RECONNAISSANCE GEOLOGY OF GUAM

AND

PROBLEMS OF WATER SUPPLY AND FUEL STORAGE

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1. INTRODUCTION

The purpose of this memorandum is to put on record some preliminary impressions of the geology of Guam, and some remarks on problems thought to be of special interest in island development.

Published and unpublished reports dealing with the geology of Guam are listed and adequately summarized in reference 3 (see selected references). The present note is neither comprehensive nor particularly original. It is rather an interim attempt at a broad integration of what was previously known of the geology of Guam with the recent findings of the Marianas Party. In a scientific sense it is premature, but enough information is at hand to substantiate a few conclusions regarding present problems and future efforts on the island that may be of interest to the operating engineer.

Guam has a maximum length of about 31 miles, ranges in width from about 4-1/2 to 8 miles, and includes an area of between 215 and 225 square miles. It is elongated northeast to southwest, and shaped rather like a peanut, with a narrow, centrally located waist. It is the largest and most southerly of the Marianas Islands, representing nearly 60 percent of the total land area of the Marianas and about 25 percent of all the land in Micronesia. Geographically centered at about 13° 27' N latitude and 144° 47' east longitude, Guam represents a limestone-veneered peak on a nearly submerged

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*/ Preston E. Cloud, Jr., geologist, U. S. Geological Survey, on assignment to the Intelligence Division, Engineer Section, GHQ, FEC. Field work was accomplished during July and August 1948.

volcanic ridge between the Philippine Sea to the west and the Pacific Ocean basin proper to the east. In a regional geologic sense it is considered to be at the eastern margin of the structurally complicated and deeply inundated Asiatic shelf and at the western edge of the Pacific basin. It is a high point on one of five or more arcuate (convex eastward) geanticlinal ridges that trend generally north to south between the Ryukyus and the Marianas-Bonins, a relationship well brought out in reference 1.

The island of Guam is sharply and subequally divided, just below the waist, into a northern limestone plateau and an area of generally higher volcanic hills to the south. The northern limestone plateau, with a maximum elevation of 674 feet above sea level, is covered, under natural conditions, with a thick growth of jungle; whereas the volcanic hills support mainly sword grass. The volcanic hills rise to a height of 1240 feet above sea level and their lower slopes to the east and, in part to the west, are blanketed with a wedgelike apron of younger limestones generally similar to those of the northern limestone plateau. The highest hills are found in the west central part of the island, where Mt. Lamlam rises to an elevation of 1334 feet, and the ridge from Mt. Lamlam at the south to Mt. Alifan (869 ft) at the north is capped by some of the older, if not the oldest, post-volcanic limestones on the island. Like the younger limestones, the older limestones of the island crest support a dense jungle vegetation that prominently defines their general distribution by contrast with the sword-grass cover of the volcanic terrain.

II. GENERAL GEOLOGY

1. Stratigraphic Succession

All the rocks of known age on Guam originated within the last 60 million of the 2 to 3 billion years of geologic time, in the era known as the Cenozoic. The total thickness of the known succession above sea level is probably over 3500 feet. The oldest of these rocks are of volcanic origin, including both consolidated outpourings of lava, and rocks that have resulted from lithification of volcanically ejected dust, ash, and blocks. The vents from which the pyroclastic material (the dust, ash, and blocks) was ejected no doubt stood above sea-level, but such debris itself fell in the sea as well as on the land. In fact the bulk of the pyroclastically derived materials examined (thought to be mainly from the upper portion of the volcanic succession) were water-laid, and some may have been transported considerable distances in the sea before coming to rest. They are thus water-laid tuffs, tuffaceous shales, and volcanically derived conglomerates-with subaerial tuffs and true agglomerates being relatively uncommon in the areas so far examined by the Marianas Party. The lavas are dark in color and resemble basalt, but many are said by petrologists who have studied them to be andesite. They commonly contain zeolite-filled amygdules. Many display a pillow-structure, indicating that they, like the pyroclastics, commonly came to rest below water, if they were not indeed the product of submarine eruption.

From preliminary examination by the Marianas Party it appears that the lava flows account for a much smaller proportion of the total volcanic succession than do the pyroclastically derived rocks, but this probably applies only to the younger volcanics. The volcanic rocks are very complicated structurally, and studies to date have not been sufficient for more than the roughest provisional subdivision. Altogether they are probably several thousands of feet thick, and it seems from the work of H. T. Stearns, formerly U. S. Geological Survey, that there is a preponderance of lava toward the base of the succession, with decreasing proportions upward as the volcanic development of the island entered a more explosive phase. The pillow lavas that are so prominently developed on the west slope of the island from Facpi Point southward are cut by numerous dikes (tabular intrusive bodies). These probably represent consolidation of lavas within the fissures through which the flows were extruded. Some, however, may have led upward to the conduits of the explosively active volcanos that provided the pyroclastic debris now to be seen as the water-laid tuffs, tuffaceous shales, and conglomerates in the higher part of the volcanic series.

Beds of tuffaceous limestone and marly material occur locally in at least the upper part of the volcanic succession, and some of these (at the entrance to the Naval Ammunition Depot, and elsewhere) have provided microfossils of probably Oligocene or Miocene age.

The post-volcanic rocks include limestone of at least three different ages, gravel, ancient soils, and lignitic beds. The limestones include raised reef rock and a large proportion of detrital limestone or lime-sandstone that is locally rich in the small, fan-shaped joints of the lime secreting alga known as Halimeda, a characteristic inhabitant of the shallower waters of lagoons and banks. By analogy with modern sediments of the Pacific islands it appears that the detrital limestones studied represent lagoonal or back-reef deposits.

The limestones contain both microfossils and larger fossils and can very probably be accurately dated when further study of the fossiliferous successions throughout the Pacific islands has been made. At the present time they are not as well understood as they should be, owing to insufficient information on modern lagoonal and reef sediments and the fact that regional biostratigraphic studies of the Pacific islands have not been followed to the point where the puzzle begins to resolve.

The raised gravels and ancient soils are of special interest in interpreting the geologic history of the island, because of their relationships to adjacent rocks. Gravels derived from reworking of older volcanic material and now deeply weathered and faulted into weathered older volcanic conglomerates can hardly be distinguished from the volcanics themselves except by structural relationships.

Even the ancient soils are open to varied interpretation. One such patch of soil has been claimed to be both a buried weathered volcanic pinnacle and a pocket-like remnant of an older soil on an older limestone surface now buried under a younger limestone. It is worth emphasizing that such problems are neither insoluble nor without practical interest. The seemingly purely academic question of whether a given patch of red clay is a soil pocket between two limestones or a weathered and buried volcanic pinnacle has important bearing on distribution and availability of ground water, as elaborated in the section on "Water Supply"

The following pages and the accompanying map (see Figure 1) summarize the presently inferred succession of rocks and sediments on Guam, exclusive of alluvial and colluvial deposits related to the present land surface. Eight separate stratigraphic units are recognized at present and the number will doubtless be increased with additional study. This succession runs in approximate downward succession from youngest (1) to oldest (8). The first word following each number is the name of the stage in the Cenozoic Era to which the unit is thought to belong.

Unit 1. Recent - Alluvium; beach and lagoonal sands and muds (lime-sands as well as detritus derived from weathering and transportation of volcanic rocks, and mixing of these sediments with others) and recent soils. Thickness, a veneer.

Unit 2. Recent - Coralliferous reef limestone, as at Toguan Bay, to the north of Merizo, and the mouth of the Taleyfac River. Coral skeletons not visibly altered. Probably the Merizo limestone of Tayama. Thickness, a veneer.

Unit 3. Pleistocene - Younger pre-Recent limestones such as comprise the northern plateau. Coral skeletons only slightly altered.

Stearns' Barrigada limestone. Includes both a detrital and locally *Halimeda*-rich lagoonal and bank facies and a reef-limestone facies with coral heads in place of growth. Yields larger fossils of dominantly Recent aspect as well as micro-fossils. The large spirally ribbed gastropod *Turbo* is a common faunal element; but a considerable variety of pelecypods (clams), gastropods (snails), and corals is known from unit 3. Total relief of northern plateau suggests the thickness to be 700 feet or more.

Associated with unit 3 are several pockets or pinacles of red clay. Mr. Josiah Bridge of the U. S. Geological Survey (personal communication) on the basis of thermal analyses and petrographic studies made of samples of this clay from some localities concludes from the high proportion of the mineral gibbsite that it represents weathered volcanic materials. One of these occurrences at a locality 1.9 miles by speedometer southeast of Agana on the road to Pago Bay was reported by H. T. Stearns (reference 7, p. 34) to be an ancient soil between two limestones. The writer of this memorandum interprets the occurrence mentioned as a clay filling of a depression on an old weathering surface, preserved, because of its position, when the marginal clays were carried away, and thus pinching out against the limestone above it. This is in agreement with Stearns' interpretation, and the outcrop is near enough to a source area of igneous material that it could well include soil derived from igneous rock without the source being a pinnacle. As there seems, at this point, to be no consistently recognizable difference between the limestones above and below this soil zone, they are not separated as distinct mappable units. In theory, however, if the interpretation suggested is correct, they are distinct; and more detailed work might prove them to be mappable. If properly interpreted the occurrence of clay mentioned represents tilting above sea level of an area of limestone adjacent to the then much smaller island of Guam to the south, followed by formation of a soil zone and development of local unconformity. Toward the north deposition of calcareous marine sediments may well have been continuous. This soil does not necessarily represent a great lapse of time, if it be thought of as having been washed out from an adjacent source of supply. But, if formed in place from weathering of the limestone, considerable time would be required for its formation.

Unit 4. Pleistocene? (and/or Pliocene?) - Peat bearing beds of the Talofofo drainage basin (not seen by the writer). Possibly an estuarine or shore-swamp equivalent of Unit 3. Thickness unknown.

Unit 5. Pliocene or earliest Pleistocene - Deeply weathered gravel consisting primarily of reworked volcanic rocks. Occurs as blanket deposits at the west side of Mt. Santa Rosa and on Mataguac Hill, these eminences being outlying volcanic patches in the northeast part of the northern limestone plateau. Thickness, a veneer.

This gravel is locally dropped into the volcanic sequence along high-angle faults and is very difficult to differentiate from some of the highly weathered volcanic conglomerates which it blankets. It is thought to have developed as a blanket spread over and out from Mt. Santa Rosa, Mataguac Hill, and probably other places prior to the deposition of unit 3 but after the deposition of unit 6. Evidence as to age may derive from dating of Foraminifera (microfossils) found in a limestone pinnacle in a road cut at the west side of the Santa Rosa volcanics. The gravel surrounds and buries this pinnacle and is clearly younger than it.

Should the pinnacle prove to belong to unit 6, as is presently inferred, it would establish Mt. Santa Rosa as an older fault block against and over which the limestones of unit 3 were laid, and would prove that the gravels of unit 5 were older than unit 3 and younger than unit 6. If the pinnacle belongs to unit 3, that interpretation will be invalid.

Unit 6. Pliocene? (and/or Miocene?) - Older pre-Recent limestone. Includes about 400 feet of limestone, at the top, that generally resembles unit 3 except for the originally aragonitic coral heads being more generally altered or dissolved away in unit 6. In unit 3 the corals are commonly relatively well preserved. There are also general faunal differences between units 3 and 6 that need analysis. Neither the base of unit 3 nor the top of unit 6 has been seen by the writer. Thus it is not known whether they are separated by some other unit or units, or by disconformable contact, or whether they grade into one another somewhere well below the surface of the northern plateau. Unit 6 is supposed on topographic evidence to be in the vicinity of 600 feet thick. Thus, according to present provisional estimates, a deep boring on Mt. Barrigada or in the vicinity of Northwest Field should encounter volcanic rocks at a depth of 1200 to 1400 feet (perhaps more) after penetrating units 3 and 6, and perhaps unit 4.

The basal 200 feet or so of unit 6 is a rather distinctive subunit that may be called the Acropora - Quidnipagus zone, from its abundant content of staghorn corals such as Acropora and the common occurrence in it of a warped tellinid pelecypod identified by Dr. Julia Gardner (U. S. Geological Survey) as Quidnipagus. This Acropora-Quidnipagus zone appears to be gradational to the upper part of unit 6. It is commonly marly and yellow to pink or rose-colored toward its contact with volcanic rocks below, but becomes paler and eventually white to cream-colored upward. Its fauna is fairly distinctive; including, besides *Quidnipagus*, a unique small ribbed *Ostrea*, an unusual small *Pecten*, and other potential index fossils. This zone may be of wide occurrence in the Pacific islands. It is, for instance, clearly represented by the basal 120 feet or so of the Palau limestone, 750 miles to the southwest of Guam, a unit of thickness (estimated by Mr. Arnold Mason, U. S. Geological Survey, to be about 700 to 800 feet) comparable to the whole of unit 6 of the Guam succession. It represents a particular shallow water facies that is apparently characteristic of large parts of the earliest post-volcanic limestones of one general age, although it is not necessarily exactly contemporaneous at all places.

The abundant staghorn corals in the *Acropora*-*Quidnipagus* zone are mostly broken and scattered about, but some are found in the normal position of growth. The fact that even a few of these delicate colonies are found unbroken is sufficient proof that the *Acropora*-*Quidnipagus* zone represents a former area of vigorous coral growth on shallow banks which were generally protected from vigorous wave action, perhaps because they lay behind the immediate sea-facing front of an actively growing coral reef. The detrital beds above it, locally containing *Halimeda* joints, are more in the nature of lagoonal sediments, suggesting that the reef, while growing upward had also grown seaward from the immediate environs of present occurrence of the higher strata.

The beds of unit 6 above the Acropora-Quidnipagus zone are also richly fossilferous at some places, and microfossils can ordinarily be found with search. Larger Foraminifera from this part of the section (at the east end of Urukthapel Island in the Palaus, and perhaps on Guam) have been identified as of Miocene age by Dr. Storrs Cole, U. S. Geological Survey. The writer of this memorandum prefers to consider correlation of these beds yet an open question and supposes that unit 6 (and the Palau limestone) may belong to the Pliocene. It seems that further regional analyses of both the microfossils and megafossils of Pacific islands would be desirable.

The limestones here referred to as unit 6 are assigned to the Mariana limestone by Tayama (reference 12, p. 184), but the limestones on Saipan that have been mapped by Tayama as Mariana limestone probably correlate with unit 3 (Barrigada limestone) of the present memorandum. Until it can be settled as to what the Mariana limestone should properly include, it seems advisable not to employ the name.

Unassigned Post-volcanic limestones. On his "Geologic Map of Guam", and on page 29 of reference 7, Stearns makes reference to thinly bedded shaly and sandy (tuffaceous) limestones that contain grains and pebbles of volcanic rock and occur in the Talafofo Valley and the foothills east of Agat. These beds are reported to be over 50 feet thick in some places. They are apparently believed by Stearns to represent the oldest limestone on Guam. Microfossils have been obtained from these rocks by the Marianas Party but they have not yet been reported upon, and the placement of the strata in question in the stratigraphic scheme here outlined is not practicable. With no more data than are at present available to the writer it seems equally possible that these rocks might represent a unit older than unit 6, as Stearns supposed, or an onlap facies of some part of unit 3 or unit 6.

Unit 7. Oligocene? (and/or Miocene?) - Volcanically derived rocks consisting primarily of water-laid pyroclastics, with minor beds of limestone and marl at least in the upper part. The thickness is estimated to exceed 1000 feet. Microfossils presumably from some part of this interval have been identified as Miocene by Dr. Cole. They include the foraminifer Nephrolepidina and if Miocene, are probably very early Miocene (as Cole recognized). It seems desirable to keep open the question whether these rocks are not wholly or in large part of Oligocene age.

Unit 8. Eocene? and/or Oligocene? - Volcanic rocks consisting largely of lava flows. The thickness is roughly estimated to be about 1000 feet. Unit 8 is here given primarily on the authority of Stearns (reference 7). This part of the Section was seen by the Marianas Party only in a brief foot traverse from Facpi Point up the west slope of Mt. Lamlam and again in jeep reconnaissance at the southwest end of Guam. Units 7 and 8 are arbitrarily and broadly defined for purposes of this preliminary discussion. The chances are that a number of mappable units can and will be recognized in these intervals when they are studied in detail over a wide area. Data from deep borings at present being made on Mt. Tenjo by the Pacific Islands Engineers may well prove of special interest in connection with the succession and thickness of the volcanic rock.

2. STRUCTURE

a. General Features.

The larger structural setting of Guam was briefly stated in the introduction to this memorandum, where reference is made to a regional analysis by Hess, (reference 1). Guam itself consists of two distinct major structural units. The northern plateau comprises essentially flat-lying limestones, cut by a few normal faults and interrupted at the surface only by the outlying volcanic patches of Mt. Santa Rosa and the vicinity of Mataguac Hill.

The southern hill-country consists of volcanic hills with a cap of older limestones (unit 6) at the west central crest-line, with aprons of younger limestone (unit 3) over the lower seaward slopes except in the southwest, and with scattered patches of limestone at intermediate elevations, especially in the Talofofo drainage basin. The structural features of the southern volcanics have not been studied by the Marianas Party. However, from casual observation, and by analogy with outlying Mt. Santa Rosa, they are thought to be probably very complex and to include thrust faulting from west to east and overturning eastward of tightly folded strata.

Mt. Santa Rosa and the volcanic patches on and near Mataguac Hill are of special interest as outliers of volcanics completely surrounded by limestone. Are they buried hills or up-faulted horst-blocks or both? Evidence from topography suggests that Mt. Santa Rosa may be bounded by faults at the northwest and southeast sides, but distribution of the rocks belies this. It may be, and is here provisionally suggested, that Mt. Santa Rosa was a block-faulted hill that moved upward along faults transecting both the volcanic sequence of units 7 to 8 and the limestones of unit 6, and against which partially overlapping younger limestones of unit 3 were deposited. The possible bounding faults would parallel the island-waist fault, for which a similar interpretation is proposed. Evidence on this point may derive from dating of the buried limestone pinnacle mentioned in the discussion of unit 5 (under "Stratigraphic succession"). A similar interpretation as partially buried lines of older faulting may obtain for alignments marginal to Mataguac Hill and similar possible volcanic outliers (not examined on the ground) beyond it.

In its particulars the structure of Guam appears to be highly complicated and only a few gross features can be pointed out at this time.

b. High-angle Faulting.

One of the geologically impressive things about Guam is the marked topographic, vegetational, and lithic break just south of the waist of the island - the northern half being a thickly jungled limestone plateau and the south half an area dominated by rolling volcanic hills that support a lush growth of sword-grass. This break was interpreted by Josiah Bridge as a northwest-southeast trending trans-island fault. The gross distribution of rock-types on the island would be accounted for by such a fault, dropping the limestone plateau down on the north side against up-thrown volcanics to the south. However, it explains an even broader range of local anomalies, some inimitable to the idea of this break being an actual fault line, to infer that movement along a fault, near but not exactly connectant with the topographic and vegetal break, occurred before or during the deposition of unit 3. Thus, it is here suggested, that the limestones of unit 3 were deposited against a fault-line scarp at the waist of the island, and that they generally overlapped southward beyond the actual fault line, burying it from view.

Probably such extensions account, in part, or in their entirety, for the aprons of limestone now to be seen on the lower seaward slopes of the volcanic hills to the south. There may have been later movement along this same fault line (suggested by apparent offset of the Pleistocene marine terraces), but if so it was probably insignificant.

In addition to the waist-line fault, and possible other partially buried faults of the same epoch of displacement that are marginal to Mt. Santa Rosa and Mataguac Hill, topographic evidence suggests that other high-angle faults may be located as shown on figure one by the Agana fault (?), the Agafo Gumas fault (?), and a few other similar topographic lineations.

The Agafo Gumas fault (?) is suggested with more confidence than the Agana fault(?). The former trends northwest-southeast about parallel to the waist-line fault and is best displayed just northeast of the stretch of road (Route No. 9) that passes Agafo Gumas between Northwest Field and North Field. At this point there is a fairly straight north-facing scarp about 100 feet high. It fades out to the northwest and southeast, but coincident alignments carry through to the northeast end of Northwest Field and the sea-bluffs east of Mt. Santa Rosa. The bluff mentioned is hard to account for as an erosional or constructional feature and very likely is a fault, but proof of this point is probably impossible to obtain. If a fault, it is downthrown to north and of decreasing throw in both directions from the center.

The very straight northeast-southwest trending scarp between NAS Agana and Harmon Field is also interpreted as a possible fault line scarp, the structural feature in question being referred to as the Agana fault (?) and thought to be downthrown on the northwest side. A fault along this line, of but slight throw at the northeast corner of Harmon Field, but increasing to several hundred feet of throw to the southwest, would account for the lowering of what appears to be the same surface from over 300 feet at Amantes Point to near sea level south of Saupon Point.

A topographic lineation suggesting another fault similar to the Agafo Gumas fault is located less than a mile southwest of and nearly parallel to the latter, and another trends northwesterly through the south central part of the Orote Peninsula.

No definite pattern of normal faulting emerges from the data at hand. However, there is strong suggestion of a tendency to high-angle fracturing along nearly parallel northwest-southeast trending lines, and possibly also nearly normal to this trend, in the northeast quadrant.

c. Reverse Faulting and Folding.

Studies on Mt. Santa Rosa have revealed the presence of thrust-faulting with major crustal displacement from west to east and sympathetic back-thrusting from east to west. This was accompanied or preceded by accordion-type folding of the strata into anticlines and synclines and overturning of folds to the east. Associated with the thrust faults, and at right angles to them, are tear faults that offset the line of thrusting. Indications of schuppen-structure are found in the occurrence of subsidiary thrusts above the surface of principal displacement.

A detailed analysis of Mt. Santa Rosa is the subject of a separate memorandum by Mr. R. G. Schmidt of the Marianas Party.

It is almost certain that thrust-faulting has also affected the southern part of the island, but studies here were only the roughest sort of reconnaissance. From the air Mt. Tenjo looks as though it might be a synclinal mountain, plunging northward into a zone of high-angle faulting in the northeast quadrant, and over-steepened on the east side against a tight anticline that is cut off on the east by a fault. Some marked folds were seen to the south-east of Mt. Tenjo in the valley of the Ylig River during aerial reconnaissance flights.

3. GEOMORPHOLOGY

a. Processes

Marine erosion, surface weathering, abrasion by materials carried in surface waters, and underground solution have worked upon and within an inherited lithic and structural pattern to produce the topographic features that one recognizes as the island of Guam. The volcanic hills weather to conventional patterns and develop what one may think of as a "normal" drainage system. Accordance of summit levels in some areas of volcanic rocks suggests dissected older surfaces of broadly bench-like nature; perhaps the most conspicuous being what appears to be a wide, tilted and dissected terrace that dips eastward from the island crest in the southern part of Guam. The limestones develop some unusual features that warrant brief special discussions.

b. Terraces and Other Evidences of Deleveling.

At Pati Point in the northeast one sees five well defined wave-cut benches or terraces, and less well defined surfaces on the higher volcanic and limestone slopes may bring the total to about 10 such features. Each bench represents a long stand of the sea at a particular level, or the land at a particular height. Any relatively low stand of the sea might, if of sufficient duration, wipe out evidence of higher and thus older benches - as erosion at or near present sea-level has done to older benches at many places. Thus the number of benches preserved on any given island shows only the minimum number of changes of sea level with respect to the land and/or of movements of land with respect to the sea in the course of more recent island history. Special sorts of evidence are required to determine whether a given surface represents movement of land or of sea and in what particular direction movement was.

The entire history of the deleveling events on Guam and other islands is not to be found in terrace features alone however. The present "reef" at Tarague Beach is clearly an erosional feature, etched by solution and wave action from an elevated bench of limestone that was once continuous across the shallow and irregular lagoon from shore to "reef" front. Cave deposits such as stalactites and stalagmites result from evaporation of dripping ground waters and thus are formed only above water-level. The occurrence of such dripstone features submerged below sea-level in caves at the foot of the bluff inshore from Tarague Beach is evidence of recent upward movement of sea-level or downward movement of the land. Drowned stream-cut valleys such as occur in southern Guam indicate present submergence of older valley-mouths. Submarine profiles, where sufficiently refined, may furnish evidence for still other deleveling events. The best that can be confidently asserted is that Guam has experienced many relative changes of land and sea since the deposition of unit 6. It is likely that at least some of the more recent benches in question resulted from changes in the actual volume of ocean water associated with Pleistocene glaciation and deglaciation.

H. T. Stearns (reference 9) has contended that the most recent relative movement of sea with reference to land in the Pacific Ocean area was a 5 foot eustatic (everywhere the same) lowering of sea-level. His evidence emphasized the elevated solution and wave-cut notch that occurs 5 to 8 feet above the present sea-level notch at so many places, but many other evidences ("raised" beach-limestones, the surfaces of atoll islands, the floors of certain caves) are in accord with this interpretation. However, the evidence of submerged cave dripstone on Guam and on Peleliu Island, Palau Group, indicates that there has also been a recent rise of sea-level, a minimum rise of 15 feet being indicated by a submerged dripstone column in an open cave near the end of the northeast peninsula of Peleliu.

The question might be raised whether the most recent shift of sea level in Micronesia has been up somewhat more than 15 feet to recovery some 5 feet short of a previous high stand or down 5 feet. Both appear to have been fairly recent events. Formation of the caves with submerged dripstone probably took a long time. It quite clearly preceded the upward movement of the sea that submerged the dripstone. Other caves have flat floors at the five-foot level and the fact that they have not been noticeably extended downward indicates that they probably represent a later period of cave formation. The logical sequence of these late events appears to be (1) cave formation, (2) submergence and drowning of dripstone deposits followed by formation of new caves with floors at or near the sea-level of this epoch, (3) emergence of 5 feet. Stearns' conclusion appears still to be a valid one.

c. Solution Features (caves, sinks, etc.)

Whereas the southern half of Guam displays a well developed surface drainage system, including several large perennial streams, observable surface runoff is essentially non-existent on the northern limestone plateau. This part of the island is a virtual sieve. Except where depressions are floored and plugged up with a soil deposit or a relatively impervious evaporite film, most of the rainfall simply runs into the ground. Even temporary and minor natural surface water courses are almost absent. This down-drainage occurs through pipe-like vertical solution channels, caves, crevasses, and the generally pervious and vuggy body of the detrital and coralliferous limestones themselves. Special concentrations of sinks occur north of Wettengel Junction and southeast from the airstrips at NAS Agana, suggesting probably similar concentrations of subsurface caverns at these places, and many other sinks are scattered over the northern limestone plateau. There are, without a doubt, a very large number of caverns of various sizes and shapes in the limestones of the northern plateau. Those so far seen by the writer fall into two main groups: (1) pipelike openings that extend straight down from below the soil level, and (2) more conventional types of caverns of domal or irregular shape, but with horizontal extent about as great as or greater than their height. Data available to the writer are not sufficient to say whether these are distinct types of openings formed under different conditions or by distinct variations of the solution process, or whether they are but end members of a series.

The seaward cliff margins of the northern limestone plateau and the limestone apron on the east side of the island are knife-edges that slope steeply landward to the terrace-surface proper and have subvertical seaward fronts. Similar features occur elsewhere but are less well developed. Hoffmeister and Ladd (reference 2) have shown that such rims develop as solution features. When rain falls on an inclined limestone surface, however slight the inclination be, and even where the limestone is highly permeable and most of the drainage is downward, some of it will run down the inclined surface dissolving 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. If the limestones of the northern plateau are of lagoonal origin they probably sloped centripetally to begin with. Over a period of time, even with minimum surface runoff, solution can and has etched out the downslope areas, leaving the peripheral rim as described.

In a more general sense, and apart from the wave-cut benches, the limestone portions of the island owe the particular details of their present expression almost entirely to the effects of solution. The limestone surfaces are everywhere pitted, pinnacled, and crevassed from the action of solvent waters, aided by the physical and chemical processes that accompany dense jungle vegetation.

That solution has played a part in the etching out of the present shallow shore-line lagoons of Guam, and in the development of the surf-line channeled ramp, is certain. However the processes and the sequential history involved in these developments are as yet too poorly understood to warrant discussion even in a provisional way. More data are needed concerning these interesting features.

d. The Lamlam-Almagosa Basin

The ridge-capping older limestones in the west central part of the southern volcanic hills of Guam widen out in the southern part of their outcrop and at this place form a locally interrupted peripheral ridge around a central basin. The bottom of this basin is several hundred feet below the surrounding ridge. Mt. Lamlam lies on the west side and Mt. Almagosa on the east side of the peripheral ridge, and the ridge and basin extend both north and south from them. The basin is broken at the middle by an isolated, east-west elongated hill. The total region involved is about 1.2 miles wide east to west by 1.5 miles long north to south.

The ridge-capping limestones of the Lamlam-Almagosa basin belong to the basal Acropora-Quidnipagus zone of unit 6 and are rich in the remains of staghorn-types of coral. They have been interpreted by Tayama (reference 12, p. 184-186) as the preserved outer reef to the north. He supposes the two segments of the basin itself to represent the ancient lagoons that lay behind these reefs, admitting, however, the possibility that they may have been modified to some extent by solution.

Attractive as this hypothesis is it must be regarded as open to query. The abundance of staghorn types of corals and scarcity of other sorts is more suggestive of bank, back-reef, or shallow lagoonal growth than it is of an outer-reef situation. The greatest concentrations of staghorn-types of corals today are in relatively protected shallow waters, and where they thrive on the reef front they are ordinarily associated with more massive types of corals that probably afford them some protection from the force of the breakers.

It is suggested, therefore, that the limestones of the Lamlam-Almagosa ridge represents an old back-reef, bank, or shallow lagoonal growth and that the growing outer reef lay beyond the present area of outcrop in this vicinity. Of course, the Lamlam-Almagosa basin may, even in that event, represent the peripherally truncated remnant of an atoll. Its present topographic expression however, could also be accounted for as the result of solution alone, with extreme development of rimmed margins similar to those described above. The chances are good that even if it is an elevated atoll remnant its original contours have been greatly modified by solution.

4. Geologic History

Stearns (reference 8) has published an abstract of the geologic history of Guam which present interpretations confirm in most essential features. The ensuing provisional summary follows the pattern of Stearns' abstract as far as possible, and "Quotes" or 'paraphrases it with modifications' as far as it is in agreement with present interpretations. Beginning with the oldest event for which there is evidence, important developments in the geologic history of Guam appear to have been as follows:

'(1) Building up of submarine volcanic materials on the Marianas geanticline. The first extrusions were chiefly flows of basaltic pillow lava (unit 8) from fissures a few feet wide. Consolidation of lavas within these fissures produced a dike-complex with cross-cutting relationships to the older lava flows. An intermittent explosive phase followed, during which varied pyroclastic materials were produced (unit 7) and deposited for the most part in shallow marine waters. Occasional lava flows occurred even during the later explosive phase.'

"(2) Cessation of volcanism".

"(3) Intense folding and overthrust faulting." Folds are overturned toward the east, and the upper blocks of major thrusts moved from west to east, with local sympathetic backthrusting from east to west.

"(4) Deposition of shallow water limestones" (unit 6) both in the detrital back-reef, bank, or lagoonal facies and through the constructional activity of reef-building corals and calcareous algae.

"(5) Renewed faulting." Inferred faults of this age are high-angle normal faults that strike northwest-southeast. They include the island-waist fault and the inferred faults at the northeast and southwest sides of Mt. Santa Rosa.

"(6) Emergence of 1300 + feet and subaerial erosion. The highest point of the island is 1334 feet above sea level and is capped with reef and detrital limestone." It is believed that during this interval gravel (unit 5) was distributed over the surface, but the gravel has now been largely removed.

"(7) Resubmergence during the Pleistocene to (about) 700 feet above the present strand...The Barrigada limestone (unit 3) was deposited...and...now forms the northern plateau." The Barrigada limestone (or unit 3) was probably deposited against fault line scarps at the waist of the island as well as at the margins of Mt. Santa Rosa, overlapping the fault lines at many places to rest against the older volcanics. Possibly the peat-bearing beds of Talofofo Valley (unit 4) were also deposited during stage 7. A subsidiary event of stage 7 is believed to be registered by the occurrence within the limestones then deposited of patches of soul. If these are truly within the limestone succession, at least a large part of the south one-third of the northern plateau was at this time emerged and soil was formed upon it or transported to it. According to the interpretation here followed the area was finally resubmerged, with removal of the soil zone from most places, registration of local unconformity, and continuation of deposition of limestone through stage 7.

"(8) Complicated series of emergences and submergences, partly as a result of changing ocean levels, ending with Guam emerged (about) 700 feet, to nearly its present level, but with the valley mouths partly drowned. Five distinct marine terraces were cut in the Barrigada limestone." The more recent faulting on the island (Agafo Gumas fault?, Agana fault?, the faults that drop the conglomerate of unit 4 into the older volcanics, and others) possibly occurred during this time.

"(9) A long stand at somewhat more than 15 feet above present sea-level." During this time caves were dissolved from the limestones below the surface of the northern plateau and dripstone deposits were formed in these caves through the evaporation of meteoric water carrying calcium carbonate in solution. Probably most of the effects of solution to be seen on the northern plateau were accomplished or started during interval 9.

(10) Eustatic rise of the sea to about 5 feet above the present

stand and formation through solution or abrasion of a sea level notch and a wave cut platform leading seaward from it. Caves with nearly flat floors at or near the five-foot level were formed during this stand of the sea.

11. "Emergence of 5 feet." Actually a eustatic fall of sea-level to its present position, as indicated by shoreline features over a wide area in the Pacific.

12. Etching of the present shallow lagoons by solution and abrasion of the wave cut platform of stage 10. Accompanied by local overbridging and repair of an older channeled ramp through algal agencies and by growth of corals at favorable localities.

The present soils and surface features of the northern limestone plateau were formed over the period of stages 8 through 12, and for the southern volcanic hills over the period of stages 5 through 12.

WATER SUPPLY

1. General Considerations

Taking the area of Guam as 225 square miles and the average yearly rainfall as 90 inches, computations show that approximately 375 billion gallons of rain fall on Guam in an average year. If the rainfall were evenly distributed this would amount to roughly one billion gallons a day. But there are days when no rain falls at all, and rainfall records from January 1919 through July 1948 show that monthly rainfall ranges from 44.5 inches (October 1924) to less than an inch (February-May in a number of years).

Over this period many months witnessed less than an inch of rain, but few witnessed much less than one-half inch and no rainless month is recorded. In a month with only one-half inch of rain, approximately two billion gallons would fall on Guam, or about 33 million gallons daily. About half of this would fall on the northern limestone plateau and half on the southern volcanic hills.

Taking probable island-wide water demand on Guam as approximately ten million gallons daily, it could be supplied continuously without permanent large capacity storage basins only if it were possible to recover at times of minimum rainfall one-third of all the rain that falls. One drinks ground water or ponded runoff, not rainfall. Although exact figures cannot be calculated, it is probably not possible to recover so large a proportion as one-third of the total rainfall and an impounding system will eventually be required if the present or a larger military and civilian population is to be maintained permanently on Guam.

On the other hand, over a period of time it is necessary to recover only about one hundredth of the total average rainfall in order to provide 10 million gallons of water daily for Guam. Wise development over a long period of time could probably yield a permanent daily water supply of several tens of millions of gallons. The problem is thus not actually one of supply, but one of recovery, storage, utilization, and prevention of contamination.

2. The Southern Volcanic Hills and Island-wide Supply

Planning of the development of a water supply by impoundment of surface runoff in the south half of the island has been sound, although it would have been desirable for more thorough surface studies of the geology to have been made prior to the initiation of a drilling program. Geologic and hydrologic investigation should continue in the south half of the island with a view to re-evaluation of the suitability of basins other than the Talofofo Valley for impoundment of surface runoff to accumulation of runoff records, and to consideration of the advisability of building more than one dam in the Talofofo Basin itself. Because of contamination problems in the northern limestone plateau an island-wide water supply, utilizing as fully as practicable the surface runoff from the volcanic hills, would be very desirable, and joint Armed Forces consideration of this problem is urged.

Ground water in the volcanic hills themselves is of insignificant quantity due to generally low permeability of the volcanic rocks and high surface runoff. However, perched water in the larger high-limestone masses issues in copious springs located at the contact of the limestone with the volcanic rocks below. These well known and large springs have been discussed in detail by Stearns and Piper. They are an excellent source of water and will serve indefinitely to augment the runoff impounded at lower levels and as an emergency supply. If necessary, production from these springs could probably be increased by better recovery at the point of outflow and by construction of adequate reservoir facilities for storage of excess water that may be drawn at times of maximum outflow.

3. The Northern Limestone Plateau

a. General Features.

Natural surface runoff of rainfall on the northern limestone plateau is very slight indeed and no permanent streams occur in this region. Most of the rain simply descends through the highly and irregularly pervious limestone to join the basal fresh water body that floats in equilibrium upon salt water below in accordance with the principles established by Ghyben and Herzberg, (see especially Wentworth, references 13 and 14, for discussion of these principles).

It is something of a euphemism to refer to this basal ground water body on Guam as a lens. Piper's data (reference 6) show that it is divisible into at least a northern and a southern portion, and special conditions certainly prevail around the volcanic inliers of Mataguac Hill and Mt. Santa Rosa. Moreover the irregular permeability of the limestone bedrock of the northern plateau must introduce further irregularities of distribution from that expectable under ideal conditions.

At any place where the normal overlapping contact between limestone and volcanic foundation rocks rises above sea level, wells drilled to this contact are almost sure to produce some water. Considerable interest would attach to any information on the distribution and topography of any buried volcanics that may reach above sea level in the area of the northern plateau. If Mataguac Hill and Mt. Santa Rosa are not partially buried fault blocks, but peaks on a volcanic erosion surface buried by the Barrigada limestone, there may be a considerable area of contact water in their vicinity. Similarly, if the soil patches between Barrigada and the southern volcanics are buried volcanic pinnacles rather than soil pockets, contact water should occur here also. Interpretations made in this memorandum minimize the possibility of such contact ground water, but convincing evidence as to the position of the limestone-volcanic contact below the northern plateau is lacking. Geophysical data on this point would be of interest. Meanwhile it is hoped that some of the wells now being drilled around Mt. Santa Rosa and Barrigada Hill by the Pacific Island Engineers will be located and carried to depths sufficient to test some of the views here expressed.

b. Basal Ground Water and the Ghyben-Herzberg Lens.

It is sufficiently certain that the principles involved in the concept of the Ghyben-Herzberg "lens" govern the distribution and recovery of water from the northern limestone, even though the shape of the body or bodies may depart widely in its particulars from that of an ideal lens. Assuming that equilibrium conditions exist, the water that percolates through the permeable limestone falls to near sea level and then either flows outward to the sea or displaces other water that does run to the sea.

Well records on Guam indicate that the level of fresh water near the center of the plateau is about 7 feet above mean low-low tide. In terms of the Ghyben-Herzberg principle, if salt and fresh water were immiscible this would imply a fresh water lens 280 feet thick at the center, pinching to a feather-edge at the beach and floating on salt water below. This follows from the principle of the U-tube, requiring that (assuming immiscibility) the thickness of the fresh water column should be found by dividing its height above sea-level by the difference between the specific gravity of marine and fresh water. Thus $T = 7/1.025-1.0 = 280$ feet. But as marine and fresh water are miscible with one another there will be a zone of contact mixing between fresh and salt water in the lens, the thickness of the zone of mixing at any place depending upon local conditions of tide, rainfall, deep circulation, pumping practices, and degree and regularity of permeability.

The limestones of north Guam are highly but irregularly permeable and it is worthwhile to quote some remarks of Wentworth (reference 13, p. 176-177) on the subject of irregular permeability and the Ghyben-Herzberg lens. "A formation consisting of moderately permeable material but broken by large, irregularly spaced fissures or caverns would have irregular permeability. The adverse effect of irregular permeability would lie in introducing large and changeable irregularity of pattern in the three-dimensional network of surfaces of equal pressure and hence of lines of flow, of velocities, and of salinities. It is evident that in formations permeable enough to meet the Ghyben-Herzberg requirement, large irregularities will promote intermixing and tend to effacement of the zone of balance, which without frictional stabilization can only be stable between immiscible liquids. In a sense, large openings of such length and direction as to lead across the zone of mixing are to be regarded as short circuits which produce potential disturbance analogous to that in an electrical network. Moreover, the movement of saline water toward fresh, or vice versa, taking place during any phase would leave residues of great importance. It therefore appears that, increasingly, irregularity of permeability would tend strongly toward effacement of the salt water - fresh water contact on which the Ghyben-Herzberg lens depends, just as would increase of general permeability.

"It appears that this variation in permeability, with some large openings going outside the favorable range of permeability, may be a very large factor in explaining the great differences in the Ghyben-Herzberg conditions on different coral limestone islands, or on different parts of the same island (underlining supplied). Not only initial differences due to structure of calcareous accumulation, but also fissures (and caves) developed near sea level by the action of fresh water probably are important here. Such an interpretation has been suggested by the writer's (Wentworth's) observations in the Marianas."

In spite of the qualifications expressed, the validity of the general principles involved in the Ghyben-Herzberg concept is sufficiently as well established and the geologic features of northern Guam sufficiently well understood that it may be confidently supposed that there is a very large body of basal ground water floating in equilibrium on salt water beneath the northern plateau.

However, withdrawal of fresh water beyond natural recharge at any point disturbs the condition of equilibrium, leading to rise of the zone of mixing in a larger or smaller area around that point - as overpumping has done in the Agana Bay region. There is a strong element of irreversibility involved in thickening of the zone of mixing (as Wentworth brings out in reference 13, p. 178-181); and, at any given point water removed from the basal lens cannot exceed normal replenishment over any considerable interval of time without disturbing the natural equilibrium. The only excuse for risking such disturbance is a serious emergency such as war or natural catastrophe.

It is to be kept in mind in connection with all ground water development around the margins of the northern plateau of Guam that production can probably be increased by the driving of horizontal infiltration tunnels located so as to skim the surface of the lens. Moreover, risk of permanent mixing is reduced as the area of skimming is increased for any particular pumping point and volume. The greater the area of the intake surface the smaller is the drawdown necessary to pump a given volume of water, and the smaller the drawdown the less is the danger of inducing inmixing of more saline water from the lower part of the lens. Horizontal infiltration tunnels at an angle to the direction of outflow (approaching parallelism to the shoreline) will probably permit the greatest "take" for a given area of pumping. Driving of infiltration tunnels inshore from caves with springs of weak flow might well open up new natural channels, permitting proportionately larger withdrawal from the vicinity of the cave without increased danger to natural conditions of equilibrium.

It is recommended that new points of marginal withdrawal from caves or infiltration tunnels not ordinarily be located within less than one-fourth mile of existing points of active withdrawal. If they are located more closely than this, special precautions should be taken against overpumping.

Caves or other large openings that may cross the boundary between fresh and salt water lead to local irregularities in the "lens" and upward extension of the zone of mixing. It is quite possible that some of the caves near the shore line do cross this boundary, and high salinity determinations at such places thus do not necessisarily condemn the site as a source of fresh water. Infiltration tunnels through more uniformly permeable adjacent rock at such places may well yield potable water.

c. The Present Water Supply Problem.

Consideration of the present problem of water supply in north Guam shows it to be threefold: (1) How may contamination be avoided, (2) how much water may be safely and continuously drawn at any given place, (3) where and how can additional basal ground water be obtained. With the excellent studies of Stearns, Piper, and Sundstrom (references 7, 6, 11) available to interested parties, it is possible to omit most discussion of past practices and records and concentrate on present and future problems.

(1) Contamination of water supply in the northern plateau is an ever-present and serious danger which can be minimized by continuous vigilance, but which probably cannot be avoided. It must be kept in mind that any fluid - gasoline, other fuel oils, or sewage - that escapes from artificial tanks or conduits, or is otherwise brought into contact with the northern limestone-surface, is likely to move immediately downward toward and eventually to the water table. A proper sewage disposal system is needed, and adequate water purification facilities should be developed to meet the existing situation and to keep pace with possible future withdrawal of larger volumes of ground water. At the same time it would be advisable to exploit, as fully as possible, the potentialities of the more sparsely inhabited south half of the island to supply drinking water from surface runoff and perched springs. Over a long period of time it may prove advisable to supplant in a large degree present utilization

of basal water from the northern plateau with surface water pumped in from the south. As long as it is necessary to draw drinking water from the north half of the island extreme precaution should be taken as regards sewage disposal, fuel lines, fuel storage centers and other possible sources of contamination in this area.

(2) How much water may be safely and continuously drawn at any given place? The obvious non-quantitative answer to this question is: as much water as can be drawn without lowering the head below that at which, on cessation of pumping, the water-level characteristic of equilibrium conditions within the lens will be rapidly and naturally restored. Approximate quantitative determination of this amount at any given place depends on pumping tests, and on observation over a period of time of normal water level. The safe pumping ratio at any particular place will vary with the season, and it is probable that it may be increased at any place of natural water outflow by driving infiltration tunnels ("Maui wells"). It would be advisable, in any instance, to establish large permanent reservoirs in which to store the extra volume of water that may be withdrawn during seasons of heavy rainfall and high outflow, and to provide all pumping stations with adjustable weirs or sumps that are kept set so as to prevent drawdown below the equilibrium level. Near the edge of the lens, where the more accessible sources of supply are located, the fresh-water level rises and falls with the tides, but with a definite lag in relation to them. Continuous safe withdrawal could be most nearly approached by setting up and enforcing elaborate instructions as to

pumping levels, or by devising a means of automatically adjusting the pumping levels as the normal water surface rises and falls with change in tide level. However, it is likely that long term observations can establish general pumping procedures that are sufficiently safe for practical purposes.

(3) Where and how can additional basal ground water be obtained? It probably does not matter particularly from what part of the lens water is drawn, if it is potable at that place and care is taken to prevent lowering of the ground water surface beyond a point to which it does not rapidly recover without increase in salinity when pumping ceases. A shaft to ground water level with infiltration tunnels extending horizontally so as to skim the top of the lens would probably produce abundant water at almost any point below the northern plateau, but it is far easier and less expensive to take the water from the edge of the lens.

It is probably safe to say that, except in the overpumped area of Agana Bay, almost any point around the northern limestone plateau that is over about two-tenths to a quarter mile inshore from high-tide line is likely to yield copious quantities of water of low salinity to a suitable infiltration tunnel. Of course, potable waters occur much closer to shore but withdrawal becomes a more delicate problem as the shore is approached. The chances of obtaining consistently potable water (assuming no contamination from above) of continuingly large amount are increased as one moves farther inland. It is also advantageous to have naturally occurring water for testing before going to the expense of artificial exploration.

In July and August 1948 the District Engineer, GUAMED, authorized Robert and Company Inc. to dispatch field parties to scout the lower margin of the northern plateau for such natural occurrences of water. From data obtained by these men, previously recorded information, and studies of the writer both in company with the GUAMED field men and alone, four general areas have been selected as most promising for future water development in northern Guam. These are indicated on Figure 1 and will be referred to as (1) the Tumon Bay area, (2) the Hilaan Point area, (3) the Tarague Beach area, and (4) the Campanaya - Taguan area. The first two areas are on the west side of the northern peninsula, the third at the north end, and the fourth on the east side. It is to be noted that on Guam any water of salinity below 800 parts per million is considered to be potable (assuming no contamination from above). Free use is made in the following discussion of data furnished by personnel of Robert and Company Inc., under contract to GUAMED.

(1) The Tumon Bay area is open to objection because so much water is already being drawn from this vicinity, and because of contamination with avgas from Harmon Field. However, water of low salinity as compared to much that is presently in use (average 174 p.p.m.) occurs in the bottom of a breached cave at Ypao Point at the south side of Tumon Bay, and additional water could probably be safely drawn from this place. If the site at Ypao Cave is utilized it would seem advisable to drive an inclined tunnel south-

ward into the cave from an elevation of about 40 feet at the north, and then continue it southeastward for about 800 to 1000 feet, so as to skim the surface of the lens as an infiltration tunnel. Exploitation of the Ypao Cave site as a source of water would still leave way for development in the area between Ypao Cave and "Tumon-Maui Well". However, it is not advisable to develop this area too extensively, if it can be avoided, because of the special dangers of contamination here.

(2) The Hilaan-Tanguisson area. At the foot of the bluffs about midway between Hilaan Point and Tanguisson Point are two caves in which occur water of salinity ranging from 74 to 594 p.p.m., and seeps of fresh water occur along the shore line at several places near there. Although the caves in question are only about one-tenth mile in from shore, the water in them is of quite favorable potability. If the water at this point is to be utilized, a long (800 to 1000 feet) sea-level infiltration tunnel should be driven inshore from the site. It is recommended, however, that the particular site of the caves not be exploited. Rather, if preliminary drilling tests be favorable, an infiltration tunnel might be driven into the base of the bluffs south of here and about one-fourth mile north of Tanguisson Point, where a tunnel entrance could be located about two-tenths mile inshore. An infiltration tunnel driven so as to skim the surface of the lens at the place suggested might well yield abundant potable water. Maximum withdrawal could probably be obtained by a Y-shaped tunnel, of which each segment was about 400 feet

long, with the entering segment normal to the shoreline and the inshore segments at 45 degrees to it.

(3) The Tarague Beach area (see Figure 2) already furnishes a large supply of fresh water from the cave known as Tarague Well No. 1, and a pumping station is being installed at a nearby cave known as Tarague Well No. 4. These sites are so near one another as to require special precaution in pumping.

Two caves, designated Tarague Wells No. 5 and No. 6 by GUAMED, are 1 and 1.2 miles respectively, east of Tarague Well No. 4 and just west of Tagua Point, at the foot of the sea-facing bluffs. Water samples from these ran 548 to 632 p.p.m. salinity. Both are extensive and could probably be developed as a source of water supply either with or without driving infiltration tunnels and without reducing the capacity for production of the presently yielding Tarague "wells". Again, if both sites are pumped, special precaution shoulc be taken against overdraft.

A cave about midway between Tarague Wells No. 1 and 4, and about 0.35 mile from the shore-line, contains water of salinity 484 p.p. m. It has been designated Tarague Well No. 7. Because of its proximity to Tarague Wells No. 1 and 4, this source should not be exploited unless those wells are abandoned. This cave was not seen by the writer.

The cave designated Tarague Well No. 8 was likewise not visited by the writer. It is said to be about 1800 feet east of Tarague Well No. 1 and 1500 feet south from the pipe-line to North Field. The range in salinity of its water is 94 to 294 p.p.m.

Midway between the so-called Tarague Wells No. 4 and 5 is a prominent area of collapse in the 200-foot bench that runs along the lower part of the main bluff at this place. This site was not visited, but its expression on the aerial photographs indicated it to be a favorable place for the occurrence of water. An infiltration tunnel at this place would probably yield abundant potable water, but if the caves east of Tagua Point are developed it may not be necessary to tap this source. This site is favored over Tarague Well No. 8 as a potential source of water because of its greater distance from the withdrawal area of Tarague Wells No. 1 and 4.

Northwestward from Tarague Well No. 1 for almost 2 miles the area of low ground between the beach and the sea-facing bluffs remains fairly wide. Although natural occurrences of water are not known along this stretch of ground it is virtually certain that potable water could be obtained at points along the foot of the bluff by tunneling to near sea-level and then driving an infiltration tunnel to skim the top of the fresh-water lens.

Other scalloped-out areas along the bluffs between Mergagan Point at the southeast and Ritidian Point at the northwest are worthy of testing if additional water is needed beyond that securable from recommended areas. Water from a cave just southeast of Pajon Point ran a salinity of 1053 p.p.m. (8/12/48); but potable water could probably be obtained from an infiltration tunnel near here, begun as far as possible from shore. Test drilling should be conducted in areas such as this, however, prior to the planning of infiltration tunnels.

(4) The Campanaya-Taguan area, a large scalloped-out and probably collapsed area between Campanaya and Taguan Points, is the only part of the eastern margin of the northern plateau that is at all promising for development of water within reasonable financial limitations. Elsewhere the sea-bluffs are too near high-tide line.

The salinity records from known water developments at the north of this area exceed the requirements for potability (1179 to 2043 p.p.m.). However, if infiltration tunnels were driven inland anywhere within the 1.3 miles southwest from Campanaya Point and sufficiently far from shore they would almost certainly tap the fresh-water lens. Of course, test drilling should precede driving of such tunnels. Tunnel construction would be difficult at this place because it might be necessary to drift in to ground water level from elevations near or above 100 feet before an infiltration tunnel itself could be started. There may also be danger of bacterial contamination in this vicinity because of a sewage outlet just south of Campanaya Point, and there may be a thicker zone of mixing because of the greater turbulence of the sea on the more generally windward side of the island and the absence of a lagoon at this place. However, this is the best potential source of fresh-water supply on the east side of the northern plateau.

IV. FUEL STORAGE

Comments on underground fuel storage are made primarily because of the relation this matter has to the problem of ground-water contamination. Underground fuel storage, like sewage disposal, should not be considered separately from the problem of water supply; and it would be preferable that it not be permitted in the north half of Guam except well within areas of rocks of low permeability.

The main site proposed for storage of underground fuel is on Mt. Tenjo. The impression of the writer is that this is a thoroughly advisable location. Supplementary sites proposed are Barrigada Hill and Mt. Santa Rosa.

Drill holes to a depth of 400 feet on Barrigada are said to have been still in limestone, and it is here advised that fuel storage anywhere in the permeable limestone of the north half of Guam involves serious risk of contamination of the natural underground water supply here. If tanks must be placed in the limestones on Barrigada Hill extraordinary precaution should be taken against leakage.

Mt. Santa Rosa consists of pyroclastic and effusive volcanic rocks, at least some of which are relatively impermeable. This seems a reasonably good location for underground fuel storage. Another site that would bear investigation for supplementing storage is Mataguac Hill, two miles west of Mt. Santa Rosa. These two small areas of volcanic rocks are the only two portions of the northern plateau that surface evidence shows to be at all favorable for underground fuel storage, so far as danger of contamination of underground water-supply is concerned.

Reference to structure sections and map in a summary of work by the Marianas Party in the vicinity of Mt. Santa Rosa (Memorandum for Record, by R. G. Schmidt, October 1948) will show that there are here two relatively wide belts of mostly fine grained pyroclastic rocks that attain altitudes above 700 feet. One of these is located immediately northwest of the main lava ridge on which the peak of Mt. Santa Rosa is situated, and the other is southeast of the same ridge.

Differences in permeability between the two sites are probably insignificant, and the more southeasterly belt has the advantage both of greater elevation, and of a greater area at this elevation (over 1000 square yards at elevations near and above 800 feet in the northeast half of the belt). The main disadvantage of this area is that increased permeability in brecciated zones along thrust faults that transect it may carry some leakage to the marginal limestones of the plateau around it. All points considered, however, this is probably the most favorable site for fuel storage in the Mt. Santa Rosa Area. It is also the site now being explored by the Pacific Island Engineers (under contract to the Navy Bureau of Yards and Docks) as a location for underground fuel storage. The only recommendation to be made here as regards this site is that tanks be placed as far southwest (toward the road and native dwelling) as may be possible in the area being drilled. This will take them away from the marginal limestones and minimize the possibility of lateral leakage to them.

V. RECOMMENDATIONS FOR FUTURE WORK

The recommendations of Sundstrom (reference 11) as regards water development in the northern plateau, and of Piper as regards water impoundment in the southern volcanic hills are here generally endorsed.

It is further recommended that an island wide program of run-off studies, studies of ground-water level and fluctuations be initiated, and accumulation and interpretation started of existing well records and histories. Stream-gauging stations should be established and maintained, and law should require that wells not in use, or drilled for purposes of information only, be cased, capped, and locked as permanent reading posts for the gathering of ground-water data. It is possible that a permanent water supply of 50 to 60 million gallons a day can be developed on Guam, but its development and wise utilization calls for frequent geological-hydrological consultation.

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