[AMERICAN JOURNAL OF SCIENCE, VOL. 253, OCTOBER 1955, PP. 553-573]

American Journal of Science

OCTOBER 1955

GEOLOGY AND WATER RESOURCES OF FALALOP ISLAND, ULITHI ATOLL, WESTERN CAROLINE ISLANDS*

S. O. SCHLANGER and J. W. BROOKHART

ABSTRACT. Falalop Island, triangular in plan and saucer-shaped in cross-section, is made up of calcareous reef detritus. Six lithologic units of the detritus were mapped, as follows: reef conglomerate; beach conglomerate; bedded sand, gravel, and boulders; boulder ramparts; beach sand; and mixed beach sand, gravel, and boulders. Foraminiferal assemblages from the bedded sand, gravel and boulders indicate that a shallow to intertidal reef existed in the near vicinity of Falalop subsequent to the thermal maximum but prior to the 6-foot stand of the sea. Asor Island on Ulithi Atoll displays conglomerate cliffs as much as 23 feet above sea level into which a bench 6 to 7 feet above sea level has been cut. This bench is taken as evidence that present-day Asor Island is a remnant of a larger island that predated the 6-foot stand of the sea. On both Falalop and Asor, benches and emerged beach rock indicate that a 2- to 3-foot stillstand occurred between the 6-foot stand and present sea level. The seaward reef fronts of Ulithi Atoll have been classified on a morphological basis into two types that show a definite distribution pattern on the atoll. Water having a chloride content of 48 to 1240 parts per million can be obtained in limited quantities from wells on Falalop.

REGIONAL SETTING

Ulithi Atoll is located at latitude 10° N. and longitude 139° E., approximately 300 miles southwest of Guam and 500 miles northeast of the Palau Islands (fig. 3).

The atoll is 16 miles long in a northerly direction, 12 miles broad in an easterly direction at its northern end, and 4 miles broad at its southern end (fig. 4).

The regional bathymetry is complex. The 2000-fathom line in the vicinity of Ulithi encloses most of the Eastern Caroline Islands. However, the 1000-fathom line closes completely around Ulithi Atoll and the adjacent islands of Gielap and Losiep. The 500-fathom line closes around Ulithi Atoll proper. Thus it is seen that Ulithi Atoll rises sharply from the northwest bank of the Caroline Swell and Basin province (fig. 3).

Hess (1948) placed the Caroline Swell and Basin province in the Pacific Basin proper and interpreted the major physiographic features of the Pacific Basin as structural features. The Pacific Basin province is bounded in the Ulithi region by the andesite line on the north, west, and south (fig. 3).

Ulithi Atoll lies near the boundary between the North Equatorial Current and the Equatorial Counter Current. Thus the Atoll receives currents from the northeast as well as from the west and southwest. The surface temperature of the waters around Ulithi ranges from 27° to 28° C., and the surface salinity

* Publication authorized by the Director, U. S. Geological Survey. Based on field work done by personnel of the U. S. Geological Survey while on temporary duty to the Office of the Engineer, Headquarters, U. S. Army Forces, Far East.

remains fairly constant at 34.5 parts per thousand (Sverdrup et al., 1942). During winter and spring the northern trade winds blow over the atoll from the northeast. Through the summer and fall, winds from the south and west predominate. Six of the ten typhoons that passed between Guam and the Palau Islands in 1951 and 1952 passed to the north of Ulithi. Two of these ten passed directly over the atoll and the remaining two passed to the south of Ulithi (Dinger and Fisher, 1953).

FIELD WORK AND ACKNOWLEDGMENTS

Field studies were conducted from November 23 to December 1, 1952. A continuous water-level recorder was installed in a sunken LCM on the western side of Falalop in order to obtain a tidal record. As shown on figure 1 the tidal range at Falalop from 7 A.M. to 2 P.M. November 25, 1952, was 2.8

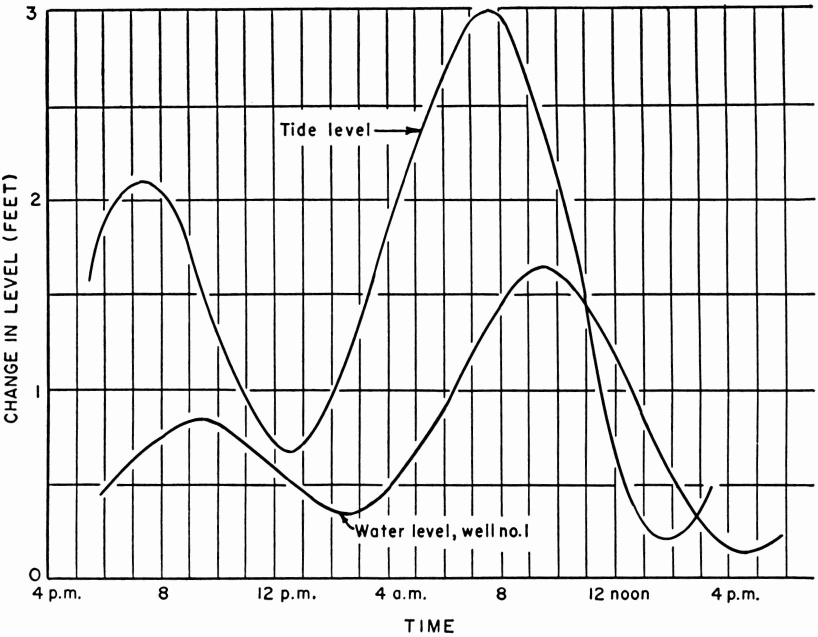


Fig. 1. Graph of tide level in the ocean and water level in well no. 1 from 4 P.M., Nov. 24 to 6 P.M., Nov. 25, 1952.

feet. The U. S. Coast and Geodetic tide tables for 1952 give 2.6 feet as the mean range and 3.4 feet as the spring range for Ulithi. On the basis of the tidal record from November 24 to 29, a sea-level datum was established and used for determining well elevations and in topographic mapping. This datum, referred to as sea level in this paper, is an average of the midheights of each daily cycle recorded. A second water-level recorder was set up on well no. 1 (fig. 2) and maintained until February 1953 by the U. S. Coast Guard detachment.

Ten wells, ranging in depth from 4.3 to 10.4 feet, were dug to procure water and lithologic samples, to observe tidally induced water-level fluctua-

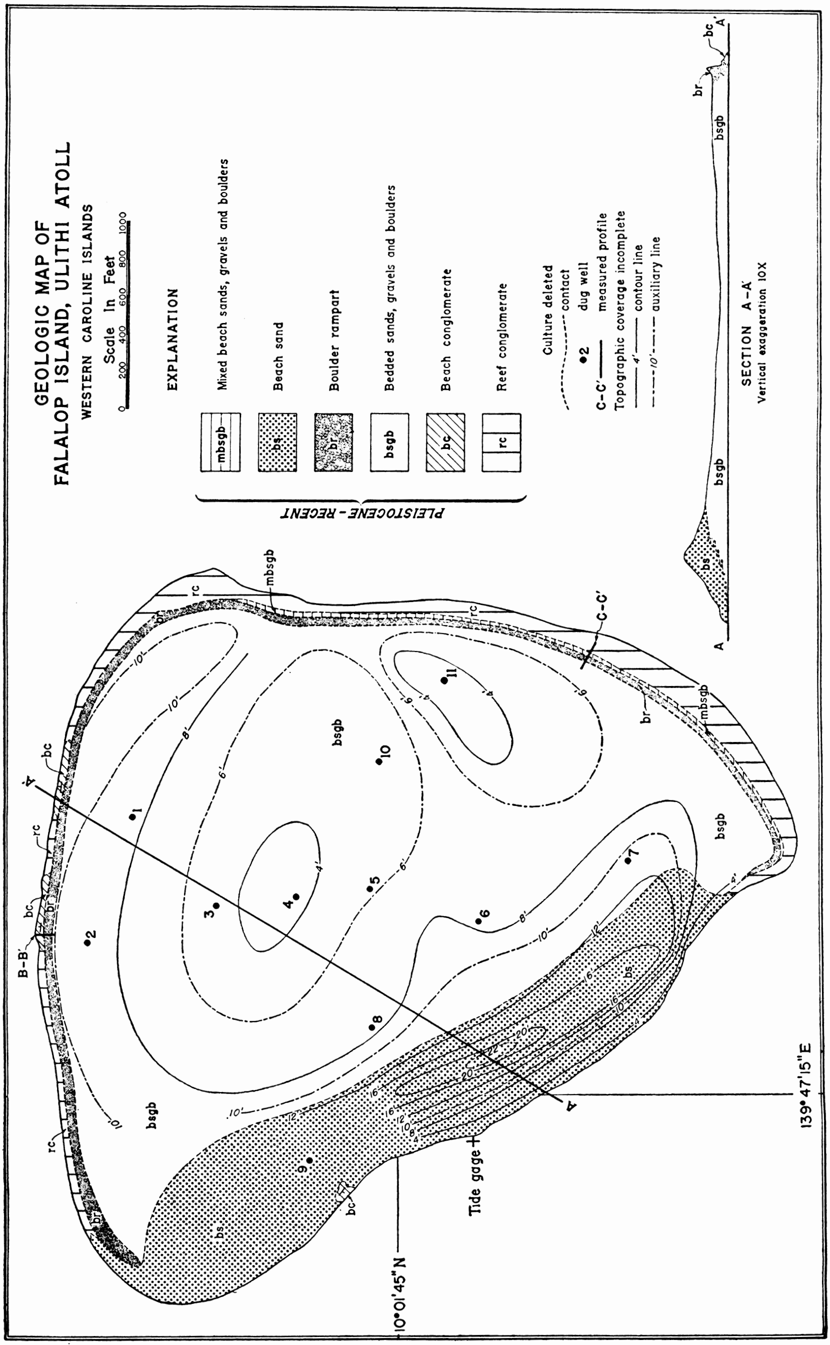


Fig. 2. Geologic map of Falalop Island.

tions, and to study the geologic section. All wells were measured for depth to water level and were sampled, at the same time, at high and again at low tide. All samples were analyzed for chloride, which ranged from 48 to 1240 parts per million.

Falalop Island was mapped geologically and topographically, and all wells were leveled in and located by a plane-table traverse. The vertical closure of this traverse was such that the elevations of the wells as given in this paper may be in error by as much as 0.5 foot in reference to the datum established.

Beach and rampart profiles were measured on Falalop, Asor, Fassarai, and Mogmog islands.

The writers wish to thank Brig. Gen. R. W. C. Wimsatt of the U. S. Air Force, and Captain W. I. Swanston and Lieutenant F. Hermes, of the U. S. Coast Guard, for their aid in transporting and maintaining the field party throughout the study. Joshua I. Tracey, Jr., of the U. S. Geological Survey, checked some of the original observations in the field.

GEOLOGY OF FALALOP ISLAND

Falalop Island, situated on the submarine promontory off the northeast corner of Ulithi Atoll, is roughly an isosocles triangle in plan (fig. 2). The base, or southwest side, is approximately 4000 feet long, and the north and east sides are approximately 3000 feet long.

The highest elevation on the island, 23 feet above the sea-level datum, is on a slightly flattened sand ridge that trends parallel to and approximately 200 feet inland of the southwest side of the island. The north and east coasts are bordered by boulder ramparts, which range in height from 3 to 16 feet above sea level. The southwest side of the island is bordered by a sand beach which is a continuation of the sand ridge. The interior of the island is saucer-shaped, sloping downward from the boulder ramparts and the sand ridge. Earth-moving operations performed during World War II obscure some of the geology of the island. The geologic map of Falalop (fig. 2) is, therefore, partly reconstructed from photographs. Six geologic units were mapped on Falalop as follows: reef conglomerate (rc), beach conglomerate (bc), bedded sand, gravel, and boulders (bsgb), boulder ramparts (br), beach sand (bs), and mixed beach sand, gravel, and boulders (mbsgb).

UNIT DESCRIPTIONS

Reef conglomerate (*rc*).—Reef conglomerate is made up of an unstratified, well-lithified, coral-boulder conglomerate in a matrix of medium- to coarse-grained algal, foraminiferal, and coral sand. This unit forms most of the shoreline around the eastern and northern coasts of the island. At present the surface of this unit is littered with loose coral boulders. That part of the unit above high-tide level is undergoing solution as evidenced by the pitted surface developed on it (pl. 1). The flatness of the surface defined by accordant pinnacle levels, coupled with the truncation of the boulders imbedded in it, indicate that this unit was planed after it was lithified.

Beach conglomerate (*bc*).—Made up of a well- to poorly stratified, coral-boulder conglomerate in a matrix of medium- to coarse-grained, foraminiferal, algal, and coral sand and gravel, this unit is found in patches overlying the

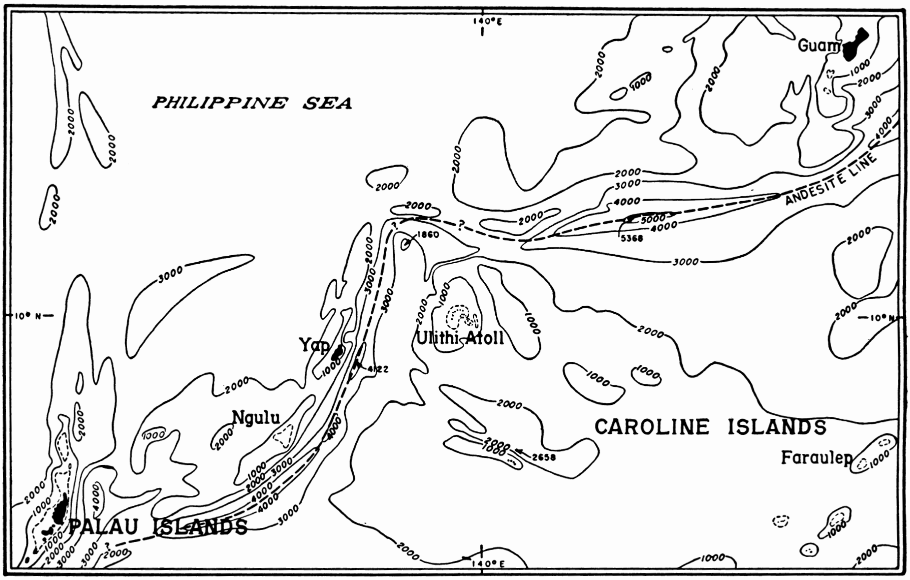


Fig. 3. Bathymetric chart of the Ulithi Atoll region. Contour interval 1000 fathoms (from H. O. Chart 5485).

reef conglomerate along the northern coast of Falalop at elevations of 2 to 3 feet above sea level. This unit probably represents a former beach deposit.

Bedded sand, gravel, and boulders (*bsgb*).—This unit forms volumetrically the greater part of Falalop. It is made up of interstratified and lensing beds of foraminiferal and algal sand, coarse-grained algal sand and gravel, and coral gravel and boulders. The following stratigraphic sections are described from wells (see figure 2 for the well locations).

Well no. 9

Elevation—10 feet above sea-level datum

Depth in feet	Lithology (see pl. 2-A)
0-1	Possibly fill. Well-rounded coral cobbles and gravel, average size 1-2 inches, some as large as 6-8 inches in diameter, in a matrix of foraminiferal sand and algal fragments.
1-3.3	Unbedded algal-foraminiferal grit and coarse sand containing cobbles of rounded coral. Approximately 20 percent algae, 20 percent Foraminifera, and 60 percent coral cobbles.
3.3-5.3	Alternating beds, 3-5 inches thick, of algal detritus and foraminiferal sand, striking N. 70° E., dipping 6° SE. These beds contain a few rounded cobble-size fragments of coral.
5.3-7.3	Alternating bands of algal detritus and coral cobbles. Irregular scattered lenses of foraminiferal sand. Algal beds strike S. 35° E., dip 25° SW.
7.3-10.3	Foraminiferal sand and rounded, polished algal detritus. Algal fragments average ¼ to ½ inch in length. Bright red *Tubipora* fragments are present.

Well no. 8

Elevation—7.5 feet above sea-level datum

0.0-4	Blackened, unbedded algal grit and foraminiferal sand containing a few angular, gravel-size fragments of coral. Possible black humus layer at 4 feet. 0.0-to 4-foot depth in this well may be fill.
4-4.5	Coral gravel in a matrix of algal-foraminiferal grit and sand.
4.5-7.5	Alternating beds of algal grit and foraminiferal sand. Individual beds are approximately 1-3 inches thick. Several of these beds are 100 percent algal detritus. These strike S. 30° E., and dip 10° NE.

Well no. 5

Elevation—5.8 feet above sea-level datum

0.0-3	Poorly bedded algal-foraminiferal grit and sand containing scattered, rounded fragments of coralline detritus.
3-3.5	Bed of coarse-grained algal detritus. Fragments range from ½ to ¾ inch in length.
3.5-5.7	Well-rounded coral boulders and cobbles in foraminiferal sand matrix. Few scattered red *Tubipora* fragments.

Well no. 2

Elevation—8.3 feet above sea-level datum

0.0-0.5	Blackened fill.
0.5-2	Coarse-grained, angular, algal detritus containing a few cobbles of rounded coral fragments.
2-2.5	Ledge of well-rounded coral cobbles.
2.5-2.75	Layer of foraminiferal sand containing a few algal fragments.
2.75-5	Alternating layers of algal detritus and well-rounded coral cobbles.
5.-6.5	Foraminiferal sands containing fine algal detritus.
6.5-8.3	Well-rounded coral boulders in a matrix of algal-foraminiferal sand.

Well no. 10

Elevation—6.2 feet above sea-level datum

0.0-3	Algal-foraminiferal sand containing rounded cobbles of coral.
3-5.7	Well-rounded coral boulders up to 18 inches in diameter in matrix of algal-foraminiferal sand.

Well no. 7

Elevation—10.0 feet above sea-level datum

0.0-3	Poorly bedded algal grit and foraminiferal sand.
3-3.25	Bed of well-rounded coral pebbles.
3.25-4.5	Bed of foraminiferal sand containing algal detritus. Bed strikes N. 40° E., dips 12° SE.
4.5-5	Bed of coarse-grained algal detritus.
5-8.2	Well-rounded coral cobbles in a matrix of foraminiferal-algal sand.

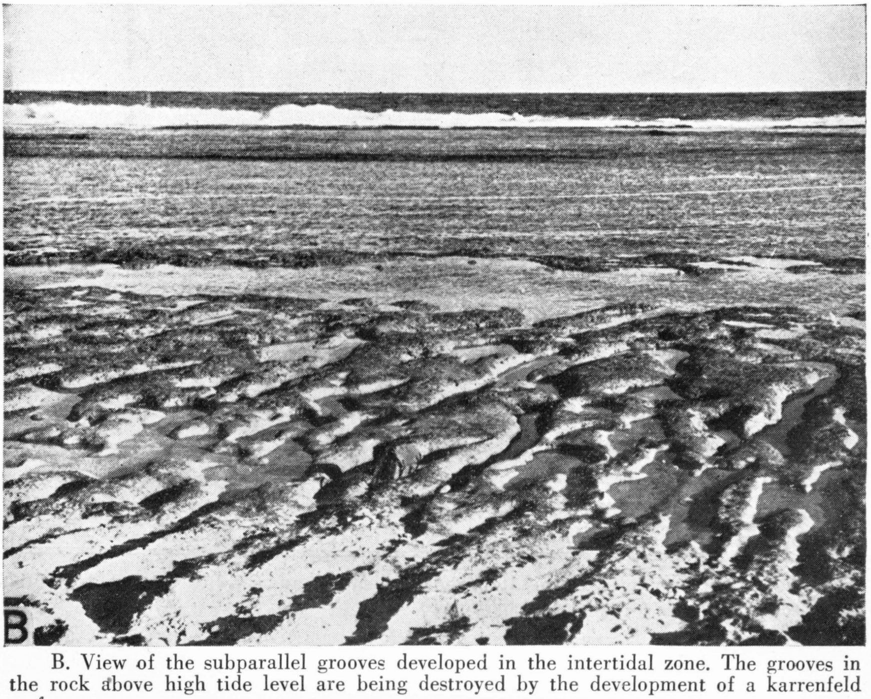
Boulder Rampart (*br*).—Loosely piled, well-rounded coral boulders and cobbles make up this unit which forms a rim around the northern and eastern coasts of Falalop (pl. 3). The maximum natural height of this rampart has been obscured by earth-moving operations. At present, however, these ramparts range in height from 16 feet at their highest point on the northern coast of the island to 3 feet on the eastern coast. The rampart at the northeast corner of the island, as shown on the map, is an interpretation based on the assumed position of the structure prior to earth-moving operations.

Beach sand (*bs*).—This unit covers the southwest coast of Falalop and forms a topographic high that parallels the coast. It is an unlithified, un-

PLATE 1

Solution effects on the reef conglomerate

A. Channels in the intertidal zone (dark area in right foreground) below the castellated surface of the rock above the high tide level.



B. View of the subparallel grooves developed in the intertidal zone. The grooves in the rock above high tide level are being destroyed by the development of a karrenfeld surface.

stratified, medium-grained sand composed of foraminiferal tests, subrounded fragments of branching, calcareous algae, and other angular to rounded calcareous clastic material.

The map delineation of this unit has been interpreted in the area of well no. 9 on the basis of talks with the natives of Falalop and on an extension of the topographic high along the southeast half of the southwest coast.

Mixed beach sand, gravel, and boulders (*mbsgb*).—This deposit is unlithified and unstratified and consists of well-rounded coral boulders in a matrix of foraminiferal and algal sands (see pl. 3-A). The unit forms a veneer

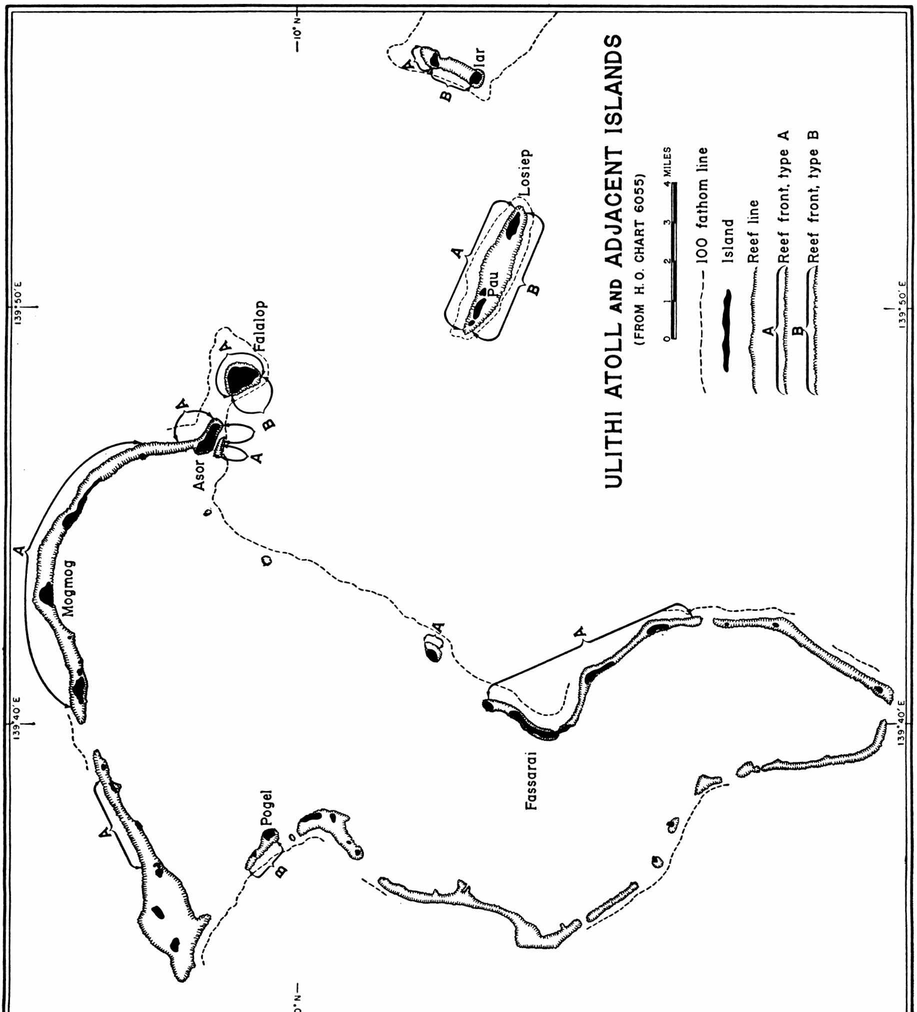


Fig. 4. Index map of Ulithi Atoll and adjacent islands showing known distribution of seaward reef types (from H. O. Chart 6055).

on the reef conglomerate at the foot of the boulder rampart. It is probably a deposit formed by storm waves that piled loose detritus on the shore.

FORAMINIFERAL ASSEMBLAGES FROM FALALOP ISLAND

Sample preparation and identification.—Foraminifera from 11 samples were identified in order to make comparisons between present-day beach assemblages and assemblages from various levels in the dug wells. Samples 9, 11, and 13 are from the beach sand (bs) and samples 1, 2, 4, 5, 6, 7, 8, and 14 are from the wells. All the samples were washed on a fine silk screen and studied under a binocular microscope.

Ruth Todd of the U. S. Geological Survey aided the writers in the identifications. Table 1 lists the Foraminifera identified and their occurrences in the samples studied.

Comparison and significance of the foraminiferal assemblages.—A comparison between the foraminiferal assemblages and the sediments associated with them yields data that are useful in interpreting the paleoecology of the deposits. The beach sand assemblages, samples 9, 11, and 13, are dominated by tests of *Calcarina spengleri*, *Baculogypsina sphaerulata*, and *Marginopora vertebralis*, all of which are characteristic of shallow water and intertidal reefs. Sample 1 from the upper part of well no. 9, and samples 6 and 7 from well no. 2 contain only these three genera. The Foraminifera from these three samples were, for the most part, well worn and polished.

Samples 5, 8, and 14 contain genera characteristic of a shallow-reef environment plus other genera which are representative of deeper water, off-reef deposits. The Foraminifera from these samples were, in general, well preserved and have retained such features as delicate spines. The sediments associated with samples 5, 8, and 14 are well worn, rounded, bedded sand, gravel, and boulders composed of reef detritus. It is thought by the writers that these sediments accumulated in an off-reef environment that received detritus from a nearby reef. The present elevation of sample site 8, which is 5.5 to 7 feet above sea level, indicates the possibility that this reef existed in the vicinity of Falalop prior to the 6-foot stand of the sea.

An alternate explanation of the elevation of sample site 8 is that the sediments represented by this sample are storm-tossed deposits laid down subsequent to the 6-foot stand. The degree of bedding and sorting displayed by the beds in well no. 7 tend, however, to belie a storm-wave origin for these sediments.

GEOMORPHOLOGY OF FALALOP

The shape of Falalop is a reflection of the oceanographic and meteorological forces acting upon it. Storm winds and waves from the north and northeast have formed the boulder rampart which extends around the windward two-thirds of the island. The sand ridge which occupies the southwestern part of the island was probably a product of the prevailing winds and waves of past geologic time as well as present-day forces. The windward reef on Falalop is a wide expanse of reef conglomerate (pl. 4-A). Wind and waves pile boulders on the windward reef thus preventing vigorous coral growth on the reef flat. The constantly submerged leeward reef supports a luxurious

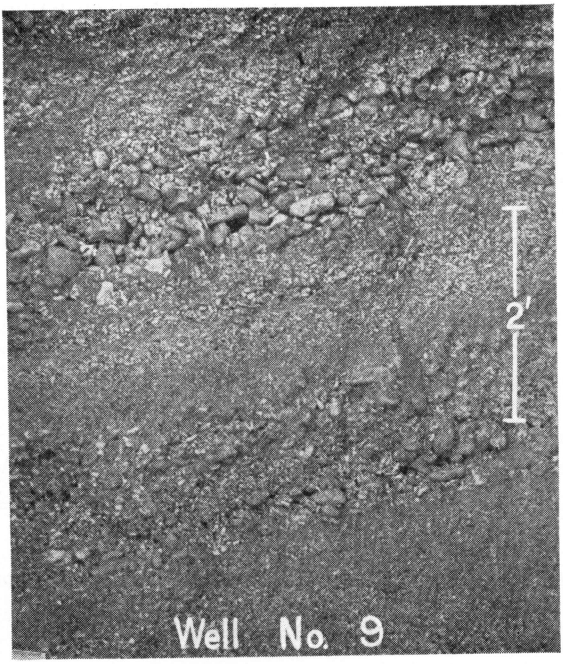
TABLE 1

Foraminiferal Assemblages from Falalop Island

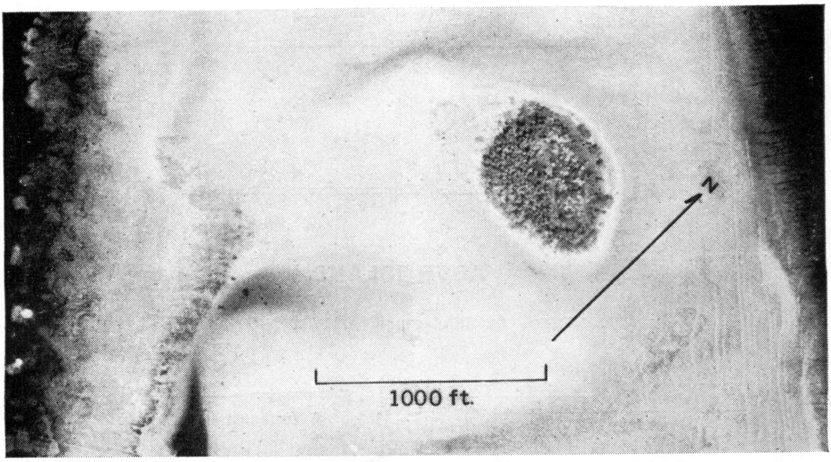
		Sample 1	Sample 6	Sample 7	Sample 9	Sample 11	Sample 13	Sample 2	Sample 4	Sample 5	Sample 8	Sample 14
		Well no. 9 3.3-5.3′ below surface. 4.7-6.7′ above sea-level datum.	Well no. 2 2.8-5′ below surface. 3.3-5.5′ above sea-level datum.	Well no. 2 5-6.5′ below surface. 1.8-3.3′ above sea-level datum.	Intertidal zone of sand beach, 1200′ SE of tide gauge.	Surface of sand beach 5-6′ above high-tide level, 1200′ SE of tide gauge.	Surface of sand beach 4.5′ above high-tide level, 600′ NW of tide gauge.	Well no. 9 9.3-10.3′ below surface. 0.7-0.3′ below sea-level datum.	Well no. 8 6.5′ below surface. 1′ above sea-level datum.	Well no. 5 3.5′ below surface. 2.3′ above sea-level datum.	Well no. 7 3.4-5.5′ below surface. 5.5-7′ above sea-level datum.	Well no. 10 3.5′ below surface. 2.7′ above sea-level datum.
REEF TYPES	*Baculogypsina sphaerulata*	C	C	C	C	C	C	C	A	A	A	A
	Calcarina spengleri	A	A	A	A	A	A	A	A	A	A	A
	Marginopora vertebralis	R	C	C	C	C	C	C	R	C	A	C
OFF-REEF TYPES	*Amphistegina madagascarensis*				C	C	C	C		A	A	A
	Amphistegina sp. (bulbous form)				C	C				C		R
	Elphidium sp.				R	R	R	R	C	C	C	R
	Carpentaria sp.									R		
	Cibicides sp.								C	R	R	C
	Cymbaloporetta bradyi							R		C	C	R
	Cymbaloporetta squamosa										R	
	Discorbis sp.									C		C
	Gypsina globulus									R	R	
	Heterostigina sp.										R	
	Peneroplis proteus									C	A	
	Pyrgo sp.									C	R	
	Spirillina vivipara								R	R		R
	Spiroloculina faeolata										C	
	Spiroloculina sp.									R		R
	Triloculina bicarenata									R		
	Triloculina terquemiana					R	R	R		C	C	C
	Triloculina transversestriata							R		R	C	
	Valvulina davidiana									C	R	
	Anomalinella rostrata									R		
	Quinqueloculina sulcata									R		

A—ABUNDANT C—COMMON R—RARE

PLATE 2



A. One wall of well no. 9 on Falalop showing the bedding and texture typical of the bedded sand, gravel, and boulders (bsgb).



B. Aerial view of Bulubul Island, on the Pau-Losiep reef, showing reef type A *to* the northeast, and reef type B to the southwest of the island.

growth of coral. The distribution of these two reef types around Falalop is shown on figure 6. This leeward reef extends 50 to 60 yards out from the beach at a depth of 3 to 4 feet. The reef platform then terminates in a submarine cliff which drops vertically to a depth of 90 to 100 feet and then slopes sharply downward at an angle of approximately 60° to depths of more than 650 feet. At approximately 25 feet below sea level on this cliff face, corals diminish greatly in abundance and appear to be almost completely absent at approximately 75 to 80 feet below sea level.

In contrast to this leeward cliff, the windward reef on Falalop displays gentle seaward slopes, the 100-fathom contour being approximately 10 times as far from the northeast coast as it is from the southwest coast (fig. 4).

GEOLOGY OF ASOR, FASSARAI, AND MOGMOG ISLANDS

Asor Island.—Asor Island, on the northeast side of Ulithi Atoll, is approximately 3500 feet long in a northwest direction, 1100 feet wide in a northeast direction at its northwest end, and 600 feet wide at its southeast end (fig. 4).

The central and eastern sections of the lagoonal coast of Asor show the greatest development of beach conglomerate seen on Ulithi Atoll. This con-

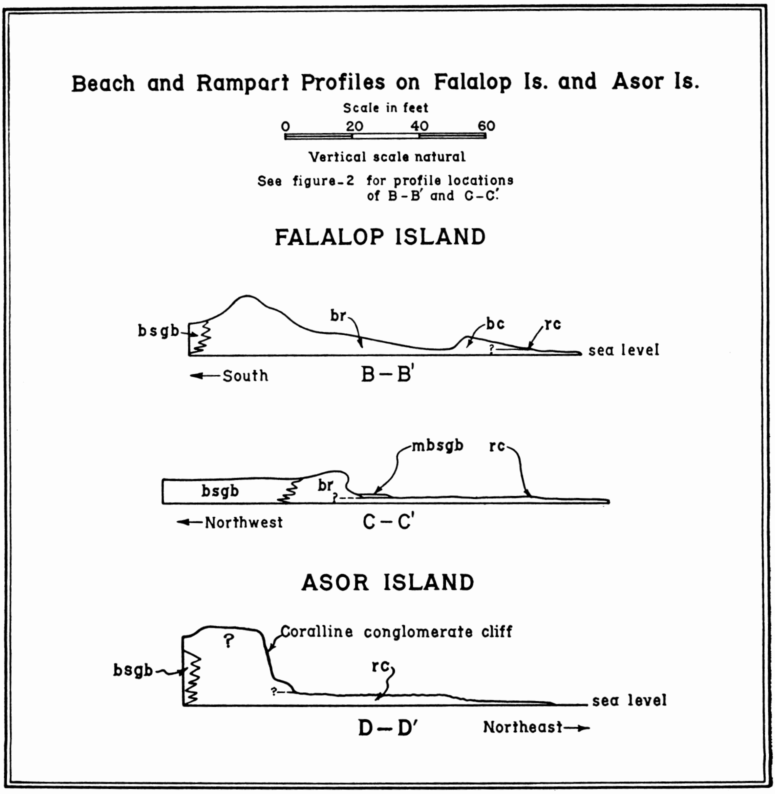


Fig. 5. Beach and rampart profiles on Falalop and Asor Islands.

glomerate is composed of well-rounded coral boulders and cobbles in a matrix of foraminiferal sand and calcareous algal gravels. Red, unbleached *Tubipora* is present in the rock. Approximately a 6-foot stratigraphic thickness of this conglomerate is present. In general the beds strike N. 70° W., parallel to the beach, dip 5° to 8° SW., and are jointed in directions both parallel and perpendicular to the strike of the beds. The northwest end of Asor displays well-developed foraminiferal sand beaches which slope gently upward inland to heights of approximately 12 feet.

The southeast end of Asor is characterized by slightly lithified coral conglomerate cliffs, which reach heights of 16 feet on the lagoonal side and 23 feet on the seaward side of the island (fig. 5, section D-D′). Section D-D′ was measured by hand level perpendicular to the northeast coast of Asor, approximately 600 feet northwest of the southeast end of the island. The central plateau on Asor is several feet lower than the crest of the lagoonal rampart. As shown on section D-D′, a bench of reef conglomerate at an elevation of 2 to 3 feet above high-tide level extends inland to the base of the high conglomerate cliff. A pitted karrenfeld surface has developed on this bench. The seaward edge of the bench slopes sharply down to sea level. The present reef to the seaward is planed coral conglomerate similar to the northern and eastern reefs on Falalop Island.

The high conglomerate cliff shown on section D-D′ is made up of coral boulders that are held together by a matrix of slightly lithified sand and gravel. A bench has been cut into this cliff at an elevation of approximately 6 to 7 feet above high-tide level. The south coast of Asor also displays a set of benches similar to those shown in section D-D′. Unlike the massive present-day boulder ramparts, which line the coasts of Falalop Island, the face of this cliff shows crude stratification. Thus the cliff face shows evidence of sorting. This stratification tends to discount a storm origin for the material forming the cliffs. The stratification, the height of the cliff, and the 6- to 7-foot bench lead the writers to believe that the southeastern end of Asor is probably a remnant of an island that existed before the 6-foot stand of the sea.

Mogmog Island.—Mogmog Island, which is approximately 2000 feet long in an easterly direction and 1000 feet wide in a northerly direction, lies on the north side of Ulithi Atoll (fig. 4). The highest points on Mogmog are on the boulder ramparts along the north coast of the island. These ramparts attain heights of 8 to 10 feet above sea level and are composed of closely packed coral cobbles and boulders. The boulder ramparts on the lagoonal side of the island are, on the average, 2 to 3 feet lower than the seaward ramparts. The center of the island is several feet lower than the lagoonal ramparts.

Beach conglomerate, which strikes east parallel to the beach and dips 5° to 10° S., is well developed on the lagoonal side of the island. This rock is a bedded, coral boulder conglomerate in a matrix of foraminiferal and algal sand and gravel. In some areas the coral boulders are lacking, and the rock is made up of lithified algal gravels and foraminiferal sands. Red, unfaded *Tubipora* fragments are common in the rock. The beach conglomerates on

PLATE 3

Shoreline deposits of Falalop Island

A. View of the east coast of Falalop showing the veneering deposit of mixed beach sand, gravel, and boulders (mbsgc) that overlies the reef conglomerate.

B. View of the low boulder rampart, right center, at the southeast corner of Falalop.

the lagoonal side of the island are jointed in two directions, one set of joints parallel to the strike of the beds, the second set perpendicular to the strike. There is only one small exposure of beach conglomerate on the northern side of the island. Foraminiferal beach sand fringes the southern coast and forms cusps on the eastern and western ends of the island.

The reef on the northern side of Mogmog is similar to the northern and eastern reefs on Falalop Island in that it is made up of reef conglomerate littered with loose coral boulders. This reef is several hundreds of feet wide on Mogmog.

Fassarai Island.—Fassarai Island is approximately 5000 feet long in a northerly direction and 300 feet wide in an easterly direction. It lies on the east side of Ulithi Atoll (fig. 4).

The only rock seen on Fassarai was a small patch of beach rock on the lagoonal side of the island. This rock strikes roughly north and dips a few degrees to the west. The beach rock on Fassarai does not contain any boulders but is made up entirely of foraminiferal sand and calcareous algal gravel. The seaward and lagoonal beaches are made up of foraminiferal sand covered with disconnected patches and veneers of coral and calcareous algal gravel.

The highest elevations on Fassarai lie on the seaward sand ridge, which rises to a height of approximately 15 feet above sea level. The lagoonal sand ridges are approximately 10 feet high. The land slopes downward inland from each ridge, these slopes meeting approximately 100 feet from the lagoonal ridge. Thus in profile the island is asymmetrical, sloping gently lagoonward.

GEOLOGIC HISTORIES OF FALALOP AND ASOR ISLANDS

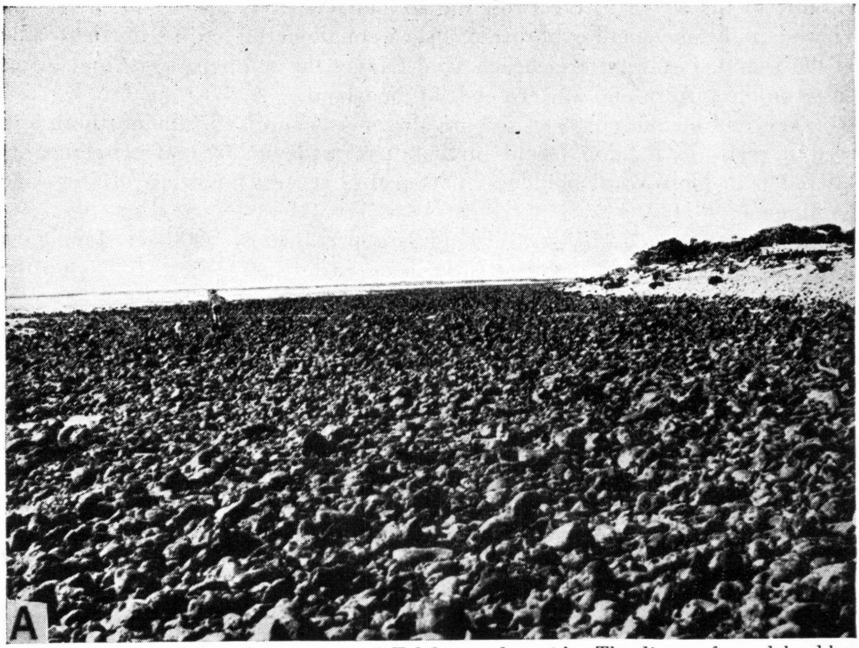
The late geologic histories of Falalop and Asor islands are intimately connected with sea-level changes that took place subsequent to the "climatic optimum." Trowbridge (1954) estimated that at the end of the thermal maximum ("climatic optimum"), which he dated at approximately 4000 years ago, the sea stood roughly 30 feet above the present sea level. After this 30-foot stand, sea level fell to slightly below the present sea level and is now rising slightly.

Hough (1953), in an interpretation of core samples from the southeastern Pacific, postulated that a warm period, which he correlated with the "climatic optimum," took place from about 5000 to 7000 years ago. Between this warm period and the present, Hough also postulated two brief cold periods which took place 3200 and 2800 years ago and two brief warm periods which took place 1900 and 1100 years ago. Hough believes that the overall trend in the last 6000 years has been from warm to cooler conditions.

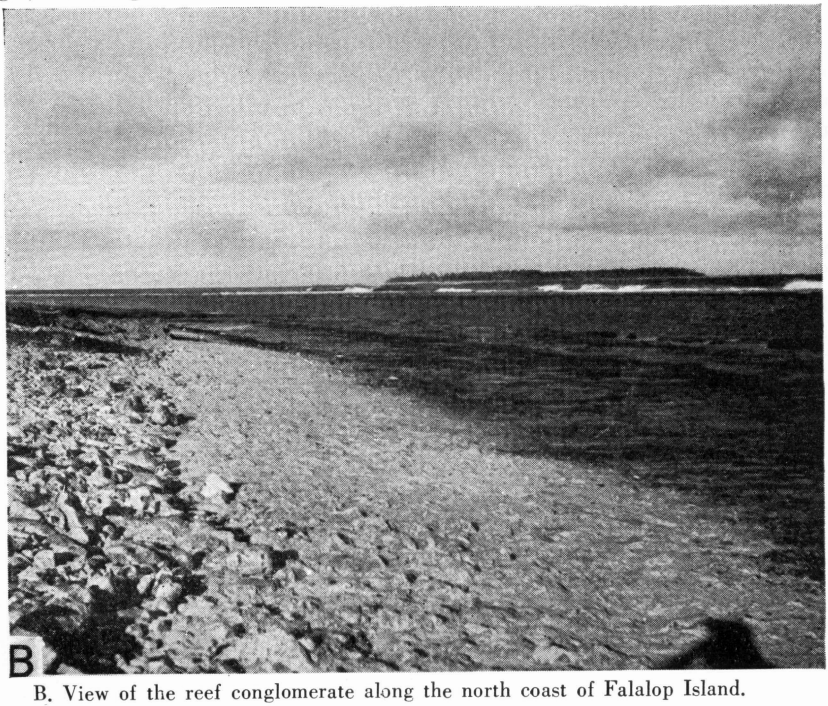
On both Falalop and Asor islands distinct topographic levels are present (fig. 5). One of these is represented by the bench cut into the conglomerate cliff on Asor at an elevation of 6 to 7 feet above high-tide level. A second level is the upper surface of the reef conglomerate (rc) which is present along the northern coasts of both Asor and Falalop at an elevation of 2 to 3 feet above high-tide level. The lowest level is the surface of the reef conglomerate that forms the seaward, intertidal reef flats on the windward coasts of Falalop, Asor, and Mogmog islands.

PLATE 4

Coastal flats of Falalop Island



A. View of the northeast coast of Falalop at low tide. The litter of coral boulders covers the reef conglomerate (rc). At high tide this area, up to the white area at the right, is submerged.



B. View of the reef conglomerate along the north coast of Falalop Island.

In this paper the 6-foot stand is considered to be a stillstand between the high level of the "climatic optimum" and present sea level. As shown on section D-D′ of figure 5, Asor Island displays benches cut into a mass of slightly lithified, poorly stratified, coral conglomerate. The writers believe that this mass represents the remnant of an island that existed prior to the 6-foot stand of the sea and that the 6- to 7-foot bench on Asor is the result of a partial planation of this island mass during the 6-foot stand. This 6- to 7-foot bench is well developed around southeastern and northeastern Asor.

As discussed previously, the foraminiferal assemblages from wells 5, 8, and 14 indicate that a reef was present in the vicinity of present-day Falalop prior to the 6-foot stand. However, high cliffs of conglomerate such as those on Asor have no counterparts on Falalop. The writers are at a loss to explain, considering the closeness of the two islands and their similar positions in respect to wind and wave effects, this dissimilarity between Asor and Falalop. Thus, there is no evidence that Falalop existed as an island, as did Asor, prior to the 6-foot stand. Subsequent to the 6-foot stand the histories of Falalop and Asor are parallel.

Between the 6-foot stand and present-day sea level there was a stillstand at approximately 3 feet above present sea level. The bench around Asor and parts of Falalop, at an elevation of 2 to 3 feet above sea level, was cut during this stillstand. This bench, cut into lithified coral conglomerate, is at present undergoing solution as evidenced by the deeply pitted karrenfeld surface which

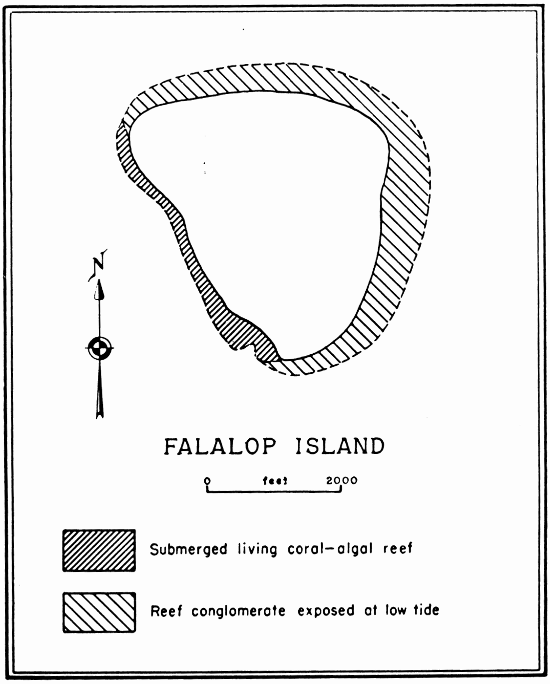


Fig. 6. Reef distribution around Falalop Island.

it now displays. Beach conglomerate (bc) on Falalop now at elevations of 2 to 3 feet above sea level may be ascribed to this stillstand.

The writers believe that the possibility of the 6-foot and the 2- to 3-foot stands of the sea correlating with the two post-"climatic optimum" warm periods postulated by Hough (1953) should be considered. If this correlation is assumed then the 6-foot stand and the 2- to 3-foot stand took place approximately 1900 and 1100 years ago respectively.

A final planation, at a level close to the present sea level, produced the wide expanse of reef conglomerate (rc) present around much of Falalop and Asor as well as the north coast of Mogmog. It is probable that previous to the planations mentioned above these islands extended further seaward than they do at present.

SEAWARD REEF FRONT TYPES OF ULITHI ATOLL AND ADJACENT ISLANDS

On the basis of field work on Ulithi Atoll and studies of aerial photographs of the atoll and the islands adjacent to it, the writers have classified the seaward reefs of the atoll and the islands into two types, designated by the letters A and B (fig. 4). These closely parallel the two main reef types set forth by Tracey, Ladd, and Hoffmeister (1948) in their classification of the reefs of Bikini Atoll.

Reef front type A is characterized by fairly regularly spaced, subparallel grooves which cut the reef front and are, in general, nearly perpendicular to it. These grooves vary widely in size but are generally 5 to 10 feet wide, as deep as 30 feet, and cut the seaward slopes of the reef for distances as great as 1000 feet. The grooves are sinuous to almost straight in plan and display both landward and seaward forks. Intersection of these grooves at low angles is also common (pl. 2-B).

The seaward slopes on which type A have developed are gentler than those on which type B have developed, as shown by the position of the 100-fathom contour on figure 4.

Reef front type B is characterized by coral-algal buttresses, which are lobate in plan and in which grooves are poorly developed. Irregular re-entrants are common. Type B is associated with steep seaward slopes (pl. 2-B).

Distribution of reef front types.—The above-described reef front types occupy well-defined positions on the reefs around Ulithi Atoll and the adjacent islands (fig. 4).

Type A is present around the northern edge of the Iar Island reef. The Pau Island-Losiep Island reef displays well-developed type A front all along its northeastern face. Around Ulithi Atoll proper type A is developed on the eastern, northeastern, and northern reefs. The western extremity of the reef all along the southern coast of Asor also falls in the type A category.

Type B reef fronts occupy the northwestern face of the Iar Island reef, the southwestern half of the Pau Island-Losiep Island reef, the southwesterly facing re-entrant on the west side of Ulithi Atoll at Pogel Island, and the southwesterly facing reefs on Falalop Island.

This distribution is similar to the reef front type distribution found at Bikini Atoll by Tracey, Ladd, and Hoffmeister (1948). However, at Bikini much evidence was found of storm damage to the seaward facing reefs on the southern and southwestern sides of the Atoll. This storm damage took the form of rectangular re-entrants, the longer dimensions of which were parallel to the reef front. and the bottoms of which were littered with collapse blocks from the pre-existing continuous reef front.

Aerial photographs of Ulithi Atoll and the adjacent islands show only one such re-entrant. This is on the reef front along the southwest coast of Falalop Island. Therefore, it seems probable that the storm damage to the lee reefs on Ulithi Atoll. which receives most of its storm waves from the northern quadrants. is less than that on Bikini, which bears the brunt of typhoon effects from the southern quadrants.

WATER RESOURCES OF FALALOP ISLAND

Pre-investigation water supply.—Prior to the present investigation the native population of Falalop depended during the rainy season entirely on rain water for washing, bathing, cooking, and drinking. During the dry season the liquid of the coconut was used for drinking and cooking; the natives washed and bathed in the sea. After the natives discovered the existence of fresh water in the wells dug during the investigation. they dug two wells near their village to augment the water supply. Inasmuch as these two wells were dug after the writers left the island they are not shown on figure 2.

At the Coast Guard station wells 1 and 2 and two distillation units are used to augment the supply obtained by rain catchment. During most of the year the station has adequate water for all requirements, but during dry seasons well water is used for washing and bathing, and the rain water is conserved for cooking and drinking.

TABLE 2

Rainfall Data in Inches for Falalop Island and Yap Islands

Falalop Island, Ulithi Atoll*		Yap Island**	
1952			
November	6.65		
December	10.01		
1953			
January	4.49	January	6.5
February	9.46	February	5.9
March	1.89	March	5.0
April	9.46	April	5.1
May	6.30†	May	10.0
June	13.76	June	9.9
July	8.98	July	16.9
August	12.85	August	16.3
September	8.94	September	12.5
October	10.74	October	11.8
November	17.66	November	10.0
December	7.37	December	9.1
TOTAL	112.54		119.0

* Record obtained from rain gauge maintained by the U. S. Coast Guard detachment.

** Average monthly rainfall based on a 27-year record, dates unspecified, compiled by Japanese observers.

† Rain gauge blown over during the typhoon of May 30, 1953. An estimated 1 inch of rain fell while the gauge was overturned.

Rainfall.—Table 2 shows the rainfall on Falalop from November 1952 through December 1953 and, for comparison, the average monthly rainfall for a 27-year period on the islands of Yap, which are about 90 miles south and west of Ulithi Atoll.

Ground water.—The permeability of the sands, gravels, and conglomerates that make up Falalop is high, and all rain that falls on the island, except that lost through evaporation and transpiration, percolates rapidly down to the water table. The fresh rainwater floats on top of the denser sea water and forms a lens according to the Ghyben-Herzberg principle (Brown, 1925). This principle, which is that of the U-tube, is that the ratio, in feet, of the elevation of the top of the lens above sea level to the depth of the bottom of the lens below sea level is equal to the difference in density between the sea water and the fresh water. Thus if the density of the rain water equals 1.000 and the density of the sea water equals 1.025, the ratio would be 1:40; that is, if the top of the fresh-water lens were 1 foot above sea level the bottom would be 40 feet below.

On Falalop the fresh-water surface lay measurably above sea level, but the lack of good vertical control in the plane-table traverse precluded the making of a piezometric map that would have shown the configuration of the upper surface.

Tidally induced water-level fluctuations in the wells.—Records obtained with a continuous water-level recorder in well no. 1 show that the water level in the well fluctuated from 1 to 2 feet with about a 2-hour lag behind the ocean tide (fig. 1). The greatest tidal fluctuation in all the wells occurred during spring tides and the smallest during neap tides. In the 10 other wells on the island changes in water levels, which were periodically measured with a tape, followed the pattern in well no. 1.

The large amount of tidally induced fluctuation in all the wells confirms the impression that the water-bearing materials are highly permeable.

Quality of ground water.—Water samples were taken from all wells at both high and low tide on November 30, 1952, December 1, 1952, and March 7, 1953. Table 3 shows the chloride content of the water, in parts per million, from the wells.

According to the Ghyben-Herzberg principle the contact between the lower surface of the fresh-water lens and the underlying sea water takes the form of a zone of mixing. This zone follows the upward-curving lower surface of the lens and intersects the upper surface of the lens around the margin of the island. Therefore, the chloride content of the water in the lens should, theoretically, increase outward from the center of the island. On Falalop the lateral variation in chloride content is erratic and does not follow the theoretical pattern. This wide lateral variation in chloride content may be due to minor local differences in permeability in the aquifer. There is also the possibility that channeled indurated rock below the depth reached by the wells permits the local flow of sea water, which upsets the lens.

The high chloride content of the water from the March 7, 1953 sampling of well no. 11 was probably caused by natives taking water from the well to water a nearby sweet potato patch. The high chloride content resulting from

TABLE 3

Chloride Content in Parts per Million of Water in Wells on Falalop Island

Well	November 30, 1952	December 1, 1952	March 7, 1953
1	352	333	628
2	76	76	92
3	—*	48	78
4	532	528	660
5	84	88	94
6	356	368	540
7	460	438	776
8	652	668	842
9	340	348	— **
10	220	216	310
11	108	138	1240

* Sample bottle broken.

** Well caved in before March 7 sampling.

this removal is indicative of how easily the lens can be contaminated by salt water.

Conclusions on ground water.—A small supply of potable water can be obtained from wells on Falalop. However, pumping from each well should be at a low rate and frequent chloride determinations should be made to detect contamination.

REFERENCES

Brown, J. S., 1925, A study of coastal ground water with special reference to Connecticut: U. S. Geol. Survey Water-Supply Paper 537.

Dinger, J. E., and Fisher, G. H., 1953, Microseisms and ocean wave studies on Guam: Naval Res. Lab. Rept. 205.

Hess, H. H., 1948, Major structural features of the western north Pacific; an interpretation of H. O. Chart no. 5485, Korea to New Guinea: Geol. Soc. America Bull., v. 59, p. 417-446.

Hough, J. L., 1953, Pleistocene climatic record in a Pacific Ocean core sample: Jour. Geology, v. 61, p. 252-262.

Sverdrup, H. U., Johnson, M. W., and Fleming, R. H., 1942, The oceans: New York, Prentice-Hall, Inc.

Tracey, J. I., Ladd, H. S., and Hoffmeister, J. E., 1948, Reefs of Bikini, Marshall Islands: Geol. Soc. America Bull., v. 59, p. 861-878.

Trowbridge, A. C., 1954, Mississippi River and Gulf Coast terraces and sediments as related to Pleistocene history—a problem: Geol. Soc. America Bull., v. 65, p. 793-812.

U. S. GEOLOGICAL SURVEY
WASHINGTON, D. C.