fathoms. In fact it is likely, from stratigraphic relationships with shallower water deposits, that the Donni beds mostly accumulated at depths that did not much exceed 100 fathoms.

MACHEGIT CONGLOMERATE MEMBER

Lithology.—The Machegit conglomerate member (new name) of the Tagpochau limestone consists of well-rounded and deeply weathered cobbles and boulders of andesite in a matrix of finer material of essentially the same composition, the whole rather loosely consolidated. It also includes a few rounded fragments of quartz-rich rock (perhaps dacite) and scattered boulders and smaller fragments of a silica and iron oxide replacement product, perhaps of limestone. The silica- and iron-oxide replaced "limestone" blocks are concentrated at the base of the conglomerate. They are believed to have been derived from the underlying transitional facies of the Tagpochau limestone, though it is not possible to identify them positively as such. There is little variation in the lithic components of the member, but the larger particles decrease in size from the base upwards. At the base the maximum diameter of the andesite boulders is about 3 feet, and toward the top it is about 1 foot.

At no place has the Machegit member been found to contain either interstitial calcium carbonate or fossils of any sort. It appears to be of limited lateral extent and nearly uniform stratigraphic level. Differentiation of the Machegit beds from parts of the Eocene Densinyama formation cannot be accomplished by inspection alone. They have been recognized only at places where stratigraphic association of such conglomerate with more orthodox facies of the Tagpochau limestone indicates a Miocene age.

Type section, thickness, areal distribution, and field relations.—The type section of the Machegit conglomerate member was measured across the area of exposures immediately east of the southern part of Machegit cliff (pl. 20*A*) and just north of Adelug cliff (Laderan Adelug), about 350 yards northwest of Donni springs (Bobo I Denni). At this place it appears to underlie the inequigranular facies and it overlies the transitional facies of the Tagpochau limestone. This section, described in a later part of the report, is 40 feet thick, but the maximum thickness of the member is probably somewhat greater, and it thins to disappearance.

The total areal extent of the Machegit conglomerate member is only about 65 acres. It outcrops as a narrow belt, 80 to 500 feet wide and 1.3 miles long, along the base of Adelug and Machegit cliffs in the east-central part of the island. Similar rocks of Miocene age are known elsewhere on Saipan only at the base of the bluff above Nicholson spring near the head of I Daog ravine (Kanat I Daog) and not quite a mile east-southeast from the south peak of Mount Tagpochau. Here a lens of conglomerate as thick as 2 feet, and too small to map, crops out for about 150 feet at, and a little above, the level of a conspicuous bend in the paved Cross-Island Highway. It lies entirely within Tertiary *e* limestones which are gradational in characteristics between the tuffaceous and inequigranular facies.

Terrain and weathering.—The belt of outcrop of the Machegit conglomerate member is so narrow that it effects little control on the topography. However, along the base of Adelug and Machegit cliffs it forms the face of a low and discontinuous scarplet which has been eroded to smooth slopes in most places.

The member is deeply weathered in all known occurrences, the andesite boulders and the surrounding matrix being altered to clay minerals. The weathered andesite boulders are various shades of red, purple, green, and gray; and the matrix is typically reddish brown from disseminated ferric oxide. A dark brown to reddish-brown clay soil 1 to 3 feet thick is developed on parts of the conglomerate. This soil is slightly acid, with a pH of about 6.

Age and origin.—Although the Machegit member has yielded no fossils, it is considered to be of early Miocene age. The evidence for this is its already noted occurrence probably beneath the inequigranular facies and surely above the transitional facies of the Tagpochau limestone, both of which contain distinctive Tertiary *e* larger Foraminifera. More specifically, the recognized occurrences of this member appear to fall entirely within enclosing rocks that belong to the lower *e* zone of *Heterostegina borneensis*.

To the east of the belt of outcrop of the Machegit member, however, the transitional facies underlies the Donni sandstone member. The position of the transitional facies underneath both the Machegit and Donni in adjacent outcrops suggests that the Machegit conglomerate and Donni sandstone members at this place are nearly contemporaneous facies, one grading laterally into the other. The Machegit thus might have been derived from a residual area of Densinyama conglomerates to the west, of which remnants are still to be seen, and could be thought of as grading seaward into the tuffaceous sandstone of the Donni member to the east. However, the seeming absence of marine fossils and interstitial calcium carbonate from the Machegit is opposed to this interpretation and might even be taken to suggest a subaerial origin for the Machegit. This problem cannot be conclusively settled on the basis of available evidence.

TRANSITIONAL FACIES

Plates 6*E*, 7*C*, 9*D*, 10*B*, 12*A*, 21*A*

Lithology.—The transitional facies of the Tagpochau limestone consists of calcareous and andesitic conglomerate, calcareous tuffaceous sandstone, and marly beds. The calcareous conglomerate and tuffaceous sandstone may be mixed in any proportion, so that the unit approaches the characteristics of the Donni member on the one hand and those of the inequigranular facies on the other. At places the facies includes concentrations of larger Foraminifera, as layers or channel-filling lenses.

Thickness, aereal distribution, and field relations.—This facies attains a maximum thickness of about 40 feet in the bluffs above Hagman beach (Unai Hagman), in the eastern point of Saipan, where it underlies the Donni member. Local unconformities are common—especially beneath, but also in the upper surface of the facies. It grades northward into the inequigranular facies of the Tagpochau limestone beneath the Donni. Similar but thinner deposits containing identical larger Foraminifera occur at the south of the coastal reentrant near the mid-length of I Naftan. Here, however, they are overlain by the inequigranular facies and themselves display strong similarities to the Donni member.

Fossils, age, and origin.—Foraminifera from the transitional facies, as tabulated under the general description of the formation, indicate correlation with both upper and lower zone *e* of the East Indies Tertiary, referred to the lower Miocene. Although only a few of the approximately 70 species of small Foraminifera known from this facies are listed in the table referred to, the total assemblage indicates accumulation at moderate to shoal depths. This implies either abrupt deepening where the facies grades to typical Donni sediments or a shallower depth range for the Donni Foraminifera than is generally attributed to these genera.

TUFFACEOUS FACIES

Lithology and field relations.—This unit is an impure clastic limestone. It is inequigranular, locally fossiliferous, well-bedded and locally cross-bedded, for the most part poorly indurated, and generally reddish brown to dark yellowish-orange. At places fragments of volcanic material constitute as much as 80 to 90 percent of this facies, but normally the percentage of volcanic material is less, and although the rock is ordinarily deeply leached, the original content of calcium carbonate was probably fairly high.

At other places smaller Foraminifera and fragments of echinoids, mollusks, and the staghorn coral *Acropora* form more than 50 percent of the rock. Tongues and interbeds of other facies of the Tagpochau limestone are common in the tuffaceous facies, and the converse is also true at some places. By a decrease in the volume of reworked impurities the tuffaceous facies grades into the marly facies.

The average grain size and its range vary widely. The larger dimensions of included fragments of reworked volcanic material are as much as 10 mm, but the average is probably near 3 mm. Interstitial matrix is 0.2 mm to less than 0.1 mm and includes both detrital particles and clear crystalline calcite.

The thickness of individual beds ranges from a few inches to 10 feet or more, and beds of clay or silt 1 to 2 feet thick are common.

Thickness, areal distribution, and typical occurrences.—This facies attains a maximum observed thickness of about 170 feet at As Rapagau, in west-central Saipan. It is best and most widely developed on the lower western slopes of Tagpochau cliffs (Laderan Tagpochau), in Mount Tipo Pale (Ogso Tipo Pale), and in the southern part of Talofofo ridge (Ogso Talofofo), but a few small interfingering patches occur elsewhere.

Terrain and weathering.—The terrain underlain by the tuffaceous facies is primarily one of moderate to gentle and fairly even slopes. It locally grades to deeply incised valleys with thick jungle vegetation. The few scarps are due to capping by purer, more compact rock, generally of another facies. Patches of the tuffaceous facies that are surrounded by more resistant types of rock generally occupy topographic depressions.

The weathering characteristics of the tuffaceous facies depend on the amount of reworked volcanic material included. Rocks with a high proportion of such impurities generally weather to an acidic soil over a saprolitic zone of several inches to many feet. As the tuffaceous content decreases the facies takes on the weathering characteristics of the purer carbonate facies. Locally the tuffaceous facies and adjacent portions of the marly facies of the Tagpochau limestone produce residual clays so thick and extensive that they are mapped as separate surficial units.

Fossils, age, and correlation.—At places beds and lenticular patches within the tuffaceous facies consist primarily of large and small Foraminifera, and fragments of echinoids, mollusks, and corals, including *Acropora* and other genera. Some beds have no megascopically recognizable fossils, but no relation was observed between purity and faunal content. Most of the few fossils identified are tabulated under the general description of the formation, but, in addition, the large Foraminifera *Miogypsinoides* and *Operculina*, and the echinoid *Sismondia*, were identified from this facies in the field. Correlation is with both upper and lower zone *e* of the East Indies Tertiary, here regarded as lower Miocene.

MARLY FACIES

Lithology and field relations.—The impure limestones that make up the marly facies of the Tagpochau limestone are characterized by argillaceous material in excess of 10 percent of total volume (estimated), moderate induration, and a generally tan to yellowish-white or yellowish-orange color. They are mostly very fine grained, generally equigranular but grading to inequigranular, and ordinarily well stratified in beds from a few inches to about 3 feet thick.

The grain size ordinarily ranges from less than 0.1 to 0.3 mm, but at places larger included volcanic and limestone particles as much as 3 mm in diameter are common. Thin sections show algal fragments, smaller Foraminifera, and occasional larger Foraminifera in a fine tuffaceous and calcitic matrix of grain size generally less than 0.1 mm. The purer parts of this facies grade into the inequigranular or equigranular facies of the Tagpochau formation.

The included impurities in the marly facies of the Tagpochau limestone are generally argillaceous or finely tuffaceous. With increased proportions of andesitic material, the marly facies not uncommonly grades into the tuffaceous facies of the Tagpochau limestone. Tongues and interbeds of other facies commonly occur within zones which on the map are shown as belonging to the marly facies.

Thickness, areal distribution, and typical occurrences.—The thickness of this facies ranges from a few feet to possibly more than 500 feet, the estimated thickness (difference in elevation from base to top) of the seemingly horizontal section at Mount Tipo Pale (Ogso Tipo Pale), southwest of Mount Tagpochau. Its largest areal representation is in central Saipan, in irregular patches that are generally marginal to the great mass of the inequigranular facies that makes up the core of the Tagpochau uplands. It also occurs widely, but in smaller patches, in other parts of the island.

Not only the thickest but also one of the most characteristic occurrences of the marly facies is at Mount Tipo Pale. At this locality it includes many beds, tongues, and lenses of other facies of the Tagpochau limestone and grades into the inequigranular facies that forms the steep slopes to the west. The marly facies is also well displayed along Mount Talofofo, in the subdivision of I Denni known as I Lisong, in east-central Fina-sisu, and at other places; but its thickness at these localities is almost invariably less than 100 feet and commonly less than 50 feet.

Terrain and weathering.—Slopes of surfaces underlain by the marly facies are as much as 20°. On them are found occasional projecting ledges of better indurated beds of the marly type, or compact beds like those of the inequigranular facies. Scarps and benches that are wholly within the marly terrain are rather subdued, and thus produce a rolling surface of linear grain.

The marly facies weathers to an alkaline clayey soil of an average depth of 2 to 3 feet. The transition from soil to rock is sharply defined. Smooth-surfaced residual limestone pinnacles are common, but they are not of the same number or size as those in the inequigranular facies. The thickness of the soil increases, and the height of the pinnacles decreases with increase in the amount of clay in the parent rock.

At a few places gradational to the tuffaceous facies, the marly facies produces a deep residual clay that is then mapped as a separate surficial unit, together with similar clays that occur over the adjacent facies.

Fossils, age, and correlation.—Fossils tabulated under the general description of the formation indicate correlation of the marly facies with both upper and lower Tertiary *e* of the East Indies succession, here regarded as lower Miocene. In addition to these, about 20 other species of smaller Foraminifera have been identified by Ruth Todd. In the field the echinoid *Sismondia* was recorded at the top of Mount Tipo Pale and at several localities in I Agag and Papago. Fragments of echinoid and molluscan shells, joints of *Halimeda*, and thin discontinuous bands of crustose coralline algae were also observed at a number of localities.

THICK RESIDUAL CLAYS OVER TUFFACEOUS AND MARLY FACIES

In the western part of the Papago district (85 acres), and on the flat summit of the southern part of Mount

Talofofo (45 acres), are extensive areas of clays thought to be residual from the underlying tuffaceous and marly facies of the Tagpochau limestone. They are known to overlie the marly facies in both the Papago and Mount Talofofo areas, and a cobble of limestone partially replaced by iron oxides was found in the clays of the Papago area. At the few places where it has been observed, the contact between the clays and the underlying marly limestone is abruptly transitional. In the Papago district the clays are as thick as 12 feet in road cuts, and a probable maximum thickness of at least 20 to 30 feet is indicated by depths of gullies and topographic relations. In the Talofofo area these clays are at least 6 feet thick and probably attain a maximum of 20 to 30 feet in large depressions. They are mapped as a separate unit because they extensively conceal the rocks from which they are presumably developed, preventing surface differentiation of the primary stratigraphic units.

The clays are mottled and banded and are plastic when wet. The banding is subparallel at any given spot, but is oriented at all attitudes between horizontal and vertical. It consists of alternating narrow bands and streaks of relatively pure, iron-free, light-gray and white kaolinitic(?) clays and lenticular bands and streaks of iron-stained reddish-brown and yellowish-brown clays. The banding is fairly uniform throughout and probably extends to the bottom of the clay bodies. Departures of this banding from a subhorizontal attitude may be due to creep or slumping.

The clays of the southern part of Mount Talofofo are not so highly mottled as those in the Papago area, and they commonly contain abundant small concretions of goethite or limonite and manganese oxides. These ferruginous and manganiferous concretions are of various shapes and sizes. Many are tubelike, attaining diameters of ½ to ¾ of an inch and lengths of 3 and 4 inches. Such may have been formed about roots of dead and decaying plants. Others are spherical or irregular.

Slopes are gentle in the areas underlain by these thick clays, the soil is slightly acid to neutral, and the vegetation is largely swordgrass, as is common to the clay soils of volcanic areas. On bare slopes the clays are extensively gullied.

RUBBLY FACIES

Plates 10*D*, 12*B*

Lithology and field relations.—The rubbly facies of the Tagpochau limestone is characterized by uneven induration, rubbly texture, poor preservation of fossil material, and general purity. The clastic limestones of this facies are inequigranular, and they range from thinly bedded to apparently nonbedded. Color ranges from gray, pink, or tan to yellowish orange.

The rock is commonly made up of angular particles or fragments as long as 40 mm in a matrix of grains from less than 0.1 to 1.0 mm in diameter. The angular particles and the matrix are generally of similar composition, and it is conceivable that this could have resulted from a sort of brecciation in place, due to shattering and slight movement of limestone that originally consisted of alternating poorly indurated beds and firmer layers. Two thin sections of nonrubbly layers within this facies (locs. C31 and C127) show a medium- to fine-grained algal and foraminiferal limestone of which 30 to 70 percent is matrix made up of bioclastic to clear crystalline calcite in grains less than 0.1 mm in diameter.

Although the rubbly facies is for the most part relatively pure and does not contain megascopically determinable volcanic material, it includes much argillaceous material that was probably derived from weathering of volcanic source materials.

Thickness, areal distribution, and typical occurrences.—The thickness of the rubbly facies ranges from a feather edge to at least 120 feet in the large quarry west of the mouth of I Eddot ravine (quarry 16 of Stearns) in south-central Saipan, and possibly to as much as 150 feet in southern I Agag, in east-central Saipan. Its largest area of continuous outcrop is along the base of I Agag cliffs (Laderan I Agag) and eastern Tagpochau cliffs, where it extends for nearly 2.7 miles in a north-to-south belt that ranges generally between 300 and 1,000 feet wide. It also occurs as smaller patches, or as inclusions or tongues, in other facies in most parts of Saipan where the Tagpochau limestone is present.

This facies is well displayed in the type section of the formation, along and near which it ranges between 60 and 95 feet thick. However, it is best displayed in the large quarry west of the mouth of I Eddot ravine, where it is well but unevenly bedded, shows a succession of thin, well-indurated to poorly consolidated layers, and displays several clay seams that probably represent outwashing of soil material from land that was nearby at the time of deposition.

The rubbly facies most typically occurs in valley floors or along the base of cliffs, where it forms 10° to 20° slopes. Layers that are more massive and better indurated than is typical of this facies form ledges on such slopes.

Soil cover on this facies is clayey and averages slightly deeper than that over the inequigranular facies of the same formation. The contact between the soil and the unweathered rock is sharply defined.

Fossils, age, and correlation.—The rubbly facies of the Tagpochau limestone contains much fossil material,

but a good deal of it is too fragmentary or too poorly preserved for positive identification. The larger Foraminifera tabulated under the general description of the formation indicate correlation with both upper and lower zone *e* of the East Indian Tertiary (lower Miocene). The echinoid *Sismondia* has been found intermittently along the south half of the long belt of the rubbly facies that ranges north to south along the lower slope of I Agag cliffs and the lower eastern slope of Tagpochau cliffs. This belt is mainly in the lower *e* *Heterostegina borneensis* zone. Joints of *Halimeda* and fragments of mollusca, were also observed in the field in some of the larger well-indurated fragments.

EQUIGRANULAR FACIES

Lithology and field relations.—This facies comprises equigranular clastic limestones that are fine- to coarse-grained, medium- to well-indurated, generally well-bedded, and generally pure. Although it seems at places to be hardly more than a well-sorted phase of the inequigranular facies, it everywhere differs from latter in lacking conspicuous fossils. Its color ranges through white, gray, tan, yellowish orange, and pink. The average grain size ranges from about 0.1 mm in the west-central part of Saipan to about 2.0 mm at Fañunchuluyan bay.

Exposures of the equigranular facies in west-central Saipan and at Fañunchuluyan bay (Bahia Fañunchuluyan) have only a medium degree of induration, but the exposures at north Kalabera cliffs (Laderan Kalabera Katan), and along the north-central ridge of the island, are highly indurated. The bedding of the unit is well developed, with layers from a few inches to 1 or 2 feet thick in west-central Saipan and in the northeastern part of As Matuis, and 6 to 10 feet thick at Fañunchuluyan bay. West of south Kalabera cliffs (Laderan Kalabera Lichan) the rock is massive and well-indurated, and bedding is indistinct. Although essentially free of megascopic volcanic material at most places, local exposures in west-central Saipan have a marly appearance.

In northeastern As Matuis and at north Kalabera cliffs the equigranular facies grades into the inequigranular facies, with accompanying increase of included fossil material.

Thickness, areal distribution, and typical occurrences.—The thickness of the facies ranges from a few feet to more than 220 feet, the thickness of the incomplete section exposed at north Kalabera cliffs (difference in elevation of horizontal beds in bluff face).

The equigranular facies occurs in three main areas and several smaller areas in west-central and northern Saipan, together covering about 1.2 square miles. The largest area of outcrop is in the lowest terrace of the west-central part of the island, east from Muchot point; but it is also exposed west of the highest terrace of south Kalabera cliffs, in the northeast part of As Matuis, and it forms a part of the cliffs on the north shore of Fañunchuluyan bay. Rocks of this type also occur as unmapped lenses, tongues, or beds within other facies.

Terrain and weathering.—Marine benching in the outcrop area of the inequigranular facies has produced a terrain of vertical scarps and essentially flat benches. Residual pinnacles do not develop markedly in the equigranular facies of west-central Saipan, but in other areas where this facies outcrops they are comparable in distribution and size to their development in the inequigranular facies. The soil that develops over the equigranular limestone is characteristically deep red and clayey, and averages 1 to 2 feet thick. The change from unweathered rock to soil is abrupt.

Fossils, age, and correlation.—Larger Foraminifera of both the *Heterostegina borneensis* and *Miogypsinoides dehaartii* assemblages have been identified from the equigranular facies. These denote a range from early into late Tertiary *e* (early Miocene).

INEQUIGRANULAR FACIES

Plates 10*A*,*C*, 11, 17*A*

Lithology and field relations.—This unit is an inequigranular, clastic limestone; very well indurated, characteristically massive and indistinctly bedded, relatively pure, and generally rich in orbitoid or miogypsinid Foraminifera. In color it is typically pink, white, yellowish, gray, or variegated. The grain size in a hand specimen may range from grains of microscopic dimension to angular fragments with an observed maximum dimension of 30 mm. Fragments as much as 10 to 30 mm long are ordinarily angular and of the same material as the matrix. Manganese oxides, hematite, and volcanic material are disseminated through the rock at some places. Normally the impurities are only minor constituents of the facies, but they constitute a major part of some small patches.

Study of 29 random thin sections showed 20 whose larger grains were dominantly larger Foraminifera and fragments of coralline algae in 20 to 40 percent of matrix composed of clear crystalline calcite and fine bioclastic debris. The dominant grains averaged 0.4 to 2.0 mm, and the matrix grains less than 0.1 mm in diameter. The coralline algal fragments are mainly of articulate forms, but there is no marked volumetric dominance of either Foraminifera or algae. The crystalline calcite of the matrix is probably an alteration product from interstitially precipitated aragonite. One slide consisted mainly of smaller Foraminifera.

Contacts between the inequigranular facies and other facies of the Tagpochau limestone are at many places gradational through a wide zone. This is due to the gradual increase in the number of lenses or tongues of one or the other facies until that lithic type becomes dominant.

Thickness, areal distribution, and typical occurrences.—The inequigranular facies ranges from a feather edge to a maximum thickness probably in excess of 900 feet, this being the incomplete composite thickness of the Bañadero cliff and Tanke cliff sections joined at the approximate contact between the faunal zones of *Heterostegina borneensis* (about 236 feet in Tanke cliffs section) and *Miogypsinoides dehaartii* (about 670 feet in Bañadero cliffs section).

The inequigranular facies is the most widely distributed rock type on Saipan, comprising the bed rock over nearly one-third of its total land area and at least 60 percent of the areas of limestone terrain above an elevation of 250 feet. The largest areas of outcrop are those which constitute the axial uplands north of Mount Achugau and the outcrops of and adjacent to Mount Tagpochau in south-central Saipan. In the north these limestones are characteristically pink or variegated and markedly pure. In the central area of Saipan they are characteristically white to very light gray or light pink and locally somewhat impure. Rocks of the latter type commonly occur as beds, tongues, or lenses within masses of other facies.

Terrain and weathering.—The terrain expression of the inequigranular limestone facies is characteristically one of flat benches at several levels, separated by vertical and near-vertical scarps. The benches or terrace surfaces have been modified by solution and tectonic action. Parts of the higher terraces are bordered along the outer or seaward edge by a serrate, pinnacled solution rampart as high as 30 feet, and some terrace surfaces are tilted to the west (notably the three terraces of south Kalabera cliffs). Caverns and small irregular caves are common along the bases of the scarps. Sink holes are found chiefly on the lower terrace surfaces of the east coast. In areas of hill and valley topography, where the inequigranular facies occurs as beds, tongues, or lenses in other rock, it commonly caps the ridges and hills.

These limestones weather to a deep red or brownish-red clayey soil having an average depth of 1 to 2 feet and a depth of 15 feet in some pockets of concentration. A thicker-than-average soil covers the upper terrace surface west of south Kalabera cliffs in northern Saipan. This may be caused by the weathering of lenses of relatively impure limestone in the inequigranular facies. The surface between the soil and the unweathered rock is generally sharply defined and marked with many smooth-surfaced residual pinnacles. Occasionally such pinnacles attain heights as great as 15 feet but the average height is 2 to 3 feet. Depressions 100 feet in circumference occur at some places. These are filled with soil and are of unknown depth.

Fossils, age, and correlation.—Under the general description of the Tagpochau limestone are tabulated the more distinctive larger Foraminifera and a selection from the more than 40 species of smaller Foraminifera which have so far been recorded from the inequigranular facies by W. Storrs Cole and Ruth Todd. Of significance paleoecologically is the common occurrence of the larger foraminifer *Cycloclypeus*. The small button-shaped echinoid *Sismondia* occurs in this facies at a number of localities in west-central Saipan and on the central slopes of Laulau ravine and to the south. Other fossils observed include a number of different poorly preserved mollusks and rare whole echinoids besides *Sismondia*, as well as fragments and spines of echinoids at many places. Fragments of coral are found occasionally and concentrations of coral heads rarely—at least one of the latter in the form of a small reef mass. About one-fourth of the thin sections studied showed joints of the calcareous green alga *Halimeda* and one consisted mainly of *Halimeda* (loc. C–17). The problematical alga *Microcodium* was seen in sections from localities B171 and S339, and the dasycladacean *Cymopolia* occurs in slides from localities B171, S339, and abundantly B107.

Correlation is with zone *e* of the East Indian Tertiary (lower Miocene). Lower *e* is represented by the larger Foraminifera of the *Heterostegina borneensis* assemblage and upper *e* by the *Miogypsinoides dehaartii* assemblage.

SISMONDIA BEDS

The small, distinctive, button-shaped echinoid *Sismondia* has been found at several localities in the inequigranular, rubbly (pl. 12*B*), marly, and tuffaceous facies of the Tagpochau limestone. C. Wythe Cooke has identified all occurrences as representing the species *S. polymorpha* Duncan and Sladen. It is also very similar to *S. convexa* Nisiyama which Cooke regards as a synonym of *S. polymorpha*.

Where the beds in which it occurs can be traced for any distance, *Sismondia* follows the trend of outcrop, with but slight stratigraphic range (maximum of possibly 40 feet in the large quarry three-quarters of a mile east of Flores point). The fact that *Sismondia* was not found at more than one stratigraphic level in any particular section suggested in the field that it might be a datum marker. It actually occurs at most places in the *Heterostegina borneensis* faunal zone, but is also known locally with larger Foraminifera characteristic of the *Miogypsinoides dehaartii* zone. It appears, therefore to range through an overlap interval between these two assemblages and near the middle of Tertiary *e*.

Faunal associates of *Sismondia*, identified by W. Storrs Cole and John W. Wells (from locs. S144, S536, S540, C102, C122, C130, C141) include *Heterostegina borneensis* van der Vlerk, *Miogypsinoides bantamensis* Tan, *Lepidocyclina* (*Eulepidina*) *ephippioides* Jones and Chapman, *L.* (*Nephrolepidina*) *parva* Oppenoorth, *L.* (*N.*) *sumatrensis* (Brady), *L.* (*N.*) *verbeeki* Newton and Holland, *Operculina* sp., *Spiroclypeus tidoenganensis* van der Vlerk, *Astreopora* n. sp., *Heliopora coerulea* (Pallas), *Leptoseris floriformis* Gerth, and *Trochoseris florescens* Felix.

Observed occurrences of the *Sismondia* beds are indicated on the geologic map.

PLIOCENE(?)

OLDER TERRACE DEPOSITS

Plate 12*D*,*E*

DESCRIPTION OF THE UNIT

General characteristics.—Like the other principal terrace deposits on Saipan, the older terrace deposits consist of reworked volcanic sands, granule sands, and thin gravels. They are separated from other terrace deposits, and are themselves divided into two sets on the basis of elevation and topography. The highest and oldest of the older terrace deposits (QTt–1) lies at altitudes between 560 and 710 feet on one or more dissected sloping terrace surfaces. A lower and therefore younger set of older terrace deposits (QTt–2) lies upon what seem to be parts of a single eastward-sloping terrace surface at altitudes between 500 and 580 feet. Composition varies according to source of materials. Thickness ranges from a feather edge to 15 feet, but is characteristically 3 to 5 feet. Total area covered by these deposits aggregates only about 21 acres.

Age and origin.—The older terrace deposits occur entirely at levels above the supposedly early Pleistocene Mariana limestone and the post-Mariana terrace deposits and cut across beds of early Miocene age. They thus are younger than early Miocene and probably older than Pleistocene. The time required for cutting the underlying bench or benches, geomorphic position, and the relatively undissected nature and good preservation of the terrace deposits suggest the upper rather than the lower part of this interval. On such flimsy evidence a late Pliocene age is tentatively suggested for the older terrace deposits described above.

Like the younger terrace deposits of the western coastal plain, and the post-Mariana terrace deposits in the east-central part of the island, the older terrace deposits (QTt–1 and QTt–2) appear to lack both fossils and interstitial calcium carbonate. Although both could have been removed by selective leaching, had they originally been present, such leaching might at least be expected to have left traces of the normally conspicuous shore-zone shells. The seeming absence of either shells or impressions of them casts doubt on a marine origin for the terrace deposits. From analogy with the similar but much younger terrace deposits of the western coastal plain, it is suggested that these are confluent fluviatile fan deposits which were formed a little later than the surface or surfaces on which they rest—probably during and immediately following emergence of the latter. Marine shells are not to be expected within such terrace deposits, but only sporadically at their basal contact with the wave-eroded benches on which they rest. Evidently Saipan has at no time since their deposition been resubmerged to lower depths, or the terrace deposits in question would have been destroyed or at least partly reworked by marine processes. The sedimentary structures and apparent lack of fossils make such marine reworking improbable.

SUPPLEMENTARY DESCRIPTIONS OF MAPPED SUBDIVISIONS

Deposits between 560 and 710 feet (*QTt–1*).—The largest patch of the highest and oldest terrace deposits included under the map symbol QTt–1 consists of quartz-rich sands that cover an area of about 14 acres at an altitude of about 660 to 710 feet along the north end of Talofofo ridge. These sands are from a few inches to about 6 feet thick, well stratified, clay banded, partly cemented with ferric oxides, and colored in tones of red, orange, yellow, dull brown, and pink. They rest on quartz-rich, water-laid conglomerates and tuffaceous sandstones of the Densinyama formation, probably their principal source material.

A second patch of quartz-rich high terrace deposits covers about an acre immediately southwest of Mount Achugau, at an altitude near 600 feet. The bench-veneering sediments at this place are reddish- to yellowish-brown and loosely consolidated granule sands with thin interbeds of pebble gravel. They are 1 to 3 feet thick and consist of abundant quartz grains as much as 4 mm in diameter, fragments of siliceous rock, magnetite grains, and ferric oxides. The siliceous pebbles in the conglomerate layers attain a maximum diameter of about 1 inch. The deposits rest in part on pink Matansa limestone (Eocene), and fill small solution pits in the limestone surface. Concentrations of almost pure magnetite sand are found at the bottom of some of the solution pits. These terrace sediments also overlie beds of deeply weathered, quartz-rich, calcareous sand and pebble conglomerate of the tuffaceous facies of the Tagpochau limestone, from which they have most probably been derived.

A third small patch of the quartz-rich high terrace deposits is found southeast of Mount Achugau at 560 to 600 feet; quartz sands loosely cemented with red and brown ferric oxides, and as much as 6 feet thick. These sands rest on both the white and pink facies of the Eocene Matansa limestone, as well as on the Sankakuyama formation.

The southernmost older terrace deposits of the highest level are at altitudes of about 600 to 670 feet at the south end of Talofofo ridge (pl. 12*D*,*E*). They differ from those to the north in their general poverty of or lack of quartz. These southern deposits are well-stratified, light- to dark-reddish, medium-grained to very coarse grained sands and granule sands from a few inches to 10 feet thick. They consist of highly weathered particles of andesite and scattered to abundant grains of magnetite that are loosely bonded with clay and ferric oxides. The average grain diameter is about 2 to 3 mm. Eastward, these deposits grade to a locally occurring quartz-rich facies that contains rounded pebbles of chert and other siliceous rocks. They overlie the truncated surface of andesitic deposits of the Hagman formation as well as tuffaceous and marly limestones of the Tagpochau formation.

Deposits between 500 and 580 feet (*QTt–2*).—The older terrace deposits included under the QTt–2 map symbol are mainly lower and therefore presumably younger than the QTt–1 deposits. They cover about 6 acres on the first terrace level below and east of the central part of Mount Talofofo at altitudes between 500 and 580 feet. They are from a few inches to about 6 feet thick and consist of quartz-rich, dark to light reddish-brown clay sands and gravels that contain well-rounded pebbles and cobbles of a variety of siliceous rocks. These deposits overlie the Densinyama formation and the tuffaceous facies of the Tagpochau limestone. They were probably derived through reworking of the already once reworked volcanic source materials provided by these units.

PLEISTOCENE

MARIANA LIMESTONE

Plates 12*C*, 13, 16, 17, 18*B*, 20*A*, 21*A*, 22

DESCRIPTION OF THE FORMATION

General characteristics.—The Mariana limestone is a mainly light colored (dirty white to brownish), coarsely porous or cavernous to less commonly compact, finely to coarsely fragmental limestone that ordinarily contains coral remains and joints of the green alga *Halimeda*. Coralline algae, small and large Foraminifera, and impressions and internal fillings of mollusks are also common. The mollusk shells are ordinarily dissolved and the corals are noticeably altered.

Facies included are: (1) the rubbly facies, of impure fragmental limestones; (2) the *Acropora*-rich facies of calcareous clays and impure limestones; (3) the massive facies of mainly unbedded, porous, clastic to constructional limestones; and (4) the *Halimeda*-rich facies which differs from unit 3 mainly in its local great abundance of *Halimeda* joints.

The grain size ranges from aphanitic to very coarse grained. Rubble deposits of rolled coral at places form coarse conglomerates, and earlier deposited material is locally reworked into pebble conglomerates. Bedding is generally massive or obscure. However, it is also locally well developed in layers from less than 1 foot to several feet thick, especially in the *Halimeda*-rich and rubbly facies. Induration is moderate, complete, or slight, depending on the facies involved, on local variations within facies and on proximity to bluffs where surface induration may occur.

There seems to be both a general east-to-west lateral gradation from *Halimeda*-rich, to massive, to rubbly or *Acropora*-rich facies, and a general descent in the section through the same sequence of facies.

The Mariana limestone differs from the older limestones of Saipan in its combination of coarsely porous and fragmental texture with nonbedded to indistinctly bedded structure (pl. 12*C*), its generally great abundance of corals and joints of *Halimeda*, its generally lighter color, and the modern aspect of its fossil assemblage.

Distinction of the Mariana from the younger Tanapag limestone, however, is at many places difficult and uncertain. The clues to the separation of these units on Saipan are the better preservation of corals in the Tanapag, the common preservation of molluscan shell material in the Tanapag as compared to its general destruction (except locally for *Cerithium*) in the Mariana limestone, and the general absence of the Tanapag limestone above the 100-foot level. Where their contact has been observed, it is an erosional unconformity.

Thickness, areal distribution, and typical occurrences.—The Mariana limestone on Saipan ranges from a feather edge to probably more than 400 feet thick, and perhaps 500 feet or more. Although no observable section is as thick as that, the Mariana limestone extends to elevations near or above 400 feet at various nearshore localities such as I Ifa cliffs (370 feet, attitude near horizontal), I Naftan cliffs (407 feet, dipping about 15° seaward) and Hagman cliffs (460 feet, dipping 12° to 25° seaward). Its extension from these places to and probably below sea level suggests that the vertical range of the formation is near 500 feet, and this vertical range is considered to approximate actual thickness.

The largest areas of outcrop of the Mariana limestones are in south Saipan, in the Chacha and Hagman areas, and at Bañadero in northern Saipan. However, it extends with only minor interruptions along the south, east, north, and northwest coasts of Saipan. Excepting the Tagpochau limestone it is the most widely distributed formation on Saipan, outcropping intermittently over about one-fourth of the total land surface.

Good exposures of short stratigraphic intervals of various facies of the Mariana limestone may be seen at many places in southern Saipan and along its eastern margin, especially in and near I Naftan and along the East Coast Highway from Talofofo stream (Sadog Talofofo) north and east to Nanasu ravine (Kanat Nanasu).

At the west of Saipan the few known outcrops of Mariana limestone are mapped wholly in the massive facies (though including some rubbly materials). It also seems probable that the shallow submarine bank that extends westward from Saipan is underlain mainly by the Mariana limestone, although probably for the most part covered by younger deposits.

Type site.—The name Mariana limestone was proposed as a formation name by Tayama (1938, p. 44) without designation of type site or type section more specific than a remark to the effect that it is the most widely distributed limestone in the southern Marianas. The best successions of the Mariana limestone on Saipan are in inaccessible sea-facing bluffs, and mapping of the island has revealed no section of appreciable thickness wherein representatives of several facies could be observed in unfaulted succession and studied at close hand. Thus designation of a type section is deferred, in the hope that geologic work in the other larger Mariana Islands may eventually reveal a suitable one. For reference purposes, however, the exposures in the area known as Dandan (southeastern Saipan) are designated as the standard for the Mariana limestone on Saipan. More specifically this standard site refers to that part of Dandan included between Wallace Highway at the north, Dandan point at the south, Laulau bay at the east, and Gonno cliffs at the west. Within this area may be seen good developments of several aspects of the massive facies of the Mariana limestone, the *Halimeda*-rich facies, and the *Acropora*-rich facies. The unconformable contacts of the Mariana limestone with both the Donni sandstone member and the inequigranular facies of the Tagpochau limestone may also be observed here.

Terrain, vegetation, and weathering.—The terrain developed on the Mariana limestone is one of wave-eroded benches and scarps somewhat modified by subaerial erosion. The overall surface of the benches is nearly horizontal, but some are tilted by faulting, and the undisturbed ones slope gently toward the sea. In south Saipan, the Chacha district, and Bañadero some of the benches are broad and of almost equal length and breadth. At other places they are elongated parallel to the coast as short series of narrow abrupt steps, rising inland. Like those of the Tagpochau limestone, the benches are mainly cultivated or are the sites of abandoned canefields or construction. The scarps between are overgrown with jungle vegetation. The occasional ravines that transect the benches are short, steep walled, and ordinarily choked with jungle vegetation. They take the shortest route to the sea. Caves, crevasses, and sinks are common, and some of the sinks are very large.

The soil that develops on the benches of Mariana limestone is ordinarily thin, and irregular residual rock pinnacles rise through and above it to heights as great as 5 or 6 feet. The interfaces between soil and rock are abrupt and irregular. At places clay wash has accumulated to thicknesses of 5 to 20 feet or so in sinks, or in broad and poorly drained depressions. At other localities highly argillaceous and deeply leached occurrences of the rubbly or *Acropora*-rich facies have yielded residual clay deposits perhaps as thick as 20 feet. For the most part the soil and clay wash is alkaline. However, the residual clay deposits and soils developed near the overlap of the Mariana limestones on igneous rocks commonly grade to neutral or acidic.

Fossils, age, and correlation.—The Mariana limestone contains scattered to locally abundant Foraminifera, locally abundant but mostly unidentified modern types of corals (few collections made because of bulk), occasional impressions and cores of mollusks, occasional fragments and rare whole tests of echinoids, and calcareous red and green algae.

Table 9 presents a partial list of fossils so far recorded from the several facies of the Mariana limestone, and from the Tanapag limestone. From this may be seen the broad similarity of the two biotas, some of their particular differences, and the modern aspect of both. On the basis of the assemblage listed a post-Miocene age is required, and the large proportion of forms that either belong to or are very closely allied to living species favors a post-Pliocene age. Significance is also attached to the presence of the distinctive coralline algae *Amphiroa*, *Porolithon*, and *Goniolithon* (fig. 6). On Saipan these have been found only in the Mariana and Tanapag limestones, and the last two have (to our knowledge) nowhere yet been recorded from established pre-Pleistocene rocks. On Saipan Foraminifera of the types of *Calcarina spengleri* and *Baculogypsina sphaerulata* were found only in the Mariana, Tanapag, and Recent sediments. To the best of our knowledge these species also are nowhere reported from authentic pre-Pleistocene beds, and may prove to be Quaternary markers.

At the same time, the presence of several extinct species of mollusks in both Mariana and Tanapag limestones indicates some antiquity and points toward a pre-Recent age. The fossils are mostly not well preserved, and what was probably once a large tropical fauna is represented in the collections studied by only a handful of species and specimens. In the opinion of Julia Gardner, however (letter of March 24, 1952, to Cloud), the mollusk fauna of the Mariana limestone suggests an older Pleistocene age on the basis of extinct elements in, and primitive development of, a fauna of generally modern aspect.

However, carbon-14 analyses given under the discussion of the age of the Tanapag limestone suggest a younger Pleistocene age for it. So does the fact that conspicuous fault movement (as at Naftan point) intervened at places between benching of the Mariana and deposition of the Tanapag. This seems to substantiate the stratigraphic distinction between Mariana and Tanapag, and leads us to favor an older Pleistocene age for the Mariana and a younger Pleistocene age for the Tanapag limestone.

The consensus of evidence relating to the age of the Mariana limestone as exposed on Saipan thus suggests early, or at least older, Pleistocene. As is true of most Pleistocene age designations away from glacial sequences or terrestial faunas, this assignment is open to question, and the need for more conclusive criteria than have so far been advanced for differentiation between Pliocene and Pleistocene in the western Pacific should be kept in mind.

Correlatives of the Mariana limestone are found in the other larger Mariana Islands, in other parts of Micronesia, and in the Ryukyus. The Naftan limestone of Tayama (1938, p. 43) is included with the Mariana limestone of the present report, it being but a part of the *Halimeda*-rich facies of the Mariana.

TABLE 9.—*Partial list of fossils from the Mariana and Tanapag limestones*

	Mariana limestone				
	Rubbly facies	*Acropora*-rich facies	Massive facies	*Halimeda*-rich facies	Tanapag limestone
FORAMINIFERA					
(Identified by W. Storrs Cole)					
Amphistegina madagascariensis D'Orbigny	×	----	×	×	×
Calcarina spengleri (Gmelin)	×	----	×	×	×
Cycloclypeus carpenteri Brady	×	----	×	×	×
Heterostegina suborbicularis D'Orbigny	×	----	×	----	×
Marginopora vertebralis Quoy and Gaimard	×	×	×	×	×
Miliolids	----	----	×	----	×
CORALS					
(Field identifications)					
Acropora	×	×	×	×	×
Favia	×	----	×	----	×
Goniastraea	×	----	×	----	×
Heliopora	×	----	×	×	×
Platygyra	×	----	×	----	×
Porites	×	----	×	----	×
Seriatopora	×	----	----	----	×
MOLLUSCA					
(Identified by Julia Gardner)					
Pelecypoda					
Arca navicularis Bruguière	----	----	----	----	×
Anadara cf. *A. maculosa* Reeve	----	----	----	----	×
scapha (Meuschen)	----	----	----	----	×
Cardium cf. *C. unedo* (Linné)	----	----	----	----	×
Chama n. sp. aff. *C. ovalis* Martin	----	----	----	----	×
sp	×	----	----	----	----
Glycymeris cf. *G. pilsbryi* Yokoyama	----	----	----	----	×
Lithophagus	----	----	----	×	×
Spondylus	----	----	----	----	×
Trachycardium unicolor (Sowerby)	----	----	----	----	×
Tridacna elongata Lamarck	----	----	----	----	×
Venus cf. *V. toreuma* Gould	----	----	----	----	×
Gastropoda					
Angaria	----	----	----	×	----
Atys cylindrica Helbein	----	----	----	----	×
Cerithium alveolum Hombron and Jacquinot	----	----	----	----	×
ianthinum Gould	----	----	----	----	×
sp	×	×	×	----	×
Cylindromitra crenulata (Chemnitz)	----	----	----	----	×
MOLLUSCA—continued					
Gastropoda—Continued					
Cypraea (*Arabica*) cf. *C.* (*A.*) *arabica* Linné	----	----	----	×	×
(*Monetaria*) *moneta* Linné	×	(1)	(1)	(1)	(1)
(*Peribolus*) cf. *C.* (*P.*) *mauritiana* Linné	----	----	----	×	×
sp	×	----	×	×	×
Strombus cf. *S. gibberulus* Linné	×	----	×	----	----
sp	×	----	×	----	×
Thericium sp	×	----	×	----	×
Trochus niloticus Linné	----	----	×	----	×
(*Infundibulum*) *maculatus* Linné?	----	----	----	----	×
Turbo (*Marmarostoma*) *argyrostomus* Linné	----	----	×	----	×
sp. (field identification)	----	----	×	×	×
Turritella	----	----	×	----	×
ECHINOID					
(Identified by C. Wythe Cooke)					
Clypeaster reticulatus (Linné)	----	----	----	×	----
ALGAE					
Amphiroa	(1)	(1)	×	×	×
Other articulate corallines	×	×	×	×	×
Porolithon	×	----	×	×	×
Other crustose corallines	×	×	×	×	×
Halimeda	×	×	×	×	×

[1] Probably present.

Origin.—The several facies of the Mariana limestone are interpreted to be related shallow-water deposits laid down on banks or in reef-dotted lagoonal areas adjacent to a high island. Along the east slope of Saipan, and to the south where the Mariana limestone overlaps volcanic or volcanically derived rocks, its more westerly and basal facies is either the rubbly facies or the *Acropora*-rich facies. Eastward toward the sea, and roughly upward in the section, is the massive facies, and, at the eastern edge of Saipan, the *Halimeda*-rich facies. The contacts between these facies are gradational and not accurately mappable, with that between the *Halimeda*-rich and massive facies (as mapped) being particularly indefinite and arbitrary. Nevertheless, even their rough delimitation does bring out the important relations noted, and subsequent studies suggest that a more sharply delimited and more distinctively *Halimeda*-rich facies could have been defined as a narrower band of initially dipping beds along the coast.

The rubbly facies evidently represents a deposit of broken and displaced coral mixed with argillaceous material derived from adjacent volcanic terrain along a relatively steep coast. The *Acropora*-rich facies is the counterpart of the rubbly facies adjacent to a gently sloping coast at the inner edge of a broader submarine bench. Although argillaceous matter from the adjacent weathered volcanic land was supplied in moderate abundance, *Acropora* was able to maintain its growth over a fairly broad area of probably shallow water.

Both distribution pattern and the nature of the rocks indicate that the relatively pure calcareous detritus which became the massive facies of the Mariana limestone accumulated not far offshore from the sites of deposition of the impure rubbly and *Acropora*-rich sediments. The massive facies finds a suggestively close counterpart in deposits of the present lagoon and banks west of Saipan, where a variety of clastic calcareous materials is gathering about small reef patches of living and dead corals and algae. The distribution of coral and algal material in the massive facies was not found to line up in such a way as to indicate well-defined linear reefs within the present limits of Saipan at the time the Mariana limestone was being deposited, although there may have been peripheral reefs in the present offshore areas. The visible deposits of the massive facies may have accumulated either on shallow banks or in lagoonal areas about the small reef masses of Mariana time.

The location of the *Halimeda*-rich facies in an offshore direction from the massive facies seems at first thought anomalous—living *Halimeda* is most abundant about Saipan today in quite shallow water within the lagoon and was not observed in any abundance seaward from the reef. However, direct observation of the bottom sediments off western Saipan reveals that the freshly detached joints of *Halimeda* are in large proportion only partly calcified and tend to be relatively light and porous. They settle in the areas of growth of *Halimeda* as loosely knit debris which is readily moved by current action. The broadest areas of seemingly thick accumulation of *Halimeda* joints on the present bottom are at the harbor entrance, where they seemingly have been concentrated by the winnowing action of the outflowing current. Such winnowing may move the relatively light and buoyant *Halimeda* fragments seaward from the denser, coarse shell and coral debris that accumulates in shallower inshore waters, while carrying to still deeper seaward waters that part of the concurrently moving fine debris that does not settle into the interspaces between *Halimeda* particles.

A possible alternative explanation is that because of more intense or more direct sunlight, or for other reasons, *Halimeda* growth during Mariana time was concentrated at greater depths and distance from shore than at present (*Halimeda* does not ordinarily flourish in intense equatorial sunlight at shallow depths). In either event, it is not inconsistent that the *Halimeda*-rich facies of the Mariana limestone should lie offshore from the massive facies or that both deposits accumulated on the same general bank area.

SUPPLEMENTARY DESCRIPTIONS OF MAPPED SUBDIVISIONS

RUBBLY FACIES

Lithology and field relations.—The rubbly facies of the Mariana limestone is an inequigranular, ordinarily well-bedded, poorly indurated, porous, fossiliferous, argillaceous, clastic limestone. Most generally it consists of pebble- and cobble-sized fragments of coral and coralline algae, indurated limesand, fragments of Tagpochau limestone (Miocene), and mollusk shells imbedded in a highly argillaceous, very coarse- to medium-grained matrix which has a dominating grain diameter of 2 to 3 mm. At places, however, fragments of coral are rare or absent and the rock is made up of broken pieces of coralline algae, inequigranular Miocene limestone, and previously indurated Mariana limestone in a matrix of calcareous sand, with or without argillaceous impurities. Quartz grains are abundant in highly argillaceous zones within the facies, presumably having been derived from the volcanic terrain to the west. Characteristic colors are yellowish to dull brown, tan, or white; the white parts lacking argillaceous impurities. The bedding dips east to southwest at angles between 12° and 20°. This dip appears to be mainly or wholly initial.

The rubbly facies differs from other facies of the Mariana limestone by its conspicuously and coarsely fragmental nature, by a general abundance of broken and randomly oriented coral and algal fragments, by its poor state of induration, and by its large proportion of argillaceous impurities.

Thickness, areal distribution, and typical occurrences.—The thickness of the rubbly facies ranges from a feather edge at its landward margin to a probable maximum of almost 400 feet at or near its contact with the massive facies along the east coast.

The facies forms a broad seaward dipping belt along the east side of the island, continuous from southern Kalabera on the north to Hagman peninsula on the south. This belt is nearly a mile wide where it underlies the central part of Hagman peninsula, but narrows to about 800 feet in the Halaihai district. The average width is about one-half mile. Seaward (eastward), the rubbly facies grades laterally into the massive facies of the Mariana limestone. It accounts for more than one-sixth of the total land area underlain by the Mariana limestone, and its area of outcrop is about 2 square miles. The best exposures are in the Talofofo area, and a good section can be observed in the wide vertically walled valley leading northward from the point where the East Coast Highway crosses Talofofo stream.

Terrain and weathering.—The most extensive area of exposure of the rubbly facies is an elevated marine terrace that cuts across it at altitudes between 80 and 300 feet. Dissection of the now gently rolling terrace surface by intermittent streams has produced mostly broad and shallow valleys and a few narrow steep-walled ravines. Only a few sink holes are found on this surface. The sediments are apparently too weakly bonded to favor the development of caves, which, by collapse would become sinks.

Soils on the rubbly facies to the north of Donni stream (Sadog I Denni) are light yellowish brown to reddish brown, kaolinitic, neutral in pH, and from 1 to 5 feet thick. Residual pinnacles of limestone ordinarily project through the soil cover. In the Talofofo area, a true soil cover is largely absent, the limestone surface instead being blanketed by reddish-brown, medium-grained, quartz-bearing, clayey terrace sands. The terrace sands range from a few inches to as much as 10 feet thick where they fill pockets in the limestone surface.

Fossils, age, and correlation.—Fossils from the rubbly facies of the Mariana limestone are, for the most part, poorly preserved. Fragments of the corals *Porites* and *Heliopora* commonly make up a large part of the rock; impressions or cores of mainly fragmentary mollusks are locally abundant; a few Foraminifera are known, and algal fragments are common. A partial list of fossils is given, and age and correlation are considered under the general description of the Mariana limestone.

THICK RESIDUAL CLAYS OVER THE RUBBLY FACIES

In the western part of Hagman peninsula, and west of Halaihai beach, areas aggregating about 320 acres are underlain by thick and dominantly residual clays over the rubbly facies of the Mariana limestone. These clays are mottled yellowish to dark brown and gray, the yellow and brown colors being due to hydrous ferric oxides. Hematite is rare or absent. Alternation of bands, streaks, or patches of iron-free, gray, kaolinitic(?) clay with iron-bearing, yellow and brown clays produces the mottling. The clays are neutral to slightly acid at the surface, but become more acidic with depth.

A maximum thickness of about 40 feet of clay was recorded in the vicinity of Chacha wells, but a commoner thickness is only 5 to 10 feet. Near Chacha wells the clay contains scattered fragments of iron oxide that seems to have replaced limestone. For the most part the clay is probably residual, but its considerable thickness locally and its topographic position suggest that it may in part be transported.

ACROPORA-RICH FACIES

Lithology and field relations.—The *Acropora*-rich facies is characterized by abundant fragments and rare nearly complete colonies of staghorn *Acropora* in a matrix that

is characteristically rich in argillaceous matter. Its color varies from yellowish or brownish where highly impure, to dirty white where relatively free of argillaceous matter. Bedding is thin, or inconspicuous owing to leaching of calcareous material. Such leaching leaves a yellowish or reddish-brown residual clay with whitish mottles and streaks and occasional bits of *Acropora*.

The *Acropora*-rich facies extends eastward beneath and probably in part grades laterally into the massive facies of the Mariana limestone. It is a basal and marginal facies of the Mariana limestone and represents the approximate southern equivalent of the rubbly facies.

Thickness, areal distribution, and typical occurrences.—The *Acropora*-rich facies has been recognized only in southern Saipan and occurs in only a few small patches there. It thins from about 100 feet to a feather edge by overlap and lateral transition. Its largest belt of outcrop, and probably thickest occurrence, is in western As Gonno and As Lito, where it overlaps the interbedded flows and tuffs of the Fina-sisu formation. It is also well displayed in tunnels in the south face of Gonno cliffs (Laderan Gonno), where it rests upon the Donni member of the Tagpochau limestone, and in northern Tuturam, in quarry No. 18 of Stearns.

Terrain and vegetation.—The terrain underlain by the *Acropora*-rich facies is low and gently sloping to flat. It includes one of the largest sinkholes on Saipan (Hoyon As Lito Lichan, or southern As Lito sink).

As noted above, the *Acropora*-rich facies leaches to a deep yellowish- or reddish-brown clay soil with whitish mottles. This soil is alkaline or neutral, ranging to acidic where it overlaps the Fina-sisu formation. The weathering products near its boundary with the volcanic deposits of the Fina-sisu make continuous delineation of a clear-cut basal contact impossible.

Fossils.—Staghorn *Acropora* is the dominant fossil. Few others were found, although it might be expected that such an argillaceous facies would yield a well-preserved molluscan fauna.

MASSIVE FACIES

Plates 12*C*, 13*B*–*D*, 17, 18*B*

Lithology and field relations.—The massive facies consists of clastic to constructional and inequigranular limestone. It differs from other facies of the Mariana limestone in its massive to obscurely bedded nature, its characteristically high degree of induration, its generally coarsely porous to cavernous condition, and its high degree of purity. The color of the fresh rock is dirty white, tan, yellowish to dull brown, or pinkish.

Observations of outcrops and study of random thin sections show great variation in organic components and grain size, but at the same time bring out some central tendencies. Excluding minor reefs and rubble zones, anywhere from 30 to 80 percent of the rock commonly consists of fragmental organic calcite. This is at many places dominated by fragments of crustose and articulate coralline algae, with coral fragments subordinate and other organic components volumetrically inconspicuous, except for local *Halimeda* concentrations. Grain size of this fraction ordinarily falls between 0.5 to 2.0 mm, with an upward range to about 10 mm. The remaining 70 to 20 percent is mainly matrix; mostly very fine-grained detrital to clear crystalline calcite, with grain size averaging under 0.1 mm and ranging down to 10 microns or so. As much as 10 percent or more of this space, however, may consist of small to large cavities that are commonly lined with zoned crystalline calcite.

A separately mapped subunit of the massive facies is locally represented by areas of dull-pink or pinkish, compact limestone containing abundant coralline algae. The pink color seems to be due to disseminated argillaceous impurities.

Field relations indicate the massive facies of the Mariana limestone to be laterally transitional to the *Halimeda*-rich and rubbly facies of the same formation.

Thickness, areal distribution, and typical occurrences.—Partial sections of 90 feet or so of the massive facies are visible in individual sea bluffs in southern Chacha and southern Bañadero, respectively in eastern and northern Saipan. The maximum thickness attained by the nearly flat-lying facies is estimated on the basis of abrupt range in altitude as roughly 300 feet. From this it grades to a feather edge.

The massive facies comprises well over one-half (about 7 square miles) of the terrain underlain by Mariana limestone on Saipan, and about one-seventh of the land surface of Saipan. Throughout this area it shows so little variation in broad lithic and faunal characteristics that one area is about as good as another for study.

Terrain and weathering.—The greater part of the massive facies of the Mariana limestone is found in sea cliffs and the lower wave-cut benches (pls. 16, 17, 18*B*, 20*A*, 22). The characteristic bench and scarp terrain resembles that of the purer Tagpochau limestones (Miocene), and vegetation patterns are similar.

Soil cover is scant or absent and the limestone surface is studded with ragged residual pinnacles (karrenfeld) that average 3 feet high and are as high as 5 or 6 feet. Such soil as occurs locally is a reddish clay, like that which forms over the inequigranular facies of the Tagpochau limestone. At a few places probably transported red-brown clays attain unknown but presumably considerable thickness.

Fossils, age, and correlation.—The massive facies of the Mariana limestone contains abundant but mostly fragmentary or poorly preserved fossils. Filaments and bands of coralline algae commonly make up a large part of the rock, and *Halimeda* is locally common to abundant. Heads and fragments of coral are scattered through the facies and, where abundant, may be parts of small coral algal reefs or rubble concentrations. Foraminifera, especially small varieties, are abundant at places, as are also impressions and cores of mollusks. Some of the fossils which have been identified are listed, and age and correlation are considered under the general description of the Mariana limestone.

HALIMEDA-RICH FACIES

Plates 13*A*, 21*A*

Lithology and field relations.—The *Halimeda*-rich facies of the Mariana limestone is distinctive in its commonly rich concentration of *Halimeda* joints. The greatest concentrations of *Halimeda* are further marked by well-developed bedding in layers from less than 1 foot to several feet thick. Besides *Halimeda* the detrital components of this facies include locally abundant echinoid spines, fairly common nodular coralline algae, and the usual complement of articulate corallines. Corals are at most places uncommon. Dips as great as 20° E. in this facies along a narrow coastal strip are believed to be mainly or wholly initial, for reasons discussed under "Structural geology."

The *Halimeda*-rich facies appears to include Tayama's Naftan limestone.

Thickness and areal distribution.—The *Halimeda*-rich facies is at least 120 feet thick in the sea bluffs at I Naftan, in southeastern Saipan, and it is estimated to reach 200 to 400 feet, on the basis of altitude attained by sequences that extend continuously to the sea. It frays to a feather edge and grades laterally to the massive facies of the Mariana limestone. Its area of outcrop is about 1.7 square miles in I Naftan and Hagman cliffs. Exposures available for study show little lithic variation except in relative abundance of *Halimeda* and gradation to the characteristics of the massive facies.

Terrain, weathering, and vegetation.—The *Halimeda*-rich facies is found in an area of abrupt scarps and benches that slope gently seaward. High sea cliffs are cut into it. It produces a thin soil that is brownish or dark gray to black from included manganese oxides. The interface between parent rock and soil is abrupt and irregular, and rough, pitted, residual limestone pinnacles project to several feet above the soil. Its vegetation of sugarcane on the flat surfaces and jungle on the scarps resembles that of the massive facies of the Mariana and the purer facies of the Tagpochau limestone. Along the coast, of course, all limestone benches in the zone of salt spray, regardless of facies, support only low *Scaevola* brush, vines, and grass.

Fossils, age, and correlation.—Pertinent fossils of the *Halimeda*-rich facies are tabulated and conclusions about age and correlation are given under the general description of the Mariana limestone. It is of paleoecologic interest to note that at one locality near Naftan point the shells and burrows of the rock-boring pelecypod *Lithophagus* were found in algal balls in this facies.

POST-MARIANA TERRACE DEPOSITS

DESCRIPTION OF THE UNIT

General characteristics.—The post-Mariana terrace deposits consist of iron-stained, locally quartz-rich, clayey sands and minor gravels which are derived from the reworking of volcanic source materials. They are widely distributed at altitudes between about 100 and 500 feet on the east side of Saipan, over what are probably remnants of several cut-terrace surfaces which truncate the Mariana limestone.

Altogether these deposits make up a total area of about 136 acres. They range from a feather edge to 10 feet and most commonly are 3 to 4 feet thick. Their composition varies with the source of the sediments included. They are best preserved in the Talofofo grasslands (Sabanan Talofofo) and the area called I Hasngot in east-central Saipan. Small patches of sand and pebble conglomerate, judged by their altitude to be of the same general age, are exposed at Hagman, and two small isolated patches lie on Sankakuyama rhyolite in the Achugau district.

Age and origin.—The post-Mariana terrace deposits are clearly younger than the Mariana limestone, for they cut across its truncated upper surface at different levels. Yet, they appear to be as old or older than the late Pleistocene Tanapag limestone, for they are unknown below an altitude of about 100 feet and presumably were formed about the same time as the pre-Tanapag benches on which they rest. The historical sequence thus suggests a middle to late Pleistocene age, and a Pleistocene age assignment is hardly to be doubted.

As in the older and younger terrace deposits, the seeming absence of fossils favors an origin by outwash of fluviatile materials onto emerged parts of rock benches undergoing general withdrawal from the sea. The presence of these deposits also suggests a middle Pleistocene age for the latest relative submergence to such depths, for resubmergence presumably would have removed or left signs of reworking the unconsolidated to weakly indurated terrace materials.

SUPPLEMENTARY DESCRIPTIONS OF SUBDIVISIONS

The post-Mariana terrace deposits fall into seven different categories, according to areal distribution and lithic composition:

1. In the northern part of the Talofofo grasslands, where they are well-exposed in roadcuts along the East Coast Highway, post-Mariana terrace deposits are composed of loosely consolidated, dark yellowish-brown and brownish-red, quartz-bearing clay sand, containing pebbles of chert and other highly siliceous rocks. Large and small patches of such sands, with a combined area of about 80 acres, overlie the truncated rubbly facies of the Mariana limestone and attain their greatest thickness where they fill solution cavities and depressions in the limestone surface. They reach a maximum thickness of about 8 feet, but are generally between 1 and 5 feet thick.

2. A little westward from the main area of occurrence of deposits of group 1 are terrace deposits that cap east-west trending ridges of Mariana limestone and are almost devoid of clay minerals. They consist mainly of quartz sands mixed with and partly cemented by iron oxides.

3. The post-Mariana terrace deposits attain their greatest thickness in the western part of I Hasngot and on the southern border of the Talofofo grasslands where they comprise reddish- to yellow-brown, mostly medium-grained quartz sands loosely cemented by hematite and hydrous iron oxides. These deposits overlie truncated rocks of the Hagman and Densinyama formations, the Donni sandstone member of the Tagpochau limestone, and the rubbly facies of the Mariana limestone. Their total combined area is about 30 acres, their maximum thickness about 10 feet, and their average thickness about 5 feet. They are well exposed in cuts along the Cross-Island Connecting Highway near its junction with the East Coast Highway, where they rest on volcanic conglomerate of the Densinyama formation.

4. In Talofofo, immediately south of Talofofo stream (Sadog Talofofo), and between the first and third outcrop areas described above, patches of medium-grained to very coarse grained or even granule-sized, reddish-brown and reddish-orange, stratified clayey sand lie upon flat seaward sloping ridge crests underlain by Hagman volcanic agglomerate and breccia. Their total area is about 12 acres. These sands are from 1 to 6 feet thick and are composed of weathered andesite particles probably derived from the underlying Hagman deposits. The average grain size is about 2 mm. The sands lie on ridge crests that are of generally accordant altitude and appear to be remnants of a dissected terrace surface. These ridge crests lie inland from, and are continuous seaward with, a relatively undissected terrace surface that truncates the Mariana limestone and is in large part blanketed with quartz-rich terrace sands. It thus appears that the stratified granule sands of group 4, overlying the Hagman formation, are nearly contemporaneous with the quartz-rich sands of groups 1, 2, and 3.

5. Deposits similar in texture and composition to the sands of group 4 occur in patches comprising a total area of about 8 acres on the northeast slopes of Mt. Laulau. They are medium to light red stratified clayey sands and granule sands composed of weathered andesite particles, ferric oxides, and magnetite, with much included organic material. They occur on a seaward sloping surface at altitudes between 240 and 500 feet and rest upon the Hagman formation. It is difficult to ascertain whether these deposits can be correlated with the post-Mariana terrace deposits of groups 1 through 4; but, on the basis of altitude, this correlation seems logical.

6. The post-Mariana terrace deposits at the Hagman grasslands are dark gray to light brown, coarse-grained, granule sands composed of angular to subrounded fragments of chert and other siliceous rocks, particles of andesite, quartz grains, and dark organic matter. The deposits cover an area of about 4 acres, are from 1 to 5 feet thick, and have an average grain diameter of about 3 mm. They are well stratified and lie on surfaces that cut across volcanically derived sandstone and conglomerate of the Hagman formation at altitudes between 160 and 320 feet. They grade into quartz-bearing Densinyama conglomerate along their inland margin and have probably originated in part from a reworking of this source material. On the basis of their range in altitude group 6 deposits are correlated with the post-Mariana terrace deposits of Talofofo and I Hasngot (groups 1–4).

7. Two small isolated patches of granule sand, with a combined area of only 2 acres, rest upon the Sankakuyama formation in the Achugau grasslands. The deposits are from a few inches to 3 feet thick, are well stratified, are light brown and gray in color, and are composed of weathered fragments of porphyritic dacite, dacite vitrophyre, quartz grains, and pellets of manganese oxide. The fragments range from a fraction of a millimeter to about 2 cm in diameter, the average diameter being about 3 mm. The larger rock fragments are smooth and rounded. A 6-inch layer of neutral to slightly acid soil has developed on the deposits. The sands dip 5° to 10° southeast (seaward) with the truncated surface of the underlying dacites. They lie on a terrace surface now so thoroughly dissected by erosion that only remnants are discernible.

They occur at altitudes between 340 and 480 feet and probably correlate approximately with the post-Mariana terrace deposits in other districts.

TANAPAG LIMESTONE

Plates 13*B*,*C*, 14, 15*A*,*B*, 17*B*, 18*B*, 19, 22

Lithology and field relations.—The Tanapag limestone includes mainly dirty white to brownish coral-algal reef limestone and bioclastic limestone. It is rich in fossil corals and coralline algae (pl. 14), many of which occur in the position of growth, although some are rubble. The rock is generally well indurated and coarsely porous, but without indication of bedding other than that provided by the crude alinement of corals and coralline algae in the position of growth. Where its clastic elements are mostly shell fragments or joints of *Halimeda*, coral and algal material is uncommon; but the strictly clastic sediments represent a smaller part of the total bulk of this limestone than does the coral- and algal-rich rock. Well preserved coral heads and mollusk shells are common.

Much of the Tanapag limestone so closely resembles parts of the massive facies of the Mariana limestone that it is difficult and perhaps impossible to separate them consistently. Nevertheless these units are visibly unconformable at places (as at big Agingan beach and Dandan point); and they are believed to be separated in time and to represent distinct genetic and historical phases of the rock sequence of Saipan, warranting separation as distinct formations.

Delimitation on a map, however, depends on a combination of topographic and lithic clues that might well lead to different conclusions about where the boundary between Tanapag and Mariana should be placed, either by different geologists, or by the same geologist at different times. These are:

1. Preservation of corals and mollusk shells in the Tanapag is better than it is in the Mariana limestone. In the Tanapag limestone pelecypods and gastropods tend to preserve their shells, whereas in the Mariana limestone the mollusks are ordinarily represented only as impressions or internal fillings. Large spirally ribbed *Turbo*, *Trochus*, and *Tridacna*, which rarely have their shell matter preserved in the Mariana limestone, are commoner and almost invariably retain their shells in the Tanapag limestone. The corals in the Tanapag limestone in general show little sign of alteration other than by solution.

2. Corals, especially those in their original living position, are generally much more abundant in the Tanapag limestone than in the Mariana limestone, and *Acropora* of a stubby staghorn type [cf. *A. humilis* (Dana)] is markedly abundant and well preserved in its position of growth at many places in the Tanapag limestone.

3. The Tanapag limestone appears to be characteristically restricted to altitudes of less than 100 feet, and its surface is ordinarily constructional rather than erosional.

The Tanapag is unlikely to be confused with deposits other than the Mariana limestone.

At two localities along the coast of southeastern Saipan (eastern Obyan), patches of weakly consolidated gravelly limesand with excellently preserved shells fill large cavities in the Tanapag. These may be Recent cavern fillings rather than a proper part of the Tanapag limestone.

Type site.—The name Tanapag limestone was proposed by Tayama (1939a, p. 346). Although a type locality was not given in the original paper, Tayama (oral communication) had in mind the west coast of Saipan between Tanapag and Matansa, and this locality is herewith designated as the type site. Here the exposed thickness of the limestone does not exceed roughly 10 feet, although inshore from Dogas point (Puntan Dogas) it rises to an altitude of about 60 feet. There is little question that the rock at the type site belongs to the same formation which we originally mapped as "post-Mariana raised reef limestone" all around the coast of Saipan, and which Tayama has elsewhere also called the "Chacha limestone." Because the Tanapag limestone shows no evidence of bedding, and because any section that might be described would have to be included in essentially a single exposure having the general features described for the unit as a whole, there is no need specifically to designate a type section.

Thickness and areal distribution.—Although the Tanapag limestone extends to altitudes as great as 100 feet, it is probably nowhere as much as 100 feet thick. It appears, in fact to have formed as a mainly constructional and relatively thin veneer on an emerging surface. The general thickness of occurrences with recognizable lower contacts is perhaps 10 to 20 feet, and maximum probable thickness is guessed to be not more than 50 feet.

The Tanapag limestone is most widely developed along the south and east coasts of Saipan, with its maximum extent inland being about one-fourth mile. Distribution around the northeast, north, and west coasts is much more discontinuous, and at many places its patches of outcrop are too small to be mapped separately even at the mapping scale of 1:10,000.

Weathering, terrain, and vegetation.—The Tanapag limestone has been so recently raised above the sea that it has had little opportunity to develop a soil cover from its own weathering products. It forms the only rock benches on Saipan that are essentially constructional. Except where mechanically smoothed and graded these benches characteristically are nearly bare surfaces that are studded with residual pinnacles and slope gently toward the sea.

Along the mainly cleared and graded south coast, the Tanapag surface is more nearly even than usual and has a thin deposit of brownish alkaline soil. Back against the bluff that marks its inland contact with the Mariana limestone is a thin wedge of probably transported brown clays.

Along the eastern and northern coasts, however, the surface of the Tanapag bench is very rough, with many irregular residual solution pinnacles and elevated seaward-trending grooves (pls. 14*B*–*D*, 16*B*). The grooves show their erosional origin by transecting contacts with the coral and algal deposits along their sides and bottoms (p. 14*B*–*D*) and even by cutting down into the Mariana limestone surface. Northward from Halaihai, and at Sabaneta, along the northwest coast, elevated fringing-reef flats (pls. 16*B*, 19*A*) floored with storm-washed calcareous gravel and limesand occur at altitudes of 30 to 40 feet toward the inner margin of the 15- to 40-foot Tanapag bench.

Immediately along the coast the salt spray retards the growth of vegetation other than salt-tolerating grass, vines, and thin brush. Vegetation along the seaward part of the Tanapag bench is thus likely to be sparse. In uncleared areas a little distance away from the seaward margin, however, the rough Tanapag surface supports a thickly tangled growth of low *Scaevola* brush and vines. The bench along the south coast is mostly cleared and protected by coastline windbreaks of salt-tolerant trees such as casuarina.

Fossils, age, and correlation.—A partial list of fossils so far recorded from the Tanapag limestone is given in table 9. This tabulation, together with remarks, provides a comparison between the biotal characteristics of the Tanapag and Mariana limestones. In the discussion referred to, reasons are given for concluding that both the Mariana and the Tanapag limestones are Pleistocene and that the Mariana molluscan fauna suggests an older Pleistocene age than does that of the Tanapag.

TABLE 10.—*Carbon-14 analyses of Tanapag limestone and Recent calcareous materials from Saipan*

[Determinations by L. J. Kulp except preliminary determination of Chalan Piao sample by W. F. Libby]

Geologic designation	*Nature of material*	*Field locality*	*C–14 sample no.*	*Preliminary age determination* [1]	*Corrected age determination* [2] *(Jan. 15, 1953)*
Tanapag limestone	Bioclastic limestone	C29	Lamont 142 A	>30, 000	>30, 000
Tanapag limestone	Coral *Goniastraea*	C35	Lamont 142 B	21, 000±600	19, 400±700
Tanapag limestone	*Chama* n. sp	S409	Lamont 142 C	29, 900±2, 500	28, 200±2, 500
Tanapag limestone	Bioclastic limestone	S611	Lamont 142 D	>30, 000	>30, 000
Storm wash from elevated moat on Tanapag surface.	Limesand and shell debris	S612	Lamont 142 E	1, 850±170	<200
Coral-algal mound at depth of 40 ft in lagoon entrance.	Dead crust of coralline algae	*D8* [3]	Lamont 142 F	2, 150±200	400±100
Recently emerged limesands	Pelecypod shell	Chalan Piao at depth of 1.5 ft.	Univ. Chicago 669	3, 479±200	1, 730±450

[1] Based on factor being used to convert counts per minute to years before running suite of 8 coral genera taken alive from the modern reef.
[2] Based on new conversion factor, recalculated from data on radiocarbon activity of modern coral specimens.
[3] Ecological locality; see chapter K.

Table 10 presents carbon-14 determinations by L. J. Kulp that suggest an age of the order of 19,000 to more than 30,000 years (perhaps much more, of course) for the Tanapag limestone and therefore favor a younger Pleistocene age for it. From this, and other evidence previously summarized, therefore, the Pleistocene succession of Saipan appears to be: Older Pleistocene—Mariana limestone; middle or younger Pleistocene—post-Mariana terrace deposits; and youngest Pleistocene—Tanapag limestone.

The Tanapag reef limestones extend to the approximate height at which melting of all existing glacial ice would raise the sea. Could this mean partial contemporaneity of its formation with withdrawal of the sea from the last major interglacial flood stage? Is the Tanapag limestone itself roughly correlative with some part of the last maximum glaciation?

If the latter is true, the oldest Tanapag beds would presumably offlap toward the low level of maximum glaciation, or perhaps as far as 50 fathoms below present sea level, with inhibited reef growth at greater depths. Following onlap, with waning glaciation, might be called upon to resubmerge the area, probably above the present shoreline. At this time, or earlier, a stand of the sea about 40 feet above its present level is indicated by a persistent solution notch at about 40 feet,

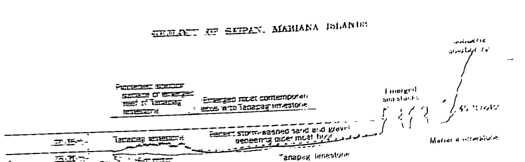

FIGURE [illegible].—[illegible] of Tanapag limestone and [illegible] along east coast north of [illegible]

and preserved reef flats at 31 to 41 feet, and a much better development of the Tanapag limestone below 40 feet than that between 40 and 100. The 15- to 40-foot bench has seaward a generally higher lip or outer margin; this suggests a stand of sea at a level of 12 to 15 feet. This level would appear to be the lowest depositional surface of the Tanapag and a briefly held late Pleistocene or early post-Pleistocene eustatic level. Below this are low bluffs, solution notches at 6 feet and present sea level, and evidences of stepwise Recent emergence.

The Tanapag limestone includes rocks which Tayama has elsewhere called Chacha limestone, as well as his typical Tanapag limestone. Probable time and facies equivalents are also found on Tinian, Guam, and among the other recently emerged reef limestones and clastic deposits of the western Pacific.

Origin.—The characteristics of the Tanapag limestone are those of a raised fringing reef, the slightly depressed landward [illegible] parts of which then and later received loose sand and gravel (areas mapped as Qm, Qt, or Qs). Along the former seaward edge of this reef is a continuous arrangement of closely spaced submarine grooves and spurs (pl. [illegible]) much like those of parts of the present fringing reef. The relations of the Tanapag reef to older and younger features are exemplified in figure 5.

PLEISTOCENE AND RECENT

YOUNGER TERRACE DEPOSITS

Lithology and field relations.—The younger terrace deposits are gravelly, sandy, and clayey accumulations of varied types of reworked volcanic source materials. They consist principally of well-rounded pebbles and cobbles of andesite, dacite, chert, and other siliceous rocks and occur mainly in a matrix of [illegible] clay matrix. Locally the deposits consist of quartz sand partially cemented with ferric oxides, and containing only a few siliceous pebbles. In other places the deposits comprise highly mottled red and gray clays that contain scattered quartz grains and thin layers of quartz-rich volcanic pebbles and cobbles. The mottling extends downward to an observed depth of 15 feet. The deposits are probably underlain mainly by the Tanapag limestone which is exposed beneath them at several places.

Northward, in the coastal area known as Matansa, the terrace deposits grade laterally into a dark-red quartz-bearing, clay soil mapped as clay wash. This material probably represents a reworked facies of the younger terrace deposits, for it lacks the rounded volcanic pebbles and cobbles that are so distinctive of the typical terrace material.

The younger terrace deposits differ from older terrace deposits in topographic position, range of lithic components, and relations with source beds.

Thickness, areal distribution, and typical occurrences.—The maximum observed thickness of the younger terrace deposits is 15 feet where the West Coast Highway crosses the wash that leads westward from Dogas stream ([illegible] Dogas) across the coastal plain. Actual maximum thickness is probably not greater than 20 to 25 feet and the deposits thin to a feather edge along their seaward margin.

The younger terrace deposits cover an area of about two-thirds of a square mile along the west coast of Saipan. They extend northward from Deep [illegible] point ([illegible]) to a point just south of [illegible] point but are best developed in the coastal plain area between As Agaton stream on the south and Dogas stream ([illegible] Dogas) on the north. For the most part they lie inland from and above an area of raised Recent limesands at altitudes between 20 and [illegible] feet. They do however extend out to [illegible] beach.

Terrain and weathering.—A gently rolling surface incised by small intermittent washes is the characteristic terrain. Gullies are common in areas underlain by the mottled quartz-bearing clays. The deposits rise inland from the emerged Recent limesands along a sharply defined scarplet 3 to 8 feet high. The younger terrace deposits are deeply weathered, especially where they now consist dominantly of mottled clays. Weathering of the volcanic material has produced clay minerals, iron oxides, and probably minor hydrous aluminum oxides. The clay is generally neutral to slightly acid at the surface. It becomes more acidic with depth, although weathering appears to be uniform and intense from top to bottom.

Origin, source, and age.—The source material was the volcanic rocks of the Densinyama and Hagman formations, which crop out in the hills along the eastern border of the coastal plain. Short intermittent streams transported the volcanic debris westward from the hills to build coalescent low outwash fans on the coastal plain. Eastward the deposits grade laterally into and overlap the volcanically derived source rocks and are continuous with alluvial deposits of present stream valleys. Neither fossils nor calcium carbonate have been found in them.

The younger terrace deposits north of As Agaton stream were derived largely from the volcanic breccia of the Densinyama formation that crops out to the east, for here they are of rounded pebbles of quartz-rich rock and abundant quartz grains. South of As Agaton stream the terrace materials are largely of pebbles and cobbles of andesite derived from the Hagman formation.

The seaward margin of the terrace deposits was embayed by marine erosion. Limesands and marsh deposits were then deposited in the embayments. Thus, although most of the terrace deposits lie topographically above the limesands, some of them lie stratigraphically below the limesands and are older. Their formation apparently began during late Pleistocene time, and they are still accumulating.

DEPOSITS FORMED BY MASS WASTING

Landslide deposits (pl. 21*A*).—Material of landslide origin covers an area of about 5 acres on the steep eastern slopes of Hagman peninsula. The deposit is about 30 feet thick at the base, where it reaches the shoreline, and 5 to 10 feet thick immediately below the rim of Hagman cliffs, at an altitude of 380 feet.

This landslide is composed of a heterogeneous mixture of large and small blocks of the Donni sandstone member of the Tagpochau limestone and blocks of massive *Halimeda*-rich Mariana limestone. Some of the limestone blocks are as much as 30 feet in diameter. Fragments of conglomerate and calcareous sandstone of the transitional facies of the Tagpochau limestone also occur in this deposit, and cobbles and boulders of andesite derived from the underlying Hagman formation are abundant toward its base.

The landslide materials rest on water-laid volcanic conglomerate and sandstone of the Hagman formation, on an irregular basal surface that slopes between 25° seaward and nearly vertical. The upper surface of the landslide slopes 25° to 35° toward the sea. A relatively recent origin is indicated by the fact that it has undergone little erosional modification. The downward movement of its materials from the cliffs above, postdates the cutting of the post-Mariana terraces, presumably in late Pleistocene or Recent time.

Areas of slow slump and creep (pl. 21*A*).—Residual and gravity-slumped blocks of massive limestone cover an area of about 6 acres in the Hagman grasslands (Sabanan Hagman) in extreme eastern Saipan. The limestone blocks lie on an elevated wave-cut terrace surface on reworked volcanic conglomerate and sandstone of the Hagman formation, and on *Halimeda*-rich Mariana limestone, at altitudes of 200 to 360 feet.

Most of the larger masses and blocks of Mariana limestone in this area appear to be in place; but large blocks are slightly offset from their original position, and both the residual patches and offset blocks are probably remnants of a once more extensive sheet of limestone. The masses of Mariana limestone that lie beneath the seaward margin of the terrace immediately south of the area of slump blocks are also such remnants.

Large blocks of massive inequigranular Tagpochau limestone, some of them 40 to 60 feet across, are mixed with blocks of Mariana limestone in the slump area. The blocks of Tagpochau limestone are derived from the limestone mass that crops out in the cliffs above the Hagman grasslands. These blocks probably crept slowly down the slopes, eventually coming to rest on the more gently sloping terrace surface among the blocks of Mariana limestone.

Another area of slow mass wasting occurs north from Hagman bay, between it and north Laulau point. This consists of almost continuous blocks of the *Halimeda*-rich facies of the Mariana limestone and is mapped as that facies. It is described in the section on structural geology.

Both of the slump and creep deposits described are still in movement, and movement may have begun at any time following post-Mariana terrace cutting. Either could probably be set in catastrophic motion seaward by a sufficiently strong earthquake.

Coarse slump rubble of steep coastal areas (pl. 17*A*).—Some steep coastal areas have no beach in the ordinary sense of the term, but only a narrow belt of surf-battered rubble deposits slumped from the cliffs above. These rubble blocks are dominantly angular and commonly tens of feet across. Such rubble deposits consist of limestone blocks alone or of blocks of both limestone and volcanic rocks, with either predominating. They are probably mainly Recent, but may be in part late Pleistocene.

ALLUVIUM AND CLAY WASH

Under the heading of alluvium and clay wash are included about 900 acres of surficial deposits that are still accumulating and that may have been accumulating since Pleistocene time. All such deposits are alluvial in the sense that they were transported by runoff waters, but distinction is made between the deposits of out-draining valleys and those of closed depressions and broad, open areas. The linear alluvial deposits of out-draining valleys commonly include a conspicuous amount of gravel, as well as clay. The deposits in closed depressions and broad, open areas at the mouths of certain valleys are primarily clay wash. The clay wash characteristically contains ferruginous and manganiferous pellets. The presence of the clay wash symbol on the geologic map normally indicates a depression or an area that is very low topographically.

The thickness of the alluvium is probably nowhere very great, but that of the clay wash almost everywhere exceeds 5 feet and may commonly be 20 to 30 feet. Valleys containing the gravelly alluvium are restricted to the east side of Saipan, and most of the clay wash is toward the west. As the deposits are still accumulating, they are at least in part Recent, but their under parts may well reach back into the Pleistocene.

RECENT

RECENTLY ELEVATED LIMESANDS

The coastal plain (pls. 20*B*, 22–24) that extends from the southwestern corner of Saipan northward along the west coast to Achugau point is for the most part underlain by recently emerged limesands. This western coastal belt ranges from ½ to less than ¼ mile wide, and includes a total area of about 4 square miles of limesand and artificial fill over limesand. These sands normally range from very fine- to very coarse-grained, are gravelly at some places, and contain many mollusk shells and Foraminifera. They resemble present beach and lagoonal limesands except that they extend to altitudes as high as 15 feet or more. Tayama (1938) reports that a hole drilled at Chalan Kiya penetrated about 8 feet of raised limesands before entering limestone. Locally, however, the deposits may be as much as 30 feet thick. They rest upon a westward-sloping, benchlike surface that is at least in part underlain by the Tanapag limestone.

This undersurface was probably once continuous with the Tanapag bench long the south side of Saipan. However, it was faulted downward about 20 feet to the west (at least in the southern part) in latest Pleistocene or early Recent time. This fault movement followed deposition of the Tanapag limestone, as here understood, but preceded the 6-foot eustatic fall of sea level which is estimated to have begun about 3,000 (±1,500) years ago (Cloud, 1954, p. 196). On the surface so provided the sands here described were accumulated, probably during retreat of the sea from its stand of about 12 to 15 feet above present sea level, beginning perhaps 10,000 to 20,000 years ago. The elevated limesands contain many marine shells, and may be in part lagoonal, but parts also suggest beach or even supratidal accumulation. Normal intertidal factors, water, wind, and storm probably all contributed to some degree in the production of a genetically complex but physically rather simple blanket of limesand. Lake Susupe (Hagoi Susupe) and the marshes around it suggest barred off lagoon remnants, slightly elevated.

Carbon-14 analysis of a pelecypod shell collected by Alexander Spoehr from 1.5 feet below the surface of undisturbed limesands at Chalan Piao in southwestern Saipan gives a corrected age of 1,730 (±450) years (see table 10). Shards associated with the shell and as much as 4 feet below it showed no marine encrustations, and this part of the deposit is therefore believed to represent high-beach or back-beach accumulation—the shell may well have been carried to its finding site by early man.

MARSH DEPOSITS

The sediments in the 600 or so acres of marsh (pl. 20*B*) consist mostly of soft, sticky, blue-gray to grayish-brown clay. The areas of marsh are all on the west coast of Saipan and mainly near Susupe lake (pl. 20*B*). They characteristically display a dense growth of cane or other grasses and occcasional small trees. Where the cane is thick it is very difficult to penetrate it on foot, even with the aid of a machete. At other places the vegetation is mainly of a species of morning glory or of the water-loving fern *Acrostichum*. Although all of the marsh is wet and boggy during the rainy season, the surface of parts of it become hard in the dry season.

One small patch of mangrove swamp is found at the mouth of Tase stream (Sadog Tase) about midlength of the west coast. This is not more than an acre or two.

GRAVEL AND SAND ON EMERGED FRINGING-REEF SURFACES

Very thin deposits of calcareous gravel and sand locally cover the lower inshore parts of emerged fringing reef surfaces at altitudes of 30 to 40 feet above present sea level (pls. 16*B*, 19*A*). These resemble deposits which may be found today on the continuously submerged parts of the fringing reef flats along the south coast of Saipan, behind the seaward margin. Outcrops of the underlying Tanapag or Mariana limestone can ordinarily be found projecting through the deposits mentioned in areas where they are mapped. Such material occurs intermittently along the inshore margin of the lower prominent bench north from Halaihai along the east coast of Saipan, and around the north and northwest coasts to Sabaneta. It extends also into grooves and former surge channels along the former seaward margins of the emerged reefs.

On the basis of the evidence cited, it was supposed in the field that these sand and gravel deposits were only a little younger than the Tanapag limestone, and probably in part contemporaneous with its upper surface. However, a carbon-14 analysis (see page 87) indicates an age of less than 200 years for a sample believed to be typical. On this evidence it would appear that some of the sands and gravels were thrown up at times of great storms or tidal waves instead of being elevated older deposits.

PRESENT REEF AND BEACH DEPOSITS

Beach deposits (pls. 18–23).—Beach deposits, as here used, applies to all intertidal and only slightly elevated deposits of the present sea—whether of sand, gravel, the lithified sands and gravels known as beach rock, or otherwise. Even a few small patches of the most recently emerged coral-algal limestone are included in this category on the geologic map. The beach sands around Saipan are almost exclusively limesands, and the gravels are largely calcareous. However, gravels of volcanic source materials are found at a few localities, and sands containing between 50 and 80 percent quartz occur at Nanasu beach (Unai Nanasu), Fahang beach, and Talofofo beach on the east coast.

At a few localities the intertidal beach sands, or sands and gravels, have been indurated so as to form beach rock (pl. 15*C*). This induration appears to occur principally by interstitial precipitation of calcium carbonate on temporarily stable beaches. Such deposits characteristically dip between 5° and 10° seaward, the general range of inclination of the beaches.

Existing organic reefs and sea level benches (pls. 13*B*, *C*, 17–24).—A barrier reef with a shallow lagoon (pls. 17*B*, 24) lies west of Saipan, becoming a fringing reef at its north and south ends (pls. 24*A*, 20*B*, 22*B*). A fringing reef surrounds much of the rest of the island. It is almost continuous along the southern coast (pl. 22) and the bays that front the east coast (pls. 18*A*, 21), but is discontinuously developed elsewhere. Some fringing reef benches extend to the shore and are barely awash at low tide, but others have their fronts separated from the shore by shallow depressions. The conspicuous reef builders are calcareous algae, corals, hydrozoans, and mollusks. Within the interstices of the frame constructed by such organisms, sediments of various sorts are trapped.

Long stretches of fringing reef are essentially erosional benches in limestone and volcanic rocks, as they are in other regions. These benches are only thinly and sporadically mantled with lime-secreting organisms

such as algae and vermetid gastropods, but they probably support a normal reef-building biota beneath their wave-breaking fronts.

Narrow stretches of intricately terraced fringing reef that extend to the normal splash level of high tide are referred to as terraced ramps (pls. 13*B*, *C*). Isolated pedestals of similar structure are called terraced pedestals. The low and small-scale terraces are really a series of rimmed basins, arranged like the paddies in a terraced rice-field, and resembling hot spring deposits. They probably are due to concurrent solution and organic abrasion at their bottoms and sides and construction at their edges.

STRUCTURAL GEOLOGY

INTRODUCTION AND SYNOPSIS

Saipan is a subaerial peak on the Mariana island arc. It is known to have been a land area intermittently since the Eocene, and to have undergone deformation and apparent changes of level at various times during the Cenozoic. The pre-Tertiary structure of the area is unknown.

The only tectonic features of any magnitude within the island itself are normal faults that trend north-northeast to northeast, approximately parallel to its long axis. They dip steeply westward and are relatively upthrown to the east by mainly dip slip movement. Shattering of the brittle rocks is indicated by minor cross faults and branch faults.

That the alinement of the principal faults on Saipan is parallel to the alinement of the island and approximately parallel to the trend of the Mariana island arc at this point suggests that these faults are related to the structural pattern of the island arc as a whole. Their orientation is consistent with an origin of the Mariana arc as an essentially north-south trending linear regional upwarp or geanticline. Fault control of the overall shape, size, and position of the island (fig. 9) seems probable.

The presently visible fault pattern may well have been outlined as early as the Oligocene, if not, indeed, in late Eocene time. There is no specific evidence of any pre-middle Miocene faulting, to be sure. The overlap of almost horizontal Tagpochau limestones (early Miocene) across the beveled surfaces of perceptibly or even conspicuously dipping volcanic rocks and sediments of Eocene and Oligocene age does not necessarily indicate pre-Tagpochau tilting, because the dips of these older beds are probably in large part initial. Yet, at least two episodes of probable upwarping and emergence before Tagpochau time may have been accompanied by some faulting, with apparent downmove-

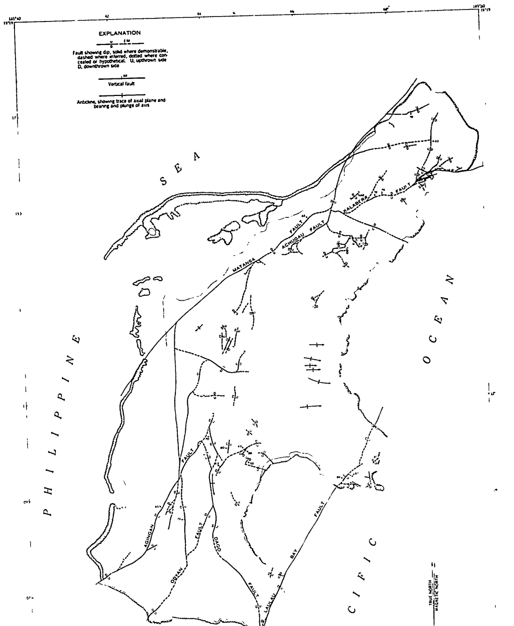

FIGURE 9.—Structural outline map of Saipan.

ment to the west and possible accentuation of initial dips by block rotation. It seems likely, therefore, that the principal fault pattern really developed by recurrent displacement through post-Eocene time, with recognizable offset attributable mainly to later Miocene and Pliocene movement.

Most of the faults observed somewhere affect the lower Miocene Tagpochau limestones, whereas few affect the probably older Pleistocene Mariana limestone. Renewed movement on old lines of faulting, or faulting along new lines, occurred in probably latest Pliocene, twice during the Pleistocene, and finally during latest Pleistocene or early Recent time.

The last mentioned fault movement slightly offset the Tanapag limestone of latest Pleistocene age. In combination with the seismic history of the region this suggests that the Mariana geanticline is still developing. It seems probable that future movements will occur along some of the existing faults or new ones parallel to them.

In addition to faulting, the rocks and sediments of Saipan are at places also affected by jointing and small-scale folds. Even more conspicuous, however, are the many primary features attributable to initial dips, slumping and sliding during sedimentation, and the effects of later compaction and mass wasting.

Although the complexity introduced into the rock sequence by the factors mentioned comes under the general heading of structural geology, only a part of it is due to tectonic deformation. The features here to be considered, therefore, are grouped according to inferred origin into (1) primary structures associated with volcanism and the deposition of sediments on sloping surfaces; (2) tectonic and possibly tectonic structures; and (3) structures due to compaction, slumping, mass wasting, and collapse. By means of the arrangement indicated it is hoped to take account not only of truly primary structures, but also of the probability that some faulting is due to sedimentary compaction or load deformation, some "folds" may reflect merely the topography of the surface on which the sediments were deposited, and anomalous bedding-fracture patterns may result from slumping and collapse.

PRIMARY STRUCTURES

VOLCANO REMNANTS, PROTRUSIVE STRUCTURES, AND LAVA FLOWS

The monoclinal structure of Mount Achugau (Ogso Achugau), in north-central Saipan, strongly suggests the remnant of a former volcanic cone. As was described under "Origin" of the Sankakuyama formation the peak of Mount Achugau is a layered sequence of dacitic flow rocks and breccias that dip 40°–50° south. Attitudes become much gentler (25° to 30°) downdip and down the flank of the inferred cone remnant. Dips may have been accentuated by later tilting in the same direction, caused by southward rotation of the fault wedge that reaches an apex just north of Mount Achugau.

Gently inclined layered masses of quartz dacite and thinly banded flow breccia in the southern part of the Sankakuyama outcrop area probably relate to domal protusions and short, stubby flows on the flank of the main volcano.

Chaotically distorted, thinly banded dacites, wherein attitudes of banding are steeply inclined to vertical, occur in the northeastern part of the Sankakuyama outcrop area. These may represent another dome or domes, also on the flank of the main volcano.

The andesite flow rock of the Hagman and Fina-sisu formations occurs as distinctly tabular and concordant bodies that are associated with both water-laid and subaerial andesitic pyroclastics. The mainly gentle dips of these flows are presumed to be initial or but slightly accentuated by later tilting. The very presence of flows suggests a sloping surface, and all of them dip in an easterly direction, away from the probable locus of original volcanic centers as also inferred from the marine to nonmarine gradation of the Hagman pyroclastic rocks.

OTHER INITIALLY DIPPING DEPOSITS

Marine tuffs and rare interlayered andesite flows in the conglomerate-sandstone facies of the Eocene Hagman formation dip parallel to the surface of the underlying Eocene(?) Sankakuyama dacites in north-central Saipan at angles of 10° to 20° (rarely 30°) (structure section *A—A′*, pl. 1). Similarly, interbedded andesitic flows and marine tuffs of the Oligocene Fina-sisu formation in south Saipan dip east at angles of 3° to 10° (structure section *D—D′*, pl. 1). In both instances the dips are interpreted as mainly or wholly initial; because the present pattern of dips is consistent with associated primary structures and the direction of probable source areas, and because it is presumed that perceptible slope would facilitate the spreading out of such lava flows.

At other places, beds within the relatively widespread breccia-tuff facies of the Hagman dip generally east and northeast between 5° and 25°. Marine conglomerate and sandstone beds of the same formation, which lie seaward (east) from and grade into the breccia facies, mostly dip eastward at angles between 5° and 18°. This general concordance of attitude and genetic association suggests that the dips are mainly initial and due to the deposition of sediments on, and their working down, a concordantly dipping slope. Dips up to 34° are commonplace among subaerial pyroclastic beds of active volcanoes, and probably somewhat less among their subaqueous counterparts.

The mainly andesitic sediments of the Densinyama formation overlap and interfinger with the Hagman formation and locally rest upon the Sankakuyama. They are most widespread in central and eastern Saipan, but extend west across the summit of Talofofo ridge. They are inclined both east and west from the crest of Talofofo ridge at dips between 5° and 20° (structure section *B—B′* pl. 1) as though here deposited over and around a preexisting axial ridge of andesitic source materials: the Hagman formation. In its northern outcrops, where the formation is thickest, and in east-central Saipan, the beds dip gently east and southeast. The attitudes of beds within the Densinyama formation are believed to be largely initial, because of the manner in which they drape over Talofofo ridge (essentially conforming to the inferred surface of deposition), and because they are only locally faulted or warped.

From the foregoing discussion, it appears that the upper Eocene Hagman rocks may represent the remnents of a mainly eastward-dipping volcanic structure, or complex, that was in part superimposed on the south flank of a slightly precedent dacitic stratovolcano. Over and around the rapidly eroding remnants of the unconsolidated Hagman deposits were laid down the mostly reworked and mainly (or wholly) marine sediments of the partly interfingering, partly overlapping, and only broadly overlying Densinyama formation. The easterly dips of the Oligocene Fina-sisu volcanic rocks conform to the broad pattern of inclination away from a generally western source area. Slumping of previously deposited sediments would account for locally anomalous attitudes, especially in the Hagman and Densinyama beds.

Other possible or probable initial dips are found in the Matansa, Tagpochau, and Mariana limestones. In both the rubbly and the *Halimeda*-rich facies (pl. 13*A*) of the Mariana limestone along the eastern margin of the island, the 10° to 20° eastward dips may be initial or partly initial. Later accentuation of such dips by eastward rotation of fault blocks is conceivable, but is not necessary to account for the facts observed. Supposed initial dips as much as 33° were recorded by J. B. Harrison (1907) within a succession of mainly horizontal coralliferous rocks on Barbados. In these beds, those dipping as steeply as 6° contained coral heads in position of growth but those at higher inclinations contained only displaced corals. Talus slopes and current bedding, as invoked by Harrison, seem likely causes of steep initial dips in limestones associated with ancient reefs or bank margins.

DEPOSITIONAL(?) FOLDS

Folds of problematical origin are found in the Donni sandstone member of the Tagpochau limestone in east-central Saipan. Northward from Chacha to I Pitot are at least five well-defined, east-plunging anticlines with observed lengths from less than ¼ mile to a little more than ½ mile. Lobes of the Donni sandstone member extend eastward along short anticlinal spurs that are separated by valleys in the rubbly facies of the Mariana limestone. Distances between fold axes range from about 500 feet to ½ mile. Their apparent heights at midlength are 30 feet to about 100 feet and they open to the west. The "folded" Donni beds overlie poorly exposed Tagpochau limestones and andesites of the Hagman and Densinyama formations, none of which appears to be folded.

Having searched in vain for a way to explain these Donni folds as tectonic features, it becomes necessary to consider how else they might be accounted for. Perhaps local currents, descending from the banks on which penecontemporaneous shallower water Tagpochau limestones were accumulating, scoured seaward-trending channels and spurs in the poorly consolidated sediments of their lower slopes. As the area continued to subside, tuffaceous sediments of the Donni beds might then have settled over such a submarine topography in a pattern of depositional anticlines and synclines. Similar depositional "fold" patterns have been observed by Cloud in subaerial tuffs near Tarawera in the Rotorua area of New Zealand, and there is no reason to doubt that such features could form subaqueously as well.

TECTONIC STRUCTURES

FAULTS

The principal faults of Saipan are high-angle faults that trend dominantly in a north-northeast to northeast direction (fig. 9; pl. 1). They are subparallel to the long axis of the island and roughly parallel to the trend of the Mariana ridge in the immediate vicinity. A scattering of minor faults branch off from or interesect the principal faults obliquely or at right angles. Where the juncture is oblique, the acute angle is generally to the south. Other minor faults, some too small to map, mostly tend to parallel the principal faults, but some have aberrant trends.

Where the surfaces of the principal faults are exposed, they dip westward at an average near 60° to 70°, but some are nearly vertical and others incline as little as 45°. They are also mostly downthrown on the west side, with little or no strike-slip component to the movement, and are thus normal faults. No reverse faults or strike-slip faults were observed on Saipan, and probably none of any significance occur there. The direction of

movement and inclination of the faults suggest that eastward rotation of fault blocks may have contributed to the prevailing easterly dips of the strata. If it did, however, the effect is believed to be a matter of accentuation of dips that were initially in the same direction.

Seemingly anomalous offsets of contacts on opposite sides of faults may result from the vagaries of strand line variation and bench cutting. Thus Mariana beds in the small upfaulted wedge that trends north from Fañunchuluyan bay were apparently raised to higher levels than equivalent beds in the adjacent terrace surface, offsetting the contact with underlying beds in the "wrong" direction.

Movements of 10 to 20 feet along old faults locally offset the Tanapag limestone of presumably late Pleistocene from Mariana limestone without appearing to displace it. Some terraces have been cut since the most recent fault movement beneath them and others are offset or tilted by faulting. Movement has apparently been recurrent along some faults at intervals from postearly Miocene, and perhaps pre-Miocene, to Recent time. Others have moved less frequently and less recently.

It has not been possible to determine actual net slip or stratigraphic separation along any of the principal faults of Saipan because of the absence of duplicated datum surfaces along or near the faults. The displacements shown on the structure sections merely suggest order of magnitude based on the relations that seemed most probable as the available data on attitudes, widths of outcrop, and thicknesses were plotted on the topographic profiles. However, the maximum net vertical displacement along any fault on Saipan probably does not exceed 300 to 400 feet, and some persistent and conspicuous faults show net displacements that may be less than 100 feet.

The most continuously recognizable fault on Saipan is the Agingan fault (fig. 9; pls. 22, 23*A*), which extends from the west side of Agingan point, at the southwest corner of the island, for 5 miles northeast and north-northeast along the western side of Fina-sisu and west of the Gallego grasslands (Sabanan Gallego) toward Mount Tagpochau. The surface of this fault was observed to dip about 65° west in the Fina-sisu area, and slickensides show evidence of dip-slip movement only. Actual displacement is unknown but is probably well over 100 feet. Most recent displacement is perhaps 20 feet downward to the west of Agingan point, where the fault offsets the Tanapag limestone. Northward in the Fina-sisu district the Tanapag limestone on the west appears to have been both deposited against and dropped along this fault. Indeed topographic relief from upthrown to downthrown side in this area well exceeds the 20 feet or so of post-Tanapag displacement, and locally exceeds 150 feet. Branch faults fan into the Agingan fault from the southeast, and the whole fault complex appears to die out abruptly into undifferentiated Tagpochau limestones about halfway up the ravine west of the I Eddot grasslands.

The Obyan (pronounced Ŏb′-zän) fault trends north-northeast from Obyan point, at the midlength of the south coast (fig. 9; pl. 22*B*). It begins in the Tanapag limestone and transects the massive facies of the Mariana limestone at the base of Gonno cliff. The Dago fault appears to cut obliquely across it from the southeast along the base of Dago cliff. The Dago fault then continues northward to the mouth of I Eddot ravine where it was lost in undifferentiated Tagpochau limestone in what seems to be a zone of minor faulting or shattering. Exposures are poor and relations very uncertain in the vicinity of I Eddot ravine, but possible general trends are shown by the lines of inferred faulting on the geologic map. Displacement is downward to the west, only 10 to 15 feet at Obyan point, where the Tanapag limestone is barely offset, but perhaps 100 to 200 feet where its pre-Tanapag effects are visible and where bench surfaces are displaced.

The important Laulau bay fault (fig. 9; pls. 20*B*, 22*B*, 23*A*), runs along the base of Naftan cliffs from the west side of Naftan point to the east side of Dandan point, presumably crosses Laulau bay, and continues along the base of Hagman cliffs, defining the eastern limits of Chacha. Movement along this fault is downward to the west and was probably recurrent. Local apparent movement varies between the 40 to 100 feet suggested by inferred displacement of bench surfaces at different places and the 200 to 300 feet or more that is doubtfully inferrable from stratigraphic relations (structure sections *C–C′*, *E–E′*, pl. 1). The fault surface is vertical through the Pleistocene limestones at Naftan point but dips only 50° to 55° west where the downdropped Mariana limestone abuts sandstone and conglomerate of the Hagman formation at Hagman cliffs. Weakly preserved suggestions of slickensides and chatter marks indicate dip-slip movement only. Its trace across Laulau bay may have been erased by subsequent sliding, as discussed in part 4.

A complex of short, high-angle faults of indeterminate displacement locally offsets the Tagpochau limestone on the west side of the Tagpochau uplands. This is shown on the geologic maps and in structure section *C–C′*, pl. 1.

The conspicuous northeast trending and branching Matansa fault drops Miocene and younger strata against Eocene andesitic rocks and Miocene limestones in the northern part of west-central Saipan from Puerto Rico to Matansa. In general it follows the lower boundary of the axial uplands, or the upper margin of the western coastal plain. Displacement along this fault is downward to the west, along a surface that dips 50° westward where observed. It may be on the order of several hundred feet locally (structure sections *A–A′*, *B–B′*, pl. 1).

The Achugau fault approximately parallels the Matansa fault and seems to merge northward with it at the mouth of Papua ravine. It drops the Miocene Tagpochau limestone on the northwest against dacitic and andesitic rocks and limestone of Eocene age to the southeast. Displacement along the Achugau fault may be 400 feet or more below Mount Achugau itself, but the fault dies out abruptly or is lost in andesitic sediments to the south. A branch fault that trends eastward from the principal Achugau fault connects with a complex of short, high-angle faults that chop the Sankakuyama dacites and adjacent rocks into small, irregular blocks.

In the vicinity of Fañunchuluyan beach the dacitic rocks of the Eocene(?) Sankakuyama formation are broken into wedge-shaped blocks by a complex of minor northeast-trending faults which also offset rocks of Miocene and Pleistocene age. These faults fan out from the northeast end of the longer Kalabera fault, a normal fault that curves to the southwest, dips 70°–75° northwest, and probably runs into the Achugau fault. Steeply dipping fault surfaces are well exposed in the cliffs at Fañunchuluyan beach, where they are intersected by the surface of a post-Mariana terrace.

A short- nearly east-west fault at the south margin of Magpi cliffs drops to the south, and a similar fault at south Kalabera cliffs drops to the north. Increasing throw on these faults from east to west may account for the westward inclination of terraces adjacent to them (pl. 16*A*). Other short faults shown on the geologic maps, but not further commented on, appear to have undergone mainly nonrotational dip-slip movement.

The andesitic rocks of the Hagman and Densinyama formations give the impression of being less affected by faulting than the more brittle older dacitic rocks and younger limestones. However, the few faults that were traced into the andesitic rocks did not preserve scarps and could not be followed for appreciable distances. Because many of the minor faults observed in these andesitic rocks could well be compaction features, structures that did not show appreciable continuity and throw were not mapped (pl. 6*D*). It is not really known whether faults in the andesitic rocks may be more numerous than is indicated on the geologic maps, or whether movement within these rocks was translated to many very small displacements instead of a few larger ones.

JOINTS

In attempting to determine whether the joints in the rocks of Saipan follow any dominant trends and whether such trends showed any stratigraphic variation, attitudes of all joints read and plotted were divided into Eocene, Miocene, and post-Miocene groups. Because most of the joints are vertical or dip at very steep angles, the dip component was left out of consideration.

It was found that the strikes of joints in the Eocene rocks are widely dispersed around the compass but tend slightly to be concentrated in a west-northwest by east-southeast direction. The strikes of joints that transect the Miocene Tagpochau limestone likewise are widely distributed but show some concentration in the north-northeast to south-southwest, north to south, and east-northeast to west-southwest directions. That is, they favor the directions within the northeast and southwest quadrants. The strikes of joints in the post-Miocene strata of Saipan show approximately the same pattern of orientation as those in the Eocene rocks, running around the compass but showing general concentration in west-northwest to east-southeast octants.

The patterns cited show a moderate tendency for joint alinement either parallel with or normal to directions of faulting, but with a scatter that covers nearly all points of the compass.

FOLDS

Folds of known tectonic origin are inconspicuous on Saipan. Broad, gentle undulations with no marked alinements are fairly common, and small drag-folds may be seen along some faults. However, well-defined, mappable folds were found at only two places, apart from the suspected depositional folds already described.

The big quarry (S19) at the east side of the mouth of I Eddot ravine, north of Wallace Highway, has been excavated essentially along the axis of a sharp anticline that is interpreted as a drag feature related to the Dago fault at its west margin. The axis of this fold strikes almost due north but is well defined for less than half a mile

A second small anticline affects the equigranular facies of the Tagpochau limestone between the north and south branches of Fanaganam ravine, in the west-central part of the island. This fold has a southwesterly trend, and the rocks on its flanks dip about 20° northwest and southeast. It is recognizable for less than one-fourth mile. Because this fold trends roughly parallel to the structural grain of the island, it may be a small tectonic feature.

STRUCTURES DUE TO COMPACTION, SLUMPING, MASS WASTING, AND COLLAPSE

Small faults interpreted as being due to load compaction (pl. 5*A*) are locally common, especially among the volcanic sediments. Such faults characteristically are steeply inclined normal faults that seem to die out upwards and downwards. At places they occur in clusters that dip (and drop) from both sides toward a central point. A well-displayed cluster is in the conglomerate-sandstone facies of the Hagman formation in its last outcrops along the sea-level bench that runs north from Hagman point to Laulau point north.

Penecontemporaneous slumping along sedimentary surfaces is an important factor in the production of various anomalous relations in those sediments that have initial dip. Chaotic bedding and the introduction of large blocks and erratic masses of divergent rock types is best accounted for by this mechanism.

Landslide deposits (pl. 21*A*), some of the results of gravity creep on gently inclined surfaces (pl. 21*A*), and the coarse slump rubble of steep coastal areas (pl. 17*A*) are described in a preceding section under "Deposits formed by mass wasting."

An unusual example of mass wasting is provided by an area of actively creeping blocks of the *Halimeda*-rich facies of the Mariana limestone along the east coast of the Hagman peninsula. This area extends for about one-half mile north to south, between North Laulau point and Hagman bay, and one-fourth mile east to west from the sea to the 250- to 450-foot bluffs above. Its southern edge is shown at the right side of plate 21*A*. Over this area, blocks of limestone that average perhaps 50 feet across and are only slightly separated from one another are creeping toward the sea. They are so closely spaced that the area is retained under the Mariana limestone symbol on the geologic maps. They are sliding on the surface of the Donni sandstone member of the Tagpochau limestone, and perhaps in part on the conglomerate-sandstone facies of the Hagman formation. This under surface dips 5°–20° toward the sea and is well lubricated as a result of the weathering of its tuffaceous components to unctuous clay. Along the margins of the bluff above the wasting area, masses of limestone as much as 150 feet long and 50 to 80 feet wide are barely separated or not yet fully free from the sheet of rock to the west. They will doubtless continue to break loose, separate into more nearly equidimensional parts, and creep seaward until they either work back to a slope too gentle for perceptible movement or exhaust their source.

Collapse structures result from the weakening of cavern roofs by solution, leading to direct downward settling of younger rocks into older. Many sinks, or sink holes, are collapse structures, but others are probably due almost entirely to solution. On Saipan several of the smaller sinks show evidence of being true collapse structures, as at I Madog point and just north of I Hasngot beach. Other collapse features are probably represented by blind-ended valleys that terminate eastward against limestone cliffs, like those north of Nanasu beach and west-southwest from Tuturam beach.

RELATION OF STRUCTURE TO TOPOGRAPHY

An unusually straight and persistent scarp in an area of block faulting, such as Saipan, is likely to be thought a fault scarp until good reason is found for believing otherwise, particularly if it conforms with established structural trends. Faults that displace previously terraced terrain are ordinarily conspicuous, and terrace displacement along them may provide unusually good data for direction, amount, and time of particular fault movements. The fact that certain faults offset some terrace surfaces but not others, or are planed off by terrace cutting, brackets the time of fault movement relative to times of successive terrace cutting.

The most marked example of terrace tilting as a clue to faulting on Saipan is found adjacent to the approximately located east-northeast trending fault that runs along Magpi ravine in northwestern Saipan. Here a fault was first postulated from the fact that the terrace surfaces as As Matuis, south of Magpi ravine, are tilted toward the west relative to the almost horizontal terrace surfaces north of the supposed fault. The presence and direction of movement of this fault were later confirmed by paleontology, although its location is still based on topographic evidence only, and the fault has not been observed. The 80-foot terrace at the west is not cut by this fault, showing that movement along it was completed before truncation of the lower terrace. A second fault that would have been indicated by westward terrace tilting, had it not been known on other evidence, is the short hinge-fault at the south side of the westward tilted terraces of south Kalabera cliffs.

If an absolute terrace chronology could ever be worked out for the Mariana Islands, it would permit close dating of many known fault movements. As it is, the evidence of sedimentation and terrace relations to faulting on Saipan fixes the time of five intervals of faulting as: (1) post-Tagpochau deposition and pre-high-terrace cutting, younger Miocene or older Pliocene; (2) post-high-terrace cutting and pre-Mariana deposition, possibly latest Pliocene; (3) post-Mariana deposition and pre-intermediate-terrace cutting, possibly early middle Pleistocene; (4) post-intermediate-terrace cutting and pre-Tanapag limestone deposition, possibly late middle Pleistocene or early late Pleistocene; and

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(5) post-Tanapag limestone deposition but before a Recent 6-foot fall of sea level, probably older Recent or latest Pleistocene.

Unusual relations of "structure" to topography are shown by the roughly paired, westward-extending, valley-filling lobes of Mariana limestone and eastward-plunging spurs of the Donni sandstone member of the Tagpochau limestone along the eastern island margin. As described in a foregoing section, these features mark the approximate axes of possibly depositional anticlines and synclines.

HISTORICAL GEOLOGY

INTRODUCTION AND SYNOPSIS

A sequence of geologic events does not constitute historical geology until the events are interrelated and interpreted in terms of paleogeography, paleoecology, and tectonic evolution. In the following pages, therefore, an effort is made to abstract and interrelate such evidence for the geologic history of Saipan and its environs.

The fragmentary record begins with the Eocene, and is pieced together from bits of evidence for the subsequent epochs of Cenozoic time (table 11). It involves the following events:

1. The formation of Eocene and Oligocene dacitic and andesitic volcanic rocks and thin Eocene limestones that make up the central core of the island; interrupted by erosion and submergence, and probable interrupted or followed by faulting.
2. The accumulation, around and over this central core, of 1,000 feet or so of older Miocene warm-water bank limestones and associated sediments.
3. Younger Miocene or Pliocene faulting; relatively up on the east and down on the west along westward-dipping high-angle faults that trend north-northeast to northeast, parallel to the long axis of Saipan. At the same time a fault wedge raised the volcanic area in the north-central part of the island relative to the Matuis uplands to the north. Erosion was necessarily concomitant with these movements.
4. Pliocene(?) emergence and continued erosion, formation of high-level terrace deposits, marine benching from the island crest to and probably below the present 500-foot level, and local east-west hinge-faulting that tilts parts of the upper terraces westward.
5. Deposition of older Pleistocene reef-complex and bank limestones below the present 500-foot level; followed by renewed faulting along old lines and by new minor faulting locally.
6. Middle(?) Pleistocene emergence from roughly the present 500-foot level to or below the 100-foot level; accompanied by benching and the formation of terrace deposits, and followed by renewal of faulting along old trends and possibly along actual lines of former movement.
7. Late Pleistocene emergence from about 100 feet above to not more than 300 feet below present sea level, probably followed by resubmergence to about 40 feet above sea level and then renewed withdrawal, or perhaps merely interrupted by a temporary stand of the sea at 40 feet. This was accompanied by deposition of a mantle of fringing-reef limestone which seems to be better preserved below than above 40 feet. The sea stood at the 40-foot level long enough to produce horizontal notches in scarp bases and around stacks. The lowest Pleistocene reef surface is about 12 to 15 feet above present sea level, where the sea may have been 20,000 years (or less) ago. The carbon-14 dating (table 10, loc. C35) and possibly eustatic nature of this level is, of course, in conflict with conventional belief which calls for extended glaciation and greatly lowered sea level at this time. Thus, only alteration may be dated.
8. Local renewal of faulting along old lines seemingly resulted in general downmovement of the western coastal plain block by about 20 feet to the west.
9. Final fluctuating emergence to slightly below present sea level, with temporary stands of the sea at about 6 feet and 2 feet above the lowest point of fall. Retreat from the 6-foot level began perhaps 3,000 (±1,500) years ago and is presumably related to withdrawal of water from the ocean to form additions to the present ice caps, following the most recent subpeak of the post glacial thermal maximum. The evidence of submerged subaerial solution features on Guam and Palau suggests emergence to some feet or tens of feet below present sea level before the 6-foot stand and probably after the 15-foot stand.
10. Slight rise of sea level in the last 100 years or so.

THE OLDEST ROCKS (EOCENE?)

The oldest rocks on Saipan that are accurately datable by fossils were deposited in late Eocene time. Dacitic rocks beneath them are also believed to be Eocene and probably late Eocene, because of the presence in the dacites of the metastable silica minerals tridymite and cristobalite, which are rare in pre-Miocene and unknown in pre-Tertiary rocks.

The oldest rock of all, however, is augite andesite, in part quartz-bearing, found as inclusions in the dacitic breccias of the tridymite- and cristobalite-bearing Sankakuyama formation. These inclusions are presumably fragments of andesitic wall rock that were torn loose from the sides of vents out of which the dacitic rocks were erupted, and they probably indicate the presence at depth of andesitic rocks older than the

Table 11.—*Summary of the inferred geologic history of Saipan*

APPROXIMATE TIME IN YEARS (mainly after Simpson, 1949, p 12)	CENOZOIC EPOCHS	REPRESENTED ON SAIPAN BY
0.01	Recent	Beginning of sea level recovery about 100 years ago 2-foot eustatic halt of sea 6-foot eustatic stand of sea Latest faulting and beginning of western coastal plain
1 million	Pleistocene	Fringing reef deposits of Tanapag limestone formed on mainly emergent but probably fluctuating surface below 100 feet, with stands of sea at about 100, 40, and perhaps 15 feet above present sea level Faulting Emergence and formation of intermediate terraces (100-150 feet) Faulting Sumergence and formation of tropical bank or lagoon and reef-complex deposits of Mariana limestone
12 million	Pliocene	East-to-west hinge faulting Emergence and formation of high terraces (+500 feet) Faulting. Mainly up on east side and down on west along west-sloping, high-angle faults parallel to the long axis of Saipan. Exact interval or intervals of faulting not known Faults probably in part preexisting and in part new at this time
28 million	Miocene	Submergence and formation of tropical marine bank limestones and associated deeper water tuffaceous sandstones of Tagpochau limestone
39 million	Oligocene	Emergence, probably faulting, and erosion Probably subsidence and formation of marine andesitic tuffs and lava flows of Fina-sisu formation Unknown (possibly faulting and probably emergence and erosion)
58 million	Eocene	Continued subsidence and formation of tropical marine bank deposits of Matansa limestone Subsidence and reworking of marine andesitic materials to form Densinyama formation Formation of subaerial and marine andesitic deposits of the Hagman formation Erosion to lowest level of presently exposed dacites Subaerial eruption of dacitic volcanic rocks of Sankakuyama formation Interval of andesitic eruptions represented by inclusions in Sankakuyama formation (Age by top control and mineralogy only. Could be younger or older than indicated here)
75 million	Paleocene	Unknown

"basement" dacites of the Sankakuyama formation. Until evidence to the contrary may be forthcoming, it seems preferable to consider that these oldest andesitic rocks represent part of the late Eocene volcanic epoch that so widely contributed to the volcanic succession of Saipan and other islands at the eastern margin of the Philippine Sea.

THE EOCENCE CORE AND THE BEGINNING OF THE VOLCANIC ISLAND ARC

Perhaps in part contemporaneous with, but mainly following the extrusion of, the older Eocene(?) andesites, dacitic lavas issued to form the Sankakuyama formation. These rocks represent the first event in the history of Saipan of which there is a substantial record. Although their Eocene age is open to question, it is believed sufficiently well assured by the evidence of superposition and mineralogy, as cited above, to warrant inclusion of Sankakuyama events as a part of Eocene history.

The Sankakuyama rocks include dacitic breccias, tuffs, flow breccias, and glassy flow rocks. The south-dipping homocline of Mount Achugau, in and about which the dacites outcrop, is interpreted as a remnant of a stratified composite volcanic cone whose Eocene center was not far north of the present peak. The pyroclastic breccias and tuffs on the flank remnants of this cone represent accumulations of explosively erupted airborne blocks and ash. Highly foliated flow breccias and associated, chaotically laminated, glassy flow rocks probably originated within protrusive domes, or by extrusion of viscous lavas from them. Some of the breccias probably developed as short, stubby, self-brecciating flows, and other breccias may have formed along the flanks of domal protrusions as avalanche flows and as talus slides. Tabular and lens-shaped bodies of foliated dacite, intercalated with pyroclastic breccias and tuffs, and not exceeding one-fourth mile long, presumably represent surface lava flows. Such flow rocks are probably very near their source. Their presence is also significant, in that it combines with the absence of marine fossils and the general appearance of most of the pyroclastic rocks to imply strongly a subaerial origin for most or all of the Sankakuyama formation as presently exposed.

The Eocene(?) Sankakuyama dacites thus provide the earliest evidence of land in the present vicinity of Saipan, just as the later Eocene andesitic marine sediments supply the oldest definite record of the sea. In fact, the well-stratified and crossbedded dacitic breccias and tuffs that form the islet of Maigo Fahang and the sea cliffs of the main island nearby are the only outcrops of the Sankakuyama formation that are even suspected to be of marine origin.

In addition to the exposures of and near the Achugau cone, sites of dacitic eruption are also indicated by mainly dacitic volcanic necks or plugs in a quarry east of Flores point and also at Mount Laulau. The dacitic deposits that presumably once surrounded these plugs, however, have since been entirely removed, and the plugs are now surrounded by andesitic breccias of the Hagman formation.

Following eruption of the dacitic rocks by an interval of unknown duration, the upper Eocene andesitic volcanic rocks of the Hagman formation were produced. Although the Hagman rocks at places overlap the dacitic rocks of the Achugau cone unconformably, this does not in itself necessarily indicate either much lapse of time, tilting, or erosion. The andesitic sediments came from different sources and would naturally wedge out against the flanks of the dacitic cone (pls. 5*D*, 17, 24*C*) at some places, just as they conform with its slopes at others. On the other hand, the unconformable contact is an irregular angular break, and the overlapping Hagman rocks are marine tuffaceous sandstones that contain fragments of dacite at and near their basal contact with the Sankakuyama. This combines with complete removal of the dacitic deposits from about the Flores and Laulau necks to suggest an appreciable erosional break between Hagman and Sankakuyama deposition.

The more westerly outcrops of the Hagman formation are unfossiliferous and presumably subaerial andesitic breccias, tuffs, and flows. These grade eastward into marine andesitic conglomerates and tuffaceous sandstones that were deposited contemporaneously below the strand line. The subaerial deposits indicate volcanic land of unknown but probably insular extent to the west. The derived marine deposits contain Foraminifera and algae that indicate a tropical to subtropical environment and depths of deposition from shallow to moderately deep. The benthonic Foraminifera have, in fact, been interpreted to indicate depths of 200 fathoms or more, although it seems from other evidence that 100 fathoms or less is more probable. The sediments, in any event, were deposited with appreciable initial dips on slopes along which sliding masses of sediments and avalanching blocks maintained intermittent turbidity.

Actual lava flows are rare within the andesitic sequence of Hagman volcanism. The few flows that are intercalated with marine sandstone and conglomerate may have been submarine, but the flows associated with breccia were most likely subaerial, pouring down the sloping surface as relatively quiet outwellings of fairly fluid lava.

From the foregoing account, it appears that Saipan during Hagman time was part of an actively volcanic tropical land area that partly coincided with and partly extended westward from present-day Saipan. Against this land the sea stood relatively higher by several hundred feet than it does at the present day. In addition to their westward extension the Hagman deposits were apparently also continuous with the andesites of Tinian. Andesitic conglomerates unlike the Fina-sisu or Densinyama beds occur beneath the overhang of Naftan point in south Saipan, and andesitic pebbles have been dredged from the Saipan channel and are found as pebbles on the beach and in beach rock along the south coast of Saipan.

Perhaps following but more likely contemporaneous with the last of the Hagman andesites, the basal volcanic breccia of the Densinyama formation produced the last fairly sure record of Eocene volcanic activity on Saipan. After the deposition of this supposedly subaerial breccia and the foundering of the western flank of the volcanic ridge of Hagman time, the sea invaded Eocene Saipan from both east and west. It reworked the rocks of the volcanic core and buried them with locally common larger and smaller Foraminifera and algae that indicate tropical or subtropical waters of the same general depth range as the Hagman. Thus were produced the thick deposits of mainly marine conglomerate and sandstone that represent the bulk of the Densinyama formation and grade upward through an increasing proportion of calcareous materials to the marine upper Eocene Matansa limestone. Densinyama marine deposits entirely overlap the highest Hagman beds in Talofofo ridge and drape over them with presumably initial dips that incline both east and west away from the axial core.

The island was by now much reduced in area. That some land still lay nearby, however, is suggested by the presence of silicified dicotyledonous driftwood, possibly fig or mulberry (oral communication from Roland Brown), that was found in marine deposits of the Densinyama formation on the east side of Densinyama ridge.

By the end of Eocene time only a few high peaks (such as Achugau and Tagpochau) projected above sea level. The remainder of present-day Saipan was overlapped by the shallow to moderately deep water, subtropical or tropical bank deposits of the Matansa limestone. These deposits cover a large part of the volcanic foundation to a depth of several hundred feet and betray their relative proximity to this foundation by the proportion of tuffaceous impurities which they contain.

The Matansa limestone is dominated by bioclastic calcareous materials that include abundant fragmentary articulate and crustose coralline algae, locally abundant larger Foraminifera, occasionally abundant miliolids and other smaller Foraminifera, local occurrences of the dasycladacean alga *Cymopolia* and the codiacean *Halimeda*, and occasional corals, echinoid spines, and mollusk fragments. Much of the fine matrix between clastic particles and tests consists of minute clear calcite grains, probably altered from aragonite. The combined evidence of these characteristics indicates a depth range from less than 10 fathoms, and probably intertidal, to 40 or 50 fathoms. It also points to accumulation in tropical waters on a bank that lay mainly below the range of vigorous reef growth and strong current sweeping and that subsided progressively so as to accumulate a thick sequence of mainly shallow-water deposits. It is believed that the Matansa sequence began with overlapping tuffaceous deposits that grade laterally into Densinyama beds and upward as well as laterally into impure pink limestone. The pink limestone presumably gives way to nearly pure white limestone that has few larger Foraminifera, but many miliolids and dasycladaceans. The fossils suggest that the white limestone accumulated in waters mainly shallower than those in which the pink and tuffaceous limestones were deposited—too shallow to favor the vigorous growth of larger Foraminifera, but perhaps still too deep for reefs.

Why reefs were not formed here during Matansa time is, of course, not surely known. The general habitat seems right for them, and bits of coral were found in the limestone. Perhaps the area was beyond the latitudinal range of vigorous Eocene reef building, or perhaps there simply was not time enough for reefs to become established after the unfavorable conditions of preceding volcanism and turbidity. Over much of the area, however, the water was probably a little too deep for vigorous reef building.

To review and interpret further, it appears that the Mariana arc as a tectonic feature probably originated before or at the same time as the conspicuous Eocene volcanism described above. This volcanism is taken to signify upward movement of magma through a buckling crust, and itself contributed importantly to the growth of the arc by piling volcanic debris on top of the inferred geanticline. In the absence of evidence to suggest a pre-Tertiary, or even a pre-Eocene history, the beginning of this geanticline seems best interpreted as an early Cenozoic event. As was mentioned, the Eocene also presents the first sure evidence of either land or sea in the area of the Mariana arc. But the land was volcanic, presumably insular, and short lived; and the implication is that the antecedent area had long been oceanic, or at least marine, and freely connected with the Pacific Ocean. At least from this time onward the structural and petrographic boundary between the Asiatic continental block and the Pacific Ocean basin can be interpreted as lying in front of the Mariana arc, and the Philippine Sea can be interpreted as a separate maritime area.

According to this interpretation, the primary arc was well defined, and a tectonically active land area stood at the present site of Saipan, before the end of Eocene time. The latest Eocene events represent relaxation of the upbuilding forces and gradual subsidence. The western reaches of early Saipan foundered. Reworking of the old volcanic materials by the encroaching tropical sea was the principal source for the sediments of the Densinyama formation, which are draped over the remnant ridge of the Hagman volcanic complex in the Talofofo area. Gradually the volcanic components decreased in volume; turbidity decreased; lime-secreting algae, Foraminifera, and other organisms became more abundant in the clearing warm waters; and the calcareous sediments that are now the Matansa limestone overlapped the subsiding volcanic foundation with increasing purity upwards.

These events extend nearly or quite to the end of Eocene time, for the fossils are indicative of a late Eocene age.

OLIGOCENE HISTORY AND THE LAST OF THE PRIMARY VOLCANIC ROCKS

The first half or two-thirds of Oligocene time have preserved no record that is identifiable as such on Saipan. The absence of recognizable deposits suggests emergence and erosion, and perhaps the fault pattern was established or elaborated at that time—but nothing is positively known.

At some time during about the last third or half of Oligocene time volcanism again became active. As Eocene volcanism appears to have made the first and major contribution to the island's volcanic core, so Oligocene volcanism put the finishing touches on it. Flows of augite andesite welled out from a local western source and spread down a gently eastward-dipping sea floor. They are interlayered with penecontemporaneous andesitic marine tuffs that contain planktonic Foraminifera of presumed late Oligocene age (*Globigerinatella insueta* zone of Trinidad and Venezuela) and benthonic genera that are reported to live only at depths of 200 or more fathoms in modern tropical to subtropical waters. Such a depth of water above the highest outcrops of this Fina-sisu formation would have carried the sea well up over the slopes to the north where Oligocene deposits are buried if present. However, reason has been given elsewhere for reducing this and comparable estimates of depth by about 50 percent or more.

The late Oligocene of Saipan is thus interpreted as a time of warm marine waters of moderate but appreciable depth that surrounded a small, mainly or wholly volcanic island or islands. This sea, in the southern part of Saipan, was periodically muddied by eastward moving submarine lava flows and by ash falls from volcanic centers that stood west of the present island.

So far as can be determined Oligocene volcanism was not extensive or prolonged. It appears that the primary volcanic core of the eastern line of islands of the Marianas in this vicinity was now almost complete.[10] The next recorded eruptive activity was of Quaternary age, and well westward from the structural crest of the older, more easterly ridge and chain of islands. Although limestone-capped Mount Tagpochau has been identified as a volcano as recently as 1944 (Hobbs, 1944, p. 2.42 map 18), that interpretation should be abandoned. There are no presently active volcanoes nearer to Saipan than Anatahan, about 60 miles north-northwest. A sulfur boil that has been reported about 25 miles to the west of Saipan (Hess, 1948, p. 434, pl. 2) probably represents the southern continuation of the western line of young volcanic centers to the west of the array of now long-dead and limestone-blanketed volcanic centers of the eastern (or frontal) island chain. The front of the arc is not likely to become again volcanically active in the foreseeable future.

THE EARLY MIOCENE BANK SEDIMENT COMPLEX

Near the end of the Oligocene, or in earliest Miocene time, erosion truncated the eastward dipping strata of the Fina-sisu beds so that they are discordantly overlapped by horizontal Tagpochau limestone. Faulting or renewal of faulting along the Agingan Fault, if then present, could have contributed to the eastward tilting of the Fina-sisu beds, but the dips are well within the realm of probability for initial dips, and faulting is not required.

Early in the Miocene epoch (Tertiary *e* of the East Indian succession) deposition of the varied marine sediments of the Tagpochau limestone occurred to a total local thickness of 1,000 feet or so. Evidence concerning the paleoecology of the deposits is provided by abundant orbitoid, miogypsinid, and other Foraminifera, many algal remains, sparse corals and thick-shelled mollusks, and sedimentary features. These indicate accumulation mostly at depths of 10 to 50 fathoms, over a variety of substrates, on and near a tropical or subtropical and mainly open oceanic bank. Corals in some of the purer limestone facies were more abundant than in older rocks, and the fact that one small coral-algal reef mound was found suggests that others rose from the shallower parts of the bank.

As the rate of accumulation and thickness of in-place shallow water deposits is directly related to rate and

amount of subsidence of the substratum, submergence of the area was gradual or frequently recurrent through Tagpochau time. The initial deposits transgress an Eocene and Oligocene core of mainly volcanic origin, and basal deposits everywhere tend to be tuffaceous, regardless of actual position in the stratigraphic sequence. Upward and outward from the core rocks the sediments became increasingly pure calcium carbonate. Eventually the pure inequigranular limestones overtopped the highest remaining peaks and the entire area was submerged.

Down the submarine slopes from these shoal-water bank deposits, however, marine reworking of the older volcanic sediments was in active progress. The tuffaceous sediments so produced incorporated a rich fauna of planktonic and benthonic smaller Foraminifera. The benthonic species include representatives of genera that today live at considerable depths in the tropics and subtropics, and among the planktonic species are indicators of warm surface water such as *Globorotalia menardii* (D'Orbigny) (Kane, 1953, p. 26). The enclosing sediments make up the Donni sandstone member and presumably graded upslope and laterally into or against equivalent calcitic facies of the Tagpochau limestone at shallower depths.

The small, east-plunging, westward-opening, essentially symmetrical, and stratigraphically isolated folds that occur in the Donni beds of east-central Saipan are interpreted as depositional features. Currents moving downward from the bank margin may have scoured out a submarine spur-and-valley topography locally. Initial dips in sediments that settled over such topographic features could then simulate tectonically formed anticlines and synclines, as discussed under structural geology.

The apparent scarcity of reefs in Tagpochau time calls for an explanation. The small reef mound mentioned indicates that the climate was tropical and that reef-building corals were present and capable of vigorous growth locally. The obvious (though not necessarily correct) explanation is that the waters were at most places a little too deep for vigorous reef building. This is consistent with the already suggested average depth of 10 to 50 fathoms.

LATER MIOCENE AND PLIOCENE

The events that have just been reviewed extend through Tertiary *e* time of the Indonesian sequence, and perhaps through the Aquitanian of the standard European time scale. Later Miocene and Pliocene history can be reconstructed only from the inferred sequence of physical events. No recognizable later Miocene or Pliocene fossils have been found anywhere on Saipan, and the only sediments that may pertain to this interval are high-terrace deposits of possibly late Pliocene age.

DEFINITION OF THE FAULT PATTERN

It is considered likely that extensive faulting occurred during the later Miocene or Pliocene, and mainly before the high emergence and extensive terrace cutting of possible late Pliocene age. Offset relations and decrease of apparent throw with decreasing age of offset rocks indicate that principal faults known came into being in younger Miocene or older Pliocene time, if not sooner. Essentially the pattern now found was then finally blocked out. It has been little changed by later recurrent movement on the old surfaces, and although pre-Miocene faulting is strongly indicated, evidence is lacking that any specific fault of the present day already existed before the Miocene. The shape and approximate position of the present island of Saipan is probably controlled by this fault pattern.

Subsequent modifications consisted primarily of fluctuations with reference to sea level, erosion of the parts that lay above sea level, and deposition of Pliocene(?) and Quaternary sediments around its flanks.

EMERGENCE, TERRACE FORMATION, AND RENEWED FAULTING

The terraces that give evidence of fluctuating sea level are the most conspicuous topographic features of Saipan. The very peak of the island is a remnant of a flat surface, and the terrain from here to the sea is mostly a succession of benches and scarps (pls. 20*A*, 21*B*, 23*B*, 24*A*). All of the benches above 100 feet transect their rock foundations with little or no regard to primary stratigraphic or structural features (pl. 13*A*) and are thus erosional. Those above 500 feet were probably cut during a single long interval of mainly steplike emergence. This same emergence probably also extended to well below present sea level before renewed submergence, but its effects at levels below 500 feet were later obscured by the overlapping older Pleistocene Mariana limestone.

How many steps, or distinct stands of the sea, were involved in the formation of these terraces cannot, of course, be surely determined. They preserve only a minimal record of the marked intervals of stability. Each prolonged stand of the sea at any given level affords opportunity not only to cut a new bench at that level, but to remove evidences of older benches at higher levels.

It is also not certain under what circumstances and by what agencies the various benches were cut, although the probabilities are circumscribed. A bench cut in limestone by a standing sea should slope only gently seaward, and it may be nearly horizontal where inter-

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[10] J. I. Tracey, Jr. (oral communication) and associates have shown that volcanic additions to the core continued into the Miocene on Guam.

tidal solution plays a leading role in bench reduction. Wide and essentially horizontal terrace benches, therefore, presumably represent relatively long stands of the sea at one level or interval. Those that slope strongly seaward (pl. 13*A*) may have been finished off by the wave action of a falling or rising sea (if not tilted tectonically).

Reason should be given for the conclusion that the terrace benches above 500 feet or so were formed before deposition of the Mariana limestone. If the epoch of submergence during which the Mariana was formed had inundated the island to levels above 500 feet, remnants of marine deposits produced at that time should be preserved at least locally at these levels. and no such remnants have been found. Because the youngest rocks across which the terraces cut are high lower Miocene, these terraces are also post-early Miocene. Moreover, as the terrace surfaces are commonly not offset by faults which are known to cross them, they presumably postdate the faulting epoch described above. This suggests the latter part of the younger Miocene through Pliocene. Because they are so well preserved, also, it seems more probable that they originated later rather than early. A younger Pliocene age is thus tentatively proposed for the origin of the upper terraces.

The only remnants of post-Tagpochau and pre-Mariana deposition known on Saipan are the "older terrace deposits" that locally mantle the 500- to 710-foot terrace levels where they cut across volcanic deposits. Because the benches on which they rest are interpreted as Pliocene, the terrace deposits are also tentatively regarded as Pliocene and are considered to represent fluviatile fan deposits that spread downward behind a withdrawing sea. No fossils were found in the terrace deposits, although extensive search might be expected to reveal marine fossils at the contacts between basal terrace deposits and underlying marine bench surfaces (such as the contact in pl. 12*D*,*E*).

The last possibly Pliocene event of which there is record was the east-west hinge faulting that is inferred to have tilted the higher terraces westward at south Kalabera cliffs and south of Magpi ravine (pl. 16*A*,*B*).

Because the facies relationships of the Mariana limestone are those of a cycle of submergence, it is inferred that its deposition was preceded by emergence to somewhat above present sea level. At the end of this supposed late Pliocene epoch of emergence and terrace cutting, therefore, Saipan was probably larger and higher than it has been at any time since then. The site of the extensive shoal banks that now lie to the west of Saipan may then have been emergent, and the land twice as extensive as present-day Saipan and larger than any post-Eocene land of this area.

PLEISTOCENE AND RECENT

Beginning with the probably older Pleistocene Mariana limestone and continuing to the present day, the calcareous sediments that were deposited and are being deposited in the shallow waters about Saipan were all generally similar warm-water deposits. They are predominantly fragmental and partly coral-algal reef limestones (pls. 12*C*, 14) such as accumulate on shallow tropical banks or in reef-fronted lagoons as part of the reef complex.

As we approach the present, however, more detail is available, events seem to be more rapidly paced, and many complexities of depositional history and changing sea level are introduced.

THE OLDER PLEISTOCENE AND ITS REEF-COMPLEX LIMESTONES

Beginning supposedly in early Pleistocene (or early Mariana) time, a relatively long, gradual or episodic submergence set in. The suggested submergence does not rule out secondary episodes of emergence, but the thick vertical sequences of shallow-water sediments that are found locally indicate submergence to be the dominating factor in Mariana sedimentation. The result of this cycle of submergence was relatively to raise the sea from somewhere below present sea level to about 500 feet above. Concurrently, the bioclastic sediments of the Mariana limestone accumulated about the flanks of the island. Corals in reef-building associations were now, for the first time, really common. Sedimentation was probably similar to that of present day reef-complex deposits about high islands—an apronlike wedge of mainly bioclastic deposits accumulated about minor reef masses in an offshore bank or lagoonal environment. Rubbly and impure limestones formed near the land and purer limestones offshore. No evidence of true barrier or fringing reefs is to be seen in these deposits, but remnants of coral-algal mounds are preserved. Linear structures of the nature of barrier or fringing reefs might also be delineated if distribution of coral-algal concentrations could be plotted in greater detail than was done during the present work.

The sea in which the Mariana sediments accumulated was tropical and quite shallow. If the fossils were restricted to the same depth ranges as living representatives of the same species and genera, it was everywhere less than 50 fathoms, at few places exceeded 25 fathoms, and was mostly less than 10 fathoms deep. In fact the general bank-lagoon-reef complex now adjacent to Saipan displays a general range of environment and ecology similar to that under which the Mariana limestone is believed to have formed. To visualize the complexity of sedimentary variation

that would result from areal shifting with time of the varied ecologic-sedimentary pattern about Saipan today gives a reasonably good idea of the problem and of the inferred depositional history of the Mariana limestone. Of course, progressive subsidence was required to produce so thick an accumulation of shallow-water deposits—and, as in all sedimentary deposits, its actual thickness at any particular place was controlled by total supply and rate of supply of materials, amount and rate of subsidence, and post-depositional removal either beneath or above water.

MIDDLE(?) PLEISTOCENE TERRACE FORMATION AND FAULTING

Following the submergence during which the Mariana limestone was deposited, renewed withdrawal of the sea occurred, extending to and perhaps well below the present 100-foot level. During this episodic emergence, most of the benches and scarps between altitudes of 100 and 500 feet along the east side of Saipan were formed. Mariana limestone benches below the 300-foot level at a few places show minor concentrations of well-preserved coral debris, presumably derived from patchy local growth on solution- or wave-eroded surfaces at the time of final withdrawal of the still tropical sea. Streams draining from areas of volcanic source rocks spread their fluviatile debris along the bench surfaces behind the withdrawing sea, producing the post-Mariana terrace deposits. At a few places in south Saipan unmapped brown clays accumulated on low parts of the emerging benches.

Faulting occurred before (or during) and also after this new cycle of emergence and bench erosion. The 180- to 200-foot surface at Fañunchuluyan bay in northeast Saipan is not offset by fault contacts between the Mariana limestone and Miocene rocks. These are post-Mariana but pre-bench-cutting faults. After bench cutting had occurred, renewed movement along the preexisting north-northeast trending Laulau, Dago, Obyan, and Agingan faults offset terraces in the Mariana limestone by amounts as much as 100 feet or more downward to the west.

LATE PLEISTOCENE EMERGENCE, FRINGING REEF FORMATION, AND LATEST FAULT MOVEMENT

The late Pleistocene history of Saipan is represented by a thinly mantling, fragmental and constructional limestone that extends from the present sea to 40 feet and locally as much as 100 feet above sea level. This, the Tanapag limestone, is interpreted as a fringing-reef complex, formed on an episodically emerging surface, in a tropical sea, around a high tropical island that was nearly the same size as present-day Saipan. The surface which it covered was either inherited directly from the end of the middle(?) Pleistocene emergence described above, or produced during renewed submergence to the 100-foot level. Because total melting of present glaciers and ice caps would raise the sea about 100 feet, it is possible that the Tanapag limestone was being deposited here at the time of the thermal maximum of the last major interglacial or interstadial epoch. Should that be the case, the Tanapag reef limestone would in part cover a surface which emerged as the result of renewed ice formation—a partial tropical counterpart of the last maximum glaciation.

Under such interpretation, other Tanapag beds should be found at the sea bottom offshore toward the lower sea level of maximum glaciation. Later rise in sea level due to melting of the glaciers presumably resubmerged the area. At such time, or during the initial fall from the 100-foot level, a stand of the sea occurred about 40 feet above its present level. This formed an extensive horizontal indentation or notch slightly above or at the base of an inshore scarp at the back of a bench that rises to about 40 feet above sea level (fig. 8). The youngest Tanapag deposits known, at the 12- to 15-foot level, were deposited (or altered?) about 20,000 years ago, according to carbon–14 determination by L. J. Kulp (table 10, loc. C35).

The Tanapag limestone patchily mantles most of the outer edge of Saipan. Except for minor weathering effects the original constructional surfaces are preserved. The limestone is rich in well-preserved corals, algae, and marine mollusks of living genera and species, and many of the corals and algae are in the normal position of growth. The lower part of the 15- to 40-foot bench is transected by radial grooves (pl. 17*B*, 19*A*) such as those that extend seaward across the fronts of present fringing reefs. At places, coral heads that grew outward from the generally abraded walls of these grooves retain the detail of the original structures (pl. 14). Even the characteristically depressed shoreward parts of some of the fringing reef surfaces of Tanapag time are, in several instances, preserved with great fidelity (pls. 16*B*, 19*A*). Analogy with the modern fringing reef environment of south Saipan is very close.

The emergence during which the Tanapag limestone formed was episodic rather than gradual, for there are remnants of Tanapag surfaces between the present sea level and the 100-foot level at roughly 12–15, 20–40, 40–60, and 50–80 feet. The surfaces above 40 feet are difficult to match with constancy even around Saipan; but the notch at about 40 feet is marked and fairly continuous (pls. 13*B*, 13*D*, 16*A*, 17*B*, 18*B*), and the 40-foot, as well as the 15-foot and 100-foot levels, may be eustatic. The Tanapag cycle is considered to end roughly at the 12- to 15-foot level. There seems to be a fairly continuous radially grooved lower bench lip near this level around the northeast end of the island (pl. 16*B*) and locally elsewhere, though it merges upward to the 20- to 40-foot bench (pl. 15*B*). Below this surface are only low erosional bluffs.

At about this time, renewed movement on the preexisting Obyan and Agingan faults dropped the Tanapag surface about 10 to 15 feet to the west on the Obyan fault and perhaps 20 feet on the Agingan fault. This is the most recent faulting recorded on Saipan, and it occurred before the 6-foot fall of sea level began some 3,000 (±1,500) years ago (Cloud, 1954, p. 196). The 6-foot eustatic notch incises the Agingan fault surface and is not offset by the Obyan fault. A latest Pleistocene or earliest Recent age is indicated for these fault movements.

EUSTATIC SHIFTS OF SEA LEVEL AND THE MOST RECENT EVENTS

Of all the records of changing relationships between land and sea the most interesting are those that are found so widely at the same general level that they are interpreted as due to actual change in volúme of sea water or capacity of the ocean basins. Such worldwide or eustatic changes of ocean level surely occurred at many times during the Pleistocene, with waxing and waning of the ice sheets. The effects of these episodes, however, may be obscured by local tectonic movements, and are probably recognizable only within the range of about 100 feet above and 300 feet below sea level.

Levels recognized on Saipan which are so widely known elsewhere that they may safely be considered eustatic are found at about 2 and 6 feet. As mentioned above a possible eustatic level is also suggested at about 15 feet, and probable eustatic levels at about 40 feet and roughly 100 feet.

The 100-foot level is suggested by the overlap of the Tanapag fringing reef limestone to approximately this elevation but no higher, and perhaps by the preservation of a former sea level notch at about this height (Stearns, 1945, p. 1075). It is generally estimated that melting of existing glaciers and ice caps would raise sea level about 100 feet, and it is conceivable that the withdrawing sea in which the Tanapag limestone was deposited ebbed during a part of the last maximum glaciation. The 40-foot level is marked by the already noted notch near that elevation along the east and northwest sides of the island (pls. 13*B*, 13*D*, 16*A*, 17*B*, 18*B*). At one place this former sea level notch even encircles mushroom-shaped sea stacks (pls. 13*D*, 18*B*) on a sloping, elevated, fringing reef surface that extends from 15 or 20 to 35 or 40 feet above sea level. The 15-foot level is marked only by the suggestion of a low bench or elevated low fringing reef surface at 12 to 15 feet along the outer edge of, and grading into, the 20- to 40-foot bench.

Supposed Pleistocene shorelines at altitudes of 100 feet and between 40 and 45 feet have also been recorded from the New Hebrides Islands, Hawaii, and the southeastern United States (Stearns, 1945, p. 1075). The evidence for eustatic levels near these altitudes is, thus, not negligible, but neither is it compelling. On the other hand, there is confusion in the published record about possible eustatic levels between 40 and 6 feet, perhaps because a number of brief stands of the sea are involved, mostly ranging between 10 and 30 feet. Records that fall near the 15-foot level suggested are: a reported 5-meter notch in the southern Marianas (Tayama, 1952, p. 197); Daly's widely recorded 16- to 20-foot stand of sea level (Daly, 1926, p. 174); the 4- to 5-meter stand of Indonesia (Kuenen, 1933, p. 67–68); and the 10- to 11-foot level in western Australia (Teichert, 1946, p. 78; Fairbridge, 1947) and perhaps in northeastern Australia (Steers, 1930, p. 7).

The 6-foot eustatic level is marked by a notch at roughly 6 feet above a similar notch of the present sea and is found around virtually all tropical Pacific limestone islands. It may correlate approximately with the end of the post-glacial thermal maximum, and the retreat of the sea from that level was presumably caused by withdrawal of water from the oceans to form additions to the present ice masses. A temporary stillstand in this process produced a bench level at about 2 feet, which shows as small, flat, erosion remnants above many modern sea-level solution flats in the western and central Pacific, and rarely as slightly elevated reef remnants and beach rock (pl. 15*D*).

As a result of these latest emergences the limesands that now cover the western coastal plain of Saipan were slightly elevated. At the same time, reef surfaces then at or near sea level were truncated by combined inorganic and organic solution and abrasion to nearly smooth sea-level benches and may thereby have contributed to the coastal plain limesands. Such surfaces now support vigorous growth of the normal reef-building organisms only on reef fronts below low tide level and in occasional depressions or areas that lie below the general surface of the beveled reef flat.

Subaerial solution features such as caves and sinks (with well preserved stalactites and stalagmites) occur below present sea level on Guam and Palau. Submerged benches at the fronts of reefs also indicate recently lower stands of sea level that cannot yet be precisely dated. If not due to local tectonic movement, these would almost necessarily reflect eustatic fluctuations of Pleistocene sea level. The many reef-slope profiles and soundings that are being made known from recent and current studies in marine geology may eventually establish the presence of particular submerged eustatic levels such as that implied by the

development of a 2- to 10-fathom bench at the front of many peripheral reefs on both sides of the equator. The submerged caves and sinks indicate emergence of some feet or tens of feet probably before the 6-foot stand of sea level, but after the 15-foot stand.

It is well known that within the last century or so the factors that led to glacial accretion and eustatic fall of sea level have been reversed (Cloud, 1954, p. 196). If the resulting slow rise of sea level continues, a vigorous growth of reef-constructing organisms should build up the reefs around Saipan, and the lagoon behind its western barrier reef should be deepened by possibly as much as 100 feet, minus sedimentary fill. Whether organic growth and sedimentation around the rest of the island would, under such conditions, give rise to a more extensive barrier-reef complex, or simply extend the fringing reef upward and landward as an overlapping deposit would depend on the rate of subsidence.

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APPENDIX A.—DESCRIBED SECTIONS

The dearth of described sections is mainly due to the lack of outcrops on Saipan that are at the same time of sufficient variability and continuous enough and well enough exposed to warrant description. The many fine bluff exposures are mostly in rather homogenous limestones, and such sections rarely display contacts between formations or even different facies of the same formation.

Thicknesses in the four described sections that follow are given in terms of feet above the base of the section for each interval, at the end of the interval description: thus "30–40 ft" indicates an interval 10 ft thick, the base of which is 30 ft stratigraphically above the base of the section; "240–250 ft" indicates an interval 10 ft thick, the base of which is 240 ft stratigraphically above the base of the section.

MOUNT ACHUGAU SECTION OF THE SANKAKUYAMA FORMATION

The incomplete type section of the Sankakuyama formation at Mount Achugau (pls. 5*D*, 17, 24*C*) was computed from a structure section (*A*—*A'*) across the sequence of dacites there exposed. This section begins at the fault contact between the dacite sequence and the inequigranular facies of the Tagpochau limestone in the bottom of Papua ravine (Kanat Papua). It extends southward up the north face of Achugau Cliffs (Laderan Achugau), across the summit of Mount Achugau, and then generally south down the back slope and along the bottom of a narrow ravine to the contact between subaerial tuffs of the dacite sequence and the marly facies of the Tagpochau limestone. Although this section is incomplete, by reason of lacking a base, it is also the thickest and most nearly complete section of the Sankakuyama formation on Saipan. Stratification is mostly obscure within described intervals.

Beds of all units of the Sankakuyama except the mixed pyroclastic facies are found along this line of section, as described below.

Interval 1 (*base of section*).—Vitrophyre breccia; light- to dark-gray and white layers of breccia containing angular fragments of dacite vitrophyre and porphyry in a vitreous tuffaceous matrix. Fragments range from minute particles to blocks 10 in. in diameter, with ordinary diameters of about 2 to 3 in. Matrix weathered to soft-pink, white, and orange clay to depths of several inches. Attitude of breccia beds variable where dragged along Achugau fault, and minor faults have sheared and broken the breccia beds in many places..........0–500 ft

Interval 2.—Massive flow rock; hard, glassy to cryptocrystalline vesicular to compact, banded dacite porphyry. In places the flow lines are highly contorted. A fracture cleavage is developed parallel to the planar flow structure Vertical jointing is pronounced and locally the rock exhibits a columnar jointing. Probably a succession of separate flows is represented in this interval, with intervening materials (if any) not observed in the section because obscured or covered by talus and weathering effects..........500–920 ft

Interval 3.—Vitrophyre breccia; light-gray to white dacitic breccia containing angular fragments of gray vitrophyre in a light-gray to white, medium-grained, vitreous, tuffaceous matrix. Vitrophyre fragments have an average diameter of about 3 in..........920–960 ft

Interval 4.—Vitric tuff; white, glassy, medium-grained, well-consolidated, dacitic tuff composed of small angular fragments and shards of vitrophyre, and similar in texture and composition to matrix of vitrophyre breccia intervals. Stained dark brown at the surface and altered to soft-white clay to depths of 1 or 2 ft..........960–970 ft

Interval 5.—Vitrophyre breccia, similar to interval 3. 970–1,050 ft

Interval 6.—Perlite breccia; light-gray to white dacitic breccia that contains markedly angular, banded fragments of perlite in a white, glassy, tuffaceous matrix. Perlite fragments from a fraction of an inch to 8 in. in diameter; average diameter about 2 in. The breccia has a pronounced flow structure that is locally contorted. Rock similar in texture and structure to vitrophyre breccia, but breccia fragments largely perlite. 1,050–1,090 ft

Interval 7.—Massive flow rock; relatively thin flow of hard, compact, glassy, dacite porphyry that pinches and swells along its strike. Rock is grayish purple to chocolate in color and has a pronounced flow structure parallel to which a marked parting is developed..........1,090–1,110 ft

Interval 8.—Vitrophyre breccia, similar to intervals 3 and 6. 1,110–1,240 ft

Interval 9.—Massive flow rock; hard, compact, aphanitic, light-gray and purplish flow or flows of dacite porpyhry. Planar flow structure well developed and consisting of alternating porous streaks and bands of compact flinty dacite, parallel to which cleavage occurs. Vesicles in porous streaks alined parallel to direction of banding. Rock traversed by closely spaced vertical joints..........1,240–1,490 ft

Interval 10.—Vitrophyre breccia; light- to dark-gray breccia containing fragments of dacite vitrophyre in a finer grained tuffaceous matrix. Vitrophyre fragments as much as 6 in. in diameter; average diameter about 2 in. Flow banding well developed..........1,490–1,615 ft

Interval 11 (*top of section*).—Vitric tuff; light-gray to white, deeply weathered, soft, closely jointed, fine- to medium-grained; weathered at the surface to white, iron-stained, somewhat unctuous clay..........1,615–1,740 ft

Total thickness rounded off to 1,800 ft as a probable minimum for the formation.

TALOFOFO RIDGE SECTION OF THE DENSINYAMA FORMATION

Although the sequence here described is designated as the type section of the Densinyama formation it is not really a simple succession of beds, but a set of scattered outcrops along and near a general line of traverse. It begins at the contact between the breccia facies of the Densinyama formation and the underlying breccia facies of the Hagman formation, about 100 yd west of the westernmost hairpin turn in the western part of the Talofofo road. From here the sequence extends generally eastward across the flat summit of Talofofo ridge It ends where the conglomerate-sandstone facies of the Densinyama formation is unconformably overlain by the inequigranular facies of the Tagpochau limestone, about 1,700 ft west of the junction of Talofofo road and the East Coast Highway.

The section was compiled principally from a barometer traverse along the Talofofo road, and it includes the principal facies of the Densinyama formation. The given thicknesses of the various intervals were computed graphically, allowing for the probability that the dips observed are largely initial. In the description that follows only well-defined major intervals are separated, and the succession is in order from bottom to top. More detailed description is neither feasible nor desirable, owing to poor exposures and the marked lateral variation of the beds.

Interval 1 (breccia facies at base of section).—Coarse, quartz-bearing, andesite breccia, with fewer pebbles and cobbles of chert, quartz porphyry, and dacite in an andesitic matrix. Andesite fragments range from ¼ inch to 3 ft in diameter. At the surface the breccia is deeply weathered to orange-red ferruginous clay. Other parts are dark and light red, purplish red, and brownish red. Interval 1, representing the breccia facies of the Densinyama formation, overlies the breccia facies of the Hagman formation. It may also in part intergrade with the Hagman breccias.. 0–240 ft

Interval 2 (lower part of lower occurrence of conglomerate-sandstone facies).—Chert boulder conglomerate makes up the basal bed of the conglomerate-sandstone facies of the Densinyama formation in the Talofofo ridge section. This interval consists principally of well-rounded pebbles, cobbles, and boulders of massive iron-stained chert and some pebbles and cobbles of andesite, all set in a finer grained matrix. The larger particles range in diameter from an inch or so to 6 ft, the average diameter of the boulders being about 1 ft. The chert boulders studied may represent replaced blocks of limestone.. 240–250 ft

Interval 3.—Pebble conglomerate, quartz-rich to quartz poor. Overlies the basal chert-boulder conglomerate of interval 2 and is made up of poorly stratified intergrading beds of pebble conglomerate.

The pebble conglomerates in which quartz is rare consist mainly of angular to rounded fragments of andesite as much as 6 in. in diameter, with an average diameter of about 1 in. Small pebbles of gray and green chert and quartz prophyry are present but not abundant. The larger rock fragments are in a matrix of reworked volcanic materials now weathered to ferruginous clays that are mottled red, white, and brown. Narrow joints in the conglomerate are filled with limonitic material.

Interfingering with, and grading laterally into, the andesitic pebble conglomerate beds are loosely cemented beds of light-brown, quartz-rich, pebble conglomerate and coarse-grained sandstone. The conglomerate beds are of well-rounded pebbles and smaller fragments of several varieties of quartz-bearing rocks. The larger siliceous fragments are set in a matrix that contains a conspicuous to dominating number of rounded to subangular quartz grains having an average diameter of about 1 mm. The sandstone layers grade laterally and vertically into the conglomerate beds, are from several inches to several feet thick, and consist principally of angular to rounded grains of siliceous rock and quartz with limonitic cement. The average grain size of the sandstones is about 1 tc 2 mm.. 250–340 ft

Interval 4 (upper part of lower occurrence of conglomerate-sandstone facies).—Andesitic conglomerate and tuffaceous sandstone quartz-bearing, well-bedded to poorly bedded, calcareous and noncalcareous, complexly intergrading, water-laid.

The basal part is poorly bedded, noncalcareous, andesitic pebble and boulder conglomerate containing scattered, angular to rounded fragments of a variety of quartz-rich rock that includes chert, quartz porphyry, and dacite. The average size of the fragments is about 2 in. Boulders attain a maximum diameter of about 1 ft.

The upper part of the sequence becomes progressively finer grained and more calcareous toward the top. Conglomerate beds are composed of well-rounded andesite fragments and abundant quartz-rich rock. They are deeply weathered at the surface and are light and dark brown, reddish brown, and gray brown. The matrix contains andesite fragments, magnetite grains, and small quartz grains. It is ordinarily calcareous. Thin conglomerate beds that contain pebbles and boulders of fine-grained Eocene limestone occur toward the top.

Water-laid tuffaceous sandstones of the upper part of the sequence are coarse- to fine-grained and occur as thin layers and lenses interbedded with the conglomerate layers. Thin beds of calcareous tuff are commonly interlayered with thin discontinuous layers of marl. Some of the tuffaceous sandstone beds contain appreciable amounts of quartz in the form of grains 1 to 2 mm in diameter. However, the principal constituent of the sandstones is andesite. Noncalcareous tuffaceous sandstone beds near the top of the sequence are fine grained and well bedded. At the surface they are composed of clay, magnetite grains, and sparingly scattered quartz grains. Weathering of disseminated ferruginous matter has colored these beds various shades of orange, gray brown, and red............. 340–460 ft

Interval 5.—Impure limestone and calcareous conglomerate; mainly light-brown to yellowish-white, very impure limestone containing disseminated small grains of andesite, siliceous rocks, and small, angular to rounded quartz grains. The base of the interval is conglomeratic and contains rounded pebbles and cobbles of white and pink Eocene limestone, andesite, chert, and other quartz-bearing rocks. It grades to and is laterally interbedded with interval 4. Both the conglomeratic and tuffaceous limestone parts contain abundant Eocene larger Foraminifera. 460–500 ft

Interval 6 (upper occurrence of conglomerate-sandstone facies, top of section).—Andesitic conglomerate and tuffaceous sandstone; coarse boulder conglomerates, pebble conglomerates, and coarse tuffaceous sandstones, all quartz-bearing and andesitic. The tuffaceous sandstones form only a small part of the sequence and occur as lenses 1 to 5 ft thick intercalated with the conglomerates. The interval is mainly a coarse boulder conglomerate that contains rounded andesite boulders as the principal constituent, but which also has subordinate pebbles, cobbles, and boulders of chert, jasperoid, quartz porphyry, and dacite. The boulders are as much as 2 ft in diameter. Boulders of Eocene limestone and coral fragments that are generally altered to limonite and hematite occur in the upper part of the sequence. The conglomerate is deeply weathered to ferruginous clays of various shades of brown, red, purple, and gray.... 500–730 ft

TANKE CLIFFS SECTION OF THE MATANSA AND TAGPOCHAU LIMESTONES

INTRODUCTORY REMARKS

The section here described was measured up Tanke cliffs, on the southwest shore of Fañunchuluyan bay (Bahia Fañunchuluyan) in northeastern Saipan. It ascends the prominent wooded bluffs and peak to the north (right) of the three conspicuous south Kalabera cliffs (Laderan Kalabera Lichan) at the center of pl. 17*A*.

It begins a little southwest of and above a cut on the East Coast Highway, at the base of a limestone bluff that marks a fault contact between dacite breccia of the Sankakuyama formation and the white facies of the Matansa limestone. From the point described the section continues upward toward the summit of Tanke cliffs to the contact between the Eocene Matansa

limestone and the Miocene Tagpochau limestone at 256 ft above its base. At this stratigraphic level the section is offset along a datum bed at the base of the Tagpochau limestone for approximately 1,000 ft southeast along a discontinuous, low, brushy, east-facing scarplet. The Miocene part of the section then continues upward to the summit of Tanke cliffs (Jap Hill triangulation station of the U. S. S. *Bowditch* survey) through 314 ft of inequigranular limestone of Tagpochau age. The lower 236 ft of the Miocene section is referred to the *Heterostegina borneensis* zone (lower Tertiary *e*) and the upper 18 ft to the *Miogypsinoides dehaartii* zone (upper *e*), with a 60-ft interval of unassigned beds between.

This section was measured by hand level, tape, and compass, and marked and described by H. W. Burke during October and November 1949, with the intermittent assistance of Benusto Reyes of Saipan. Notes on the study of thin sections were added by Cloud in 1952–54.

Measurements of thickness were computed graphically, allowing for dip of the beds which averaged less than 10° west to southwest. As dips change erratically, the computed thicknesses only roughly approximate true thicknesses, but error is thought to be minimized by the steepness of the line of section. Bedding is mostly obscure within described intervals.

The Miocene part of the Tanke cliffs section illustrates a variety of the purer limestones to be found in the Tagpochau beds, although mainly of the inequigranular facies and so shown on the geologic map. The Eocene beds of this section represent only the white facies of the Matansa limestone.

Unless otherwise noted, grain size given is based on study of rock chips only. Where supplemented by study of thin sections apparent grain size averages somewhat lower.

MATANSA LIMESTONE, WHITE FACIES

Interval 1 (base of section).—Limestone; inequigranular, with grain size 0.2 to 1.0 mm in lower part, ranging to 2.0 mm above. Color is pink to white or mottled, with abundant vermilion specks about 0.5 mm in diameter. Interval has much disseminated manganese oxide, increasing toward the top. Fossils include many smaller Foraminifera, discontinuous thin bands of crustose coralline algae, joints of *Halimeda*, and fragments of coral.. 0–3 ft

Interval 2.—Limestone; inequigranular, with grain size 0.5 to 2.0 mm. Local lenses are equigranular. Color is gray from abundant particles and grain-coatings of manganese oxide. Local enrichment in manganese oxides extends through intervals as much as 10 ft thick. Fossils include occasional *Camerina* and *Pellatispira* in some beds, abundant smaller Foraminifera, discontinuous thin bands of crustose coralline algae, joints of *Halimeda* and fragments of coral. Samples from this interval with footage above base of section are B17 (18 ft), B18 (26 ft), B19 (33 ft), and B20 (39 ft)......................... 3–50 ft

Interval 3.—Limestone; inequigranular, with grain size 0.2 to 1.0 mm. Interval is locally equigranular and contains abundant pellets about 0.1 mm in diameter. Manganese oxides occur in local zones of enrichment and as widely disseminated particles. Helically coiled smaller Foraminifera are common, along with joints of *Halimeda*, and fragments of echinoids........ 50–57 ft

Interval 4.—Limestone; equigranular, with grain size averaging 0.2 mm. Aphanitic in patches, with largest grains about 1.0 mm and with abundant 0.5 mm pellets. Bedding well developed, in layers 2 in to 1 ft thick. Thin sections from loc. B22 (at 73 ft) show 30 to 40 percent detrital articulate and crustose coralline algae, 10 to 20 percent Foraminifera and other larger organic debris, and 40 to 50 percent fine bioclastic matrix mainly less than 0.1 mm in grain diameter. The finer bioclastic material also occurs in larger fractured and displaced pieces of relatively uniform grain size. Color white to dark yellowish orange. Manganese oxide and limonite disseminated through the interval, increasing in volume upward.

Camerina is locally abundant, and *Operculina* and possibly *Biplanispira* and *Fabiania* occur at loc. B51 (at 67 ft). At B110 (at 82 ft) are *Camerina* and *Fabiania*, and B111 (at 82 ft) has *Camerina*. Sections from B23 (at 82 ft) contain *Borelis* and *Camerina*. Joints of *Halimeda* and fragments of echinoids are found in coarser material, and the dasycladacean alga *Cymopolia* was noted in thin sections from B22 (at 73 ft).........57–87 ft

Interval 5.—Limestone; inequigranular, comprises fragments of aphanitic limestone as long as 1 inch, in a matrix that consists largely of joints of *Halimeda* and 0.5 mm pellets. Aphanitic fragments generally make up about 40 percent of the rock, except where it consists entirely of small Foraminifera and coarse pellets. The color is white, with irregularly disseminated black manganese oxide particles. Thin sections from loc. B67 (at 163 ft) show the rock at the top of the interval to consist largely of fragmentary articulate and crustose coralline algae and joints of *Halimeda* in about 30 percent matrix of clear crystalline to dark bioclastic calcite mainly less than 0.1 mm in grain diameter. Many of the larger organic fragments are completely ringed by clear fine-grained calcite in thin section. Fossils other than already mentioned include small Foraminifera, possibly *Camerina*, locally abundant fragments of echinoids, and abundant specimens of the dasycladacean alga *Cymopolia* at loc. B67. Although samples B32 (at 100 ft), B33 (at 106 ft), and B67 (at 163 ft) have yielded abundant algal fragments, they have not yielded Foraminifera of correlative value..87–168 ft

Interval 6.—Limestone; inequigranular, with grain size from 0.2 to 2.0 mm and with abundant pellets from 0.2 to 0.5 mm in diameter. Patches of aphanitic limestone are present at the bottom and top of the interval. Near the base are local patches of breccia, the fragments of which are surrounded by pinkish clay. Particles of manganese oxide, limonite, and hematite are disseminated through the interval. Thin sections from loc. B75 (at 182 ft) show fragments of articulate and crustose coralline algae. Crusts of the latter are scattered in and surrounded by a matrix of bioclastic to clear crystalline calcite mainly less than 0.1 mm in grain diameter and accounting for about 70 percent of the rock volume. Other organic remains include a few Foraminifera, abundant spines and fragments of echinoids, occasional small gastropods, and occasional specimens of the dasycladacean alga *Cymopolia* (B75, at 182 ft). *Camerina*, *Gypsina*, *Heterostegina*, *Victoriella*, and *Spiroclypeus*? occur in samples B68 (at 169 ft) and B69 (at 175 ft). Sample B75 (at 182 ft) shows only algae..........................168–195 ft

Interval 7.—Limestone; consisting of fragments of inequigranular, finely pelleted (0.1 mm diameter), white limestone as long as 3 in. in a matrix of aphanitic, pink to brown limestone that contains much argillaceous material. Thin sections from loc. B72 (at 218 ft) show fragmentary articulate and crustose coralline algae in grains mainly from 0.5 to 2 mm diameter surrounded by matrix mainly less than 0.1 mm in grain diameter. Besides algal fragments, bits of echinoids and corals were noted, as well as occasional Foraminifera. Species of *Streblus* and *Gypsina* occur in samples B77 (at 206 ft) and B72 (at 218 ft) 195–213 ft

Interval 8.—Limestone; inequigranular, with grain-size from 0.2 to 0.5 mm, and including occasional fragments of aphanitic limestone as long as 1 in. Thin sections from B85 (at 236 ft) show 50 to 60 percent fragmentary articulate and crustose coralline algae, and varied small and occasional large Foraminifera, in a fine matrix of dark bioclastic and some clear crystalline calcite with grain diameter less than 0.1 mm. Probable *Camerina*, miliolids and other smaller Foraminifera, abundant fragments of mollusks and coral, joints of *Halimeda* and local thin bands of crustose coralline algae were noted at the outcrop and *Camerina saipanensis* was identified by Cole from a sample in the laboratory. Patches of the matrix consist largely of smaller Foraminifera and fragments of other fossils. Sample B80 (at 224 ft) also contains probable *Camerina saipanensis*. Other samples from interval 8 include B70 (at 218 ft), B71 (at 212 ft), and B81 (at 230 ft)............................213–256 ft

Contact between Eocene Matansa limestone and Miocene Tagpochau limestone.

Offset traverse 1,000 feet southeast through brush along a discontinuous, low, east-facing scarplet and continue upward from datum bed.

TAGPOCHAU LIMESTONE, INEQUIGRANULAR FACIES

LOWER TERTIARY *E*, HETEROSTEGINA BORNEENSIS ZONE

Interval 9.—Limestone; inequigranular, grain size 0.2 to 1.0 mm; pink at top and base, grading to aphanitic and pinkish white toward the middle. Helically coiled Foraminifera about 1.0 mm in diameter are abundant in and characteristic of the interval. *Lepidocyclina* (cf. *Eulepidina*), fragments of mollusks and echinoids, and joints of *Halimeda* are also common. Sample B73 (at 263 ft) contains *Heterostegina borneensis* and associated larger Foraminifera of the *H. borneesis* faunal zone...256–272 ft

Interval 10.—Limestone; inequigranular, consisting of white grains as much as 2.0 mm across in a pink porcelaneous matrix. Both large and small Foraminifera are common, and other fossils include fragments of shell material, joints of *Halimeda*, and thin bands of crustose coralline algae. Sample B79 (at 271 ft) contains the *Heterostegina borneensis* fauna............272–288 ft

Interval 11.—Covered..........................288–306 ft

Interval 12.—Limestone; aphanitic, with 0.1 mm pellets; white. Thinly discoidal larger Foraminifera occur in occasional concentrations. Sample B107 (at 319 ft) is from interval 12. Thin sections from B107 show microgranular limestone with many smaller Foraminifera and algal fragments, including many specimens of the dasycladacean alga *Cymopolia*, but no larger Foraminifera....................................306–310 ft

Interval 13.—Limestone; inequigranular, consisting of white grains as much as 2.0 mm across in a pink aphanitic matrix that contains pellets 0.1 to 0.5 mm in diameter. Fossils include large and small Foraminifera, fragments of molluscan shells and echinoids, and joints of *Halimeda*. Samples B108 (at 325 ft) and B106 (at 332 ft) both contain *Heterostegina borneensis*..310–322 ft

Interval 14.—Covered..........................322–375 ft

Interval 15.—Limestone, white and inequigranular, with grains from 0.2 to 1.0 mm across in a porcelaneous, pelleted groundmass wherein the pellets average about 0.1 mm in diameter. Helically coiled Foraminifera about 1.0 mm in diameter are common in and characteristic of interval 15. Other fossils include *Lepidocyclina* and other large Foraminifera, molluscan fragments, and thin discontinuous bands of crustose coralline algae. Samples B104 (at 364 ft) and B50 (at 370 ft) both contain *Heterostegina borneensis*....................................375–385 ft

Interval 16.—Limestone; pink to white and inequigranular, with grains from 0.2 to 3.0 mm across, in an aphanitic, pelleted matrix wherein individual pellets average about 0.5 mm in diameter. Thin sections from B84 (at 376 ft) show about 50 percent fragmental articulate and crustose corraline algae and scattered small and large Foraminifera in about 50 percent matrix of fine bioclastic and clear crystalline calcite with a grain diameter less than 0.1 mm. *Lepidocyclina* and local concentrations of small Foraminifera (including *Austrotrillina howchini*) and coarse pellets are common. Other fossils include pieces or heads of coral, impressions and fragments of mollusks, and thin discontinuous bands of crustose coralline algae. Samples B84 (at 376 ft), B86 (at 382 ft), and B87 (at 388 ft) are from interval 16, and B84 contains *Heterostegina borneensis*........385–403 ft

Interval 17.—Limestone; mostly inequigranular, with grains from 0.2 to 1.0 mm across in an aphanitic, pelleted matrix wherein individual pellets are 0.1 to 0.5 mm across. Aphanitic limestone occurs locally. The rock is mottled flesh pink and white, with many vermillion specks locally. Large and small Foraminifera and joints of *Halimeda* occur throughout, and locally the rock is dominated by thin discontinuous bands of crustose coralline algae imbedded in abundant 0.5 mm pellets. Samples B54 (at 403 ft) and B59 (at 409 ft) are from this interval, and B54 includes the lower Miocene (Rembangian) *Cardium* (*Fragum*) *javanum*....................................403–421 ft

Interval 18.—Limestone; consists of angular white fragments, 3.0 to 20 mm in longest dimension, in a rust-colored, aphanitic groundmass. The large fragments themselves consist of grains 0.5 to 2.0 mm across. *Lepidocyclina*, other large Foraminifera, and fragments of mollusks occur in both large fragments and matrix. Sample B88 (at 421 ft) is from interval 18..421–426 ft

Interval 19.—Limestone; white to pink and inequigranular, with grains from 0.2 to 3.0 mm across. *Lepidocyclina* and other large Foraminifera are common, and small Foraminifera and fragments of mollusks are very abundant. Sample B90 (at 433 ft) yielded section of *Cycloclypeus*..................426–441 ft

Interval 20.—Covered..........................441–456 ft

Interval 21.—Limestone; consists of white, angular fragments as long as 10 mm distributed through a rust-colored matrix of smaller fragments and large Foraminifera. The large fragments themselves are of equigranular limestone with an average grain size of 0.2 mm. *Lepidocyclina*, other large Foraminifera, and joints of *Halimeda* occur in interval 21. Samples B92 (at 442 ft), B91 (at 450 ft), and B93 (at 456 ft) contain the *Heterostegina borneensis* fauna..................................456–470 ft

Interval 22.—Limestone; inequigranular and flesh pink, with grain size ranging from 0.2 to 2.0 mm. Fragments of echinoids and mollusks, and joints of *Halimeda* are abundant. Sample B97 (at 467 ft) is from interval 22..................470–472 ft

Interval 23.—Limestone; white to pink and inequigranular, with grains ranging from 0.2 to 4.0 mm across. Contains large and small Foraminifera, spines of echinoids, and joints of *Halimeda*. Samples B94 (at 474 ft), B99 (at 484 ft), and B112 (at 490 ft) all contain large Foraminifera that probably represent the *Heterostegina borneensis* faunal zone.............472–492 ft

UNASSIGNED TERTIARY *E* BEDS

Interval 24.—Limestone; consisting of white angular fragments as long as 3 cm in a rust-colored, aphanitic matrix. The larger fragments themselves are inequigranular limestone with grain size mainly near 0.1 to 0.2 mm. In lower beds of the interval they are sheathed in yellowish earthy material. Observed fossils include only fragments of mollusks and joints of *Halimeda*....................................492–503 ft

Interval 25.—Limestone; pink to mottled white and equigranular, with grains averaging 0.2 mm across. Grains become coarser toward top of interval where rock is brecciated and filled with reddish-brown earthy material. Foraminifera and joints of *Halimeda* seen..........................503–513 ft

Interval 26.—Limestone; inequigranular, with grain size from 0.5 to 3.0 mm and averaging 1.0 mm. Upper foot of interval largely of small Foraminifera and pellets set in a translucent yellow matrix. The matrix of the rock is generally rust colored, but larger fragments are white. Large and small Foraminifera, fragments of mollusks, and joints of *Halimeda* are abundant....................................513–518 ft

Interval 27.—Limestone; about 40 percent of the rock is aphanitic groundmass surrounding patches that consist mostly of fragments of fossils. Color ranges from rust at base to white at top. Large and small Foraminifera, joints of *Halimeda*, fragments of coral and mollusks, and thin concentric bands of crustose coralline algae are locally abundant. Sample B102 (at 521 ft) is from this interval..................518–529 ft

Interval 28.—Limestone; pink to white and largely aphanitic, with abundant small (0.5 mm) spindle-shaped Foraminifera comprising the only megascopic component of the interval as well as the only recognizable fossils..............529–534 ft

Interval 29.—Limestone; white and inequigranular, with grain size generally from 0.2 to 2.0 mm. Angular fragments of porcelaneous limestone as long as 3 cm occur locally. *Lepidocyclina* and other larger Foraminifera are common; and smaller Foraminifera, thin discontinuous bands of crustose coralline algae, and joints of *Halimeda* are also present............534–552 ft

UPPER TERTIARY *E*, MIOGYPSINOIDES DEHAARTII ZONE

Interval 30.—Limestone; mostly white angular fragments as long as 10 mm in a generally pink matrix that consists largely of Foraminifera and fragments of other fossils as long as 1 mm. Many fragments of manganese oxide and tuffaceous material are present. *Miogypsinoides*, *Lepidocyclina*, and other larger Foraminifera are abundant; and smaller Foraminifera, fragments of mollusks, and joints of *Halimeda* are common. Samples B98 (at 553 ft), B95 (at 559 ft), B96 (at 565 ft), and B101 (at 570 ft) all contain *Miogypsina* and B98 has yielded *Miogypsinoides dehaartii*. The interval represents the known span of the *M. dehaartii* faunal zone in the Tanke cliffs section...552–570 ft

Top of interval 30 is at peak of Tanke cliffs and top of described section.

BAÑADERO CLIFFS SECTION OF THE TAGPOCHAU LIMESTONE

The Bañadero cliffs section extends from about 160 ft above sea level at the juncture of Bañadero and Magpi cliffs to an elevation of about 833 ft at the top of Pidos Kalahe. As the poorly defined beds appear to be nearly horizontal and the line of traverse is very steep, the probable total thickness is about 670 ft.

The entire section is a nearly uniform, pinkish, massively bedded to unbedded (pl. 11*C*), inequigranular limestone of upper Tertiary *e*, zone of *Miogypsinoides dehaartii*, as shown by 27 separate collections ranging from 6 feet above the base of the section (B122) to the top of Pidos Kalahe (B139).

This is the thickest continuous section of the inequigranular facies and of the *Miogypsinoides dehaartii* faunal zone. *Heterostegina borneensis* occurs at locality B27, just a few hundred feet north from and only slightly below (topographically) the base of Bañadero cliffs. This suggests that the base of the section is near the juncture of the *H. borneensis* and *M. dehaartii* faunal zones, and indicates a tie with the Tanke cliffs section.

It is on the basis of this section that the round figure of 1,000 ft has been estimated for the thickness of the Tagpochau limestone. If the 236 ft of *Heterostegina borneensis* beds from the Tanke cliffs section is added to the 670 ft of the *Miogypsinoides dehaartii* faunal zone in the Bañadero cliffs section, the result is a reasonably good composite section of 900 ft of Tagpochau limestones. In the Tagpochau type section (see p. 63) the *H. borneensis* zone is even thicker than here: 400 to 500 ft. Thus, 1,000 ft seems a reasonable round figure for the Tagpochau limestone as a unit.

MACHEGIT CLIFFS SECTION, MACHEGIT CONGLOMERATE MEMBER OF TAGPOCHAU LIMESTONE

The Machegit cliffs section here described is the type section of the Machegit conglomerate member of the Tagpochau limestone. It was measured across the area of exposures below and slightly east of the southern part of Machegit cliffs (pl. 20*A*), in the southern part of east-central Saipan. At this place the Machegit conglomerate overlies the transitional facies and apparently underlies the inequigranular facies of the Tagpochau limestone. Assuming the conglomerate to have insignificant dip, this section is about 40 ft thick, but the maximum thickness of the member may be somewhat greater, and it thins to disappearance The section begins at the basal contact about 1,000 ft N. 57° W. of the pump house at "Donni Spring No. 1" and extends due west for 260 ft to the upper contact.

Interval 1 (*basal*).—Conglomerate; deeply weathered, variegated, composed of rounded and subrounded pebbles, cobbles, boulders of andesite, and scattered fragments of silica-and-iron-replaced "limestone" and dacite porphyry. The fragments are surrounded by a coarse-grained, thoroughly decayed, tuffaceous matrix. They range in size from pebbles less than 1 in. in diameter to boulders 3 ft in diameter, with an average diameter of about 1 ft. Some of the dacite fragments contain minute scattered grains of pyrite and sphalerite in the groundmass. Andesite boulders are weathered to gray, green, red, and lavender clay materials that retain relict textures. The matrix of the conglomerate is weathered to clay that is stained red and brown by hydrous ferric oxides..........................0–30 ft

Interval 2 (*top*).—Conglomerate; deeply weathered, variegated, andesitic conglomerate as described for interval 1, but less coarse. The fragments of interval 2 range in size from less than 1 in. to only about 1 ft in diameter, their average diameter being about 6 in..30–40 ft

APPENDIX B—ECONOMIC GEOLOGY

INTRODUCTION

The economic geology of Saipan is here briefly summarized, with emphasis on metallic and nonmetallic mineral resources and construction materials. Although of only local significance, the island is so remote that it seems desirable to put the information at hand on record.

The ensuing discussion is intended as a general appraisal only, founded on studies that were mainly incidental to basic geologic investigations. Detailed exploration at potential source sites would be needed to formulate reliable estimates about tonnage, availability, and cost of recovery.

Recoverable metallic resources include probably not less than 7,000 tons of manganese oxide concentrates and nothing else of significance. A small deposit of yellow ocher could provide a temporary local source of pigment; but iron is limited to thin lateritic crusts, bauxite is unknown, and the precious metals are mineralogical curiosities only.

Nonmetallic mineral resources include minor quartz sand, calcite sand, pumiceous dacitic abrasives, mostly calcareous sand and gravel in limited amounts, and ceramic clays. Masonry construction and decorative stone is plentiful but of limited variety. The phosphate deposits appear to have been exhausted.

Available engineering construction materials are ample to supply likely local demands.

Information concerning tonnage of manganese ore mined by the Japanese and the location of reported sites for bauxite was obtained in December 1948 from Vidal Sonada. He was one of nine Japanese reported as remaining on Saipan, and the only resident then familiar with the locations and history of Japanese mineral investigations on Saipan. Before the war Mr. Sonada was employed by the Nanyo Kogyosio (South Sea Islands Mining Company) and Nanyo Boeki (South Sea Islands Import and Export Company) on Saipan as a prospector for manganese ores. His knowledge of mining and prospecting operations on Saipan is believed to be reliable.

METALLIC MINERAL RESOURCES

MANGANESE ORE

Manganese oxides on Saipan occur: (1) as large, irregular, massive, powdery to crystalline bodies in compact inequigranular limestone; (2) in crystalline to powdery layers, thin stringers, and irregular fillings in tuffaceous limestone and calcareous sandstone; (3) as narrow veins and veinlets in dacitic breccias; (4) in concretionary and earthy form associated with hydrous ferric oxides in lateritic soil mantles on deeply weathered andesite breccia, andesite tuff, and impure limestone; and (5) as disseminated flecks and grains in massive inequigranular limestone, tuffaceous limestone, and andesitic tuff. The first three types are minable on a small scale, and exploration for mine sites was begun by the Japanese in about 1939. Perhaps 13,500 tons of high-grade manganese oxide was taken from five principal areas before and during World War II.

Rough estimates of ore shipped by the Japanese from the areas mentioned and that stockpiled are as follows:

	Shipped (tons)	*Stockpiled (tons)*
Achugau area	5,000	3,000
Talofofo area	500	......
Donni area	500	......
Papago area	2,000	......
Hagman area	?	2,500
Total	8,000	5,500
Total high-grade ore mined		13,500 tons.

Recoverable reserves in terms of concentrated ore might be anywhere from one-half to ten or twelve times the total already mined. Extensive exploration would be required to obtain a reliable extimate, however, and exploitation would probably require concentration of lean ore and shipment to a distant market. Although the total manganese at depth on Saipan might be considerable, mining and concentration would be so expensive that these ores are not believed to be of commercial importance in the present world market.

In addition to the five areas mentioned above, small deposits of manganese oxides also occur at a coastal reentrant in the district of I Naftan, north of Naftan point; and shows of manganese oxide are frequent among the tuffaceous and clayey limestones and volcanic rocks, expecially in or near zones of sedimentary overlap and in deposits presumed to have accumulated in moderately deep water.

The location, geologic setting, and workings of the six principal areas are indicated on the economic geology map (pl. 25), and descriptions of sites follow.

ACHUGAU AREA

The Achugau area includes all known occurrences of manganese in the dacite outcrops in the northern part of east-central Saipan, as well as one pit mine in andesite at the north edge of the dacite. This area probably contains the greatest volume of manganese on the island. The main workings are scattered over an area of nearly 96 acres and centered about 4,000 ft due west of the main road junction at Kalabera. An old, almost impassable road leads to the workings from Little Burma Road one-half mile northwest of the road junction at Kalabera.

The workings consist of about 15 trenches, several small open pits, and several adits. They penetrate tuff, vitrophyric tuff, flow rock, and vitrophyric breccia, all dacitic. The vitrophyric tuff and breccia are locally altered to pink siliceous or yellowish-brown waxy clays. At places they are overlain by a dark-gray, mottled, highly plastic, probably transported clay. The alteration to pink clay extends to unknown depths adjacent to mineral veins and seems to be confined to areas where mineralization has been intense.

The manganese oxides at this locality occur in four principal ways: (1) as narrow veins as wide as 1½ in in the vitrophyric tuff and breccia; (2) as cementing material, with jasperoid silica, filling the interstices of brecciated flow rock; (3) as narrow ramifying veinlets forming stockworks in strongly brecciated dacite; and (4) as surficial concentrations. The ore is crystalline to powdery in texture and is probably a mixture of the commoner oxides of manganese.

A hydrothermal origin is suggested by the occurrence of the manganese oxides as fracture fillings, forming narrow veins that apparently extend to depth, as well as by their association with chalcedony and jasperoid, filling open spaces in brecciated dacite. The ore may have been deposited from ascending solutions in open spaces at shallow depth, and at relatively low temperature. The surficial concentrations presumably resulted from weathering.

The Japanese constructed a cobble-surfaced road to the deposit, a concrete sorting platform, and a walled wash basin. The wash basin was built at the junction of two intermittent streams. A wooden riffle was found nearby. The basin consists of a rectangular rock-walled structure about 20 ft wide, 30 ft long, and 8 ft deep. Water was diverted from the natural drainage channels into the basin through specially constructed culverts.

Three small piles of from 1 to 5 tons of high-grade manganese oxide lumps lie on the old sorting platform, about 100 ft southeast of the sorting platform, and at the edge of the wash basin. Stock piles of from one to several hundred tons each occur near several of the pits in the main workings. About 5,000 tons of ore was mined and shipped from the locality during 1939 and 1940. Partial analysis of a high-grade sample of the concentrate [1] showed 55.19 percent Mn, 1.42 percent SiO_2 and 0.47 percent Fe_2O_3.

Besides the site described, an isolated pit mine is found about 0.6 mile northwest of the main highway junction at Kalabera and 100 yd south of Little Burma Road in an open field (pl. 6*A*). Manganese oxides occur here in large irregular pockets and narrow seams in deeply weathered andesitic tuffs and in a mass of yellowish-brown chert, possibly a replacement of limestone. The deposit is near the contact between dacite breccia of the Sankakuyama formation and overlying andesitic tuff of the Hagman formation. The andesitic tuff is weathered to clay and hydrous ferric oxide. It is not known whether manganese oxides also occur in the dacite breccia, because the breccia is not exposed in the mine. This cut is about 100 ft long, 50 ft wide, and 15 ft deep. Just north of it is a stockpile containing an estimated 1,000 tons of high-grade manganese oxide.

A second isolated pit mine is about 400 yd southwest of the one just described. It is a small, shallow, L-shaped opencut, with limbs about 100 feet long, 20 feet wide, and 4 to 5 feet deep. Manganese oxides occur in irregular spaces and narrow fissures in dacitic tuff and breccia, and in large pockets and narrow layers in weathered dacite breccia and tuff. A stockpile of high-grade ore estimated to contain between 500 and 1,000 tons lies just north of the cut.

The enlarged inset map on plate 25 also shows the locations of minor occurrences of manganese oxides associated with chalcedony in dacite breccia, and narrow ramifying veinlets in stockwork deposits and shear zones.

TALOFOFO AREA

Manganese oxides are found on the east face of Mount Talofofo, about 800 ft southeast of a former Japanese radio station, in the inequigranular facies of the Tagpochau limestone. They are fine-grained to powdery and in part crystalline. They occupy solution cavities, joints, and other openings in the limestone 10 to 30 ft above its contact with underlying conglomerate of the Densinyama formation. Pockets several feet wide, apparently once contained solid manganese oxide, but are now mined out.

The main workings consist of an irregular pitlike opening and two short adits about 30 ft long. The latter extend horizontally from the pit into the limestone just below the terrace rim which forms the crest of Mount Talofofo. On the terrace surface above the main workings are several small pits and caves, from which a small amount of ore was probably obtained. A stockpile of about 1 ton of high-grade ore lies near the large pit. The Japanese mined about 500 tons of ore from this locality.

DONNI AREA

The deposits of manganese oxides in the Donni area occur in a cliff face above a limestone bench. Mine workings are located to the north of and about 50 ft above a road that runs east through a narrow defile in Machegit cliffs past Donni Spring No. 2 (Bobo I Denni). Like the Talofofo deposits, those at this locality fill openings in the inequigranular facies of the Tagpochau limestone. Geometric projection suggests that they are at least 60 ft above the basal contact of this facies with the underlying Machegit conglomerate member or with concealed volcanic rocks. The mine workings consist of two horizontal and possibly connecting adits, each about 100 ft long. Short drifts lead off the main adits. Five hundred to 1,000 tons of ore were mined from this locality, according to Mr. Sonada.

PAPAGO AREA

The largest individual deposit of the Papago manganese area (pl. 10*A*), now essentially mined out, lay at the top of a scarp in the inequigranular facies of the Tagpochau limestone, 850 ft due north of the peak of Mount Laulau. This was also the largest single deposit of manganese oxide in limestone found on Saipan. About 1,000 tons of ore were mined from the main pit, which is about 50 ft square and 20 ft deep. The remaining manganese oxide, found in small openings, is mostly soft and extremely fine grained, but in places is coarsely crystalline. Mining was done by hand, as the ore was soft enough to dig with hand tools. Blocks of limestone gangue came free as waste.

About 20 short adits and several small pits were excavated in the limestone along the terrace scarp immediately northeast and northwest of the main pit, and several small shafts were sunk along the top of the terrace remnant. A small part of the production in the Papago area came from these workings.

North and northeast of the main Papago manganese pit and its adjoining diggings dozens of small manganese prospect pits and trenches were sunk into the limestone. The workings are clustered on the hillside immediately above and north of a limestone quarry which lies about one-fourth mile north of the peak of Mount Laulau. The manganese is found principally in the inequigranular facies of the Tagpochau limestone, but is also in the transitional facies. It fills joints and solution cavities in the limestones and is a fine grained, sooty variety.

The prospect pits and trenches are small, from a few feet to 12 or 15 ft deep, with the diameter of the pits not exceeding 15 ft or so and the trenches mostly short. A few adits extend from some of the trenches or into parts of the limestone scarps of the area. Apparently all excavation was by hand, sites probably being determined by shows of manganese oxide at the surface. Probably not more than 1,000 or 2,000 tons of high-grade ore was obtained from these pits.

HAGMAN AREA

The Hagman occurrences were extensively worked by the Japanese, but most or all of the ore mined remains stockpiled in the area. The main workings occur on the north-sloping surface of the point of land north of Hagman beach. The workings can be reached only with difficulty from the sea or by a narrow foot trail. The trail leads along the base of the prominent limestone cliffs above and north of Hagman beach, over the top of the cliff, and finally down the northern slope of the point, trending parallel to and somewhat north of the cliff edge at the point.

The workings consist of several pits or shafts, a short entrance trench, and a large tunnel and room dug into the transitional facies of the Tagpochau limestone. The entrance trench is 7 ft wide. It drives in about 40 ft to a room about 50 ft long, 10 to 20 ft wide, and 6 to 8 ft high. From this room extend two small drifts about 20 ft long and 7 ft high. Minor workings extend off either side of the main access trench. Most of the manganese ore taken from this locality was probably mined from the large room.

In the main deposit manganese oxides cement the upper part of a coarse limestone breccia that contains abundant larger Formaminifera. A zone, 3 to 10 in thick, rich in manganese oxides, occurs at the contact between the limestone breccia and an overlying, calcareously cemented 4-ft sandstone bed. The latter is in the gradational zone between the transitional facies of the Tagpochau limestone and the overlying Donni sandstone member of the same formation. Thin stringers of manganese oxide are also found in the calcareous sandstone bed. An analysis [2] of high-grade ore from the massive manganese zone showed 40.95 percent Mn, 2.59 percent SiO_2, 0.86 percent Fe_2O_3, and 2.89 percent Al_2O_3. An analysis [2] of a 3-ft channel sample from the transitional limestone breccia gave 7.46 percent Mn, 10.10 percent SiO_2, 2.43 percent Fe_2O_3, and 7.02 percent Al_2O_3 Although this is very low-grade ore, it could be concentrated by washing if there were enough to make it worthwhile.

North of the main mine several vertical pits extend down to the manganese oxide zone in the breccias of the transitional facies, some penetrating the Donni sandstone member to reach it. At one place a short adit is driven horizontally into the breccia.

Four stockpiles in the vicinity of the main workings at the Hagman locality aggregate about 2,500 tons of high-grade ore. The largest stockpile is about 500 ft north of the main mine entrance. The others are near the entrance.

Manganese oxides are disseminated, in differing concentrations, throughout the sedimentary breccia of the transitional facies of the Tagpochau limestone in this vicinity. The breccia thins markedly east and west from the main manganese working. At a point 1,600 ft west-southwest, high on the bluffs above and west of Hagman beach, it is only 3 to 6 ft thick. However, at this point it includes much interstitial manganese oxide. The Japanese tested this site by means of a 50-ft adit into the hillside, with several branching drifts at right angles to the adit. A little ore was obtained, and about 20 tons of ore of fair grade are stockpiled about 200 ft southeast of the adit entrance.

NAFTAN AREA

Manganese oxides at I Naftan occur along the south side of the coastal reentrant between Naftan and Dandan points. They are in the transitional facies of the Tagpochau limestone, as at the Hagman locality. No exploration has been attempted. A few large blocks of solid, high-grade manganese oxide as much as 5 ft square (pl. 10*B*) may be seen at the Naftan locality. As the transitional facies pinches out in all directions within a short distance, it is doubtful that much manganese ore is present in this area.

OCHER

A small deposit of yellow ocher occurs at the top of the cliffs above Hagman beach. The location is shown on the enlarged inset map of the Hagman manganese locality on plate 25.

The ocher is a layer or irregular pocket about 4 to 6 ft thick of unknown but probably small lateral dimensions. It consists of extremely fine grained and amorphous, ocher-yellow, hydrous ferric oxides mixed with fine-grained clay and associated with the Donni sandstone member of the Tagpochau limestone. It may have originated through alteration of an iron-rich lens in the Donni sandstone. The deposit is of possible importance only as a local source of pigment.

IRON

No commercial deposits of iron ore occur on Saipan, although a few hundred pounds of the metal could probably be obtained from some of the thin laterite crusts developed over deeply weathered andesitic breccia and tuff. This laterite consists of hydrous ferric oxides, hematite, and minor amounts of manganese oxide. It forms boxworks and hard crusts as thick as 1 foot. The crusts have developed by intense weathering of breccia and tuff of the Densinyama formation. Commonly the iron oxides cement concentrations of residual quartz grains derived from the tuff.

REPORTS OF BAUXITE

To our knowledge no bauxite occurs on Saipan. Because it has several times been reported to occur there (Tayama, 1938, H. T. Stearns, written communication; Bridge, 1948, p. 33–34), however, the results of searches made for it are here summarized.

According to Mr. Sonada, the Japanese may have sampled for bauxite at a locality toward the south end of Talofofo ridge in central Saipan. At the site to which he took us andesitic breccia of the Hagman formation is overlain with sharp unconformity by a thin mantle of stratified, very coarse grained, intensely weathered, dull-reddish sand. This material is described on earlier pages as older terrace deposits (Pliocene?). It somewhat resembles the stratified bauxite deposits of northernBabelthuap, in the Palau Islands, and both overlie deeply weathered andesitic pyroclastics.

It is not known whether the Japanese sampled the terrace sand or the underlying weathered breccia for bauxite. Material analysed by U S. Geological Survey chemists, however, included a channel sample through the terrace deposit and a composite sample from altered andesite boulders in the underlying breccia. Both showed Al_2O_3 content to be well under 30 percent, with a high percentage of Fe_2O_3 and insolubles.

The only other locality which the Japanese may have sampled for bauxite is in the Achugau manganese area about 4,000 ft due west of the main road junction at Kalabera. At the possible sample site the dacitic bedrock is overlain by mottled, brownish-gray to black, highly plastic, finely gritty clay that attains a thickness of several feet. This clay, which is of very limited extent, was probably not derived from weathering of the dacite, but was transported to its present position. Analysis of this material showed less than 30 percent Al_2O_3 and a high percentage of insolubles.

An unpublished account by H. T. Stearns mentions bauxite mines a half mile southwest of the former village of "Galaperai" (Kalabera). It is said that these were opencuts into the decomposed surface of rhyolite (the dacite of this report), chiefly exploratory, in process of excavation at the time of the American invasion of Saipan, and too small to be of value. This description could apply to the workings of the Achugau manganese area, and it seems probable that Stearns was misinformed about the occurrence of bauxite here. Nevertheless, two samples were

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[1] Analysis by F. Todoriki, Mitsubishi Mining and Metallurgical Laboratory, January 13, 1949.

[2] Analysis by H. Kurama, Mitsubishi Mining and Metallurgical Laboratory, Omiya, Japan, June 10, 1949.

taken of possibly alumina-rich materials, one from a point about ½ mile S. 80° W. from the main road junction at Kalabera, and the other about 200 yd east of the main Achugao manganese workings. The first was of a reddish-brown clay soil on the Donni sandstone member of the Tagpochau limestone, and the other of the Donni sandstone member itself. Analyses [1] of these samples are as follows:

	Clay over Donni sandstone member (weight percent)	Donni sandstone member (weight percent)
Insoluble SiO_2	42.52	41.68
Al_2O_3	25.66	24.75
Fe_2O_3	8.22	11.22
Loss on ignition	22.30	22.01
	98.80	99.71

Robert Chapman, a representative of the Reynolds Metals Company, visited Saipan in November 1945 to sample the red and brown clay soils developed over various facies of the limestone and volcanic rocks at widely separated localities on the island. Analyses of these samples provided by the Reynolds Metals Company showed all to run well under 30 percent Al_2O_3 and high in insolubles and Fe_2O_3.

REPORTS OF GOLD AND SILVER

Tayama (1938) reported that traces of gold and silver are associated with grains of pyrite, arsenopyrite(?), and sphalerite in some quartz-bearing boulders of the conglomerate sandstone facies of the Densinyama formation. The sulfides occur as grains less than 1 mm in diameter scattered through the groundmass of fine-grained dark- and light-gray pebbles of quartz porphyry and dacite. They also occur as larger grains and crystalline aggregates in pebbles and cobbles of fine- to coarse-grained quartz and chert. The presence of minute quantities of gold and silver in such rocks appears to be of purely academic interest.

NONMETALLIC MINERAL RESOURCES

PHOSPHATE

Phosphate was mined by the Japanese principally in the northwest part of the Bañadero district. This area is now partly covered by the abandoned North Field airstrip. The phosphate ore occurred in closely spaced solution pits in the Tagpochau and Mariana limestones, on a broad erosional bench between 160 and 180 ft above sea level and at the base of the Bañadero cliffs. A smaller deposit at the foot of Magpi cliffs was similar to the occurrence mentioned except for being situated entirely in the Tagpochau limestone. At both localities individual solution pits are 1 to 3 ft in diameter, as deep as 6 ft, and roughly cylindrical. Both deposits appear to be mined out.

The phosphatic material on Saipan is a brownish to salmon-colored mixture of tricalcium phosphate, clay, and probably some iron sesquioxides. It occurs as pellets, crusts, or earthy fillings. Calcium phosphate of this type occurs on many Pacific islands. The deposits are generally believed to have formed by reaction of guano-derived phosphoric acid with the underlying limestone in accordance with the formula

$$2H_3PO_4+3CaCO_3\rightarrow Ca_3(PO_4)_2+3H_2O+3CO_2$$

(Rodgers, 1948, p. 406–407). The solution pits were probably formed concomitantly with the phosphates as a result of the phosphatization process. The deposits on Saipan (and presumably those on Rota) differ from those on many Pacific islands in that Miocene as well as Pleistocene limestones were involved in the phosphatization reaction. This difference, however, is probably not significant because most of the phosphate islands have only young limestones.

According to reports mining was done entirely by hand. The ore was sacked at loading chutes at Bañadero and hauled to Chalan Kanoa where it was crushed and loaded into a large concrete bin. Rodgers (1948, p. 401) reports that 88,000 metric tons of phosphate rock was mined on Saipan, presumably all of it shipped to Japan.

QUARTZ SAND AND OTHER ABRASIVE MATERIALS

Quartz-bearing sand has a possible use as an abrasive material for sandblasting. It occurs locally on Saipan both in terrace deposits and beach sands. Quartz-rich beach sand would be better than the terrace deposits because it is easily accessible, clean, and loose. Total volume of all quartz-rich sand on Saipan, however, is small, and the deposits could be exploited only on a minor scale and for local use. Principal occurrences are shown on plate 25.

The greatest volume of quartz sand is found in the post-Mariana terrace deposits and the younger terrace deposits. These include a large proportion of quartz grains mixed with and loosely bonded by hematite and hydrous ferric oxides. The quartz grains range in diameter from less than 1 mm to about 6 mm and may constitute as much as 75 percent of the total volume of the sand.

Quartz sand of the post-Mariana terrace deposits is well exposed in cuts along the Cross-Island Connecting Highway near its junction with the East Coast Highway. Here the sand averages about 5 ft thick over an area of about 6 acres and attains a maximum thickness of 10 ft.

Probably the best source of sand in the younger terrace deposits is about one-fourth mile east of the West Coast Highway and about the same distance south of the Chamorro village of Tanapag.

Loosely consolidated quartz sand, lithically very like the terrace sand, is found in parts of the Densinyama formation, especially in cuts along the western part of the Talofofo road.

Fairly clean sand containing 50 to 80 percent quartz mixed with calcareous and volcanic material occurs at the small beaches of Unai Nanasu, Unai Fahang, and Unai Talofofo.

Limesand was used by the U. S. Naval Net Facility on Saipan for sandblasting rusted harbor buoys. The sand was obtained mostly from Laulau beach along the East Coast Highway. Much of the west coast of Saipan is also bordered by beaches of medium- to coarse-grained limesand and minor amounts of calcareous gravel, and most of the smaller beaches on the east coast are composed of similar but more gravelly deposits. The more extensive emerged beach and lagoonal limesands of the western coastal plain are described elsewhere.

The Donni member of the Tagpochau limestone and parts of the Densinyama formation contain fine-grained calcareous sandstone that could be used for grinding and polishing material if powdered and properly sized. The tuff and dacite vitrophyre breccia of the Sankakyuama formation might also provide scouring, grinding, or polishing materials.

CLAY

Pottery shards are widely distributed on Saipan and presumably are derived from pottery manufactured from local clays. In several areas andesitic tuffs and impure limestones are overlain by dark-red to variegated plastic clays that might be used in the manufacture of bricks or pottery. One of the more favorable areas of possible ceramic clay is outlined on plate 25.

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[1] Analyses by F. Todoriki, Mitsubishi Mining and Metallurgical Laboratory, Omiya, Japan, January 13, 1949.

SAND AND GRAVEL

Calcareous sand and gravel are present in large quantity along the beaches, and inland from the west coast. The calcareous sand and gravel have a possible use as concrete aggregate, as fill for embankments, and, with the addition of a clay binder, as base course for roads. For use as aggregate, however, it is inferior to crushed limestone which is abundantly available.

Poorly consolidated andesitic sandstone and conglomerate occur locally in the Hagman grasslands. This is the only source of relatively fresh volcanic sand and gravel on Saipan, and a very small one at that.

BUILDING AND DECORATIVE STONE

The best source of decorative and dimension stone on Saipan is the inequigranular facies of the Tagpochau limestone. Several quarries were developed in this limestone during World War II, the largest and most easily accessible of which is 1,200 yd due west of Dandan beach. In this quarry joints are widely spaced and the rock can be blasted out in large blocks. It is a compact, massive rock suitable for building stone and has a variegated color of a generally pink tone that should be attractive on a polished surface.

Andesite possibly suitable for dimension stone or trim occurs in the Fina-sisu formation along the western spurs at the south end of Fina-sisu. This is a flow about 80 to 100 ft thick, and it crops out over an area about 500 ft wide and ½ mile long. It strikes north-northeast and dips 8° to 10° E.–SE. The rock is dark gray to greenish, fine grained, locally vesicular, and intensely weathered at the surface. It is closely jointed, and in places shows columnar jointing. Fresher but somewhat altered rock is exposed in old tunnels along the south side of two of the deeper west-trending ravines in the area. To establish a quarry in fresh rock would require removal of a thick weathered zone. The area described, however, provides the only reasonably favorable locality on Saipan for quarry sites in fresh andesite.

ENGINEERING CONSTRUCTION MATERIALS

Local sources are adequate to supply any likely local demands for riprap, aggregate, or materials suitable for subgrade, base course, wearing course, surfacing, embankment, and fill. Only applications and the names of source units will be mentioned here. The geologic map (pl. 1) shows the distribution of source units, and their characteristics and properties are described elsewhere.

The best sources of riprap and aggregate are the inequigranular and equigranular facies of the Tagpochau limestone, the pink and white facies of the Matansa limestone, the massive Mariana limestone, and andesitic and dacitic flow rocks of the Fina-sisu, Hagman, and Sankakuyama formations. Drilling and blasting are necessary to free the rock for removal. A limited demand for surfacing and wearing course could be met by crushed andesite or dacite flow rock of the units just noted, but extensive needs might lead to utilization of the limestones mentioned.

Materials suitable for subgrade are provided by the conglomerates and breccias of the Hagman and Densinyama formations, and to a lesser extent by the Donni sandstone member and tuffaceous facies of the Tagpochau limestone, and the pyroclastic rocks of the Fina-sisu formation.

The best material for base course and fill is found in the rubbly, poorly consolidated limestones, which are in part argillaceous and in part markedly pure. Such limestones include the rubbly and *Acropora*-rich facies of the Mariana limestone, the rubbly and parts of the tuffaceous and marly facies of the Tagpochau limestone, and shatter zones along some faults through limestone. The purer rubbly limestones that have large amounts of fine calcareous material display self-binding properties when wetted and rolled, owing to solution and reprecipitation of calcium carbonate. These limestones can ordinarily be dug without blasting. Beach sands, and the elevated lime sands of the western coastal plain could be made suitable for fill and base course with the addition of a clay binder, as could the pumiceous rhyolite breccias of the Sankakuyama formation.

Embankments could be made of calcareous, clayey, tuffaceous sandstones, such as characterize the Donni sandstone member and parts of the tuffaceous facies of the Tagpochau limestone, various terrace deposits, parts of the Fina-sisu formation, and lesser parts of the Hagman and Densinyama formations. Large areas of clay are found over the tuffaceous and marly facies of the Tagpochau limestone and the rubbly facies of the Mariana limestone, as well as in broad depressions, alluvial outwash areas, and over purer limestones. This material is suitable for earth embankments, especially when used as a binder with granular coarse aggregate.

INDEX

PLATES 5–24

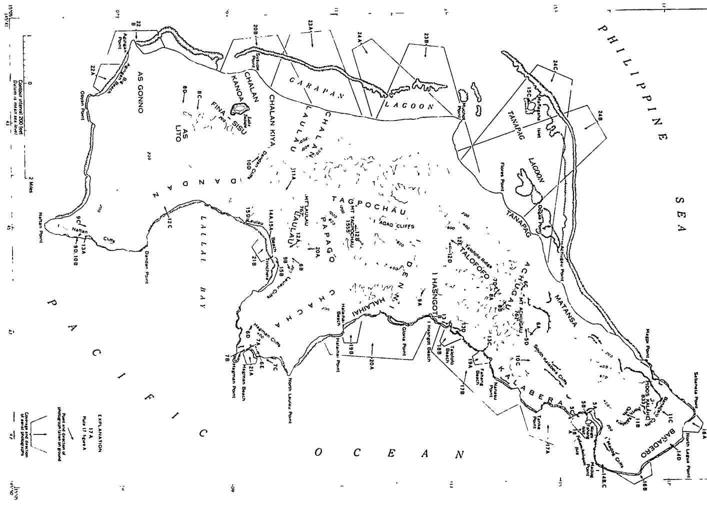
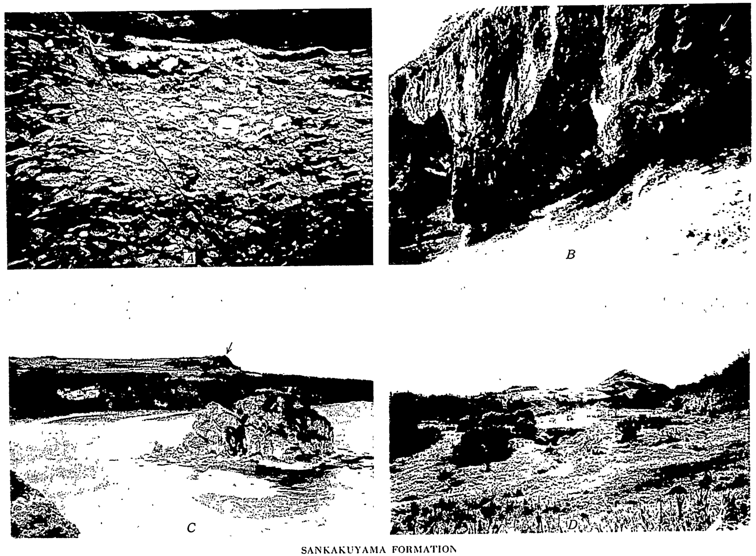


FIGURE 10.—Sites of rock and terrain photographs on plates 5–24, Saipan, Mariana Islands.



SANKAKUYAMA FORMATION

A. Mixed dacitic pyroclastic rocks at Fañunchuluyan beach. Angular fragments are inches across.

B. Massive dacite with distorted flow banding (arrow) above, dacitic vitrophyre breccia below. Fañunchuluyan beach. See also plate 16*B*.

C. Mixed dacitic pyroclastic rocks in Maigo Fahang islet, Tagpochau limestone at peak. Beveled faults in bluff beyond. Solution rampart beneath arrow at upper terrace margin. (H. T. Stearns, 1944).

D. Swordgrass- and casuarina-covered terrain of dacitic volcanic rocks extends left (south-southeast) from prominent triangular peak of Mount Achugau, an inferred cone remnant showing high initial dips.

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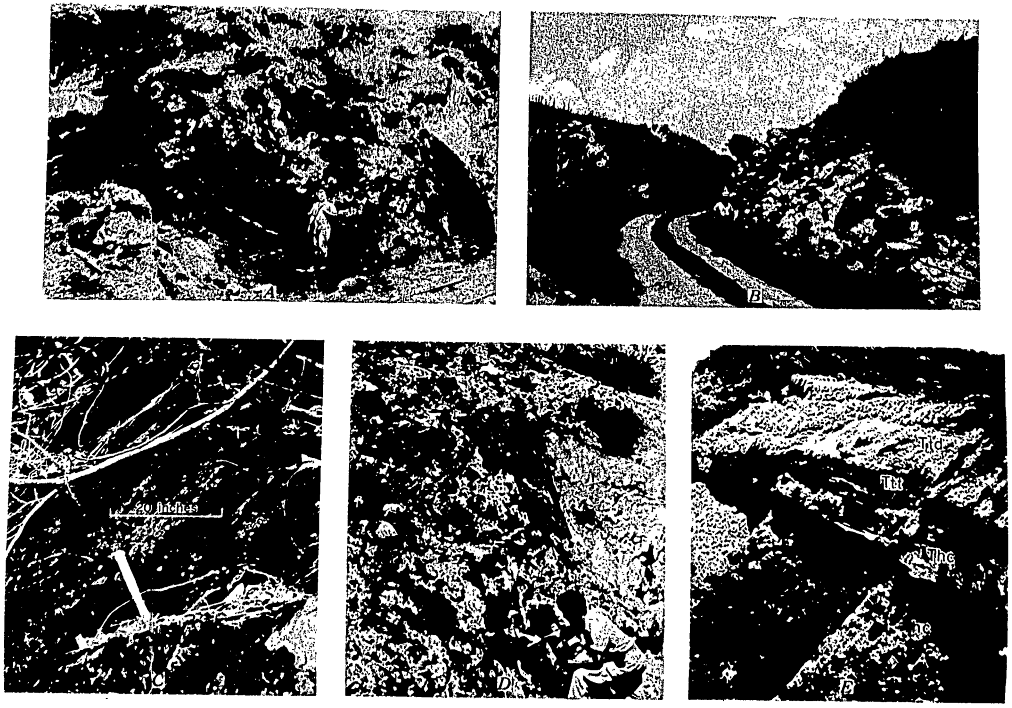


SANKAKUYAMA AND HAGMAN FORMATIONS

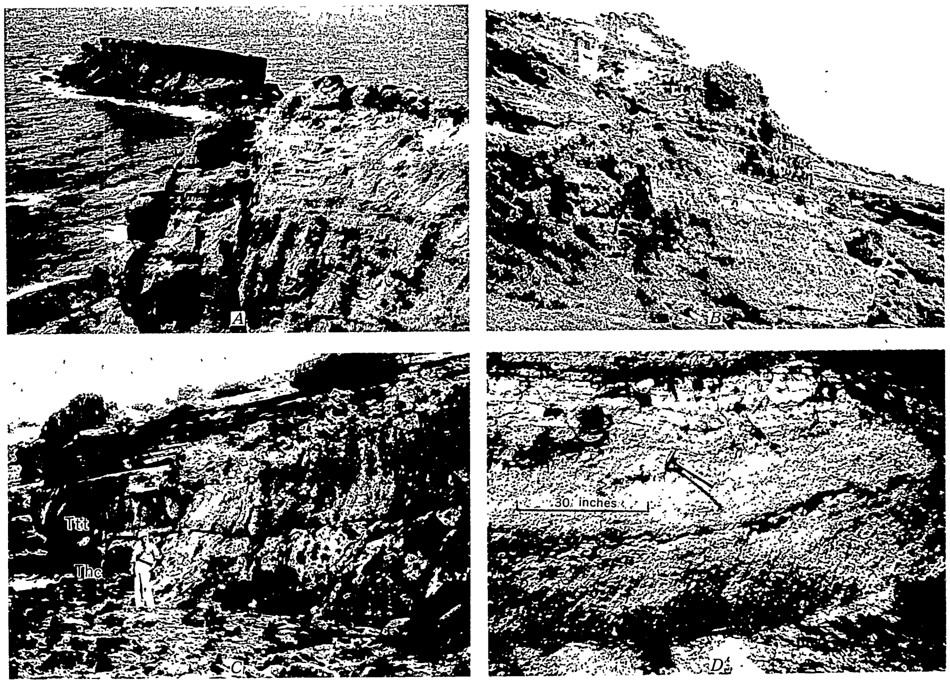
A. Manganese in tuffs near base of Hagman formation in northeast part of central Saipan. (H. T. Stearns, 1944)

B. Andesitic breccia of Hagman formation along former railroad grade north of Trinchera. (H. T. Stearns, 1944)

C. Columnar structure in dacite flow rock of Sankakuyama formation on southwestern flank of Mount Achugau.

D. Conglomerate-sandstone facies of Hagman formation along unmapped minor fault at Hagman cliffs.

E. Conglomerate-sandstone facies of Hagman formation (Thc) in lower bluffs of Hagman beach, overlain by transitional facies (Ttt) and Donni sandstone member (Ttd) of Tagpochau limestone at top of bluff.



HAGMAN AND DENSINYAMA FORMATIONS

A. Conglomerate-sandstone facies of Hagman formation above Hagman beach, capped by Mariana limestone in islet at left (H. T. Stearns, 1944).

B. Conglomerate-sandstone facies of Hagman formation in bluffs above Hagman beach. Dips 15° ± toward observer. (H. T. Stearns, 1944).

C. Sea level bench in andesitic conglomerate of Hagman formation (Thc) north of Hagman beach. Transitional facies of Tagpochau limestone (Ttt) in upper two-thirds of low bluff here includes thin-bedded limestone and calcareous conglomerate.

D. Conglomerate-sandstone facies of Densinyama formation along Talofofo road. Rock is quartz-rich and contains impure limestone fragments.

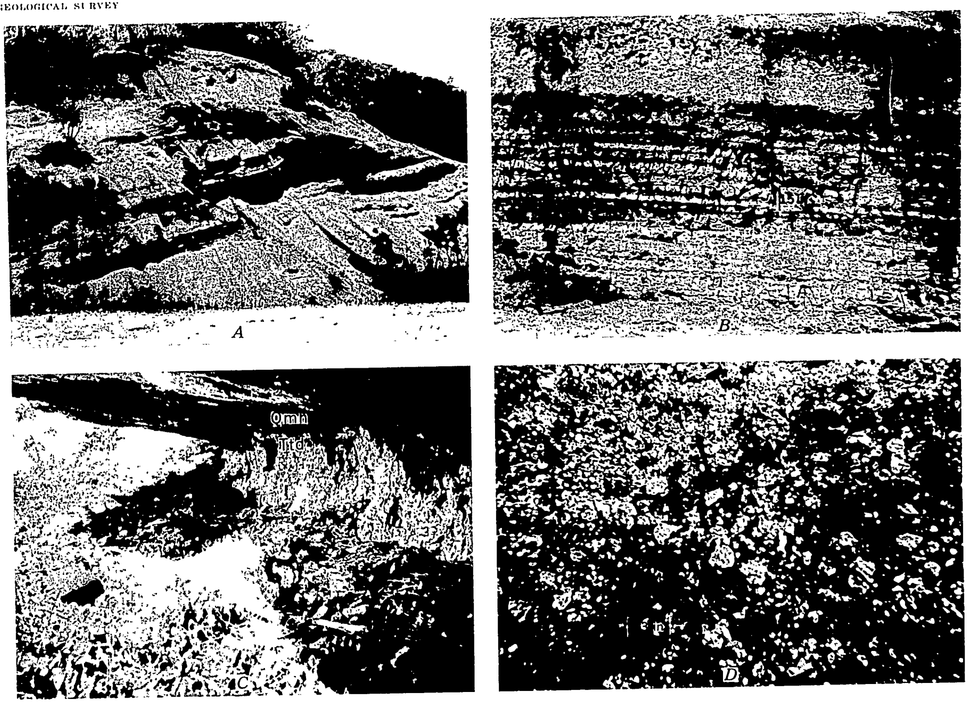
DENSINYAMA FORMATION, MATANSA LIMESTONE, AND FINA-SISU FORMATION

A. Impure calcareous conglomerate of Densinyama formation along the Talofofo road. Larger fragments are limestone.

B. Impure, camerinid-rich beds of pink facies of Matansa limestone in northeast part of central Saipan.

C. Spheroidally weathered cobbles from columnar-jointed augite andesite flow of Fina-sisu formation at Fina-sisu.

D. Detail of spheroidally weathered, saprolitic, augite andesite flow of Fina-sisu formation at Fina-sisu.



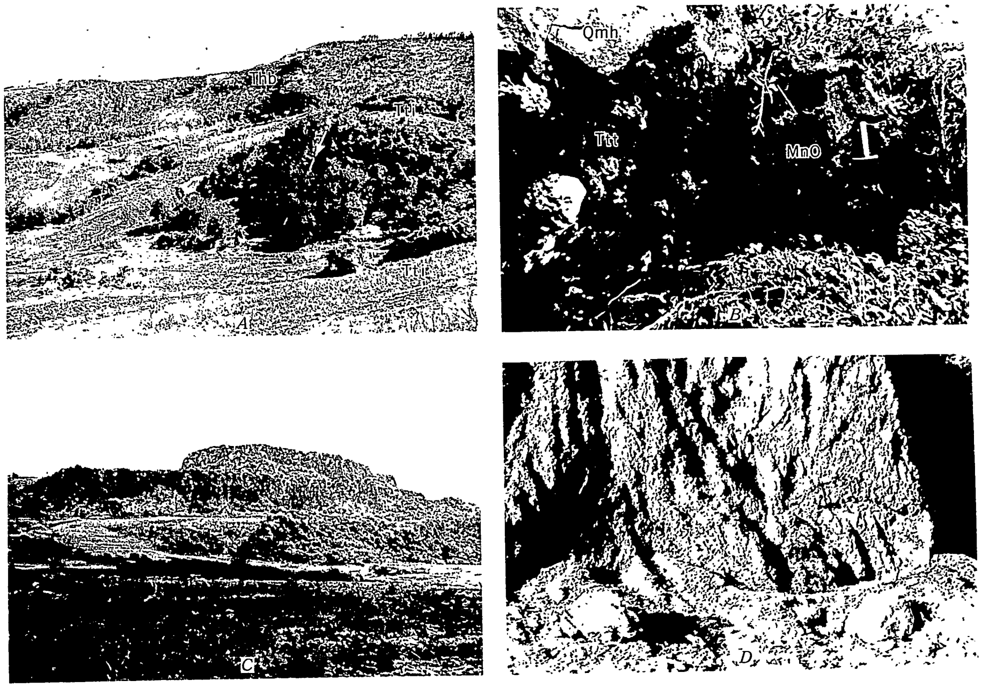
TAGPOCHAU LIMESTONE: DONNI SANDSTONE MEMBER AND TRANSITIONAL FACIES

A. Globigerina-rich "tuff" beds of Donni sandstone member along East Coast Highway in I Hasngot district.

B. Globigerina-rich "tuff" beds of Donni sandstone member in cut near top of Laulau cliffs. (H. T. Stearns, 1944).

C. Donni sandstone member (Ttd) under overhanging ledge of Mariana limestone (Qmh) along fault scarp north of Naftan point. Overhang simulates, but is not, an emerged sea-level notch.

D. Conglomeratic limestone of transitional facies with numerous orbitoid Foraminifera as pea-sized pebbles.



TAGPOCHAU LIMESTONE: TRANSITIONAL, INEQUIGRANULAR, AND RUBBLY FACIES

A. Chute (arrow) descends from main Papago manganese mine in impure limestones of inequigranular facies (Tti) at Deep Laulau ravine (Kanat Tadung Laulau). Hagman breccia-tuff facies (Ttb) in background. (H. T. Stearns. 1944).

B. Five-foot block of manganese oxides at top of transitional facies (Ttt); Mariana limestone (Qmh) above. Coastal reentrant north of Naftan point.

C. Inequigranular facies in west-tilted south Kalabera cliffs. Foreground flat is 200- to 280-foot terrace bench. (H. T. Stearns, 1944). White spots are shell-impact marks.

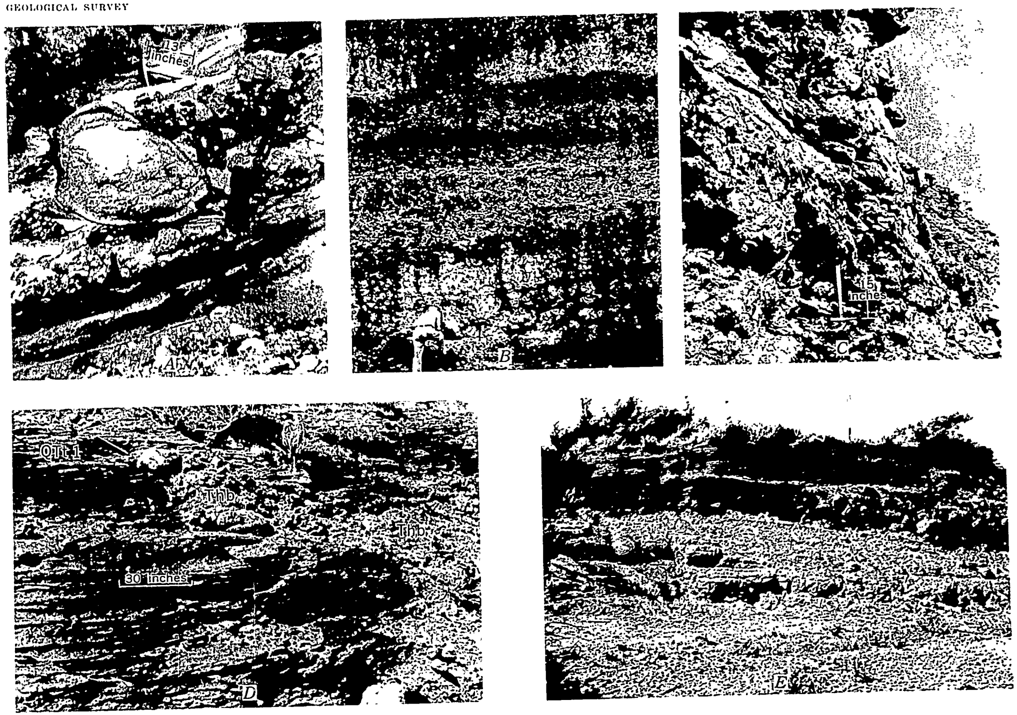
D. Rubbly facies in development locally called cascajo. Wedge of old "soil" outwash at left. Quarry S16 at Dandan cliffs.

TAGPOCHAU LIMESTONE: INEQUIGRANULAR FACIES AND SOILS

A. Pineapple patch on thin, stony soil over inequigranular facies in I Eddot ravine.

B. Gullied, thick (to about 5 feet) henna clay soil over inequigranular facies at base of north Kalabera cliffs.

C. Inequigranular facies in 600-foot cliff of Laderan Bañadero. Rarity of bedding surfaces is characteristic of these bank-type deposits.



TAGPOCHAU LIMESTONE, OLDER TERRACE DEPOSITS, AND MARIANA LIMESTONE

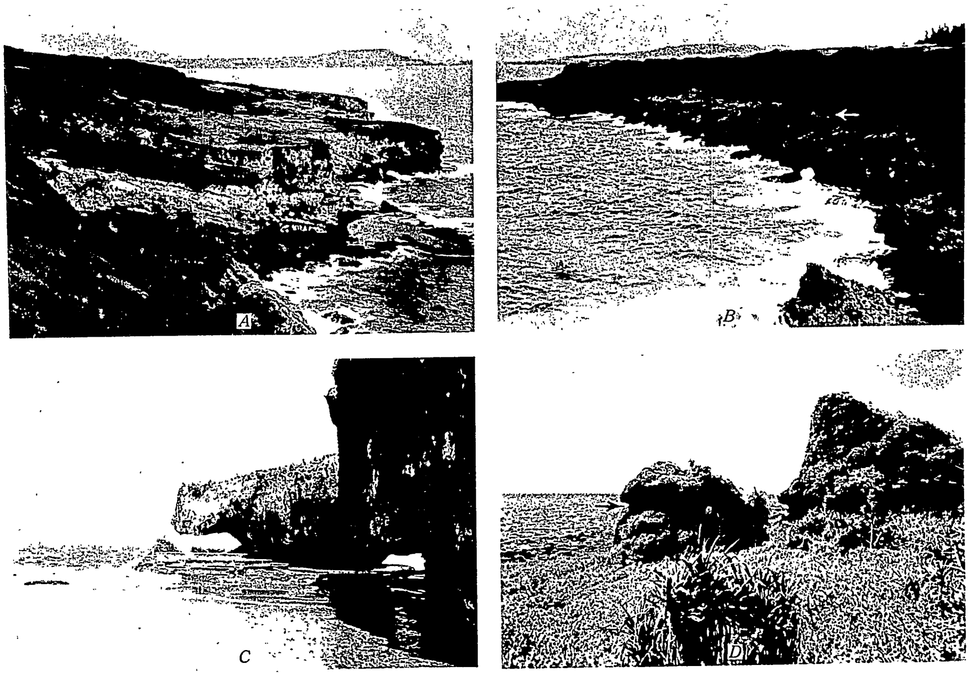
A. Transitional facies of Tagpochau limestone containing andesite cobbles and boulders. Many of the white spots in lower part of photograph are *Eulepidina*. Outcrop between Hagman formation and Mariana limestone in south side of coastal reentrant at Naftan.

B. Rubbly facies of Tagpochau limestone in large quarry at base of I Agag cliffs. Man is standing at *Sismondia* beds.

C. Massive facies of Mariana limestone in quarry S26 near east coast at Dandan. Cavernous coral and algal reef limestone.

D. Detail of older terrace deposits (QTt 1) to left of photograph *E*. Buried pinnacle of Hagman andesitic breccia (Thb) at center.

E. Older terrace deposits in top 10 to 12 feet truncating breccia-tuff facies of Hagman formation along island crest in I Denni district.



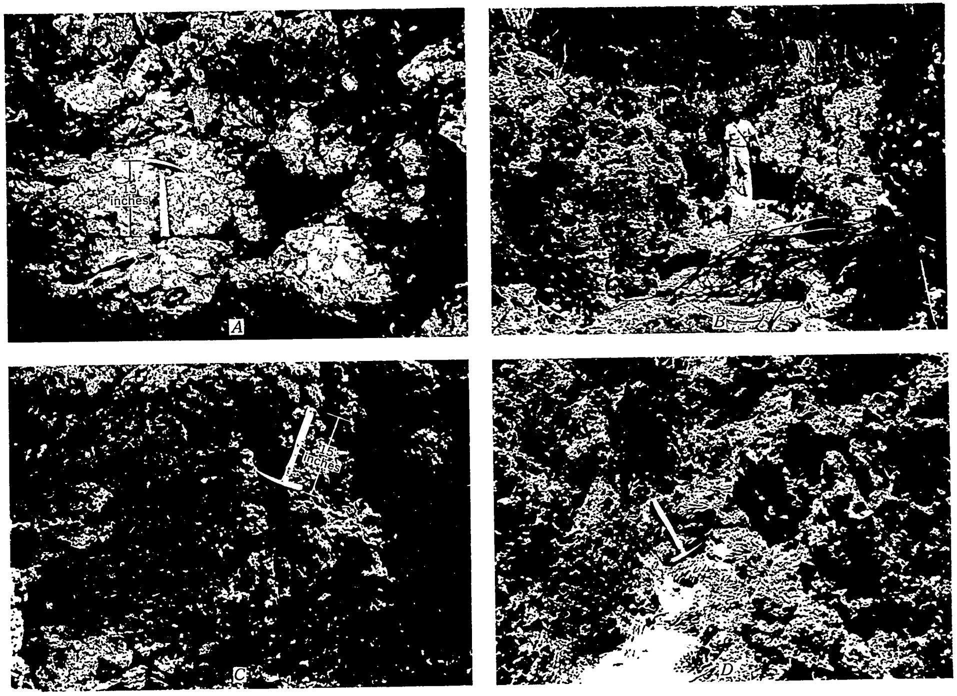
MARIANA LIMESTONE, TANAPAG LIMESTONE, AND EXISTING COASTAL FEATURES

A. *Halimeda*-rich Mariana limestone in top third of bluff, underlain by Hagman conglomerate-sandstone facies. Sloping bench near 100 to 160 feet above sea level cuts across steep initial dips north of Naftan point. (H. T. Stearns, 1944).

B. Tanapag limestone covers 20- to 40-foot bench south of I Hasngot beach. Massive facies of Mariana limestone occurs above, with terraced ramp and notch at shore. Arrow marks 40-foot notch.

C. Tanapag limestone caps bluff above terraced ramp and merged notches of present-day and 6-foot sea at Fahang beach. (H. T. Stearns, 1944).

D. Emerged sea stacks of massive Mariana limestone on 20- to 40-foot bench north of Talofofo beach (see also pl. 18*B*). Solution notch (arrow) near 40-foot level.



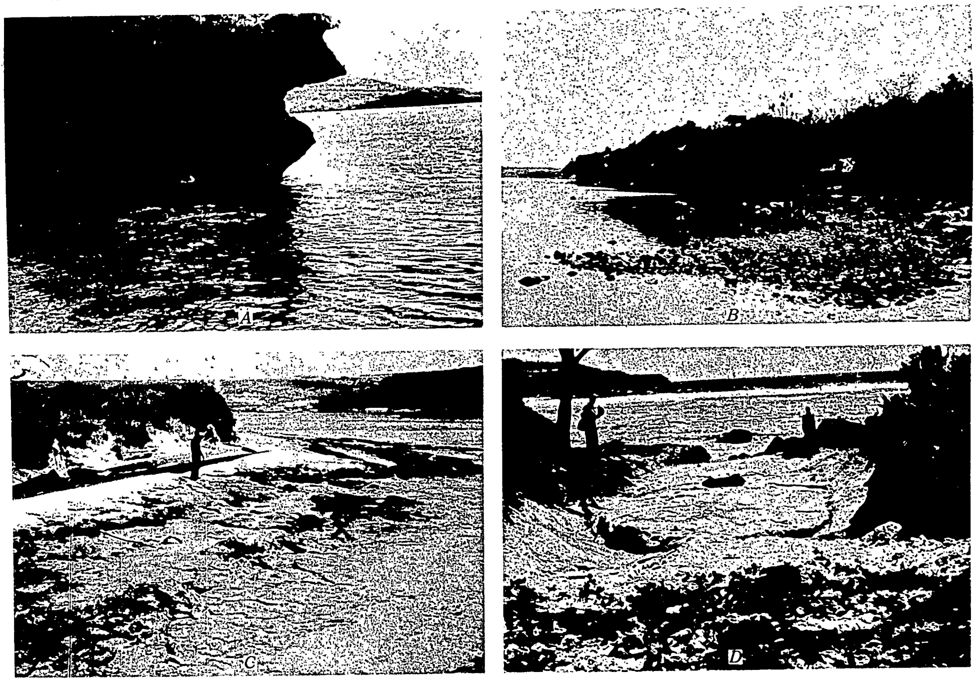
TANAPAG LIMESTONE AND ELEVATED SURGE CHANNELS

A. Coral- and algal-rich Tanapag limestone immediately above inequigranular facies of Tagpochau limestone (not visible in picture) in cave at Laulau beach.

B. View along emerged surge channel (bottom 15 ± feet above sea level) in margin of emerged fringing reef north of Madog point

C. Detail of coral- and algal-rich Tanapag limestone in side wall of emerged surge channel of photograph *B.*

D. Tanapag limestone and loose coral fragments in emerged surge channel southeast of north Lagua point.



TANAPAG LIMESTONE, 6-FOOT NOTCH, AND RECENT BEACH ROCK

A. Double notch in Tanapag limestone at Laulau beach. High tide near maximum indentation of present notch; elevated notch 5 to 6 feet above.

B. Double notch on northeast side of Trinchera. Midtide view of present and 6-foot notches. (H. T. Stearns, 1944).

C. Recent beach rock at south side of Mañagaha islet. Figure at high tide level.

D. Large emerged groove at Laulau beach. with layer of beach rock perhaps formed when the sea stood about 2 feet above its present level.

MATUIS HIGHLANDS NORTHERN PLATFORM TERRACE BENCHES AND ELEVATED SHORELINE FEATURES

PLATE 16

[Photographs by U. S. Navy Squadron VU-7 (B), June 1949]

A. View south over wave-cut northern or Bañadero platform (120–180± feet). Bañadero cliff, capped by Pidos Kalahe (P) in middle distance. West-tilted south Kalabera terraces (K) beyond, with Mount Tagpochau (T) on right skyline. In right lower foreground is 20- to 40-foot bench in Tanapag limestone with 40-foot notch (arrows) in cliff and around mushroom stacks at upper margin.

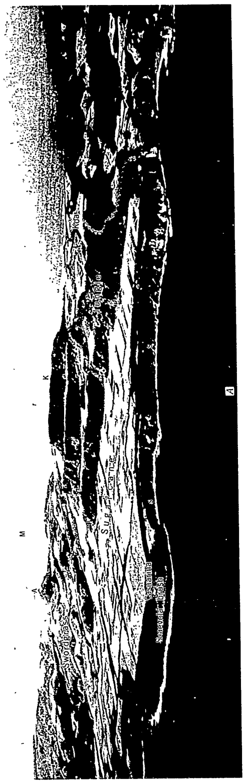
B. View southwest over Madog cliffs. Elevated grooves (g) on lower (12- to 15-foot and 20- to 40-foot) benches are at front of elevated upper Pleistocene fringing-reef flat (m) cut in Mariana limestone, but grooves are veneered with Tanapag limestone. West-tilted south Kalabera cliffs (K) in middle distance, with Mount Tagpochau (T) on skyline. Dacite flow (f) of plate 5*B* in cliffs of Fañunchuluyan bay to right of islet. Notch (arrow) in Madog cliff near 230 feet altitude. Above is 200-foot± platform, with rampart viewed from opposite side in plate 5*C*.

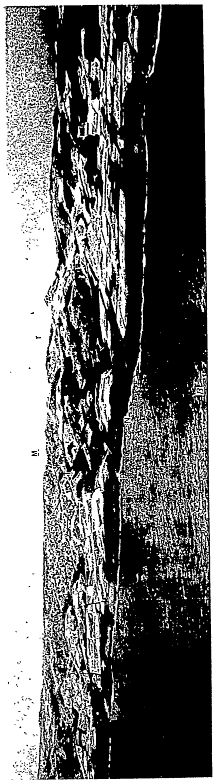
PLATE 17

[Photographs by U. S. Navy, February 1944]

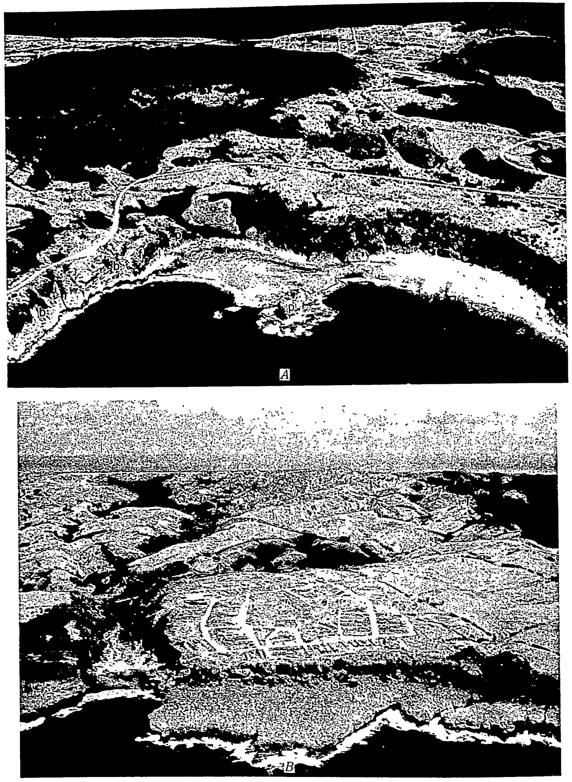
A. View west across west-tilted south Kalabera terraces (K) in inequigranular facies of Tagpochau limestone. Line of inverted V's marks approximate route of Tanke cliff section of white Mariana and inequigranular Tagpochau limestones. Principal outcrop area of Sankakuyama formation surrounds peak of Mount Achugao (A). Dacite flow (f), breccia (b), and mixed pyroclastic rocks (p) of Sankakuyama formation in sea bluffs at right. Massive Mariana limestone in lowest benches. Coarse slump rubble (s) along coast. White foamline marks western barrier reef (r) stretching beyond Mañagaha islet (M).

B. Sankakuyama formation extends south (left) from Mount Achugao (A) to plunge beneath the gullied spur and ravine topography of the Densinyama and Hagman formations in the volcanic highlands south from Talofofo road (T) and above the lower benches in left half of photograph. Arrow points to notched stacks on 20- to 40-foot bench. Talofofo (T), Fahang (F), and Nanasu (N) beaches of mixed quartz and calcium carbonate sand on east side of island; barrier reef (r) and Mañagaha islet (M) on west.





DISTINCTIVE TERRAIN OF VOLCANIC ROCKS AND LIMESTONES, VEGETATION PATTERNS, AND SHORELINE FEATURES



VOLCANIC ROCKS AND TERRAIN, AND ELEVATED AND PRESENT SHORELINE FEATURES

PLATE 18

[Photographs by U. S. Navy Squadron VU-7 (B), June 1949]

A. View northwest over Fañunchuluyan beach and fringing reef. Dacitic mixed pyroclastic rocks (p), flow (f), and breccias (b) of Sankakuyama formation in sea-facing bluffs at left, and dacitic pyroclastic rocks capped by Tagpochau limestone in Maigo Fahang islet at center foregound.

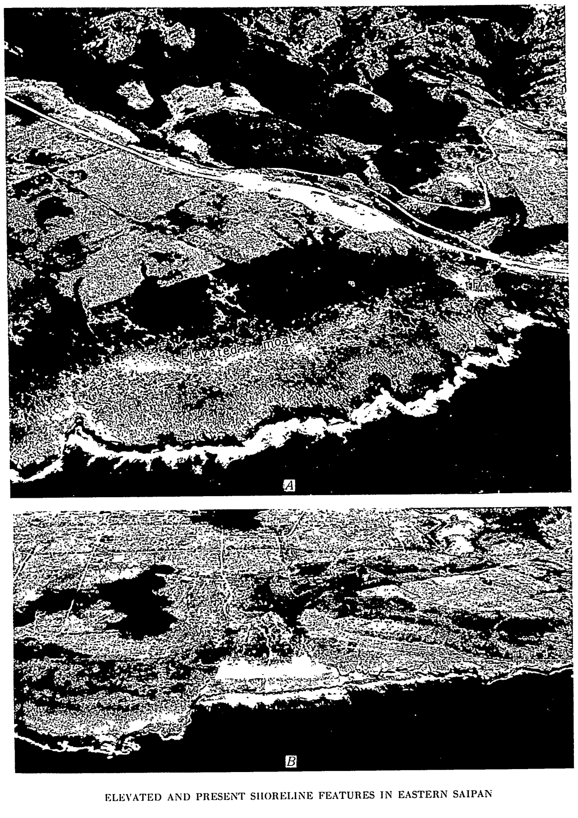
B. View west up Talofofo drainage basin in Densinyama and Hagman rocks south from the Talofofo road (T) along ridge at right. Buildings on massive Mariana limestone. Talofofo beach of mixed quartz and calcium carbonate sand at left. Elevated sea stacks (s) of plate 13*D* against cliff at back of low, radially grooved bench in Tanapag limestone, and 40-foot solution notch (arrow) at base of cliff and around stacks.

PLATE 19

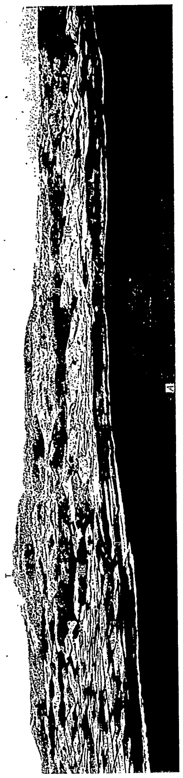
[Photographs by U. S. Navy Squadron VU-7 (B), June 1949]

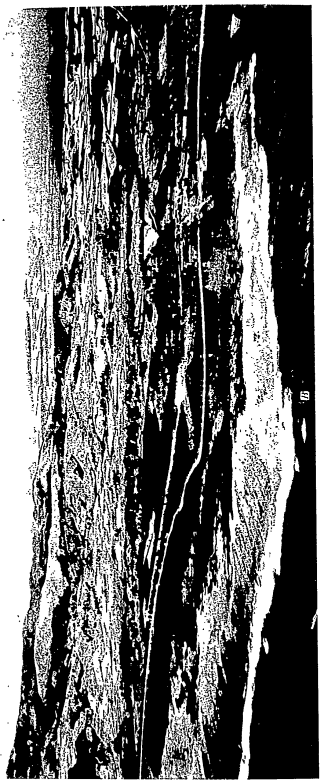
A. View northwest over elevated fringing-reef surface at back of 20- to 40-foot bench south of Fahang beach (F). The crescent-shaped light band is recent storm fill, along the former reef flat depression or moat, seaward from which are elevated grooves lined with upper Pleistocene Tanapag fringing reef limestone. Upper bench in massive Mariana limestone. Outcrops in background are dacite breccia of Sankakuyama formation.

B. View southwest over Halaihai beach and environs, showing modern fringing reef front and grooves below white surfline. Tanapag limestone veneers low bench on both sides.



ELEVATED AND PRESENT SHORELINE FEATURES IN EASTERN SAIPAN





GEOMORPHIC AND STRUCTURAL FEATURES OF SOUTHWESTERN SAIPAN

PLATE 20

[Photographs by U. S. Navy, February 1944]

A. View west across Mount Tagpochau (T), showing the complicated series of wave-cut benches that step down from 1,555 feet at its summit to sea level. Conspicuous reef-fronted beach at left center is Unai Halaihai (H), and lowest bench that extends north and south from it is of Tanapag limestone, with the 40-foot notch (arrow) at the base of the cliffs behind and with elevated notched stacks (S) on its surface. Benches inland rise across massive and then rubbly facies of Mariana limestone to Donni clay hills belt (Ttd) below wooded Machegit (M) and Adelug (A) cliffs.

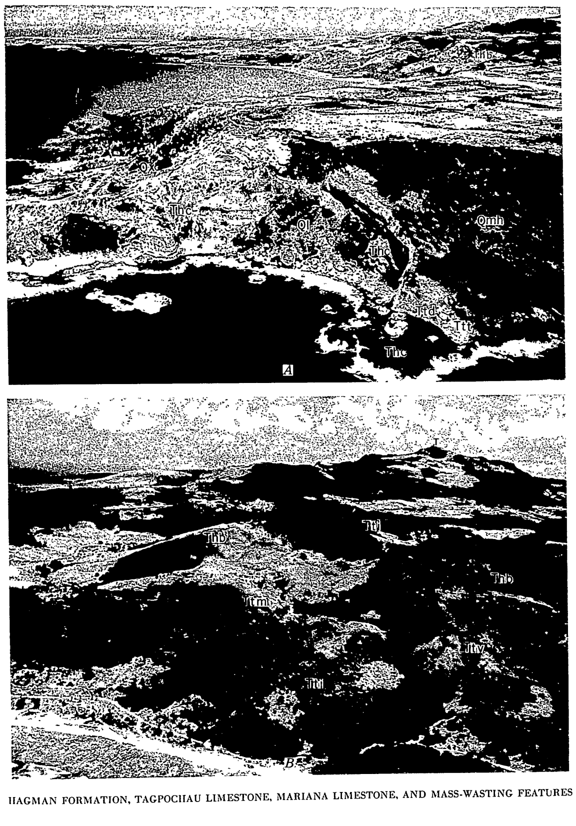
B. View east across the offshore reef and shallow lagoon that front the low western coastal plain in the vicinity of Susupe point. Lake Susupe and marshland in right middle ground. The northern, limestone part of the Fina-sisu hills (F) lies beyond the Agingan fault (f) immediately east of Lake Susupe with the Dago depression (d) and Dandan spur (D) beyond. The southern and southwestern spurs of Mount Tagpochau rise to the left, and the Hagman peninsula and upfaulted cliffs (H) are in the center distance beyond Laulau bay.

PLATE 21

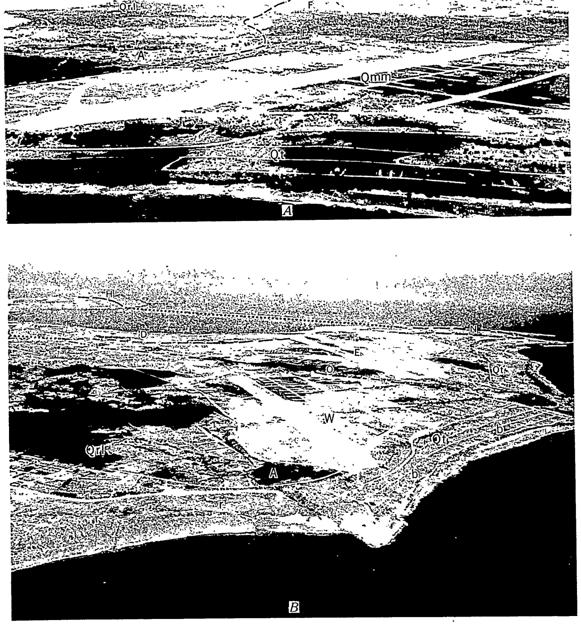
[Photographs by U. S. Navy Squadron VU-7 (B), June 1949]

A. View west across Hagman peninsula, Laulau bay, and south Saipan, showing conglomerate-sandstone facies of Hagman formation (Thc) in bluffs above Hagman beach and in sea-level bench at lower right. Above these rocks are the transitional facies (Ttt) and Donni sandstone member (Ttd) of the Tagpochau limestone to the conspicuous dip slope on the right. Pits on lower right slope are in Donni outcrop above transitional facies of Tagpochau and below *Halimeda*-rich facies of Mariana limestone (Qmh) in area of slow creep. Landslide at center (Ql) and creep debris at left (Qx) and right (Qmh). Breccia-tuff facies of Hagman formation (Thb) in distant Laulau volcanic area.

B. View northwest over the Laulau volcanic area toward Mount Tagpochau (T). Breccia-tuff facies of Hagman formation (Thb) in center and right middle ground overlapped by tuffaceous (Ttv), marly (Ttm), and inequigranular (Tti) facies of Tagpochau limestone. Laulau beach and fringing reef at lower left.



HAGMAN FORMATION, TAGPOCHAU LIMESTONE, MARIANA LIMESTONE, AND MASS-WASTING FEATURES



FAULT-CONTROLLED TOPOGRAPHY AND ELEVATED MARINE SURFACES OF SOUTH SAIPAN

PLATE 22

[Photographs by U. S. Navy Squadron VU-7 (C), June 1949]

A. View north over 120-foot (100–160 feet altitude) Mariana platform (Qmm) and western coastal plain of recent limesands (Qrl) toward Mount Tagpochau on skyline. Bench under western coastal plain has dropped to its present position by recurrent movement along Agingan (A) and other faults. Tanapag limestone (Qt) veneers surface of 12- to 60-foot coastal bench. Fina-sisu hills (F) separate northern part of western platform segment from coastal plain.

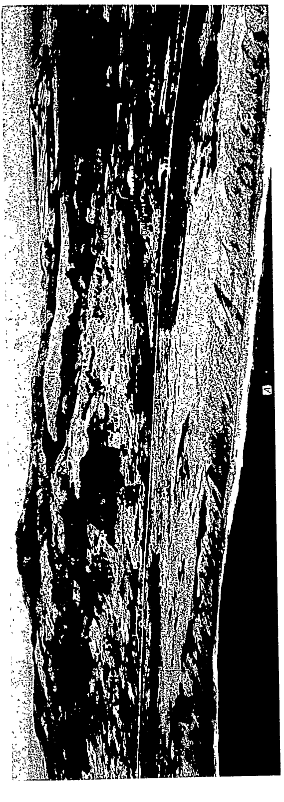
B. View east over faulted 120±-foot western (W) and 200±-foot eastern (E) segments of southern Mariana limestone platform. Low south coast bench is floored by Tanapag limestone (Qt), with fringing reef seaward and Agingan beaches (b) at lower right. Western coastal plain limesands (Qrl) and broad fringing reef (r) are at lower left. Movement along Obyan (O), Dago (D), and Agingan (A) faults is downward to the west. Naftan (N) and Hagman (H) fault ridges in distance are mainly upthrown east of the Laulau bay fault.

PLATE 23

[Photographs by U. S. Navy, February 1944]

A. View east across offshore reef (r) and very shallow Garapan lagoon to Mount Tagpochau and adjacent Tagpochau limestone terrain. Hagman peninsula and cliffs (H) in right distance. Local high clay content of undifferentiated Tagpochau limestone (Tt) gives rise to poorly drained acidic soil and swordgrass-covered spur. Marly facies of Tagpochau (Ttm) produces rolling terrain covered with swordgrass and brush. Inequigranular limestone facies (Tti) presents jungle-covered scarps. Wide fan of clay wash (Qc) spreads out from between southwestern spurs of Mount Tagpochau and mingles with coastal plain limesands (Qrl) toward the beach (b). Dark matter in inner half of lagoon is mainly green algae, eelgrass, and local patches of casuarina cones; that on and along reef flat is mainly coral-algal rubble and coralline algae.

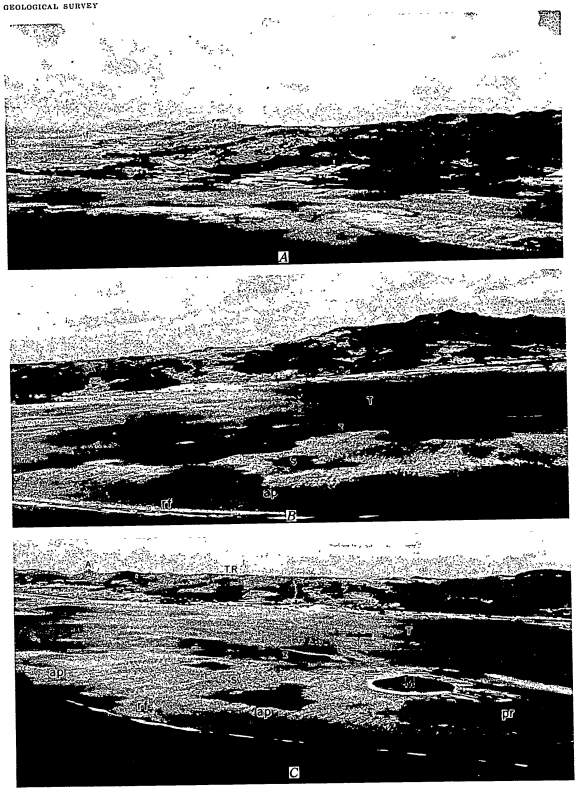
B. View east over very shallow Garapan lagoon and former city of Garapan to the terraced western slope of the Tagpochau highlands. Uneven definition of terraces and location of some deep ravines is related to mixing of marly (Ttm), tuffaceous (Ttv), and weakly indurated equigranular facies (Tte), with dominating inequigranular facies (Tti) of Tagpochau limestone. Some patches of the tuffaceous facies (Ttv) are so impure that leaching of them produces swordgrass-covered clay slopes over a weathering product that resembles a pyroclastic rock. Point Muchot (M) appears to be the product of longshore drift of coastal plain limesands (Qrl) mainly from the south. The formerly marshy area behind it (p) was once a brackish pond closed off by growth of the spit. Dark appearance of very shallow lagoon bottom is caused by luxuriant growth of green alga *Halimeda* and some eelgrass locally.



A

B

GEOMORPHIC FEATURES OF SOUTHWESTERN SAIPAN



GENERAL STRUCTURE OF THE WESTERN SLOPE, REEF, AND LAGOON, NORTHWARD FROM MOUNT TAGPOCHAU

PLATE 24

[Photographs by U. S. Navy Squadron VU-7 (B), June 1949]

A. View northeast along axial ridge from northern slopes of Mount Tagpochau, at right, northward along central volcanic ridge to Matuis highlands in distance. The northward narrowing and pinchout of both western coastal plain and lagoon is well shown. The barrier reef (b) that lies 2 miles offshore and encloses a lagoon 2 to 8 fathoms deep at the center of the island grades northward to a shoreline fringing reef (f) that is nowhere as much as a fathom deep at low tide.

B. View south across barrier reef and Tanapag lagoon in foreground to Mount Tagpochau on right skyline showing the principal levels of the terraced western slope of Mount Tagpochau and linear zones of reef and immediately back-reef lagoon. Inward from the outer reef flat (rf), is a zone of small bosses and mounds of palmate *Acropora* and *Porites* (ap), then a shallow limesand area with scattered staghorn types of coral (s), and finally a zone of luxuriant growth of the eelgrass *Zostera*. Beyond are the deeper (but still shallow) waters of Tanapag lagoon (T).

C. View southeast across the western barrier reef and Mañagaha islet (M) to level summit area of mainly andesitic Talofofo ridge (TR) and dacitic Mount Achugau (A). Reef zones are as in photograph *B*, but in addition a marked development of small reef patches (pr) rises from the clean limesand bottom around Mañagaha islet.

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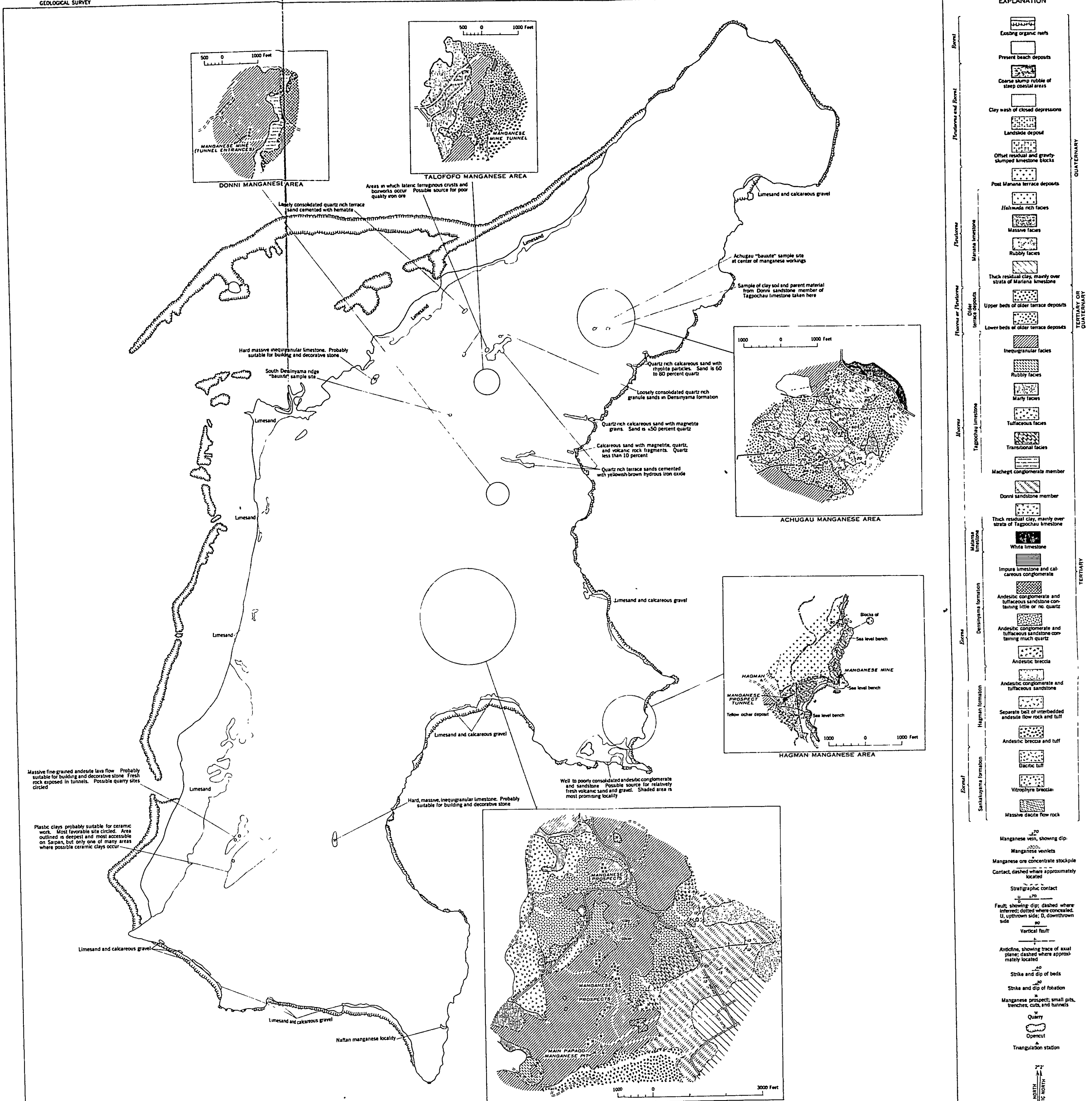
PROFESSIONAL PAPER 280 PLATE 25



Prepared by R. G. Schmidt and P. E. Cloud, Jr., in part utilizing data provided by H. W. Burke

MAP OF THE ECONOMIC GEOLOGY OF SAIPAN, MARIANA ISLANDS

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UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROFESSIONAL PAPER 280 CHART 1

Age	Unit		Distinctive features	Areal distribution and approximate acreage	Thickness (feet)		Weathering characteristics	Terrain and vegetation	Conspicuous fossils	Inferred origin
					Total range	Common range or average				
QUATERNARY RECENT	Present reef and beach deposits		Fringing and barrier reefs, terraced ramps, and pedestals. Beach sand and gravel (mostly calcium carbonate), beach rock, and minor slightly emerged reef limestone.	Shoreline and offshore	A veneer					
	Gravel and sand on emerged fringing reef surfaces.		Poorly sorted gravel and sand, consisting of organically derived calcareous fragments	Linear patches parallel to and just inshore from east and north coasts. 67 acres.	A veneer			Linear shallow trenches parallel to and bordering coast. Ordinarily supports thick growths of low, tangled brush.	Recent types of Foraminifera, corals, and mollusks.	Largely(?) debris washed up by great storms. May in part include primary moat deposits.
	Marsh deposits		Soft sticky blue-gray to grayish-brown muck in and around several permanent ponds and sloughs	Depressions in west Saipan, south from Matansa. Largest area surrounds Lake Susupe. 600 acres.	A veneer			Marshland. Vines, ferns, and thickly tangled, tall, tough grasses. About 11 acres of mangrove near Tanapag.		
	Recently emerged limesands		Loose unbonded limesands, coarse and gravelly at places; contains numerous mollusk shells and Foraminifera.	Strip along west coast, south from northern Matansa, widening toward south and interrupted by areas of fill 1,650 acres, half filled over.	0-30 ?	8-12	Not noticeably affected by weathering	Gently sloping to flat coastal plain area. Supports low leguminous brushes, tangled grasses, scattered trees.	Recent marine shells and pottery shards to 6-ft depth locally	Complex shoreline and nearshore processes
PLEISTOCENE AND RECENT	Alluvium and clay wash		Includes the primarily clay deposits of closed or nearly closed depressions and the linear clay and gravel or clay deposits of out-draining valleys.	Localized in depressions and valleys in many parts of island. 900 acres.	0-30 ?	5±	Locally gullied by rill wash at margins of larger deposits.	Occurs in broad or narrowly linear depressions. Commonly cultivated, or with vegetation of grasses or vines.		
	Deposits formed by mass wasting		Chaotically mixed blocks of limestone naturally transported to or nearly residual on present sites	Two small patches at bluff top and on hillslope above Hagman beach. Coarse slump rubble of steep coasts. 11 acres.	- - -	- - -				Landslide, creep, and slump
	Younger terrace deposits		Mostly gravels and gravelly and sandy clays of reworked volcanic materials. Locally includes ferruginous quartz sands, and grades laterally into material mapped as clay wash.	Strip along and a little inshore from north part of west coast. Mostly from 20 to 80 feet above sea level. 420± acres.	0-20 ?	8±	Nonsiliceous components are largely weathered to clay minerals and the deposit is mainly a gravelly clay.	A gently rolling surface incised by small intermittent washes and gullies. Cultivated, or with abandoned cane, grasses, or brush		Fluviatile outwash deposits from contiguous sources to the east.
PLEISTOCENE	Tanapag limestone		Coral and algal-rich emerged reef limestone, highly porous and open in texture. Shell material of mollusks and coral skeletons generally well preserved, serving to distinguish from Mariana limestone	Generally linear patches, parallel to and mostly adjacent to coast, and extending from sea level to 100 ft above. 1,050 acres.	< 50	10-20?	Natural weathered surface very rough, with many pinnacles and irregular ridges of 1 to 6 ft amplitude.	Mantles lowest raised marine bench or occurs as isolated patches. Surface mostly rough, with little soil, bare or with low brush.	Mostly living species. Carbon-14 determinations and position indicate late Pleistocene age.	An emerged tropical fringing reef only slightly modified by chemical erosion
	Post-Mariana terrace deposits		Iron stained, locally quartz-rich, clay sands and minor gravels of volcanic source materials, at elevations between 100 and 500 ft.	Scattered irregular occurrences on seaward slopes of east-central Saipan and north shore of Laulau bay. 136 acres.	0-10	3-4	Some alteration to thin clay soil	Mostly gently sloping surfaces planted to sugarcane; small patches north of Laulau bay are steep, gullied, and swordgrass covered.		Fluviatile outwash deposits on marine benches
	MARIANA LIMESTONE	Summary of formation	Generally coarsely porous, nonbedded to indistinctly bedded, dirty white to brownish, bioclastic to constructional limestones. Mollusk shells are ordinarily dissolved away and coral skeletons noticeably altered. Corals more abundant than in older rocks, and fossils of different sorts.	Along south, east, north and northwest coasts, with largest areas of outcrop in south, in east peninsula, and in north. Small outcrops elsewhere below altitudes of 500 ft. 7,430 acres.	0-500±	400±	Mantled by generally thin clay soil through which project irregular residual rock pinnacles as high as 6 ft. Rock is porous; caves and crevasses are common.	Wave-cut scarp and bench topography; mostly planted to cane, with small trees along property lines. Jungle on and near scarps and locally on beaches.	Foraminifera, corals, mollusks, echinoids, and algae mostly of living species.	Bank, lagoonal, and reef-complex limestones formed in shallow tropical waters
		Halimeda-rich facies	Bioclastic limestone distinctive in its rich concentration of the calcified, small, fan-shaped joints of the green alga *Halimeda*.	Southeast peninsula (I Naftan) and northeast part of east peninsula (Chacha). 1,130 acres.	0-400 ?	?	Mantled by thin, brownish to black, somewhat powdery, clay soil through which project limestone pinnacles.	Wave-cut scarp and bench topography. Vegetation of low thick brush, sparse swordgrass, cane, or jungle growth.	As above	Concentrations of light-weight but large-grained calcareous debris, grading shoreward to varied bioclastic and constructional deposits.
		Massive facies	Generally massive to obscurely bedded, dirty white to brownish; coarsely porous to cavernous, well indurated, bioclastic to constructional limestone, with coral and algal remains common and at places abundant. A pink subfacies occurs locally.	Essentially as Mariana limestone in general, includes considerably more than one-half of total outcrop of Mariana limestone. 4,480 acres.	0-300±	200-300?	Same as second box above	Same as second box above	Same as second box above	Bank, lagoonal, and reef-complex deposits. Probably similar to bulk of deposits presently forming west of Saipan
		Acropora-rich facies	Rich in broken fragments of the staghorn coral *Acropora*, mostly clay bonded, but in part fairly pure calcium carbonate with occasional *Acropora* colonies in position of growth.	A narrow northeast to southwest belt near central part of south Saipan, and small occurrences nearby. 200 acres	0-100	50?	Leaching of calcareous material leaves a thick, yellowish to red-brown, mottled clay cover.	Gently sloping to flat. Mostly cultivated, but partly in old cane, tangled grass, or leguminous brush	Staghorn *Acropora* the dominant fossil. Associated rocks indicate post-Miocene age.	Mainly locally derived though fragmentary staghorn coral mixed with clay from adjacent gently sloping volcanic shores
		Rubbly facies	Conspicuously and coarsely fragmental limestones, generally rich in broken and randomly oriented coral and algal fragments, poorly indurated and with a generally large amount of clay contamination.	Outcrops as a broad belt along east coast from southern Kalabera at north to Chacha at south. 1,300 acres.	0-400	200-300?	Where terrace deposits absent, it is generally weathered to brownish clay soils 1-5 ft thick, around scattered limestone pinnacles.	Gently rolling cane-covered benches, with rare tree-clusters, cut by shallow valleys and narrow ravines with jungle vegetation.	Foraminifera, corals, mollusks, echinoids, and algae mostly of living species.	Displaced coral and calcareous sediments, mixed with clay from adjacent volcanic terrain along a relatively steep coast
		Clays over rubbly facies	Yellowish to brown and gray, mottled, kaolinitic clay	Western margin of eastern peninsula (Chacha). 320 acres.	0-40	5-10	The unit is the product of weathering	Flat or very gently sloping clay-covered surfaces, with rows of small trees growing along property lines.		Product of weathering of rubbly facies of Mariana limestone.
TERTIARY PLIOCENE	Older terrace deposits		Generally quartz-rich, iron-stained, clay sands and minor gravels of volcanic source materials, occurring in two sets between altitudes of 500 and 710 feet.	A few small patches in central and north-central Saipan to southern slope of Mt Achugau. 21 acres.	0-10	3-5	Locally yields thin clay soil which, with washing out of finer sediments, leaves surface film of quartz and magnetite.	Gently sloping to level surfaces, with growth of swordgrass or scrubby leguminous trees.		Fluviatile outwash deposits on marine benches
MIOCENE	TAGPOCHAU LIMESTONE	Summary of formation	Mainly a complex of varied calcareous facies that intergrade with one another and are distinguished from other limestones on Saipan by their contained fossils. Commonest and most distinctive facies is pure inequigranular limestone. Also includes impure limestone, as well as sandstone and conglomerate of volcanic source materials.	Widespread. Underlies nearly half of Saipan, and forms most of axial ridge. 13,170 acres.	0-1,000?	300-600?	Solution produces clay soils around residual limestone pinnacles, gradational contacts where impure. Caves, crevasses, and sinkholes abundant.	Characterized by scarp and bench topography with general north-northeast orientation. Scarps as high as 600 ft. Benches with irregular surfaces. Dense jungle when not cleared for cane.	Foraminifera, corals, echinoids, mollusks, decapods, and algae of early Miocene (Tertiary *e*) age.	Clastic deposits of shallow to moderately deep, tropical, marine waters.
		Tagpochau limestone undifferentiated.	Mostly somewhat impure limestones not conveniently placed in any named facies of Tagpochau limestone because of intermediate or mixed nature.	Mainly in south-central Saipan in large, irregular patches extending south from Mt. Tagpochau. 600 acres.	0-500?	200-300?	Mostly weathers to clay soil with outcropping ledges but few or no residual pinnacles	Whaleback ridges and steep slopes interrupted by abrupt scarplets. Vegetation thick swordgrass, with local scrub trees and patches of jungle vegetation.	Essentially as above	Accumulated in marine waters of shallow to moderate depth within reach of clay contamination from land.
		Inequigranular facies	Generally massive to obscurely bedded, pure, compact and well-indurated, pink to white, inequigranular limestone.	Widespread, especially in and adjacent to Mt. Tagpochau and axial ridge north of Mt. Achugau. 9,720 acres.	0-900±	200-500?	Weathers to red clay soil, around many smooth-surfaced residual pinnacles. Underground are caves, sinkholes, and crevasses.	Steep to vertical jungle-covered scarps separated by gently sloping benches, with cane and woodlots. Minor brush and swordgrass locally.	Same as above.	Accumulation of mainly bioclastic calcareous sediments on open sea banks (or in lagoons?) of moderate to shallow depth.
		Equigranular facies	Well-bedded to massive, well-indurated to moderately indurated, mostly rather pure, generally white, fine- to coarse-grained but dominantly equigranular limestone.	West-central and northern Saipan. Especially in lowest terrace east from Muchot point, in As Matuis; and Fanunchuluyan bay. 770 acres.	0-220±	100-200?	Generally as above, except residual pinnacles sparse in outcrop area of west-central Saipan	As above, except area east from Muchot point is low, and tends to overgrowth of vines, grasses, and brush.	Same as above	Same as above
		Rubbly facies	Unevenly indurated, fairly pure, generally white limestone that characteristically consists of aggregated angular fragments without obvious bedding. At places thinly bedded and locally with argillaceous impurities.	Mainly in eastern and southern part of east-central Saipan in north-south belt along base of Tagpochau and I Agag cliffs 350 acres.	0-120±	100±	Weathers to clayey soil in sharp contact with underlying limestone.	Cliff bases and valley floors have 10°-20° slope angles. Vegetation is old cane, a few trees, and minor jungle growth.	Same as above	Intermediate between above and below
		Marly facies	Well-bedded, thinly to thickly bedded, marly limestone of generally yellowish color and moderate degree of induration.	Mostly in central Saipan, in irregular patches submarginal to mass of inequigranular facies. 1,280 acres.	0-500±	100-150?	Weathers to alkaline clayey soil around scattered residual limestone pinnacles. Transition generally sharp.	Slopes as much as 20°, with occasional projecting ledges and subdued scarplets. Vegetation is swordgrass, with scattered brush, jungle growth, and cane.	Larger Foraminifera, mollusks, echinoids, and algae of early Miocene age.	Accumulated in marine waters of shallow to moderate depth within reach of clay contamination from land.
		Tuffaceous facies	Poorly indurated, mostly thin-bedded, somber colored, calcareous rocks that include varying and generally large proportions of reworked andesitic materials.	Mainly in west and south-central Saipan, west, south, and southeast of Mt. Talofofo. Few small patches in north. 390 acres.	0-170±	100-150?	Dependent on proportion of andesitic contaminants. More impure phases form clay soil over rotted rock. Deep and extensive residual clays described below	Moderate slopes that locally pitch into sharp valleys or border low scarps of purer limestones. Vegetation varied.	Foraminifera, staghorn coral (*Acropora*), occasional mollusks, and echinoid fragments of early Miocene age.	Accumulated in tropical marine waters of shallow to moderate depths adjacent to residual volcanic highs.
		Clays over tuffaceous and marly facies.	Mottled and banded reddish-brown, yellowish-brown, red, gray, and white clays, plastic when wet. Banding subparallel; at all attitudes between horizontal and vertical.	Central and southern part of east-central Saipan, southern end of Mt. Talofofo and lower east slopes of Mt. Tagpochau. 130 acres.	0-30?	10-20?	The unit is the product of weathering	Gently sloping to nearly flat, with tangled grasses and occasional copses of small leguminous trees.		Product of weathering of tuffaceous and, in part, of marly facies of Tagpochau limestone.
		Transitional facies	Calcareous tuffaceous sandstone, marl, and calcareous andesitic conglomerate, at places with larger Foraminifera comprising a large volume of the rock.	Mainly linear outcrops in east, just east of Machegit and Adelug cliffs, and at Hagman and I Naftan. 90 acres.	0-40+	40?	Produces thin clay soil	Gentle slopes or parts of cliff faces; supports jungle, swordgrass, and sugarcane.	Foraminifera, corals, echinoids, and algae of early Miocene age.	Clastic marine deposits, gradational between relatively pure and relatively impure calcareous facies or to volcanic rocks.
		Machegit conglomerate member	Andesitic conglomerate, with same quartz-rich rocks. Resembles conglomerates of Densinyama formation, but associated with and overlying beds rich in lower Miocene Foraminifera.	East-central Saipan, narrow band at base of (east of) Machegit cliff. 40 acres.	0-40	20-40	Forms clay soils with rock-weathering effects extending downward tens of feet. Relict textures preserved in boulders.	Low and discontinuous, sloping terrace, with cane, tangled grasses, and low brush.	No fossils found, but larger Foraminifera of associated rocks are Miocene.	Reworked conglomerates of the Densinyama formation
		Donni sandstone member	Tuffaceous and calcareous and well-bedded and generally thinly bedded, poorly indurated sandstones, rich in smaller Foraminifera.	Outcrop belt on east slope of Saipan from Achugau at north to Laulau at south. Also at Fanunchuluyan, Hagman, I Naftan, and elsewhere. 800 acres.	0-200	100+	Weathers to expanding (bentonitic?) clays that yield only a thin soil layer and are easily removed by rill wash.	Intricate pattern of narrow ravines separated by short, rounded spurs. Swordgrass is typical cover, but jungle, Formosan koa, and cane grow locally	*Globigerina*, *Orbulina*, and many other smaller Foraminifera. Early Miocene age indicated by rare larger Foraminifera and stratigraphic associations	Moderately deep marine environment adjacent to source area of reworked volcanic sediments.
OLIGOCENE	FINA-SISU FORMATION	Summary of formation	Well-stratified, andesitic marine tuffs and interlayered andesitic flows that are mostly less than 10 to 20 ft thick but range to 80 to 100 feet thick.	South Saipan in Fina-sisu and As Lito districts. 500 including tuffs and all flows	0-400+ (inclusive)	?	Deeply weathered, clay soils as deep as 20 feet; few natural outcrops.	Area of outcrop gently rolling and mostly cultivated, but locally with tangled grasses and copses of Formosan koa	Smaller Foraminifera of the late Oligocene (Tertiary *d*?) *Globigerinatella insueta* zone. Rare discoasters and Radiolaria.	Marine tuffs and interbedded lava flows, probably deposited in moderately deep tropical waters.
		Thicker flow rocks	Greenish-gray, vesicular, aphanitic to finely porphyritic, augite andesite. Locally with columnar jointing.	South end of Fina-sisu ridge and in northwestern As Lito. 70 acres.	80-100?	90	Clay at surface, grading down to rotten rock. Joint blocks weather spheroidally.	Eastern dip slopes gentle, with thick clay soil and tangled grasses. Faceted wooded spurs and short valleys face up dip along west margin.	Smaller Foraminifera of associated tuffs are of late Oligocene age.	Presumably submarine lava flows
EOCENE	MATANSA LIMESTONE	Summary of formation	Pure to impure, inequigranular, white to pink or dark-red clastic limestone containing a distinctive upper Eocene foraminiferal assemblage.	North-central Saipan, patches between Fanunchuluyan and Talofofo. 310 acres.	0-500+	200-500?	Mostly similar to inequigranular facies of Tagpochau limestone. See above.	Mostly similar to inequigranular facies of Tagpochau limestone. See above.	Larger Foraminifera of late Eocene (Tertiary *b* age). Also calcareous algae and rare corals	Clastic bank deposits of tropical marine waters of shallow to moderate depth.
		White facies	White to locally pinkish white, sparingly foraminiferal, inequigranular, generally pure, clastic limestones.	North-central Saipan, mostly on east slopes, patches between Fanunchuluyan and Talofofo. 195 acres.	0-300+	300?	Same as above	Same as above	Same as above	Same as above
		Pink facies	Pink to dull-red, richly foraminiferal, inequigranular, slightly to moderately impure, clastic limestone.	North-central Saipan, on both east and west slopes adjacent to Mt Achugau. 85 acres.	0-150	100?	Weathers to red clay soil on rough limestone surface.	Jungle-covered scarps and sloping benches covered with cane, brush, some jungle growth and patches of swordgrass.	Same as above	Same as above
		Transitional facies	Dull-white, tan or reddish-brown, tuffaceous to marly limestone and conglomerate, with locally abundant larger Foraminifera. Overlies or grades laterally to upper beds of the Densinyama formation and resembles limestone-conglomerate facies of Densinyama.	North-central Saipan, along and near Talofofo Road, on both east and west slopes of Talofofo ridge. 30 acres.	0-140+	100?	Weathers to a thin, stony, red, neutral to slightly acid soil.	Steep slopes cut by short, narrow, steep-walled ravines. Swordgrass abundant, and casuarina forms thick stands locally	Same as above	Same as above, but nearer to source of contamination with reworked volcanic debris.
	DENSINYAMA FORMATION	Summary of formation	Volcanic breccia, tuffaceous sandstone, calcareous sandstone, tuffaceous limestone, and conglomerate. Rock types in fragments varied; with andesite the most abundant and quartz or quartzose rocks the most distinctive.	North-central Saipan and extending south through east-central Saipan in generally linear belt 1,200 acres.	0-800±	200-600?	Forms clay soils, with rock-weathering effects extending downward tens of feet. Relict textures preserved in boulders.	Rough and cut by closely spaced, steep-walled ravines at north. Less dissected to south. Swordgrass abundant, casuarina common on ridge crests.	Foraminifera of late Eocene (Tertiary *b*) age. Also echinoid spines and coral and algal fragments.	Mainly by reworking of preexisting volcanic and penecontemporaneous calcareous source materials in and adjacent to a tropical sea.
		Limestone-conglomerate facies	Impure limestone and calcareous conglomerate, with abundant reworked volcanic constituents and larger Foraminifera. Very similar to parts of transitional facies of Matansa limestone, but associated with rocks characteristic of Densinyama formation.	Central Saipan, on east and west slopes of Mt. Talofofo. 30 acres.	0-50±	10-20	Weathers to a thin, stony, red, neutral to slightly acid soil.	Spurs and gentle to steep slopes that break to ravine heads or low bluffs. Swordgrass thick, with copses of casuarina locally	Same as above.	Reworking of preexisting volcanic and penecontemporaneous calcareous source materials in a nearshore tropical environment.
		Conglomerate-sandstone facies	Intergrading, well-stratified beds of tuffaceous sandstone and volcanic conglomerate, with interstitial calcium carbonate and marine fossils locally. Predominantly andesitic and in part with abundant free-quartz,	Same as second box above. 955 acres.	0-500±	100?	Same as second box above	Same as second box above	A few upper Eocene Foraminifera locally	Formed by reworking of preexisting volcanic source materials in a nearshore but in part moderately deep marine environment.
		Breccia facies	Unsorted deposits of angular fragments of andesite and less abundant dacitic volcanic rocks and chert.	North-central Saipan, on east and west flanks of central and northern parts of Talofofo ridge. 215 acres.	0-250±	60-100?	Weathers to sticky clays on the surface of which are pebbles and cobbles of siliceous rock or spheroidally weathered andesite.	Intricately dissected, exposures common, swordgrass thrives where clay mantle present.	No fossils found, but Foraminifera from associated rocks are late Eocene.	Subaerial pyroclastic deposits
	HAGMAN FORMATION	Summary of formation	Andesitic rocks of both subaerial and marine detrital facies, as well as massive andesite flow rock. Essentially quartz-free throughout.	Mainly in east- and west-central Saipan, in As Akina and Talofofo. Also in southeast-central, south, and north-central parts. 800 acres.	0-1,100±	?	Forms thick clays at surface, grading downward to rotted rock with relict textures.	Intricately dissected, with dense swordgrass, occasional casuarina, and local Formosan koa copses. Relief subdued in south.	Foraminifera of late Eocene (Tertiary *b*) age; other fossils locally	Mafic pyroclastic rocks and lava, in part reworked in a moderately deep to shallow tropical marine environment.
		Conglomerate-sandstone facies	Well-stratified to poorly stratified conglomerates and sandstones, locally containing interstitial calcium carbonate and marine fossils.	East from mid-width of Saipan in central, southeast central, and south parts. Also in sea bluffs at Hagman and I Naftan. 270 acres.	0-400 +	?	Most outcrops in bluff faces; surface weathering yields acidic clay soils.	Precipitous swordgrass-covered slopes and bare cliffs at Hagman and I Naftan. Elsewhere not distinctive.	Foraminifera of late Eocene age. Also calcareous algae, discoasters, and Radiolaria.	Reworked pyroclastic deposits which came to rest nearshore in shallow to moderately deep marine water
		Breccia-tuff facies	Poorly consolidated, largely unstratified and andesitic breccias and tuffs that lack fossils and interstitial calcium carbonate.	Central and southeast Saipan. In south Talofofo, north As Akina and Mt. Laulau. 520 acres.	0-600+	?	Forms iron-stained clays with rock alteration extending tens of feet downward. Matrix more weathered than included fragments.	In general is intricately dissected, with swordgrass cover, scattered casuarina, and local copses of Formosan koa.	No fossils found, but Foraminifera from associated rocks are late Eocene.	Subaerial pyroclastic deposits
		Flow rock facies	Massive, gray to greenish-gray, coarsely porphyritic, augite-hypersthene andesite in tabular bodies that range from 30 to 80 ft. thick. Also olive-gray, finely porphyritic, vesicular, augite andesite.	Small patches in east- and west-central Saipan. 10 acres.	0-100	60-80?	Clay at surface grades down to rotten rock	Outcrop areas too small to develop distinctive characteristics.	Foraminifera from associated rocks are late Eocene.	Andesitic lava flows
EOCENE (?)	SANKAKUYAMA FORMATION	Summary of formation	Dacitic rocks, mainly breccias and massive flow rocks. Glassy, in part conspicuously laminated and locally vesicular	North-central Saipan, at Mt. Achugau and to about 1 mile east and south from it. 455 acres.	?-1,800+	?	Only locally altered to clay where vesicular or tuffaceous.	Steep, rough, and rocky, with swordgrass or xerophytic ferns, and local copses of casuarina.	No fossils. Inferred to be Tertiary because of abundance of tridymite and cristobalite in the rocks.	Mostly or wholly subaerial pyroclastic debris and lava flows.
		Mixed pyroclastic facies	Well-bedded silicic tuffs and breccias, commonly cross bedded, and with unusual "brick-work" sedimentary structure.	Islet of Maigo Fahang and sea cliffs at south Fanunchuluyan beach. 5 acres.	?-160+	?	Unweathered	Bare sea-facing bluffs and sea level bench, capped by resistant rocks.	Same as above	Water-laid(?) pyroclastic debris
		Tuff facies	Thinly bedded, glassy tuffs and lapilli tuffs comprised of angular particles of dacite vitrophyre, quartz, dacite and glass shards and small grains of quartz, oligoclase, and magnetite.	Minor occurrences in north-central Saipan, at upper Nanasu and north Fahang ravines, and at Mt. Achugau. 10 acres.	?-400+	?	Weathers at surface to 1 to 5 ft of acidic reddish-brown clay soil.	Gentle swordgrass-covered slopes breaking to 150-ft cliffs in upper Nanasu ravine.	Same as above	Subaerial volcanic ash and lapilli
		Breccia facies	Mostly banded and laminated, gray to white breccias and flow breccias of angular to subrounded fragments of dacite vitrophyre and perlite in a glassy tuffaceous matrix. Most of facies is vitrophyric, some is also perlitic.	Patches occur through outcrop area of formation in north-central Saipan. 240 acres.	?-400+	?	Locally altered to clay where vesicular or tuffaceous. Mainly of fresh appearance.	Steep to gentle, rocky slopes cut by steep-walled ravines. Supports swordgrass, xerophytic ferns, and local casuarina.	Same as above	Subaerial pyroclastic debris and autoclastic flow breccias.
		Flow rock facies	Tabular or lens-shaped bodies of massive, glassy quartz dacite of chocolate, reddish, or pinkish color. Observed areal dimensions of individual bodies not exceeding ¼ mile.	Patches occur through outcrop area of formation in north-central Saipan. 200 acres.	0-500? (individual flows to 60 ft.)	?	Essentially unweathered except for partial devitrification of dacite glass.	Generally caps prominent rocky ridges and hills. Vegetation sparse swordgrass or xerophytic fern.	Same as above	Viscous lava flows and domal protrusions

SUMMARY OF GEOLOGIC UNITS OF SAIPAN

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UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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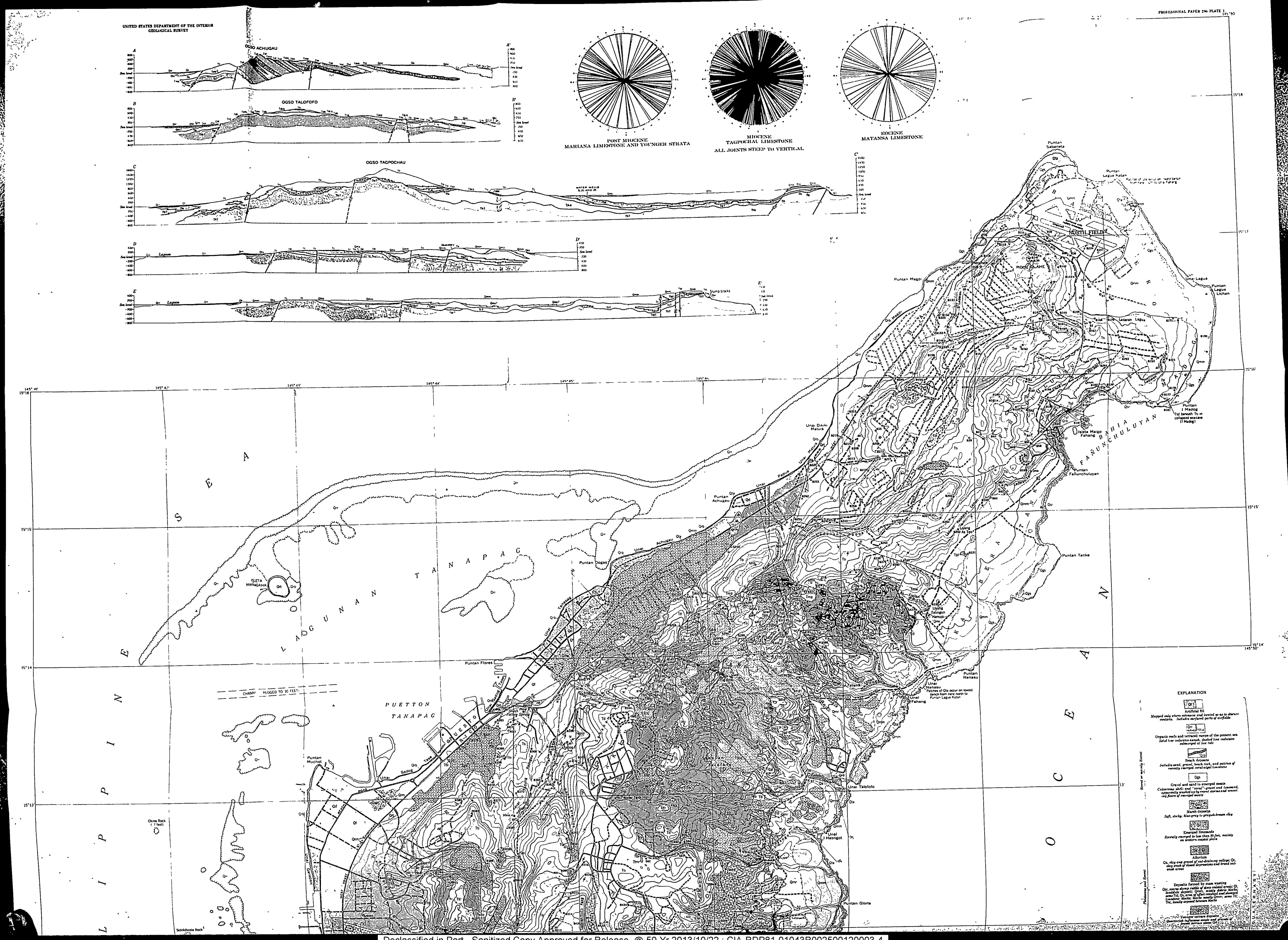
S A I P A N		INDONESIAN FAUNAL ZONATION (van Bemmelen, 1949, p. 79-103, 108)			EUROPEAN EQUIVALANTS AS PUBLISHED							PROBABLE SERIES AND ZONE EQUIVALENTS (this report)		TENTATIVE EUROPEAN STAGE EQUIVALENTS (this report)	
Nature of rocks and sediments	Formation or unit	Mammals (after von Koenigswald)	Mollusks (after Martin and Oostingh)	Foraminifera (after van der Vlerk, Umbgrove, and others)	Umbgrove 1931, p. 73	Glaessner 1943		van der Vlerk 1948	van Bemmelen 1949, p. 108						
Limesand, alluvium, etc.	Post-Tanapag sediments	Recent Sampong fauna			RECENT			RECENT and uppermost part of CENOZOIC	HOLOCENE		QUATERNARY	post h	QUATERNARY	RECENT	
Coral-algal reef limestone	Tanapag limestone, less than 50 feet	Ngandong fauna			PLEISTOCENE				PLEISTOCENE					PLEISTOCENE	
Reworked volcanic sediments on terrace surfaces	Post-Mariana terrace deposits	Trinil fauna													
Clastic and coral-algal limestone	Mariana limestone, 500± feet maximum above sea level	Djetis fauna	Bantamian												
Reworked volcanic sediments on highest terrace surfaces	Older terrace deposits(?) (a veneer)	Kali-Glagah fauna	Sondian	h	PLIOCENE				Astian	PLIOCENE	NEOGENE	h	UPPER TERTIARY	PLIOCENE	Sicilian Astian Plaisancian
		Tji-Djulang fauna	Cheribonian ?						Plaisancian						
									Pontian						
?	?	MIOCENE MAMMAL ZONES OF JAPAN (Takai, 1939)	Tjiodengian (restricted)	g	MIOCENE	Pontian Sarmatian	MIOCENE		Sarmatian	MIOCENE		g		MIOCENE	Pontian Sarmatian
		Togarian	Preangerian (Njalindung and Tjilanang)	f_3		Tortonian Helvetian		CENOZOIC	Vindobonian			upper f			Tortonian Helvetian
			Rembangian (Glaessner 1943, restricts to f $_{1-2}$)	f_2		Burdigalian						lower f			Burdigalian
		Hiramakian		f_1					Burdigalian						
				e_5		Aquitanian						upper e			? Aquitanian
Clastic orbitoidal limestones in six facies, and Machegit conglomerate and Donni sandstone members	Tagpochau limestone, 1000 feet maximum above sea level			e_4					Aquitanian						
				e_3		Chattian	OLIGOCENE			OLIGOCENE		lower e			
				e_2											
				e_1											
?	?														
Interbedded andesitic flows and marine tuffs	Fina-sisu formation, more than 400 feet			d	OLIGOCENE	Rupelian			Stampian		PALEOGENE	? d	LOWER TERTIARY	OLIGOCENE	? Chattian Rupelian Tongrian
?	?			c		Lattorfian			Sannosian			c			
Clastic camerinid limestones Conglomerate, sandstone, breccia, tuff, and minor limestone Conglomerate, sandstone, tuff, breccia, and andesitic lava	Matansa limestone, 500± feet Densinyama formation, 800± feet Hagman formation, 1500± feet		Nanggulian	b	EOCENE	Wemmelian Ledian	EOCENE		Ludian Bartonian	EOCENE		b		? EOCENE	? Ludian Bartonian Auversian
Dacitic breccia, tuffs, and flows	? Sankakuyama formation, more than 1800 feet			a		Lutetian Ypresian			Lutetian Ypresian			a			Lutetian Cuisian Ypresian
? Paleocene not recognized. Here to be considered loosely as part of Eocene	?					Thanetian Montian	PALEOCENE		(Missing)			? a?		PALEOCENE	Thanetian Montian

STRATIGRAPHIC UNITS OF SAIPAN COMPARED WITH STANDARD FAUNAL AND STAGE ZONATION

373761 O - 56 (In pocket)

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROFESSIONAL PAPER 280 PLATE 1



EXPLANATION

Artificial fill
Mapped only where extensive and located so as to obscure contacts. Includes surfaced parts of airfields

Organic reefs and terraced ramps of the present sea
Solid line indicates awash, dashed line indicates submerged at low tide

Beach deposits
Includes sand, gravel, beach rock, and patches of recently emerged coral-algal limestone

Gravel and sand in emerged moats
Calcareous shell- and "coral"-gravel and limesand, apparently washed up by recent storms and veneering floors of emerged moats

Marsh deposits
Soft, sticky, blue-gray to grayish-brown clay

Emerged limesands
Recently emerged to less than 80 feet, mainly on western coastal plain

Alluvium
Qa, *clay and gravel of out-draining valleys;* Qc, *clay wash of closed depressions and broad outwash areas*

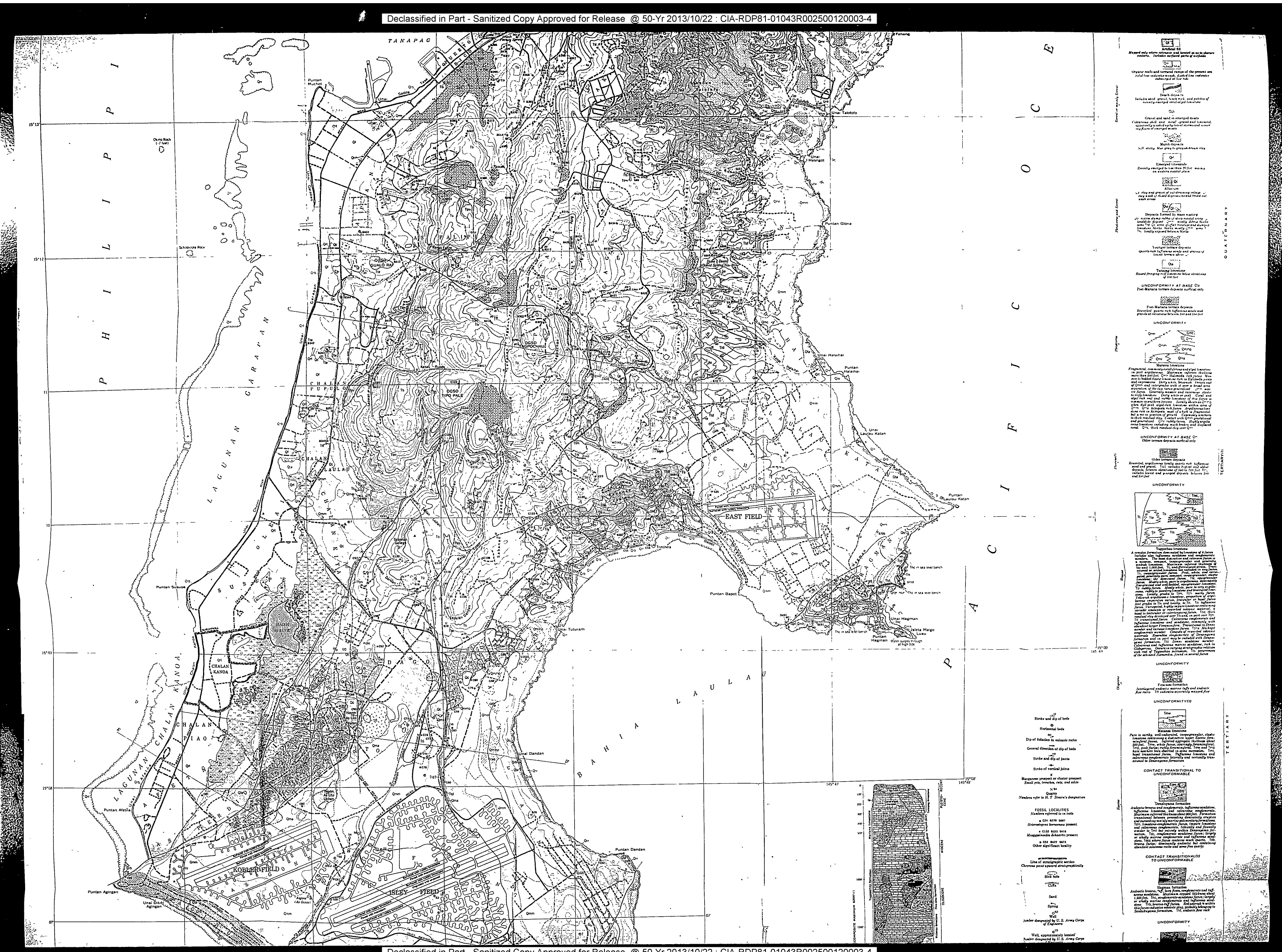
Deposits formed by mass wasting
Qsr, *coarse slump rubble of steep coastal areas;* Ql, *landslide deposit;* Qmm, *mostly debris blocks, some* Ttd, Qs, *area of effort residual and slumped limestone blocks; blocks mostly* Qmm; *some* Tt; Thc, *locally exposed between blocks*

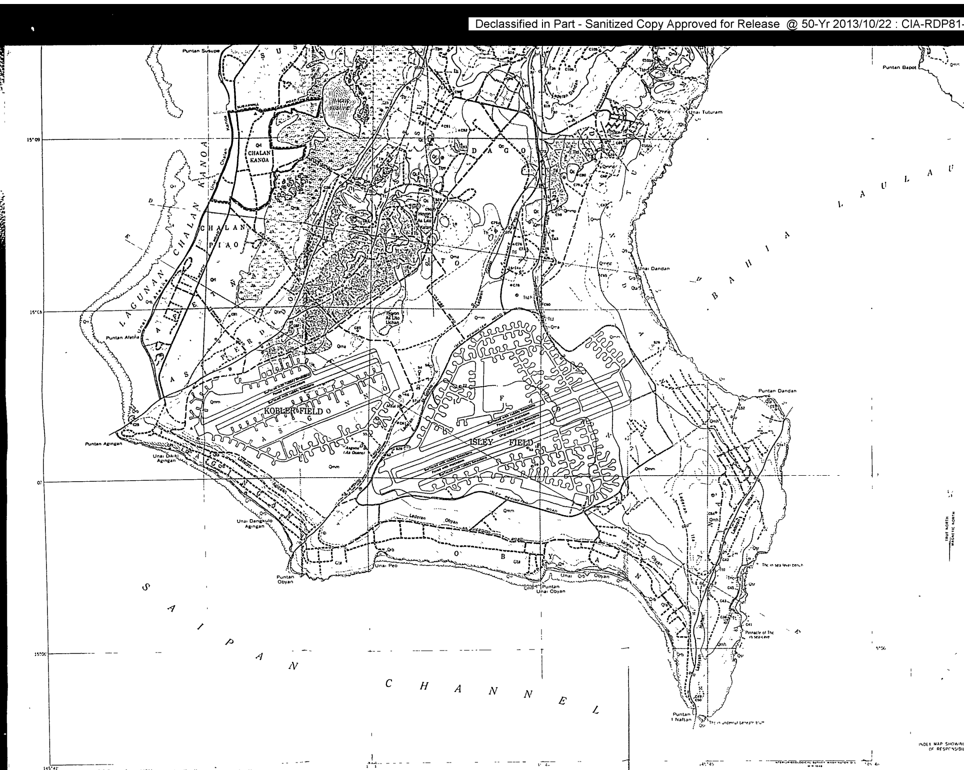
Younger terrace deposits
Quartz-rich tuffaceous sands and gravels of lowest terrace above Qrl

Recent or mainly Recent

Pleistocene and Recent

QUATERNARY


PHILIPPINE SEA
PACIFIC OCEAN
TANAPAG
LAGUNAN GARAPAN
BAHIA LAULAU
EAST FIELD
KOBLER FIELD
ISLEY FIELD
CHALAN KANOA
CHALAN PIAO
CHALAN LAULAU
Puntan Muchot
Puntan Susupe
Puntan Agingan
Puntan Afetna
Puntan Glone
Puntan Hatshar
Puntan Laulau Katan
Puntan Blaput
Puntan Dandan
Unai Talofofo
Unai Hasngot
Unai Laulau Katan
Unai Hagman
Unai Dandan
Unai Tututam
Isleta Maigo Luao
15°13'
15°12'
15°11'
15°10'
15°09'
15°08'
15°07'
Artificial fill
Organic reefs and terraced ramps of the present sea
Beach deposits
Gravel and sand in emerged moats
Marsh deposits
Emerged limesands
Alluvium
Deposits formed by mass wasting
Younger terrace deposits
Tanapag limestone
UNCONFORMITY AT BASE Qts
Post-Mariana terrace deposits
UNCONFORMITY
Mariana limestone
UNCONFORMITY AT BASE Qm
Older terrace deposits
UNCONFORMITY
Tagpochau limestone
UNCONFORMITY
Fina-sisu formation
UNCONFORMITY
Matansa limestone
CONTACT TRANSITIONAL TO UNCONFORMABLE
Densinyama formation
CONTACT TRANSITIONAL TO UNCONFORMABLE
Hagman formation
UNCONFORMITY
QUATERNARY
TERTIARY
Strike and dip of beds
Horizontal beds
Dip of foliation in volcanic rocks
General direction of dip of beds
Strike and dip of joints
Strike of vertical joints
Manganese prospect or shaler prospect
Quarry
FOSSIL LOCALITIES
Line of stratigraphic section
Sink hole
Cliffs
Sand
Spring
Well



Base adapted from U. S. S. Bowditch Survey of 1944. Hydrograph [illegible]. Additions and modifications to topography, drainage and culture by Pre[illegible] Schmidt and Harold W. Burke from aerial photography by U. S. A[illegible] names from Preliminary gazetteer of geograph[illegible] names [illegible] Saipan [illegible] Jr. Geological Surveys Branch, Office of the Engineer, Far East [illegible]

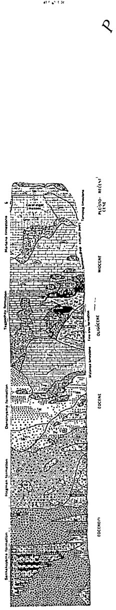
GEOLOGIC MAP AND SECTIONS OF SAIPAN, MARIANA ISLANDS

Scale 1:20,000

½ 0 ½ Mile

2000 0 2000 Feet

Contour interval 40 feet, except where dashed, 20 feet
Datum is mean sea level
Polyconic projection
Position of geographic grid approximate



INTERPRETIVE COLUMNAR SECTION

Heavy lines separate formations and major surficial units. Lines undulating where erosional and jagged where interfingering. Thickness approximate only along any given vertical line

Strike and dip of beds

Horizontal beds

Dip of foliation in volcanic rocks

General direction of dip of beds

Strike and dip of joints

Strike of vertical joints

Manganese prospect or cluster prospect
Small pits, trenches, cuts and adits

Quarry
Numbers refer to H. T. Stearn's designation

FOSSIL LOCALITIES
Numbers referred to in texts

● C24 B279 S687
Heterostegina borneensis present

▲ C132 B323 S416
Miogypsinoides dehaartii present

● C53 B422 S673
Other significant locality

Line of stratigraphic section
Chevrons point upward stratigraphically

Sink hole

Cliffs

Sand

Spring

Well
Number designated by U. S. Army Corps of Engineers

Well, approximately located
Number designated by U. S. Army Corps of Engineers

Maui well

Multiple lane, paved road

Double lane, all weather road

Single lane, all-weather road

Jeep track

Trail

Triangulation station

GLOSSARY

As	the place of
Bahia	bay
Bobo	spring
Dankulo	big
Dikiki	little
Hagoi	lake
Hoyon	large sink
I	the, that, this
Isleta	small island
Kanat	ravine
Katan	north
Laderan	cliff or cliffs
Lagunan	lagoon
Lichan	south
Liyang	cave
Ogso	mount, mountain, hill, ridge
Puetton	harbor
Puntan	point
Sabanan	grasslands (mostly swordgrass)
Sadog	fish water, or ravine in which fresh water occurs
Unai	beach

point, generally pure, compact, inequigranular, clastic limestone; the dominant facies. Tts equigranular facies. Mostly white, pure to argillaceous, dominantly fine-grained and well-bedded, equigranular limestone. Tts, rubbly facies. Mostly white, pure to very argillaceous, rubbly to powdery limestone and brecciated limestone. Locally grades to Ttm. Ttm, marly facies. Yellowish argillaceous limestone, proportion of argillaceous impurities varies, lenticular or basal facies that grades to Ttr and locally to Tt. Tt, tuffaceous facies. Variegated, highly impure limestone containing variable amounts of reworked volcanic material; a basal to lenticular or interfingering facies. Ttc thick residual clay developed over Tts and, in part, over Ttm. Tt transitional facies. Calcareous conglomerate and tuffaceous limestone and sandstone, commonly with abundant larger Foraminifera. Transitional to Donni member and various limestone facies. Tm Machegit conglomerate member. Consists of reworked volcanic materials. Resembles conglomerate of Densinyama formation and in part may be included with Densinyama formation. Td Donni sandstone member. Calcareous and tuffaceous marine sandstone rich in Globigerina. Occurs in varying stratigraphic relation with rest of Tagpochau succession. Tts occurrences of the echinoid Sismondia found in several facies

UNCONFORMITY

Fina-sisu formation
Interlayered andesitic marine tuffs and andesitic flow rocks. Tf indicates accurately mapped flow

UNCONFORMITY(?)

Matansa limestone
Pure to earthy, well indurated, inequigranular clastic limestone containing a distinctive upper Eocene foraminiferal fauna. Inferred aggregate thickness about 300 feet. Tma, white facies, sparingly foraminiferal. Tmp, pink facies, richly foraminiferal. Tma and Tmp have nowhere been observed in same succession. Tmt, basal transitional facies. Tuffaceous limestone and calcareous conglomerate laterally and vertically transitional to Densinyama formation

CONTACT TRANSITIONAL TO UNCONFORMABLE

Densinyama formation
Andesitic breccia and conglomerate, tuffaceous sandstone, tuffaceous limestone, and calcareous conglomerate. Maximum inferred thickness about 800 feet. Formation transitional between preceding dominantly eruptive and succeeding mainly marine sedimentary formations. Tcm, limestone-conglomerate facies, impure limestone and calcareous conglomerate, lithically and faunally similar to Tmt but entirely within Densinyama formation. Tcc, conglomerate sandstone facies, largely or wholly marine conglomerate and tuffaceous sandstone, Tccq where facies contains much quartz. Tcb breccia facies, dominantly andesitic but containing abundant siliceous rocks and some free quartz

CONTACT TRANSITIONAL(?) TO UNCONFORMABLE

Hagman formation
Andesitic breccia, tuff, lava flows, conglomerate and tuff arenaceous sandstone. Maximum exposed thickness about 1,500 feet. Thc, conglomerate-sandstone facies, largely or wholly marine conglomerate and tuffaceous sandstone. Thb breccia tuff facies. Red asterisk within this facies indicates volcanic plug, probably belonging to Sankakuyama formation. Tha andesite flow rock

UNCONFORMITY

Sankakuyama formation
Dacitic volcanic rocks, including flow rock, breccia, tuff and mixed pyroclastic rocks. Computed partial thickness 1,800 feet, true thickness may be much greater. Tsp mixed dacitic pyroclastic rocks. Tst dacitic tuff. Tsb vitrophyric and perlitic dacite breccia. Red asterisk indicates volcanic plug, of which two are known in areas of the Hagman breccia tuff facies. Tsf massive dacite flow rock

Oligocene

Eocene

Eocene(?)

TERTIARY

Normal stratigraphic contact
Approximately parallel to bedding of overlying deposits. Solid where demonstrable, dashed where inferred or approximately located

Interfingering or intergradational stratigraphic contact
Separates laterally intergrading or interfingering beds. Solid where demonstrable, dashed where inferred or approximately located. Intervals of even contact indicate approximate parallelism to bedding

Highly generalized stratigraphic contact
Roughly separating facies not mapped in detail, dotted where concealed

Trace of fault, showing dip
Solid where demonstrable, dashed where inferred or approximately located, dotted where concealed. U, upthrown side; D, downthrown side

Trace of vertical fault

Trace of anticlinal axis
Terminal arrow indicates direction of apparent plunge. Solid where demonstrable, dashed where inferred or approximately located, dotted where concealed

Geology by Preston E. Cloud, Jr., Robert George Schmidt and Harold W. Burke, 1948-1949
Paleontologic field control by W. Storrs Cole

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROFESSIONAL PAPER 280 PLATE 2

Trace of vertical fault

Trace of anticlinal axis
Showing trace of axial plane and bearing and plunge of axis. Solid where demonstrable, dashed where approximately located, dotted where concealed

Strike and dip of beds

Horizontal beds

General direction of dip

Strike and dip of banding in volcanic rocks

Strike and dip of joints

Strike of vertical joints

Line of stratigraphic section
V's point upward stratigraphically

Reef of coral and algae

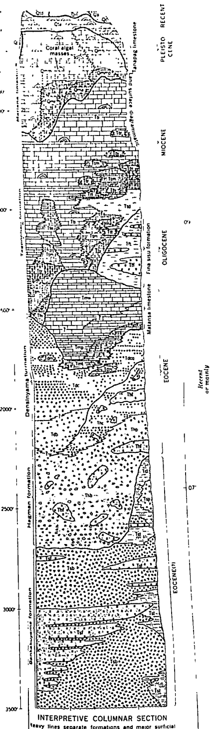
GLOSSARY

(Approved geographic names are entirely in the Chamorro language as on this map. The following translations provide cross reference to the text where the generics are in English)

Katan=north
Lichan=south
Hagoi=lake
Kanat=ravine
Laderan=cliff or cliffs
Ogso=mount, mountain, hill, ridge
Sabanan=grasslands (mostly swordgrass)

Base adapted from U. S. S. Bowditch Survey of 1944. Hydrographic Office Miscellaneous Chart 11 500-36. Native place names from "Preliminary gazetteer of geographic names for Saipan," prepared by Preston E. Cloud, Jr. Geological Surveys Branch, Office of the Engineer, Far East Command

INTERIOR-GEOLOGICAL SURVEY WASHINGTON D.C.



INTERPRETIVE COLUMNAR SECTION

Heavy lines separate formations and major surficial units. Lines undulating where erosional and jagged where interfingering. Thickness approximate only along any given vertical line

EXPLANATION FOR INTERPRETIVE COLUMNAR SECTION

Series	Symbol	Unit	System
Recent or mainly Recent	Qgs	Calcareous gravel and sand in elevated moats	QUATERNARY
	Qr	Recently emerged limesands	
Pleistocene and Recent	Qa	Alluvium	
	Qc	Clay wash	
	Qtd	Younger terrace deposits	
Pleistocene	Qta	Tanapag limestone	
	Qp	Post-Mariana terrace deposits	
	Qm*	Mariana limestone	
	Qmh	*Halimeda-rich facies*	
	Qmm and Qmmp	*Massive facies (p pink)*	
	Qma	*Acropora-rich facies*	
	Qmr	*Rubbly facies*	
Pliocene(?)	Ttd*	Older terrace deposits	TERTIARY(?)
Miocene	Tt*	Tagpochau limestone	TERTIARY
	Tti	*Inequigranular facies*	
	Tte	*Equigranular facies*	
	Ttr	*Rubbly facies*	
	Ttm	*Marly facies*	
	Ttv	*Tuffaceous facies*	
	Ttt	*Transitional facies*	
	Ttma	*Machegit conglomerate member*	
	Ttd	*Donni sandstone member*	
Oligocene	Tf*	Fina-Sisu formation	
	Tft	*Interbedded tuffs and flows*	
	Tff	*Andesite flow rock*	
Eocene	Tm*	Matansa limestone	
	Tmw	*White facies*	
	Tmp	*Pink facies*	
	Tmt	*Basal transitional facies*	
	Td*	Densinyama formation	
	Tdm	*Limestone-conglomerate facies*	
	Tdc	*Conglomerate-sandstone facies, quartz poor*	
	Tdcq	*Conglomerate sandstone facies with abundant free quartz*	
	Tdb	*Breccia facies*	
	Th*	Hagman formation	
	Thc	*Conglomerate-sandstone facies*	
	Thb	*Breccia-tuff facies*	
	Thf	*Andesite flow rock*	
	Ts*	Sankakuyama formation	
	Tsp	*Mixed dacitic pyroclastics*	
	Tst	*Dacitic tuffs*	
	Tsb	*Vitrophyric and perlitic, dacite breccias*	
	Tsf	*Massive dacite flow rock*	

*Letter symbol appears on map only. Shown here for cross-reference

TRUE NORTH
MAGNETIC NORTH

15° 05
145° 50

Geology by Preston E. Cloud, Jr., Robert George Schmidt, and Harold W. Burke, 1948-49. Paleontologic field control by W. Storrs Cole

GENERALIZED GEOLOGIC MAP AND SECTIONS OF SAIPAN, MARIANA ISLANDS

Scale 1:31,680

1 0 2 Miles

5000 0 10000 Feet

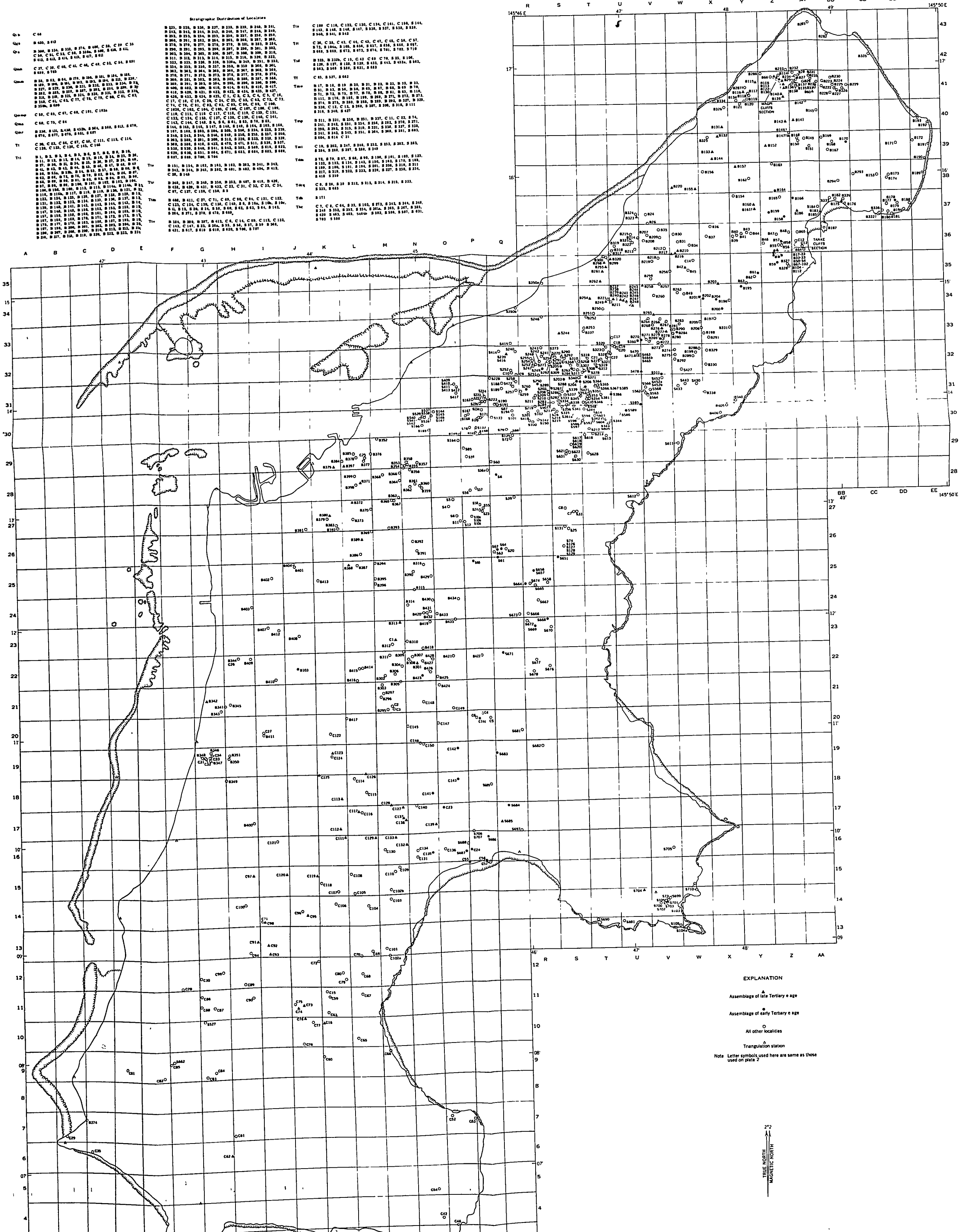
Contour interval 100 feet
Datum is mean sea level

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROFESSIONAL PAPER 280 PLATE 4

Stratigraphic Distribution of Localities

Qrb	C 66
Qgs	B 405, S 612
Qta	B 300, B 334, B 338, B 374, B 406, C 28, C 29, C 35, C 50, C 51, C 53, C 58, S 350a, S 409, S 410, S 411, S 412, S 413, S 414, S 415, S 417, S 611
Qmh	C 37, C 39, C 40, C 41, C 46, C 49, C 52, C 54, S 691, S 699, S 705
Qmm	B 28, B 63, B 64, B 179, B 180, B 181, B 184, B 188, B 189, B 190, B 191, B 192, B 193, B 194, B 215, B 226, B 227, B 229, B 230, B 231, B 232, B 233, B 234, B 235, B 282, B 285, B 286, B 287, B 293, B 294, B 299, B 317, B 318, B 319, B 321, B 324, B 328, B 331, B 332, B 339c, B 340, C 61, C 63, C 77, C 78, C 79, C 80, C 81, C 83, S 350b, S 690
Qmmp	C 59, C 65, C 67, C 68, C 101, C 102a
Qma	C 60, C 75, C 84
Qmr	B 338, S 131, S 430, S 452b, S 564, S 568, S 613, S 670, S 676, S 677, S 678, S 681, S 697
Tt	C 30, C 82, C 86, C 87, C 88, C 111, C 113, C 114, C 120, C 125, C 126, C 145, C 146
Tti	B 1, B 2, B 3, B 4, B 5, B 6, B 7, B 8, B 9, B 10, B 11, B 12, B 13, B 14, B 15, B 16, B 24, B 25, B 26, B 27, B 29, B 30, B 31, B 34, B 35, B 36, B 37, B 39, B 40, B 41, B 42, B 43, B 44, B 45, B 46, B 47, B 48, B 49, B 50, B 52a, B 52b, B 54, B 55, B 57, B 59, B 60, B 61, B 62, B 66, B 73, B 76, B 79, B 82, B 84, B 86, B 87, B 88, B 89, B 90, B 91, B 92, B 93, B 94, B 95, B 96, B 97, B 98, B 99, B 100, B 101, B 102, B 103, B 104, B 106, B 108, B 109, B 112, B 113, B 114a, B 114b, B 115, B 116, B 116b, B 117, B 118, B 119, B 120, B 121, B 122, B 123, B 124, B 125, B 126, B 127, B 128, B 129, B 130, B 131, B 132, B 133, B 134, B 135, B 136, B 137, B 138, B 139, B 140, B 141, B 142, B 143, B 144, B 145, B 146, B 147, B 148, B 149, B 150, B 152, B 153, B 155, B 156, B 157, B 158, B 159, B 160, B 161, B 164, B 165, B 166, B 167, B 168, B 169, B 170, B 171, B 172, B 173, B 174, B 175, B 177, B 178, B 183, B 186, B 187, B 195, B 196, B 197, B 198, B 200, B 201, B 202, B 203, B 204, B 205, B 206, B 207, B 208, B 209, B 210, B 212, B 213, B 214, B 216, B 217, B 218, B 219, B 220, B 222, B 223, B 224, B 225, B 228, B 236, B 237, B 238, B 239, B 240, B 241, B 242, B 243, B 244, B 245, B 246, B 247, B 248, B 249, B 252, B 253, B 254, B 255, B 256, B 257, B 258, B 259, B 260, B 261, B 262, B 264, B 265, B 266, B 267, B 268, B 270, B 276, B 277, B 278, B 279, B 281, B 283, B 284, B 290, B 291, B 295, B 296, B 297, B 298, B 301, B 302, B 303, B 304, B 305, B 306, B 307, B 308, B 309, B 310, B 311, B 312, B 313, B 314, B 315, B 316, B 320, B 322, B 323, B 325, B 326, B 336, B 339a, B 349, B 351, B 353, B 354, B 355, B 356, B 357, B 358, B 359, B 360, B 361, B 362, B 363, B 364, B 365, B 366, B 367, B 368, B 369, B 370, B 371, B 372, B 373, B 376, B 377, B 378, B 379, B 380, B 381, B 382, B 383, B 385, B 386, B 387, B 388, B 389, B 391, B 393, B 394, B 395, B 396, B 398, B 399, B 400, B 402, B 409, B 410, B 414, B 415, B 416, B 417, B 418, B 420, B 421, B 422, B 423, B 424, B 425, B 427, B 430, B 433, B 434, B 435, C 1, C 2, C 3, C 4, C 5, C 16, C 17, C 18, C 19, C 20, C 24, C 25, C 55, C 62, C 72, C 73, C 74, C 76, C 91, C 92, C 93, C 95, C 96, C 98, C 100, C 102b, C 103, C 104, C 105, C 106, C 107, C 108, C 109, C 110, C 115, C 116, C 117, C 118, C 119, C 129, C 131, C 133, C 134, C 135, C 137, C 138, C 139, C 140, C 141, C 143, C 144, C 148, S 4, S 6, S 61, S 65, S 76, S 85, S 144, S 145, S 146, S 147, S 149, S 164, S 165, S 166, S 167, S 168, S 203, S 204, S 205, S 206, S 224, S 228, S 229, S 240, S 243, S 244, S 246, S 249, S 250, S 255, S 257, S 260, S 263, S 289, S 309, S 312, S 320, S 323, S 328, S 339, S 360, S 386, S 416, S 422, S 470, S 471, S 511, S 536, S 537, S 538, S 539, S 540, S 541, S 542, S 583, S 589, S 616, S 628, S 651, S 664, S 671, S 683, S 684, S 685, S 686, S 687, S 689, S 700, S 704
Tte	B 151, B 154, B 162, B 163, B 182, B 263, B 341, B 342, B 343, B 344, B 345, B 392, B 401, B 403, B 404, B 412, C 26, S 148
Ttr	B 346, B 347, B 348, B 350, B 352, B 407, B 419, B 426, B 428, B 429, B 431, B 432, C 23, C 31, C 32, C 33, C 34, C 97, C 127, C 128, C 150, S 5
Ttm	B 408, B 411, C 27, C 71, C 89, C 90, C 94, C 121, C 122, C 123, C 124, C 130, C 136, C 149, S 8, S 10a, S 10b, S 10c, S 11, S 12, S 20, S 24, S 58, S 60, S 62, S 63, S 64, S 143, S 264, S 371, S 378, S 478, S 688,
Ttv	B 384, B 390, B 397, B 413, C 6, C 14, C 99, C 112, C 132, C 142, C 147, S 23, S 36a, S 55, S 56, S 57, S 59, S 368, S 421, S 617, S 618, S 619, S 620, S 706, S 707
Tto	C 109, C 110, C 122, C 130, C 134, C 141, C 150, S 144, S 145, S 146, S 147, S 536, S 537, S 538, S 539, S 540, S 541, S 542
Ttt	C 36, C 38, C 43, C 44, C 45, C 47, C 48, C 56, C 57, S 73, S 104a, S 105, S 656, S 657, S 658, S 660, S 667, S 668, S 669, S 672, S 673, S 674, S 701, S 702, S 710
Ttd	B 333, B 339b, C 15, C 42, C 69, C 70, S 25, S 106, S 126, S 127, S 128, S 129, S 433, S 442, S 452a, S 562, S 563, S 566, S 586, S 621, S 682
Tf	C 85, S 527, S 662
Tmw	B 17, B 18, B 19, B 20, B 21, B 22, B 23, B 32, B 33, B 51, B 53, B 56, B 58, B 65, B 67, B 68, B 69, B 70, B 71, B 72, B 75, B 77, B 78, B 80, B 81, B 85, B 110, B 111, B 176, B 185, B 199, B 269, B 271, B 272, B 273, B 274, B 275, B 280, B 288, B 289, B 292, B 327, B 329, B 330, C 12, C 13, S 268, S 307, S 308, S 310, S 311, S 318, S 340, S 437
Tmp	B 211, B 221, B 250, B 251, B 337, C 11, C 22, S 74, S 241, S 242, S 251, S 254, S 256, S 262, S 270, S 271, S 290, S 292, S 315, S 319, S 321, S 336, S 337, S 338, S 341, S 342, S 345, S 351, S 364, S 369, S 381, S 603, S 604, S 614, C 21
Tmt	C 10, S 202, S 247, S 248, S 252, S 253, S 282, S 283, S 284, S 286, S 287, S 288, S 349
Tdm	S 72, S 79, S 87, S 88, S 90, S 100, S 101, S 102, S 125, S 132, S 133, S 134, S 142, S 150, S 163, S 170, S 188, S 189, S 190, S 191, S 194, S 201, S 208, S 210, S 211, S 217, S 219, S 222, S 223, S 226, S 227, S 258, S 334, S 418, S 259
Tdcq	C 9, S 26, S 30, S 212, S 213, S 214, S 215, S 333, S 335, S 665
Tdb	S 171
Thc	C 7, C 8, C 64, S 33, S 103, S 273, S 343, S 344, S 346, S 348, S 352, S 353, S 354, S 361a, S 365, S 367, S 385, S 420, S 463, S 465, S464b, S 592, S 596, S 597, S 631, S 703, S 598



EXPLANATION

▲
Assemblage of late Tertiary e age

●
Assemblage of early Tertiary e age

○
All other localities

△
Triangulation station

Note Letter symbols used here are same as those used on plate 2

2°2'
TRUE NORTH
MAGNETIC NORTH

Scale 1:31,680
2500 0 7500 Feet

FOSSIL LOCALITY FINDING MAP FOR SAIPAN, MARIANA ISLANDS

LOCALITY LIST

(B 1, Z41, Tti = locality MSB 1, grid location Z41, from stratigraphic unit symbolized by Tti)

MAGPI CLIFFS SECTION
B 1, Z41, Tti
B 2, Z41, Tti
B 3, Z41, Tti
B 4, Z41, Tti
B 5, Z41, Tti
B 6, Z41, Tti
B 7, Z41, Tti
B 8, Z41, Tti
B 9, Z41, Tti
B 10, Z41, Tti
B 11, Z41, Tti
B 12, Z41, Tti
B 13, Z41, Tti
B 14, Z41, Tti
B 15, Z41, Tti
B 16, Z41, Tti
TANKE CLIFFS SECTION
B 17, AA36, Tmw
B 18, AA36, Tmw
B 19, AA36, Tmw
B 20, AA36, Tmw
B 21, AA36, Tmw
B 22, AA36, Tmw
B 23, AA36, Tmw
B 24, V37, Tti
B 25, AA41, Tti
B 26, V37, Tti
B 27, AA41, Tti
B 28, AA41, Qmm
B 29, AA41, Tti
B 30, W36, Tti
B 31, W36, Tti
TANKE CLIFFS SECTION
B 32, AA36, Tmw
B 33, AA36, Tmw
B 34, W36, Tti
B 35, V36, Tti
B 36, X36, Tti
B 37, X36, Tti
B 38, AA41, Qta
B 39, Y36, Tti
B 40, Y36, Tti
B 41, Y36, Tti
B 42, W35, Tti
B 43, Y36, Tti
B 44, Y36, Tti
B 45, W35, Tti
B 46, Z36, Tti
B 47, Z36, Tti
B 48, Z36, Tti
B 49, W34, Tti
TANKE CLIFFS SECTION
B 50, AA36, Tti
B 51, AA36, Tmw
B 52a, Z35, Tti
B 52b, Z35, Tti
B 53, AA36, Tmw
B 54, Z35, Tti
B 55, Z36, Tti
B 56, Z36, Tmw
B 57, Z36, Tti
B 58, Z36, Tmw
B 59, Z35, Tti
B 60, AA41, Tti
B 61, Y35, Tti
B 62, Y35, Tti
B 63, Y34, Qmm
B 64, AA36, Qmm
B 65, AA36, Tmw
B 66, Z41, Tti
TANKE CLIFFS SECTION
B 67, Z36, Tmw
B 68, Z36, Tmw
B 69, Z36, Tmw
B 70, Z36, Tmw
B 71, Z36, Tmw
B 72, Z36, Tmw
B 73, Z35, Tti
B 75, Z35, Tmw
B 76, Z35, Tti
B 77, Z36, Tmw
B 78, Z36, Tmw
B 79, Z35, Tti
B 80, Z36, Tmw
B 81, Z36, Tmw
B 82, Z35, Tti
B 84, Z35, Tti
B 85, Z36, Tmw
B 86, Z35, Tti
B 87, Z35, Tti
B 88, Z35, Tti
B 89, Z35, Tti
B 90 Z35, Tti
B 91 Z35 Tti
B 92, Z35, Tti
B 93 Z35, Tti
B 94, Z36, Tti
B 95, Z36, Tti
B 96, Z36, Tti
B 97, Z36, Tti
B 98, Z36, Tti
B 99, Z36, Tti
B 100, Z36, Tti
B 101, Z36, Tti
B 102, Z36, Tti
B 103, J22, Tti
TANKE CLIFFS SECTION
B 104, Z35, Tti
B 106, Z35, Tti
B 108, Z35, Tti
B 109, Z35, Tti
B 110, AA36, Tmw
B 111, AA36, Tmw
B 112, Z36, Tti
B 113, Z41, Tti
B 114a, Z41, Tti
B 114b, Z41, Tti
B 115, Y41, Tti
B 116, Y41, Tti
B 116b, Y41, Tti
B 117, Y41, Tti
B 118, Y41, Tti
B 119, Y41, Tti
B 120, Y41, Tti
B 121, X40, Tti
MAGPI CLIFFS SECTION
B 122, Z41, Tti
B 123, Z41, Tti
B 124, Z41, Tti
B 125, Z41, Tti
B 126, Z41, Tti
B 127, Z41, Tti
B 128, Z41, Tti
B 129, Z41, Tti
B 130, Z41, Tti
B 131, X40, Tti
B 132, X39, Tti
B 133, X39, Tti
B 134, Y41, Tti
B 135, AA41, Tti
B 136, AA41, Tti
B 137, AA41, Tti
B 138, AA41, Tti
B 139, Z41, Tti
B 140, Z41, Tti
B 141, AA40, Tti
B 142, AA40, Tti
B 143, Z40, Tti
B 144, X39, Tti
B 145, AA40, Tti
B 146, Z39, Tti
B 147, Z39, Tti
B 148, AA39, Tti
B 149, AA39, Tti
B 150, AA39, Tti
B 151, AA39, Tte
B 152, Z39, Tti
B 153, CC38, Tti
B 154, Y37, Tte
B 155, W38, Tti
B 156, X38, Tti
B 157, Y38, Tti
B 158, Z37, Tti
B 159, Z37, Tti
B 160, Y37, Tti
B 161, Y37, Tti
B 162, Y38, Tte
B 163, Z38, Tte
B 164, Z38, Tti
B 165, Z37, Tti
B 166, AA37, Tti
B 167, BB39, Tti
B 168, BB39, Tti
B 169, BB39, Tti
B 170, BB39, Tti
B 171, DD39, Tti
B 172, EE38, Tti
B 173, DD38, Tti
B 174, DD38, Tti
B 175, BB37, Tti
B 176, BB37, Tmw
B 177, DD37, Tti
B 178, DD37, Tti
B 179, DD37, Qmm
B 180, DD37, Qmm
B 181, DD37, Qmm
B 182, BB37, Tte
B 183, BB37, Tti
B 184, AA37, Qmm
B 185, AA37, Tmw
B 186, AA37, Tti
B 187, BB38, Tti
B 188, DD37, Qmm
B 189, EE38, Qmm
B 190, EE39, Qmm
B 191, EE39, Qmm
B 192, EE40, Qmm
B 193, EE40, Qmm
B 194, DD37, Qmm
B 195, Y34, Tti
B 196, X34, Tti
B 197, X33, Tti
B 198, X33, Tti
B 199, W32, Tmw
B 200, X34, Tti
B 201, W34, Tti
B 202, X34, Tti
B 203, X35, Tti
B 204, X34, Tti
B 205 W33, Tti
B 206 W33 Tti
B 207 V36 Tti
B 208 V36 Tti
B 209, V36, Tti
B 210, W36, Tti
B 211, U34, Tmp
B 212, V36, Tti
B 213, U36, Tti
B 214, U36, Tti
B 215, U36, Qmm
B 216, W36, Tti
B 217, W36, Tti
B 218, V35, Tti
B 219, V35, Tti
B 220, W36, Tti
B 221, T34, Tmp
B 222, BB41, Tti
B 223, BB41, Tti
B 224, BB41, Tti
B 225, BB41, Tti
B 226, BB41, Qmm
B 227, BB41, Qmm
B 228, BB41, Tti
B 229, BB41, Qmm
B 230, BB41, Qmm
B 231, AA41, Qmm
B 232, AA41, Qmm
B 233, Z42, Qmm
B 234, AA41, Qmm
B 235, AA41, Qmm
B 236, AA41, Tti
B 237, U34, Tti
B 238, U34, Tti
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B 258, V34, Tti
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B 263, V34, Tte
B 264, V33, Tti
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B 267, V33, Tti
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B 269, V33, Tmw
B 270, V33, Tti
B 271, V32, Tmw
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B 274, W32, Tmw
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B 276, V33, Tti
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B 282, BB43, Qmm
B 283, W33, Tti
B 284, W33, Tti
B 285, AA43, Qmm
B 286, Z41, Qmm
B 287, Y41, Qmm
B 288, W32, Tmw
B 289, W32, Tmw
B 290, W33, Tti
B 291, X33, Tti
B 292, W32, Tmw

B 293, BB38, Qmm
B 294, BB38, Qmm
B 295, M21, Tti
B 296, M21, Tti
B 297, M21, Tti
B 298, T35, Tti
B 299, T35, Qmm
B 300, T35, Qta
B 301, N22, Tti
B 302, M22, Tti
B 303, M21, Tti
B 304, M22, Tti
B 305, M21, Tti
B 306, M22, Tti
B 307, N22, Tti
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B 312, M22, Tti
B 313, M23, Tti
B 314, N24, Tti
B 315, N24, Tti
B 316, N25, Tti
B 317, U38, Qmm
B 318, U36, Qmm
B 319, U36, Qmm
B 320, U35, Tti
B 321, U38, Qmm
B 322, U36, Tti
B 323, U37, Tti
B 324, U37, Qmm
B 325, X39, Tti
B 326, X40, Tti
B 327, Z33, Tmw
B 328, Z33, Qmm
B 329, X32, Tmw
B 330, X32, Tmw
B 331, X33, Qmm
B 332, CC37, Qmm
B 333, BB37, Ttd
B 334, X41, Qta
B 335, CC42, Ttd
B 336, DD37, Tti
B 337, T33, Tmp
B 338, X31, Qmr
B 339a, BB37, Tti
B 339b, BB37, Ttd
B 339c, BB37, Qmm
B 340, Y31, Qmm
B 341, H21, Tte
B 342, G21, Tte
B 343, G21, Tte
B 344, H22, Tte
B 345, H21, Tte
B 346, G19, Ttr
B 347, G19, Ttr
B 348, G19, Ttr
B 349, H18, Tti
B 350, H18, Ttr
B 351, H19, Tti
B 352, M29, Ttr
B 353, N29, Tti
B 354, N28, Tti
B 355, N29, Tti
B 356, N28, Tti
B 357, N29, Tti
B 358, N29, Tti
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B 363, M28, Tti
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B 366, M28, Tti
B 367, M27, Tti
B 368, M28, Tti
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B 370, L27, Tti
B 371, L28, Tti
B 372, L27, Tti
B 373, L27, Tti
B 374, B7, Qta
B 375, K28, Ttv
B 376, M29, Tti
B 377, L29, Tti
B 378, L29, Tti
B 379, K27, Tti
B 380, K27, Tti
B 381, J27, Tti
B 382, K27, Tti
B 383, K27, Tti
B 384, L29, Ttv
B 385, L29, Tti
B 386, L29, Tti
B 387, L25, Tti
B 388, L25, Tti
B 389, L26, Tti
B 390, N25, Ttv
B 391, N26, Tti
B 392, N26, Tte
B 393, M27, Tti
B 394, M25, Tti
B 395, M25, Tti
B 396, M25, Tti
B 397, L28, Ttv
B 398, L28, Tti
B 399, L28, Tti
B 400, H17, Tti
B 401, J25, Tte
B 402, I25, Tti
B 403, H24, Tte
B 404, J25, Tte
B 405, X30, Qgs
B 406, X30, Qta
B 407, I23, Ttr
B 408, J23, Ttm
B 409, H22, Tti
B 410, I23, Tti
B 411, I20, Ttm
B 412, I23, Tte
B 413, K25, Ttv
B 414, L22, Tti
B 415, L22, Tti
B 416, L22, Tti
B 417, L20, Tti
B 418, N23, Tti
B 419, N23, Ttr
B 420, N24, Tti
B 421, O22, Tti
B 422, P22, Tti
B 423, N22, Tti
B 424, O21, Tti
B 425, O22, Tti
B 426, N22, Ttr
B 427, N22, Tti
B 428, N22, Ttr
B 429, N25, Ttr
B 430, N24, Tti
B 431, N24, Ttr
B 432, N24, Ttr
B 433, O24, Tti
B 434, O24, Tti
B 435, O23, Tti

C 1, M23, Tti
C 2, M21, Tti
C 3, M21, Tti
C 4, P20, Tti
C 5, P20, Tti
C 6, P20, Ttv
C 7, S27, Thc
C 8, S27, Thc
C 9, Q32, Tdcq
C 10, Q32, Tmt
C 12, AA36, Tmw
C 13, AA36, Tmw
C 14, W35, Ttv
C 15, K11, Ttd
C 16, K10, Tti
C 17, U33, Tti
C 18, U32, Tti
C 19, U32, Tti
C 20, U32, Tti
C 21, T33, Tmp
C 22, T32, Tmp
C 23, O17, Ttr
C 24, P16, Tti
C 25, L29, Tti
C 26, H22, Tte
C 27, I20, Ttm
C 28, F12, Qta
C 29, B7, Qta
C 30, G12, Tt
C 31, G19, Ttr
C 32, G19, Ttr
C 33, G19, Ttr
C 34, G19, Ttr
C 35, C6, Qta
C 36, N2, Ttt
C 37, N2, Qmh
C 38, O3, Ttt
C 39, O3, Qmh
C 40, O3, Qmh
C 41, O2, Qmh
C 42, N4, Ttd
C 43, O3, Ttt
C 44, O3, Ttt
C 45, O3, Ttt
C 46, O4, Qmh
C 47, O3, Ttt
C 48, O3, Ttt
C 49, N1, Qmh?
C 50, N1, Qmh
C 51, N1, Qta?
C 52, O7, Qmh
C 53, O7, Qta
C 54, N5, Qmh
C 55, P15, Tti
C 56, P18, Ttt
C 57, P15 Ttt
C 58 M2, Qta
C 59 K11 Qmmp
C 60 K9 Qma
C 61 H7 Qmm
C 62, G6, Tti
C 63, K11, Qmm
C 64, O3, Thc
C 65, L10, Qmmp
C 66, M9, Qrb
C 67, L11, Qmmp
C 68, L12, Qmmp
C 69, L13, Ttd
C 70, L13, Ttd
C 71, I14, Ttm
C 72, J12, Tti
C 73, J11, Tti
C 74, J11, Tti
C 75, J11, Qma
C 76, J10, Tti
C 77, J10, Qmm
C 78, J10, Qmm
C 79, K12, Qmm
C 80, K12, Qmm
C 81, D9, Qmm
C 82, E9, Tt
C 83, G9, Qmm
C 84, G9, Qma
C 85, F9, Tf
C 86, G11, Tt
C 87, G11, Tt
C 88, G11, Tt
C 89, H12, Ttm
C 90, H11, Ttm
C 91, H13, Tti
C 92, I13, Tti
C 93, I13, Tti
C 94, H13, Ttm
C 95, J14, Tti
C 96, J14, Tti
C 97, H15, Ttr
C 98, I14, Tti
C 99, G13, Ttv
C 100, H14, Tti
C 101, M13, Qmmp
C 102a, M12, Qmmp
C 102b, M15, Tti
C 103, M14, Tti
C 104, L14, Tti
C 105, L15, Tti
C 106, K14, Tti
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C 110, M16, Tti
C 111, K16, Tt
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C 113, K18, Tt
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C 134, N16, Tti
C 135, N16, Tti
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C 138, M17, Tti
C 139, N17, Tti
C 140, N17, Tti
C 141, N18, Tti
C 142, O19, Ttv
C 143, O16, Tti
C 144, P20, Tti
C 145, N20, Tt
C 146, N19, Tt
C 147, O20, Ttv
C 148, N21, Tti
C 149, O21, Ttm
C 150, N19, Ttr

S 4, O27, Tti
S 5, O27, Ttr
S 6, Q28, Tti
S 8, O27, Ttm
S 10a, P27, Ttm
S 10b, P27, Ttm
S 10c, P27, Ttm
S 11, O27, Ttm
S 12, P27, Ttm
S 20, Q26, Ttm
S 23, P27, Ttv
S 24, P27, Ttm
S 25, S26, Ttd
S 26, S30, Tdcq
S 33, S27, Thc
S 36a, P28, Ttv
S 30, Q27, Tdcq
S 55, P27, Ttv
S 56, P28, Ttv
S 57, P28, Ttv
S 58, P27, Ttm
S 59, P28, Ttv
S 60, Q29, Ttm
S 61, Q25, Tti
S 62, Q28, Ttm
S 63, Q28, Ttm
S 64, Q28, Ttm
S 65, P25, Tti
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S 73, V14, Ttt
S 74, S28, Tm
S 76, P30, Tti
S 79, Q30, Tdm
S 85, P29, Tti
S 87, Q30, Tdm
S 88, Q30, Tdm
S 90, R30, Tdm
S 100, R30, Tdm
S 101, Q30, Tdm
S 102, R30, Tdm
S 103, V14, Thc
S 104a, W13, Ttt
S 105, V13, Ttt,
S 106, V14, Ttd
S 125, Q29, Tdm
S 126, S28, Ttd
S 127, S28, Ttd
S 128, S26, Ttd
S 129, S26, Ttd
S 131, S26, Qmr
S 132, P30, Tdm
S 133, Q30, Tdm
S 134, P30, Tdm
S 142 R30, Tdm
S 143, P30, Ttm
S 144, O30, Tti
S 145, O30, Tti
S 146, O30, Tti
S 147, O30, Tti
S 148, P30, Tte
S 149, O30, Tti
S 150, R30, Tdm
S 163, P31, Tdm
S 164, O29, Tti
S 165, N30, Tti
S 166, N30, Tti
S 167, P30, Tti
S 168, P30, Tti
S 170, P30, Tdm
S 171, P30, Tdb
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S 189, Q31, Tdm
S 190, Q31, Tdm
S 191, Q31, Tdm
S 194, Q30, Tdm
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S 211, R31, Tdm
S 212, T30, Tdcq
S 213, T30, Tdcq
S 214, S30, Tdcq
S 215, S30, Tdcq
S 217, S30, Tdm
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S 227, P31, Tdm
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S 252, Q32, Tmt
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S 273, S32, Thc
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S 320, T32, Tti
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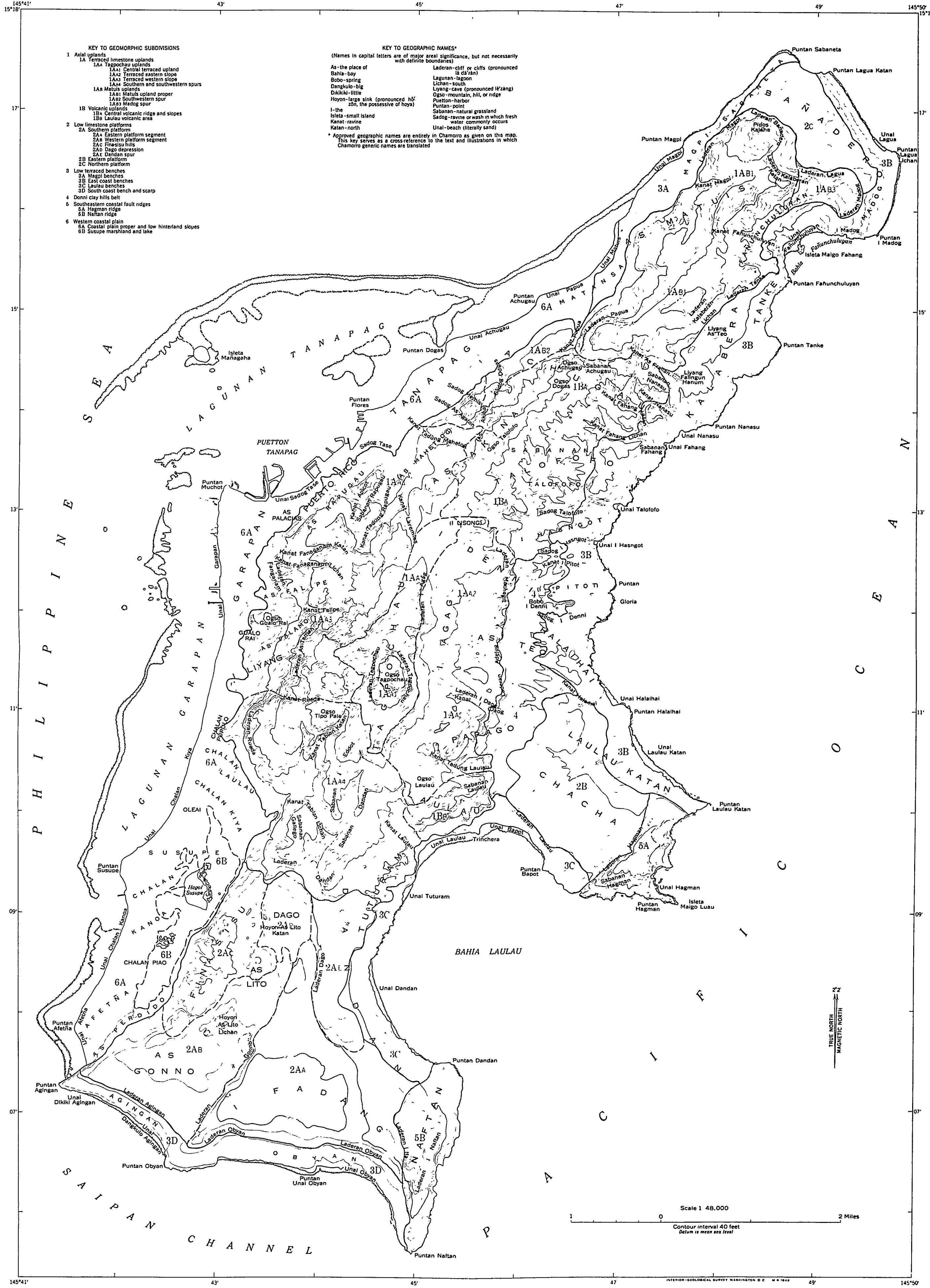
S 334, S31, Tdm
S 335, S30, Tdcq
S 336, S31, Tmp
S 337, S31, Tmp
S 338, S31, Tmp
S 339, S31, Tti
S 340, S31, Tmw
S 341, S30, Tmp
S 342, T30, Tmp
S 343, T30, Thc
S 344, T30, Thc
S 345, S31, Tmp
S 346, T31, Thc
S 348, T31, Thc
S 349, T30, Tmt
S 350a, R33, Qta
S 350b, Q34, Qmm
S 351, T31, Tmp
S 352, T31, Thc
S 353, T31, Thc
S 354, T31, Thc
S 358, U32, Tmw?
S 360, U33, Tti
S 361a, S30, Thc
S 364, T31, Tmp
S 365, T31, Thc
S 366, T31, Thc
S 367, T31, Thc
S 368, S32, Ttv
S 369, S32, Tmp
S 371, T31, Ttm
S 378, T32, Ttm
S 381, T31, Tmp
S 385, T31, Thc
S 386, TU31, Tti
S 409, O31, Qta
S 410, O31, Qta
S 411, O31, Qta
S 412, O31, Qta
S 413, O31, Qta
S 414, Q32, Qta
S 415, Q33, Qta
S 416, Q32, Tti
S 417, O31, Qta
S 418, R30, Tdm
S 420 T31, Thc
S 421, T31, Ttv
S 422 Q31 Tti
S 437 W32, Tmw?
S 430, W31 Qmr
S 433, W31 Ttd
S 442, W31, Ttd
S 452a, V31, Ttd
S 452b, V31, Qmr
S 463, U32, Thc
S 464b, U32, Thc
S 465, U32, Thc
S 470, U32, Tti
S 471, U32, Tti
S 478, V32, Ttm
S 511, V32, Tti
S 527, G10, Tf
S 536, O30, Tti
S 537, N30, Tti
S 538, N30, Tti
S 539, N30, Tti
S 540, N30, Tti
S 541, N30, Tti
S 542, N30, Tti
S 562, V31, Ttd
S 563, V31, Ttd
S 564, V31, Qmr
S 566, V31, Ttd
S 568, V31, Qmr
S 583, U30, Tti
S 586, U30, Ttd
S 589, U30, Tti
S 592, T30, Thc
S 596, T30, Thc
S 597, T30, Thc
S 598, S30, Thc
S 603 T30, Tmp
S 604, T30, Tmp
S 611, W29, Qta
S 612, U27, Qgs
S 613, T29, Qmr
S 614, T30, Tmp
S 616, T29, Tti
S 617, S29, Ttv
S 618, S29, Ttv
S 619, S29, Ttv
S 620, S29, Ttv
S 621, S29, Ttd
S 622, S28, Qmr
S 628, T29, Tti
S 630, S29, Qmr
S 631, S29, Thc
S 651, S25, Tti
S 656, R25, Tti
S 657, R25, Ttt
S 658, R25, Ttt
S 662, F9, Tf
S 664, R25, Tti
S 665, R25, Tdcq
S 666, R24, Tti
S 667, R24, Tti
S 668, R23, Tti
S 669, R23, Tti
S 670, R23, Qmr
S 671, Q22, Tti
S 672, R23, Ttt
S 673, Q24, Ttt
S 674, R25, Ttt
S 676, R22, Qmr
S 677, R22, Qmr
S 678, R22, Qmr
S 681, Q20, Qmr
S 682, R18, Ttd
S 683, Q19, Tti
S 684, Q17, Tti
S 685, Q17, Tti
S 686, P18, Tti
S 687, O18, Tti
S 688, O18, Ttm
S 689, P18, Tti
S 690, T13, Qmm
S 691, U13, Qmh
S 697, Q17, Qmr
S 699, V14, Qmh
S 701, V14, Ttt
S 702, V14, Ttt
S 703, V14, Thc
S 704, U14, Tti
S 705, V16, Qmh
S 706, P17, Ttv
S 707, P17, Ttv
S 710, W14-W15, Ttt

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROFESSIONAL PAPER 280 PLATE 3



KEY TO GEOMORPHIC SUBDIVISIONS

- 1 Axial uplands
  - 1A Terraced limestone uplands
    - 1AA Tagpochau uplands
      - 1AA1 Central terraced upland
      - 1AA2 Terraced eastern slope
      - 1AA3 Terraced western slope
      - 1AA4 Southern and southwestern spurs
    - 1AB Matuis uplands
      - 1AB1 Matuis upland proper
      - 1AB2 Southwestern spur
      - 1AB3 Madog spur
  - 1B Volcanic uplands
    - 1BA Central volcanic ridge and slopes
    - 1BB Laulau volcanic area
- 2 Low limestone platforms
  - 2A Southern platform
    - 2AA Eastern platform segment
    - 2AB Western platform segment
    - 2AC Fina-sisu hills
    - 2AD Dago depression
    - 2AE Dandan spur
  - 2B Eastern platform
  - 2C Northern platform
- 3 Low terraced benches
  - 3A Magpi benches
  - 3B East coast benches
  - 3C Laulau benches
  - 3D South coast bench and scarp
- 4 Donni clay hills belt
- 5 Southeastern coastal fault ridges
  - 5A Hagman ridge
  - 5B Naftan ridge
- 6 Western coastal plain
  - 6A Coastal plain proper and low hinterland slopes
  - 6B Susupe marshland and lake

KEY TO GEOGRAPHIC NAMES*

(Names in capital letters are of major areal significance, but not necessarily with definite boundaries)

As-the place of	Laderan-cliff or cliffs (pronounced lá dá'rán)
Bahia-bay	Lagunan-lagoon
Bobo-spring	Lichan-south
Dangkulo-big	Liyang-cave (pronounced lē'zāng)
Dikikiki-little	Ogso-mountain, hill, or ridge
Hoyon-large sink (pronounced hō'zōn, the possessive of hoya)	Puetton-harbor
I-the	Puntan-point
Isleta-small island	Sabanan-natural grassland
Kanat-ravine	Sadog-ravine or wash in which fresh water commonly occurs
Katan-north	Unal-beach (literally sand)

* Approved geographic names are entirely in Chamorro as given on this map. This key serves as a cross-reference to the text and illustrations in which Chamorro generic names are translated

Scale 1 48,000
1 0 2 Miles
Contour interval 40 feet
Datum is mean sea level

INTERIOR—GEOLOGICAL SURVEY WASHINGTON D C M R 1949

TOPOGRAPHIC AND GEOMORPHIC MAP OF SAIPAN, MARIANA ISLANDS