NATURAL HISTORY OF IFALUK ATOLL: PHYSICAL ENVIRONMENT

BY

JOSHUA I. TRACEY, JR.
U. S. GEOLOGICAL SURVEY

DONALD P. ABBOTT
HOPKINS MARINE STATION OF STANFORD UNIVERSITY

TED ARNOW
U. S. GEOLOGICAL SURVEY

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INTRODUCTION

SETTING

Ifaluk is a small atoll in the western Caroline Islands, now part of the Trust Territory of the Pacific Islands. The atoll lies at latitude 7°15′ N. and longitude 144°27′ E. in the western equatorial Pacific and about 360 nautical miles due south of Guam. It is 435 miles due west of Truk and 400 miles due southeast of Yap, the nearest high island formed of volcanic rocks. Fais, an upraised limestone island 117 feet high, is about 275 miles to the northwest. Ifaluk's nearest neighbor, Woleai Atoll, is about 35 nautical miles to the west; and five other atolls lie within a radius of about 100 nautical miles (fig. 1).

Geologically, Ifaluk is a coral island, rising from a submarine ridge south of the Mariana Trench and northwest of the East Caroline Basin. Oceanographically, it is in a region of eddies which are influenced on the north by the westward-flowing North Equatorial Current and on the south by the eastward-flowing Equatorial Counter Current (U. S. N. Hydrographic Office, 1944).[1] The atoll consists of a subcircular reef about 2.5 miles long and 1.5 miles wide, surrounding a nearly circular lagoon only a mile in longest diameter (figs. 2, 3). The dimensions are shown in table 1, where they are compared with those of Bikini, a large atoll in the northern Marshall Islands (Emery *et al.*, 1954, p. 22), and Raroia, a large atoll in the Tuamotu Archipelago (Newell, 1956, p. 329).

The four islands on the reef at Ifaluk are here designated by the names used by the inhabitants and follow the phonetic spelling proposed by Sarfert (1938) and modified by Burrows and Spiro (1953). These names and their equivalents accepted by the United States Board on Geographic Names (1955), are as follows:

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[1] Dates in parentheses refer to Literature Cited, page 71.

PRESENT PAPER	BOARD OF GEOGRAPHIC NAMES
Ifaluk Atoll	Ifalik Atoll
Falarik Island	Ifalik Island
Falalap Island	Flalap Island
Ella Island	Ella Island
Elangalap Island	Moai Island

Falarik, Falalap, and Ella, which occupy most of the eastern half of the peripheral reef, are fringed to seaward by a reef flat 100 to 600 feet wide. The western sweep of the reef is almost wholly awash except for tiny Elangalap Island and ranges in width from 1,000 to 1,700 feet. One pass nearly 500 feet wide and about 30 feet deep cuts through the reef just east of Ella Island. It is blocked by several strategically located coral knolls, but a small ship of the AKL class, 177 feet long and 936 tons displacement, can enter under favorable conditions. Falalap Channel, a narrow waterway separating Falarik and Falalap Islands, is much smaller and is shallow enough in places to be waded across at high water.

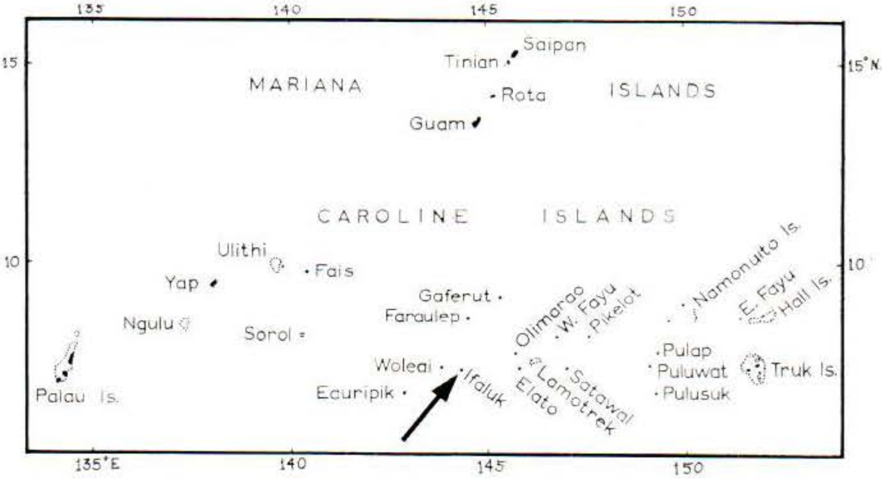

FIGURE 1.—Map of western Caroline Islands and southern Mariana Islands.

The four islands are almost completely covered by vegetation above the high water mark. The flora and fauna are typical of the wetter low-lying coral islands of this region which are not close to high islands or larger land masses. Along with native species, there occur a number of animals and plants introduced by man for food, decoration, or other purposes. About 260 persons live in four villages on the larger islands of Falarik and Falalap, but neither Ella nor Elangalap is regularly inhabited. In culture and physique the

FIGURE 2.—Ifaluk Atoll, aerial photo from 2,500 feet by U. S. Navy.

inhabitants are Micronesians, though occasional individuals show evidence of mixture with Oriental, Caucasian, or Melanesian stocks. These people live a largely traditional atoll existence, little disrupted by more than a century and a half of intermittent and usually fleeting contacts with the world beyond the Carolines. The ethnology of Ifaluk has been dealt with by Damm and Sarfert (1938) and by Burrows and Spiro (1953), while further background information on the region is summarized by Gressitt (1954) and in the Trust Territory handbook (U. S. Navy Dept., 1948).

Table 1.—Dimensions of Ifaluk, Bikini, and Raroia Atolls

	IFALUK	BIKINI	RAROIA
Length of atoll (miles)	2.5	26	27
Breadth of atoll (miles)	1.5	15	9
Area of atoll (square miles)	2.5	273	155
Area of lagoon (square miles)	1.1	243	131
Area of reef, awash (square miles)	0.9	27	15
Area of islands, vegetated (square miles)	0.5	2.4	2.3
Maximum depth of lagoon (fathoms)	11	32	35

THE EXPEDITION

The field work on Ifaluk in 1953 was carried out as part of a five-year Coral Atoll Program sponsored by the Pacific Science Board under the National Academy of Sciences–National Research Council. This program also included studies on Arno Atoll, the Marshall Islands (in 1950), Onotoa Atoll, the Gilbert Islands (in 1951), Raroia Atoll, the Tuamotu Archipelago (in 1952), and Kapingamarangi Atoll, south of the eastern Carolines (in 1954).

Personnel of the Ifaluk expedition included Edwin G. Burrows, anthropologist of the University of Connecticut, who was on Ifaluk from June 22 to September 12, and was leader of the expedition during this period; Marston Bates, biologist, of the University of Michigan, June 22 to September 12; Donald P. Abbott, marine biologist, of the Hopkins Marine Station of Stanford University, June 22 to November 9, and leader of the expedition from September 12 to the end; Joshua I. Tracey, Jr., geologist, of the U. S. Geological Survey, September 12 to 26; Ted Arnow, hydrologist, of the U. S. Geological Survey, June 22 to 24 and September 12 to 26; Frederick M. Bayer, zoologist, of the U. S. National Museum, September 12 to November 9; and Robert R. Rofen, ichthyologist, of the George Vanderbilt Foundation, September 12 to November 9.

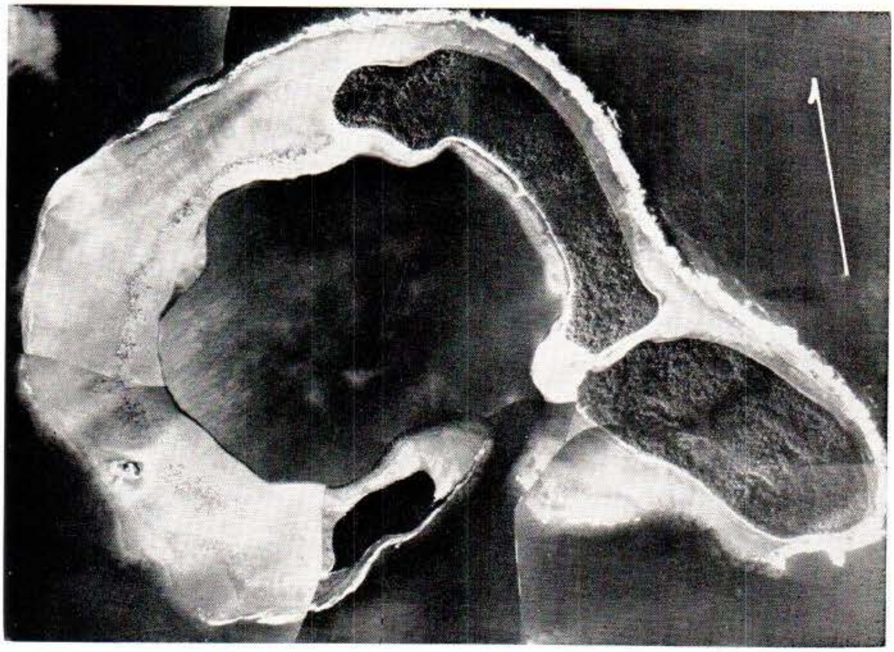

FIGURE 3.—Ifaluk Atoll, uncontrolled photomosaic by U. S. Navy.

It was the purpose of the expedition to carry out a natural history survey of the atoll and, in particular, to study the natural history of Micronesian man in his island environment. In broad, this program involved: (a) a survey of the physical environment of the atoll, including its geography, geology, hydrology, and climate; (b) a survey of the fauna and flora of the land and adjacent sea, including its composition, distribution, and something of its general ecology; and (c) a study of man and his way of life, with emphasis on human utilization of, interaction with, and effect on, the physical and biological environment. Ifaluk Atoll was chosen for the study primarily because its inhabitants adhere more closely to traditional ways than do the peoples of most Pacific atolls, and because Burrows was already familiar with the local people and conditions through an earlier study (1953).

The expedition left Guam on U. S. Coast Guard ship *Nettle* on June 20, 1953, arriving at Ifaluk on June 22 with Burrows, Bates, Abbott, and Arnow. Two days later Arnow departed on the *Nettle*. The period June 25 to September 12 was devoted primarily to studies of the people and their terrestrial environment. Projects included a complete census of the population; qualitative and quantitative studies of human diet; plane-table mapping of the two larger islands for vegetation zones, trails, houses, and agricultural areas; and the systematic collecting of specimens of the land flora and insect fauna. A preliminary survey of the reefs and lagoon was made to determine general physical and biological zones and to select representative areas for fuller study later. Burrows devoted considerable time to the collection of song texts. Finally, wells were dug at sites selected earlier by Arnow for hydrological and geological studies.

The Trust Territory ship *Metomkin,* which arrived September 12, picked up Burrows and Bates and landed Arnow, Tracey, Bayer, and Rofen. The next two weeks were devoted primarily to geological and hydrological work. Water-level recordings were made in the lagoon and in representative wells, and well-water samples were taken for analysis; Falarik Island was surveyed and mapped for contours and composition; a rough geological reconnaissance of the reefs, lagoon, and other islands was made; and the serious collecting of fishes and marine invertebrates was begun. On September 26 the *Metomkin* arrived to pick up Tracey and Arnow. The remaining members of the expedition concentrated their efforts on the environment, biota, and general ecology of the reefs and lagoon until the expedition left Ifaluk for Guam on November 9, aboard the U. S. Coast Guard ship *Planetree*. A more complete account of the expedition and some of it's findings is given by Bates and Abbott (1958).

The present report is the first to be published in the Bishop Museum Bulletin series under the title "Natural History of Ifaluk Atoll." Later reports in the set will deal with the fauna and flora, the general ecology, and the human ecology of Ifaluk. In this volume Abbott is primarily responsible for the introduction, the section on climate, and the general editing of the report; Arnow, for the hydrology and the section on tides; and Tracey, for the geology.

ACKNOWLEDGMENTS

The field work on Ifaluk was made possible by the cooperation of many organizations and individuals, and it is a pleasure to acknowledge their assistance.

Particular thanks are due the Pacific Science Board, especially the Executive Director, Harold J. Coolidge; the secretary of the Washington office, Lenore Smith; and the secretary of the Honolulu office, the late Ernestine Akers.

Financial support was received from the Military Geography Branch of the Office of Naval Research (Contract N7onr-29104, NR 388001). Loans of personnel or equipment were provided by the U. S. Geological Survey, the U. S. National Museum, the U. S. Coast and Geodetic Survey, the U. S. Navy, Bernice P. Bishop Museum, the George Vanderbilt Research Foundation, the University of Michigan, the University of Connecticut, the Hopkins Marine Station of Stanford University, and the Academy of Natural Sciences of Philadelphia.

Transportation for the expedition was furnished by the Military Air Transport Service, the U. S. Navy, the U. S. Coast Guard, and the Administration of the Trust Territory of the Pacific Islands. Particular thanks are due the following persons: Mr. Alfred M. Hurt, Executive Officer, Trust Territory of the Pacific Islands, Guam; Captain William I. Swanston, Commander, Marianas Section, U. S. Coast Guard; Lieutenant Commander Antone E. Clark, Executive Officer, Coast Guard Depot, Guam; Lieutenant Commander James G. Cowart, Commanding Officer, USCGC *Nettle* (WAK-169); Lieutenant Richard E. Weinacht, Commanding Officer, USCGC *Planetree* (WAGL-307); Rear Admiral Ernest W. Litch, Commander Naval Forces Marianas; Captains Wilton S. Heald and William C. Johnson, Jr., Headquarters, Naval Forces Marianas; Captain Jesse S. McAfee, Commanding Officer, Naval Supply Depot, Guam; Commander Leo C. Machen, Assistant Force Communication Officer, and Lieutenant Thomas C. Powers, Public Information Officer, Naval Forces Marianas.

U. S. Navy Utility Squadron FVU-5 flew two sorties over Ifaluk and provided the expedition with excellent aerial photographic coverage of the atoll.

Albert Bronson of Guam very kindly loaned the expedition a skiff, and Gerrard H. Fisher assisted us in many ways during our stay on Guam.

Finally, we are most deeply indebted to the people of Ifaluk Atoll, whose hospitality and friendly cooperation contributed a great deal toward making our stay pleasant and rewarding. Special thanks are due the late chiefs Fagolier, Maroligar, and Toroman; to those men who worked most closely with us,

Tatogoetil (Tom), Yaniseman, Bakalimar, Tachiwelimeng, Tewajiliaro, Yarofalimal, Talimeira, Sagolimar, Sepemal, and Gavileisei; and to visiting Ulithi islander Antonio Taidau. Ifalukian knowledge of many aspects of the natural history of the atoll is both extensive and intensive; if these men served as our assistants in some matters, they served as our teachers and colleagues in others.

It is with profound regret that we record the death of Edwin G. Burrows, expedition leader, in July 1958.

PHYSICAL ENVIRONMENT

CLIMATE

The expedition obtained measurements of atmospheric pressure, air temperature, ocean and lagoon water temperatures, rainfall, and relative humidity for a period of approximately four months. Readings were taken daily between 0800 and 0900 hours local time (Greenwich time plus 10 hours). All observations on land were made at elevations not exceeding 10 feet above mean sea level. The data, collected by Bates and Abbott, are tabulated in tables 2 to 6 and are shown graphically in figure 4.

The atmospheric pressure (table 2) ranged from 1,004 to 1,011 millibars (29.65 to 29.86 inches); 85 percent of the readings fell between 1,007 and 1,010 millibars. On June 27, 1953, a strong gale with winds up to Beaufort force 9 (41 to 47 knots) struck the island, and during its passage the barometer reading dropped to a low of 995 millibars.

The daily range in air temperature (table 3) was measured in the school building, an elongate thatched shelter open on two sides and located in a large clearing near the south end of Falarik Island. The extremes were 73°F. and 91°F. The maximum daily range was 15°, the minimum daily range was 5°, and the average daily range during the four-month period of observation was 11° between a mean daily high of 87.5° and a mean nightly low of 76.5°F. Temperature means and ranges recorded on Ifaluk correspond fairly closely to those reported from Yap and Truk (U. S. Dept. Commerce 1956; U. S. Navy Dept., 1948).

Ocean-water temperatures (table 4) were recorded daily on the windward reef and in the lagoon. Reef temperatures were taken off the eastern coast of Falarik Island, about 0.3 miles north of the southeast tip of the island. The observer waded out on the reef flat to the seaward reef margin or even beyond, the exact position depending upon the state of waves and tide, usually to water at least knee deep but occasionally shallower, and sampled the bottom water. At the lowest tides, temperatures were measured in surge channels.

Lagoon shore temperatures were measured similarly off the southwest shore of Falarik, about 1,000 feet north of the extreme southern tip of the island. The windward reef temperatures recorded showed a mean of 83.7°F. and extremes of 79.2° and 86.2°F. Lagoon temperatures were closely similar, with a mean of 83.8°F. and a range of 80.6° to 86.4°F. during the period of observation. These temperatures are slightly lower than shore temperatures recorded earlier at Yap, Palau, Truk, and Guam (U. S. Dept. Commerce, 1952).

Table 2.—Atmospheric pressure at Ifaluk Atoll (1953) in millibars, observed between 0800 and 0900 hours

DAY	JULY	AUGUST	SEPTEMBER	OCTOBER
1	....	1008	1008	1010.5
2	....	1009	1008	1010.5
3	1009	1009	1008.5	1010
4	1009	1007.5	1008.5	1010
5	1010	1009	1009	1009
6	1010	1009	1010	1009.5
7	1010.5	1009	1010	1009
8	1011	1006.5	1008	1009
9	1010	1007.5	1008.5	1008
10	1009	1006	1009	1010
11	1010	1008	1008	....
12	1010	1007	....	1008
13	1010	1008	....	1007
14	1009	1007	1008.5	1006
15	1008	1007	1008.5	1006
16	1008	1008	1008.5	1007
17	1009	1009	1008.5	1007
18	1008	1009	1006	1007
19	1008	1009	1005.5	1007
20	1007.5	1009	1007	1008
21	1007	1008	1008.5	1009
22	1009	1007	1009	1008
23	1007.5	1006	1008	1007
24	1008	1006.5	....	1008
25	1008	1006	1008.5	1009
26	1008	1005	1009.5	....
27	1006	1004	1009.5	1007.5
28	1007	1006	1009.5	1008.5
29	1007.5	1008	1010	1008
30	1007.5	1008	1010	1008
31	1007	1008.5	....	1008
Max.	1011	1009	1010	1010.5
Mean	1009	1008	1009	1008
Min.	1007	1004	1005.5	1006

Table 3.—Daily maximum and minimum air temperatures (°F.), Falarik Island (1953)*

	JULY		AUGUST		SEPTEMBER		OCTOBER	
DAY	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
1	....	....	91	76	90	77	91	79
2	86	76	90	77	90	80	88	75
3	87	76	88	74	90	80	87	77
4	89	76	84	73	90	76	91	77
5	87	76	82	75	89	77	90	77
6	90	77	82	76	88	75	89	78
7	88	77	82	77	85	77	90	78
8	90	78	86	75	88	78	90	78
9	90	78	80	74	91	76	90	77
10	88	77	82	74	88	76	90	77
11	90	76	84	74	86	76	....	....
12	89	78	84	76	....	....	90	75
13	89	77	87	78	91	76	88	76
14	89	78	88	76	86	76	87	79
15	90	75	82	76	89	74	....	76
16	80	73	83	74	84	74	....	77
17	88	76	88	78	87	76	....	80
18	81	73	86	77	88	73	....	76
19	88	75	89	76	82	75	87	76
20	82	76	89	77	86	76	86	76
21	88	77	88	77	84	76	87	77
22	89	76	88	77	....	76	88	78
23	85	78	86	75	89	79	89	75
24	86	76	86	77	....	....	87	78
25	89	76	85	80	88	77	90	76
26	87	77	88	75	87	77	....	....
27	90	78	88	77	88	77	90	76
28	89	77	85	74	90	77	88	77
29	91	77	88	78	90	76	87	74
30	91	77	89	80	91	78	82	77
31	88	78	90	78	....	....	86	79
Monthly								
Max.	91	78	91	80	91	80	91	80
Mean	88	76.5	86	76	88	76	88	77
Min.	80	73	80	73	82	73	82	74
Daily variation (° F.)								
Max.	15		15		15		15	
Mean	11		10		11		11	
Min.	6		5		7		5	

* Differences between this table and that published in Arnow (1955) represent corrected figures.

The rainfall measurements at Ifaluk (table 5) were made during the wettest season, though rainfall is distributed throughout the entire year. At least a trace was recorded on 83 percent of the days of observation, and the rainfall exceeded one inch on 11 percent of the days of observation. A total of 54.25 inches of rainfall was measured in 131 days. The average annual rainfall at Ifaluk is probably between 100 and 120 inches, based on a consideration of annual precipitation data from Guam, about 90 inches; from Yap, 122 inches, from Truk, 132 inches, and from Koror, Palau, 148 inches (U. S. Dept. Commerce, 1956); and from Lamotrek, 104 inches (U. S. N. Hydrographic Office, 1943). The figures from Yap, Koror, and Truk are normal annual figures computed from station records and adjusted to the period 1921 to 1950. The

Table 4.—Ocean water temperatures (°F.) at Ifaluk (1953), taken between 0800 and 0900 hours

DAY	JULY		AUGUST		SEPTEMBER		OCTOBER	
	Windward reef	Lagoon	Windward reef	Lagoon	Windward reef	Lagoon	Windward reef	Lagoon
1........	......	......	84.7	84.2	84.4	84.6	84.6	84.3
2........	......	......	84.0	84.7	83.8	84.7	82.8	84.0
3........	......	......	79.2	84.6	83.5	84.4	85.6	85.5
4........	......	......	85.6	84.0	84.0	84.6	85.1	84.8
5........	......	......	......	......	84.2	85.5	83.7	83.5
6........	......	......	82.0	80.6	83.7	85.3	83.8	85.6
7........	......	......	83.5	81.9	83.8	83.7	84.2	85.3
8........	......	......	82.8	81.5	85.1	85.6	86.0	85.5
9........	......	......	79.7	81.5	84.4	84.2	85.6	85.1
10........	......	......	81.0	82.4	83.1	84.0	85.1	84.9
11........	......	......	81.5	81.7	84.4	84.7	......	......
12........	......	......	83.5	83.7	84.0	84.4	84.4	85.6
13........	84.6	84.4	82.8	83.7	84.0	84.0	85.8	85.1
14........	84.2	83.7	82.8	81.9	86.2	86.2	83.8	85.3
15........	80.2	81.3	82.4	83.1	82.6	84.0	82.2	81.9
16........	83.3	83.7	83.8	82.9	84.4	84.9	83.1	83.5
17........	79.7	82.8	84.6	84.2	84.2	84.4	83.5	82.4
18........	83.7	82.0	84.2	84.7	83.1	81.3	84.9	84.7
19........	83.8	83.1	83.5	84.2	83.8	......	83.5	83.3
20........	84.2	82.4	83.5	83.3	81.9	82.2	84.6	84.6
21........	84.2	84.2	83.5	82.2	......	......	86.2	86.0
22........	83.5	83.8	83.7	82.4	84.2	83.5	84.0	85.7
23........	83.7	84.2	83.3	83.8	82.0	82.4	82.4	83.1
24........	84.0	84.2	82.4	83.8	81.1	82.2	84.2	84.6
25........	83.7	83.8	84.2	85.3	82.4	83.5	84.7	84.7
26........	85.5	86.2	82.0	83.1	82.2	83.5	......	......
27........	85.6	85.8	82.4	83.5	84.6	......	85.3	85.6
28........	84.4	84.6	81.3	82.4	84.2	84.0	83.3	84.7
29........	84.6	84.4	82.9	83.5	85.7	86.4	83.8	82.9
30........	83.3	83.1	82.9	83.7	84.4	84.6	84.0	84.2
31........	86.2	85.6	83.3	82.0	......	......	83.7	83.7
Max...	86.2	86.2	85.6	85.3	86.2	86.4	86.2	86.0
Mean..	83.8	83.8	82.9	83.1	83.7	84.2	84.4	84.6
Min....	79.7	81.3	79.2	80.6	81.1	81.3	82.2	81.9

Table 5.—Rainfall (in inches) at Ifaluk, 1953

DAY	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER
1	0.00	0.24	0.30	0.01	0.18
2	0.54	0.15	0.16	0.55	2.03
3	0.34	1.90	0.00	0.02	......
4	0.12	0.54	0.19	0.12	1.35*
5	0.20	0.18	0.00	0.14	0.01
6	0.00	0.95	0.74	trace	trace
7	0.00	0.05	0.02	0.00	0.03
8	trace	2.55	0.39	0.10	0.05
9	trace	3.20	0.00	0.13	......
10	0.02	0.81	0.15	0.28	......
11	0.02	1.15	0.13	......	......
12	0.20	0.11	......	0.84*	......
13	0.25	0.25	1.97*	0.53	......
14	0.08	0.61	0.76	0.01	......
15	0.00	0.50	0.91	0.70	......
16	2.98	1.06	0.54	0.40	......
17	0.68	0.00	0.15	0.01	......
18	1.44	0.00	2.70	0.92	......
19	0.24	0.00	1.03	0.99	......
20	0.16	0.02	0.40	0.24	......
21	0.16	0.33	0.09	0.35	......
22	0.30	0.15	0.12	0.00	......
23	0.00	1.67	0.00	0.32	......
24	0.05	0.00	......	0.04	......
25	0.32	0.00	0.87*	0.51	......
26	0.00	0.59	0.11	......	......
27	0.05	0.25	trace	0.13*	......
28	0.11	1.16	0.00	0.47	......
29	0.10	0.09	0.25	3.56	......
30	0.30	0.00	0.00	0.02	......
31	0.06	0.00	......	0.00	......
Total	8.72	18.51	11.98	11.39	......
Daily:					
Max.	2.98	3.20	2.70	3.56	......
Mean	0.28	0.60	0.40	0.37	......
Min.	0.00	0.00	0.00	0.00	......

* 48-hour reading.

figure for nearby Lamotrek Atoll is the average for a four-year record. Native informants have no recollection or legends of a drought on Ifaluk (Burrows and Spiro, 1953).

Relative humidity measurements (table 6) were taken with a sling psychrometer under the shelter of the open schoolhouse. Daily relative humidity readings made between 0800 and 0900 hours ranged between extremes of 77 and 100 percent, with a mean daily reading of 86.6 percent. Similar mean humidities are reported for Yap and Truk (U. S. Navy Dept., 1948).

Ifaluk Atoll is too small and too low to have any marked modifying influence on the climate in its vicinity, and to a great extent the conditions measured reflect the climate of the open sea in this region of the western Carolines. For interrelationships of the climatic variables measured, see figure 4. The vast water mass of the ocean serves to buffer the variations in air temperature at the low elevations prevailing, for no point on any islet is more than 15 feet above mean sea level or more than 1,000 feet from either sea or lagoon. Daily variations in air temperature generally bracket the prevailing shore water temperatures, which in turn reflect the surface temperature of the open sea, usually 83° to 84°F. in the period July to November (U. S. N. Hydrographic Office, 1943).

Table 6.—Relative humidity (percent) at Ifaluk, 1953, observed between 0800 and 0900 hours*

DAY	JULY	AUGUST	SEPTEMBER	OCTOBER
1	84	88	87	89
2	88	90	85	96
3	92	100	88	80
4	95	81	89	96
5	90	84	80	92
6	84	85	84	85
7	84	86	82	86
8	84	88	85	82
9	83	100	92	85
10	84	88	84	95
11	92	98	82	....
12	85	83	....	83
13	81	91	86	92
14	84	85	85	83
15	100	90	98	79
16	95	83	84	79
17	100	81	89	81
18	89	85	96	83
19	92	84	91	95
20	82	82	96	84
21	89	88	91	84
22	89	89	82	81
23	85	85	81	....
24	85	86	....	....
25	90	81	85	....
26	79	82	88	....
27	80	81	77	....
28	79	88	86	....
29	85	93	81	....
30	100	85	85	....
31	83	83	....	....
Max.	100	100	98	96
Mean	87	87	86	86
Min.	79	81	77	79

* Differences between this table and that published in Arnow (1955) represent corrected figures.

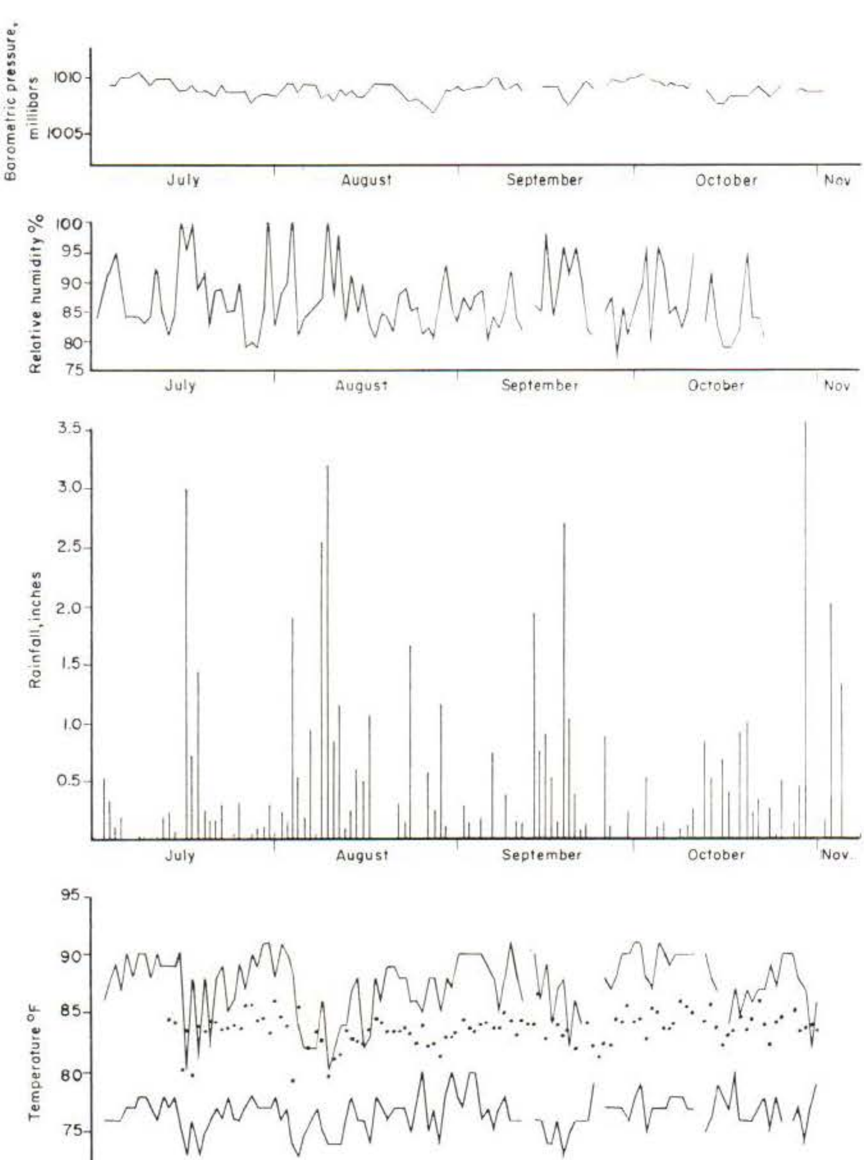

FIGURE 4.—Ifaluk climate, July to early November 1953. In bottom graph upper and lower lines indicate maximum and minimum air temperatures for 24-hour period preceding observation; dots show ocean temperatures taken on windward reef.

Local depressions in both air and shore water temperatures are associated with rainfall. Shore water temperatures are lowered not only by the direct addition of cool rainwater from above, but by the subsurface runoff of fresh water through beach sands from the margin of the subterranean Ghyben-Herzberg lens, especially during periods of low water. Relative humidity over the islands is probably slightly higher than that over the surrounding sea, owing to increased evaporation-transpiration. Sea winds are rarely saturated, and the average night relative humidity over the open sea in this area is estimated as 82 to 86 percent (U. S. N. Hydrographic Office, 1943). Relative humidities of 100 percent were recorded only during showers.

Clouds were not systematically observed, but even on sunny days cumulus cloud cover usually ranged from 25 to 50 percent.

Ifaluk is so far to the south (lat. 7°15′N.) that it is affected by strong and steady northeast trade winds for only a small part of the year. The period of November or December to March, the season called *vang* on Ifaluk, is characterized by steady east to northeast trades with a mean velocity of about 12 knots and by a lowered rainfall, a scarcity of breadfruit, and an abundance of flying fish. In late March and April the trades become fitful and interspersed with calms, and the winds change as summer conditions approach in the Northern Hemisphere. From June through October or November they are irregular, coming from the east, west, or southwest, and average about 6 knots. This summer season, called *rag* on Ifaluk, is a time of calms and intermittant westerlies, heavier rains, and an abundance of breadfruit. Wind waves during the period we were on the island were mostly low to moderate: 2 or 3 to 5 feet in height.

Many of the tropical storms that develop into large typhoons in the northwestern Pacific start as small disturbances to the east, toward Truk. Most of these pass well north of Ifaluk, but each year the island is affected by squally weather and heavy rains that are the result of small storms nearby or large ones at some distance. Full-fledged typhoons strike the island rarely. Burrows and Spiro (1953) report that the four oldest men on the island recalled six large storms. During the worst of these, in 1907, all breadfruit trees were destroyed and most coconut trees were blown down. This typhoon was mentioned by Sarfert (1938) as the great storm that struck the atoll two years before he arrived in 1909 with the Hamburg South Sea Expedition. The story of this typhoon was told to us by Tom Tatogoetil and by Toroman, the third ranking chief, who recalled the event clearly. The first winds blew from the northeast, toppling trees but carrying no large waves over the islets. This phase was followed by a lull, presumably when the eye of the storm passed over the atoll. Then the winds came again, this time from the south. Waves which the informants recalled as taller than the coconut trees swept over Ella Island and the southern reefs. The seas poured over Falalap Island, killing 34 villagers and leaving great sharks floundering in the central taro swamp.

Falarik suffered destruction of villages and forest, but only one life was lost. Other effects of this typhoon are discussed in later sections of this paper. As it was apparently the only storm in the memory of the oldest men that actually put water over the islands, it is probably the only large typhoon that passed near or over the atoll in considerably more than half a century.

In summary, Ifaluk has a tropical rainy climate with relatively small seasonal changes. The temperature and barometric pressure are monotonously uniform throughout the year. Wind and rainfall, influenced by seasonal shifting of the doldrum belt, are more variable. The greatest variations are related to the passage nearby of tropical storms or rare typhoons.

TIDES

Tide data were obtained by Arnow for the period September 13 to 25, 1953, by means of a Stevens type-F water-level recorder which was placed in the lagoon near Falarik Island (fig. 7; pl. 1). Part of the actual tide record is shown in figure 5. The tide data were analyzed by the U. S. Coast and Geodetic Survey, which computed the following elevations shown in feet:

Mean higher high water	0.95
Mean high water	0.75
Mean sea level	0.00
Mean low water	—0.75
Mean lower low water	—1.55

These elevations are indicated on the right side of figure 5.

The primary benchmark established on Ifaluk is an *X* chiseled in a limestone slab on Falarik Island. The slab is embedded in the ground 20 feet west of the west end of the Fan Nap, which is the men's house (fig. 7). The altitude of the *X* is 3.57 feet above mean sea level, as determined from the tide data. All surveyed elevations on Falarik Island are related to this benchmark. The relation of the reefs and shorelines to these tidal levels is shown in cross sections (pl. 2).

Tide data were not obtained for the ocean. However, a comparison was made between the tide data obtained in the lagoon and the predicted ocean tides as published by the U. S. Coast and Geodetic Survey for Woleai Atoll, which is about 35 nautical miles from Ifaluk. No direct correlation was noted, other than that the observed tide in the lagoon preceded the predicted tide in the ocean 90 percent of the time. The average calculated precedence of the lagoon tides was 45 minutes and the maximum precedence was an hour and 48 minutes. This sequence is a reversal of what would normally be expected, and apparently the tides in the open ocean at Ifaluk differ considerably from the predicted tides.

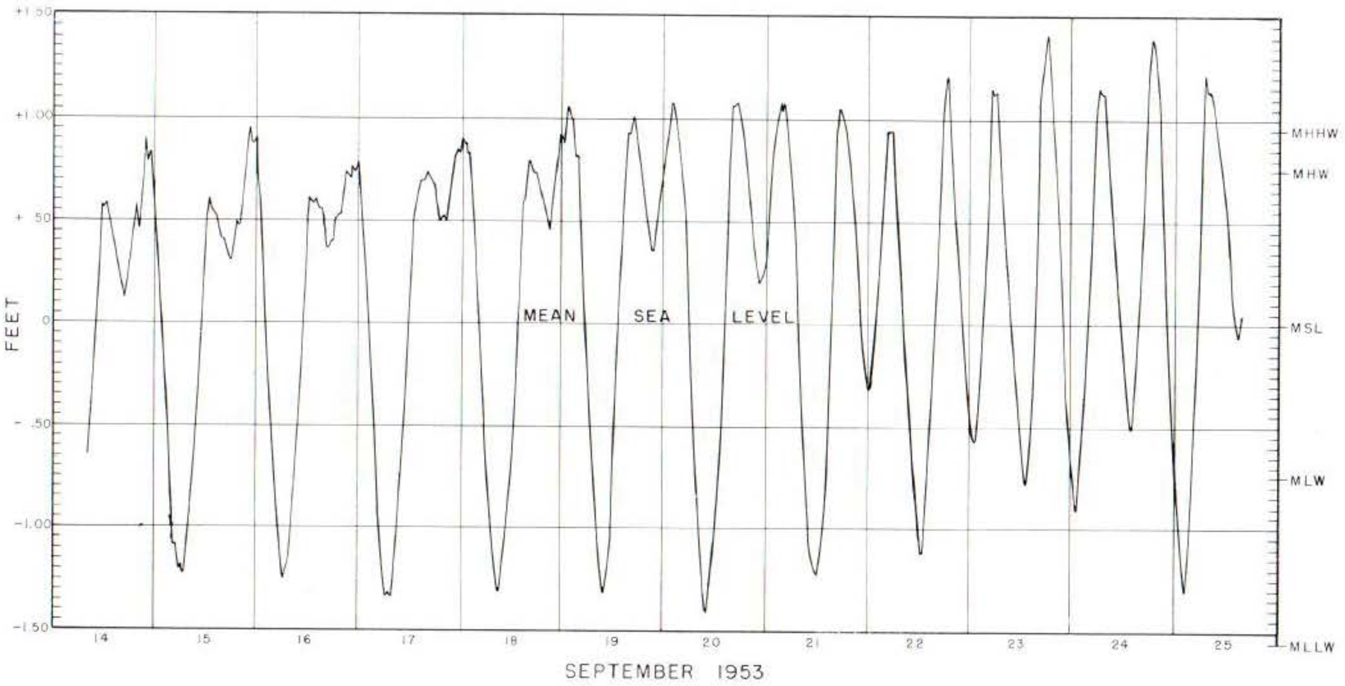

FIGURE 5.—Tidal graph of Ifaluk lagoon, September 14-25, 1953; mean tide ranges on right.

The highest spring tides are several tenths of a foot above the computed mean higher high water. The lowest tides are as much as a foot below mean lower low water, giving an extreme tidal range of about 3.5 feet. The lowest tides during our stay on Ifaluk in October 1953 were about 1 foot below the lowest tides recorded on the tide gage in the period of its operation.

The height of water on a reef is dependent not only on the stage of the tide but on the head of water piled on the reef by waves. The head produced ranges from less than an inch for very low waves to 1.5 feet for strong (7-foot) waves (Munk and Sargent, 1954). It is much higher for storm waves.

GEOLOGY AND HYDROLOGY[2]

The geologic and hydrologic field work on which this section of the report is based was part of more extended investigations of the geology, soils, and water resources of certain Pacific islands by the U. S. Geological Survey, supported by the Office of Chief of Engineers, U. S. Army, and by the U. S. Trust Territory.

Because of the short time spent by the geologists on the atoll, much of the reef work reported here includes observations and detailed transects made by the biologists, particularly Donald Abbott. Lagoon samples were collected by Bayer and Abbott with the help of Yaniseman, the native school teacher. Detailed observations of the lagoon bottom and outer terrace, to depths of 60 to 80 feet, were made at a number of places by Robert Rofen, who dived with an aqualung to collect fishes. The general subdivisions of the reef and lagoon were agreed upon in the field. The manuscript was reviewed by E. D. McKee, S. O. Schlanger, and H. S. Ladd, whose helpful comments are appreciated.

The topographic and geologic map of Falarik Island (fig. 7) was made with plane table and telescopic alidade by Tracey and Arnow. The map was contoured in the field. We used a 4-foot contour interval and one auxiliary 2-foot interval, assuming datum to be about mean low water level. After tide and well data had been computed, all contours were related to mean sea level, about one foot higher. Mean sea level is not only the most significant level relative to ground-water fluctuation, but it was found to be approximately the level of the break in slope around the island where the base of the beach joins the reef (pl. 2). It is, therefore, a more significant zero contour for the islands than either mean low water, which is halfway out on the reef, or mean lower low water—the usual datum of hydrographic charts—which is near the edge of the reef.

The planimetry for the geologic map of Ifaluk Atoll (pl. 1) was traced from an uncontrolled photomosaic made from vertical photographs flown at 5,000 feet by the U. S. Navy (Utility Squadron FVU-5) in 1952 (fig. 3). A second photographic flight was made in 1953 to obtain both vertical and

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[2] Publication authorized by the Director, U. S. Geological Survey.

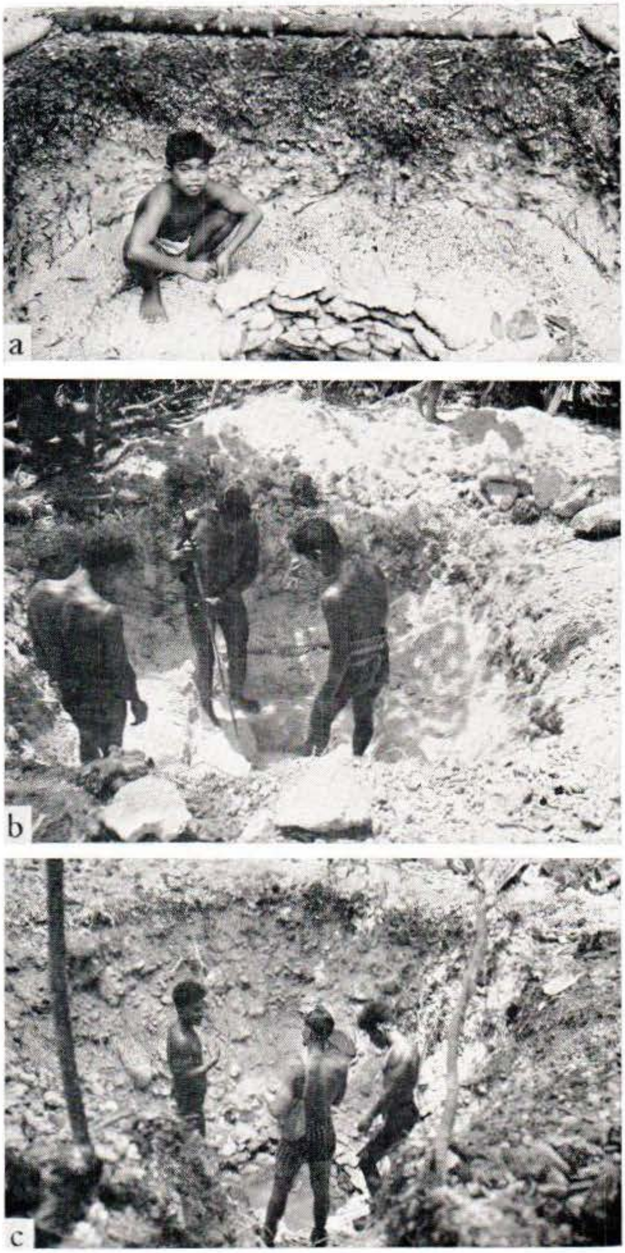

FIGURE 6.—**a**, well 14, Maia Channel line, section C-C′, Falarik Island; **b**, workmen digging well 21, section E-E′, Falalap Island; **c**, well 27, Ella Island, dug through poorly stratified coarse rubble and sandy gravel on southern rampart. Well locations are shown in plate 1 and figure 7 (photographs by Marston Bates).

oblique photographs at 2,000 feet (figs. 2, 20, 21). These photos were used in the field work. Zoning of the reefs, examination of the islands, and contouring of the lagoon were done from the photographs.

The outlines of reef and islands and the shape of the atoll are reasonably accurate. The dimensions and outline of Falarik Island on the photomosaic, compared to the plane-table survey (fig. 7), show distortion amounting in places to ± 5 percent. Points on Ella and Elangalap Islands were found by triangulation to be relatively close to their true positions on the photomosaic. The map is as accurate as the Hydrographic Office Chart 5425-G made from a Japanese sketch survey in 1921.

Reef zones that were recognized in the field were traced around the atoll in the photographs (fig. 18). The lagoon was contoured on stereoscopic pairs of lagoon photographs. Contour lines of approximately equal intervals were drawn around shoals and banks. Points of known depth were labeled from cross-lagoon traverses and from soundings plotted from H. O. 5425-G, and the contours were than adjusted over the lagoon. Depth cannot be judged accurately in aerial photographs, for underwater shoals or banks appear to change in depth, shape, and relative position from one pair of photographs to the next, depending on angle of incidence with the water and on angle of sunlight in the photograph. No claim is made for great accuracy of the lagoon contours. They cannot be used for precise work or for navigation. The shape of the lagoon bottom is considered reasonably accurate, however.

GEOLOGY OF ISLANDS

The principal sediments forming the islands are related in their distribution to the broad physiographic divisions of each island (fig. 7; pls. 1-3). In general, the seaward, or outer, side of each island is a ridge, or boulder rampart, formed of large cobbles and boulders; the lagoon shore is a low sand flat, here called the lagoon flat. Between the two is an interior basin, swampy in places, formed of gravel grading into sand on the one side and into cobbles and boulders on the other. Sediments are poorly sorted but are crudely to well bedded. They are divided into five mapped units based primarily on grain size, secondarily on age. Older units that form islands proper are designated *Ob*, older boulders and cobbles of the boulder rampart; *Og*, older gravel and sandy gravel of the interior basin; and *Os*, older sand and gravelly sand of the lagoon flat. These three units grade into one another. Younger units that form the shores and very recent additions to the island are *Yb*, younger boulders and coarse gravel of the seaward beaches (including very recent additions to the boulder rampart) and *Ys*, younger sand and gravelly sand of the lagoon beaches (including very recent additions to the sandy flats). Consolidated rocks on the islands are limited to patches of lithified beach conglomerate on the seaward side (*Ocg*), and remnants of bedded beach conglomerate remaining on the reef.

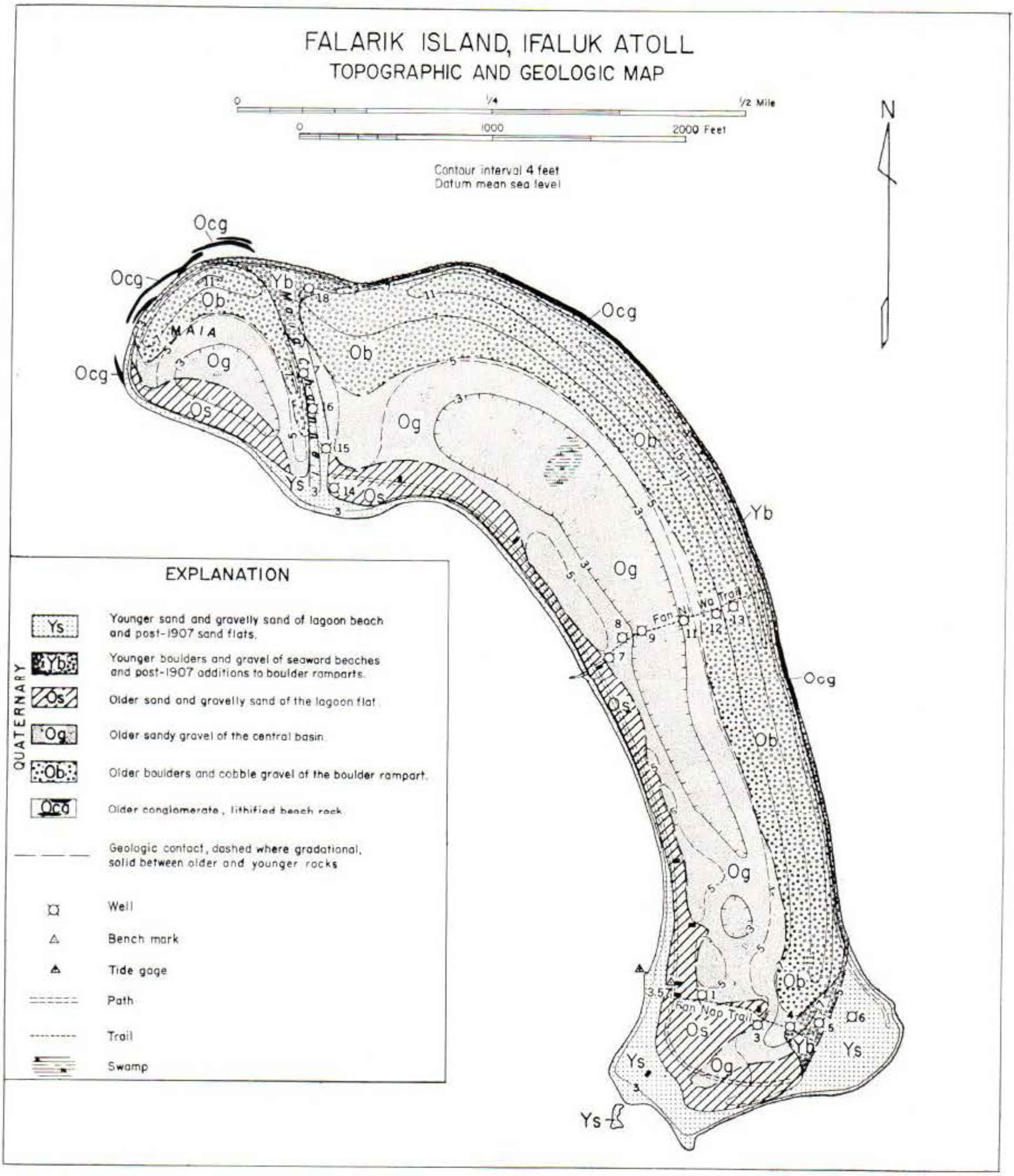

Figure 7.—Topographic and geologic map of Falarik Island.

These units are based on observations made on surface exposures and in pits dug on the four islands (table 7). Elevations refer to the ground surface at the top of the pit, or well, and are given in feet above mean sea level. The three lines of wells on Falarik Island were surveyed, whereas on the other islands the water level in the well was measured and the difference to mean tide level was estimated. Locations are shown on the geologic map (pl. 1), and inferred correlations between the geologic units are shown in the cross sections (pl. 2).

FALARIK ISLAND

Falarik Island is about 5,500 feet long by 1,200 feet wide, and covers 150 acres. The topography and geology are shown in figure 7. The configuration of the boulder ramparts indicates that the north end of the island was formerly separate. The former island is still called Maia, and it was separated from the main island by a narrow channel, called Maia Channel, that is now filled.

The seaward beach throughout most of its length is a cobble or boulder beach, *Yb*, consisting of boulders reworked from the seaward slope of the boulder rampart. Along parts of the shore the intertidal zone is a truncated conglomerate, *Ocg*, that cannot be differentiated from rock under the boulder flat on the reef. At the north end of the island several concentric lines of eroded beach rock are on the reef flat as much as 100 feet from shore, indicating that the present shoreline has been eroded back. The boulder rampart is prominent along the coast for most of its length, and at its maximum is more than 15 feet above mean sea level (fig. 7). The crest of the rampart is generally 75 to 150 feet from the shoreline, and in several places consists of two low ridges not shown on the topographic map. Rounded cobbles and boulders, containing little or no gravel or sand matrix, and scattered massive angular blocks 1 to 3 feet in length form the steep seaward face and the crest of the rampart. The size of boulders and the number of large blocks decrease down the gentle backslope of the rampart to merge with the pebble gravel of the interior basin. Soil is limited to black leafmold, thin in crevices and hollows on the crest and thicker on the backslope. The absence of sand and gravel on the crest and seaward slope is apparently a surficial feature, for all wells through the rampart showed boulders and cobbles packed in gravel and sand (table 7, well 13; also well 19 on Falalap Island). The loose boulders at the surface appear to be a "lag concentrate" caused by the washing downward of loose sand and fine gravel.

The ends of the boulder rampart of Falarik Island curve lagoonward and become subdued in height and shape. The boulder gravel that forms the ends of the arcs grades to pebble gravel and locally to gravelly sand with few boulders. The break in slope at the foot of the backslope of the boulder rampart is in some places well defined, and serves as a dividing line between the rampart and the interior basin as well as a gradational contact between boulder and cobble gravel (*Ob*) and pebble gravel (*Og*). In other places long flat

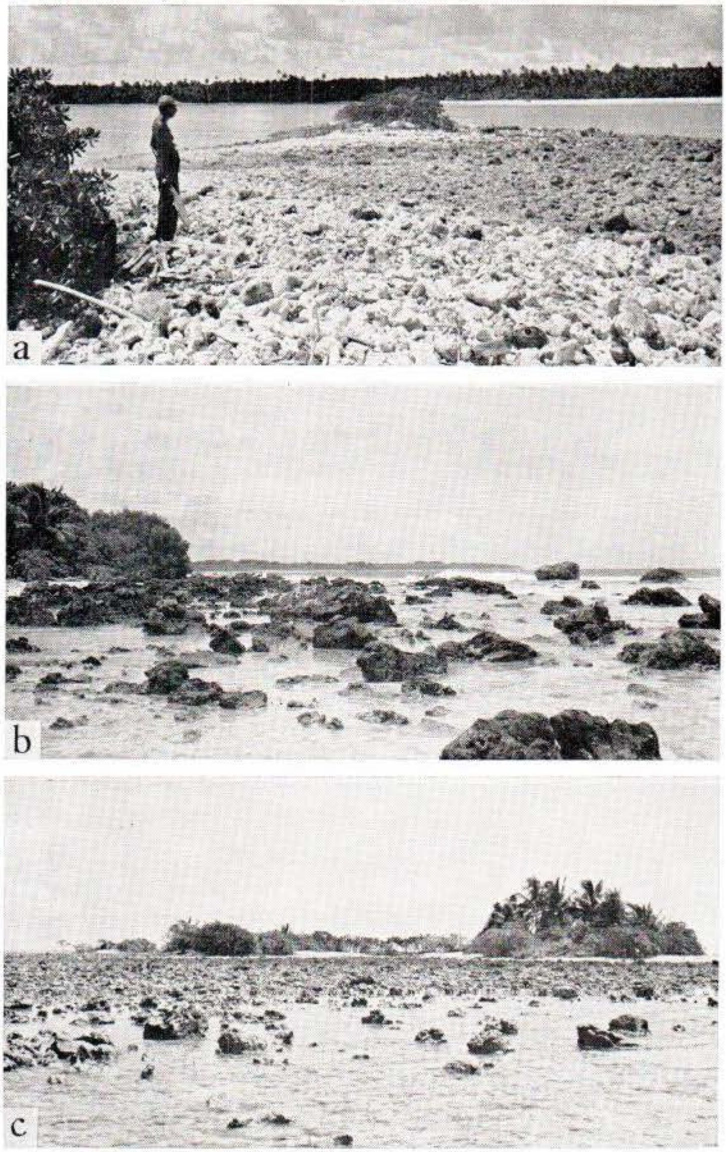

FIGURE 8.—Boulder flats on reef: **a**, rock bar at east end of Ella Island; boulders and gravel piled up by 1907 typhoon form extension of boulder rampart (photograph by Abbott). **b**, blocks on reef flat off southern shore of Ella Island thrown up by 1907 typhoon; largest block, to right of photograph near reef edge, is a *Porites* colony 18 feet in diameter; slight nip near its base formed by intertidal solution in less than 50 years (photograph by Marston Bates). **c**, loose coral rubble on reef flat southwest of Elangalap Island (photograph by Abbott).

trains of cobbles extend 100 feet or more beyond the break in slope onto the interior basin. Where the division is indefinite, the contact is taken along the 5-foot auxiliary contour.

The interior basin of Falarik Island is less than 3 feet above mean sea level in most places. Some small areas are naturally swampy or ponded, and many large pits have been dug for taro cultivation. Coconut palms grow over much of the basin; breadfruit trees, on the better drained parts. The entire area is underlain by dark-gray sandy gravel (*Og*), ranging from sandy cobble gravel with a few scattered boulders near the boulder rampart to a very sandy pebble gravel or gravelly sand at the lagoon flat. Well 11 (table 7) is typical of this unit. Black humus or leafmold covers most of the gravel of the

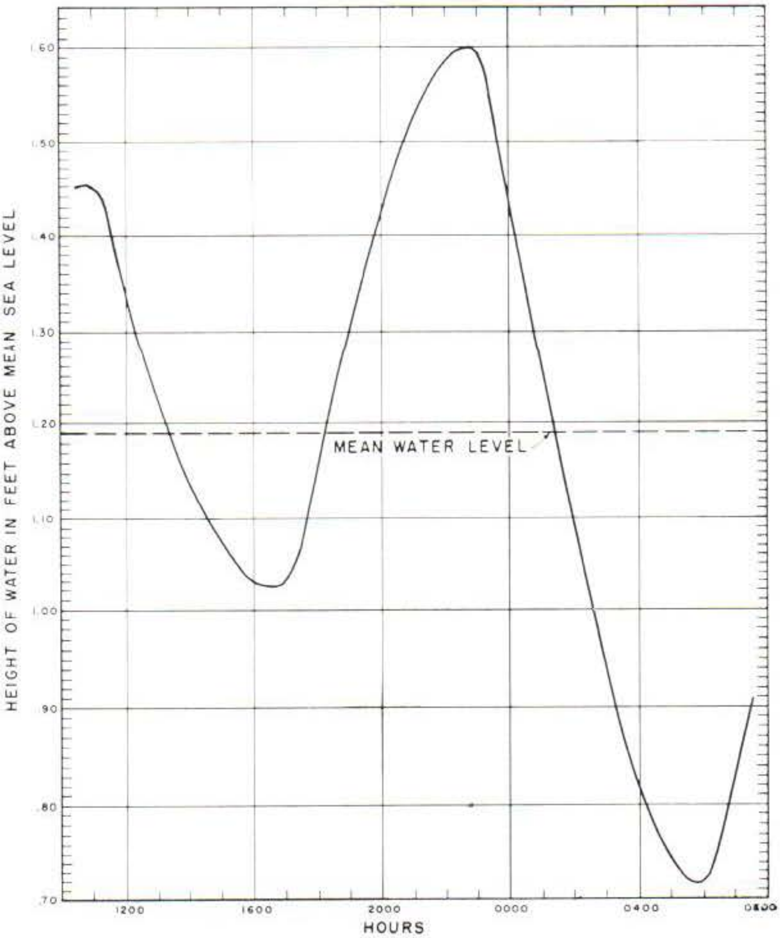

Figure 9.—Hydrograph for well 6.

interior basin, and black carbonaceous matter is found in the top 6 inches of the gravel. Swampy and ponded areas are covered with rotted leaves and with a thick dark-brown muck of finely divided organic material containing a small amount of limy sand and silt. The soil of this unit appears to correspond to Stone's Arno Series (1951), later renamed the Arno Atoll Series by Fosberg (1954). Phosphate has been reported from Ifaluk Atoll by Haneda (Foster, 1956, p. 216). No confirmation of the presence of phosphate was found in this investigation. Phosphatic soils in this region are called "Jemo soil" by Fosberg (1954), and attributed by him to a former *Pisonia* forest. Although Ifaluk has no *Pisonia* forests now, they may have grown on Ella Island until comparatively recently.

Table 7.—Descriptions of material in dug wells on Ifaluk Atoll (from surface to, or a little below, water level at time of examination)

FALARIK ISLAND

WELLS ON FAN NAP TRAIL, CROSS SECTION A-A' (PL. 2)

DEPTH (FEET)	WELL 3	ELEVATION 4.5 FEET
0-0.5	Gravel, sandy, dark brown carbonaceous, containing rootlets; abundant small pebbles 1-3 cm.	
0.5-3.5	Sand, white, fine to coarse, unsorted, not bedded, containing abundant worn Foraminifera 0.5-1 mm.	
3.5-4.5	Gravel, coarse, with coarse sand matrix; thin brown humus or fine silt at top of unit, either a former soil profile or, more likely, an accumulation by percolation of fine material at high water level	
	WELL 4	ELEVATION 8.3 FEET
0-1.6	Sand, light brown, medium to coarse, containing rootlets	
1.6-2.4	Gravel and sand, dark brown carbonaceous, containing roots, probably a former soil layer	
2.4-7.5	Sand, light brown, coarse, few rootlets, grading near base to gravelly sand	
	WELL 5	ELEVATION 5.1 FEET
0-0.5	Sand, brown, moderately carbonaceous, coarse, containing scattered small pebbles and abundant rootlets	
0.5-2.5	Gravel, sandy, light brown, gray or buff, grading down to gravelly sand with about 10 percent pebbles 1-5 cm., rarely 15 cm. diameter; sand very coarse to coarse with abundant Foraminifera	
2.5-5	Sand, buff, very coarse with few pebbles, gradational from unit above	
	WELL 6	ELEVATION 3.5 FEET
0-1.2	Sand, light brown to tan, dark brown in top 0.2 foot, very coarse to coarse with scattered small pebbles and rootlets	
1.2-3.8	Sand, very coarse, gravelly, tan, with 10-50 percent pebbles in irregular patches; rudely stratified and channeled	

WELLS ON FAN NI WA TRAIL, CROSS SECTION B-B′ (PL. 2)

WELL 7 ELEVATION 3 FEET

0-2	Gravel, medium gray with brown carbonaceous sand matrix; rootlets persist to water level. Pebbles and granules about 25 percent of gravel, mostly worn coral fragments; sand matrix dominantly foraminiferal, coarse with fine carbonaceous material; section poorly exposed

WELL 8 ELEVATION 3.2 FEET

0-2	Gravelly sand and sandy gravel, dark brown to gray carbonaceous, similar to well 7

WELL 9 ELEVATION 2.7 FEET

0-2	Sand, light brown to tan, very coarse with some fine material forming a "binder" or matrix, and clayey to touch when wet; granule layer at 0.8 foot

WELL 11 ELEVATION 3.7 FEET

0-0.5	Sand, very coarse, containing scattered pebbles and boulders; brown to black humus in top 0.1 foot
0.5-2.5	Sand, coarse, gravelly, with scattered worn coral fragments; matrix clayey to touch when wet
2.5-4	Boulder gravel; large boulders and cobbles in a coarse sand matrix with some fines, clayey to touch when wet; above water level this apparently has effect of indurating gravel slightly

WELL 12 ELEVATION 5.0 FEET

0-0.5	Gravel: boulders and pebbles in a granule and coarse sand matrix; dark brown humus and abundant rootlets in top of 0.2 foot
0.5-4	Very coarse gravel: boulders and pebbles in a coarse shell-foraminiferal matrix; scattered cobbles and boulders of rounded coral 3-30 cm. are about 5 percent of the rock; packed pebbles 4 mm. to 3 cm. about 70 percent; coarse sand and granules about 20 percent; and very fine material about 5 percent (a heavy wrecking bar was needed to drive the last foot or so of this well at about water level, and packed cobbles were firmly set in matrix although no true cementation was seen; this appears to be related to the clayey consistency and slight induration noted at water level in other wells)

WELL 13 ELEVATION 8.1 FEET

0-3	Gravel, pebble to boulder, medium gray to brown, grading down to tan sandy gravel; boulders dominant at top
3-6	Gravel, sandy, grading to very coarse gravelly sand; concentrations of pebbles in irregular patches form 10-50 percent of rock
6-7	Boulders and pebbles, 75 percent, in coarse sand matrix

WELLS ON MAIA CHANNEL LINE, CROSS SECTION C-C′ (PL. 2)

WELL 14 (fig. 6, *a*) ELEVATION 4 FEET

0-1.2	Pebble gravel, sandy; black humus at top, grades down through gray to brown; rootlets abundant; pebbles mostly 1-5 cm.
1.2-3.5	Sand, foraminiferal, very coarse, containing scattered pebbles

WELL 15 ELEVATION 2.2 FEET

0.0-0.1	Humus, very sandy
0.1-1.2	Sand, gravelly, very coarse, crudely stratified; thin, discontinuous white fragmental beds (shells, algae) and scattered concentrations of pebbles in coarse foraminiferal sand

WELL 16 ELEVATION 1.9 FEET

0-0.1	Sand, dark brown, coarse, containing rootlets
0.1-1	Sand, gravelly, foraminiferal, medium to light brown; pebbles 1-5 cm. form about 25 percent of gravel

WELL 17 ELEVATION 4.5 FEET

0-0.1	Brown humus
0.1-4	Sand, light brown to tan, coarse, foraminiferal; pebbles scattered through section

WELL 18 ELEVATION 7.3 FEET

0-0.1	Gravel, brown, sandy, with humus
0.1-0.6	Gravel, coarse, with sand matrix; pebbles 2-12 cm., sand mostly Foraminifera
0.6-1.2	Coral gravel; packed coral fragments 2-5 cm., some round cobbles, no matrix
1.2-4.3	Sand and gravel, bedded; gravel layers 0.2-0.5 foot thick of rounded coral fragments separated by layers of sand or fine gravel; looks like a beach or bar deposit
4.3-7	Covered, probably same as above

FALALAP ISLAND

CROSS SECTION E-E' (PL. 2)

WELL 19 ELEVATION ABOUT 11 FEET

0-1	Cobbles and boulders with very little sand matrix, thin humus on top
1-11	Boulder gravel, coarse sand matrix; large boulders concentrated at 4, 6, and 10 feet

WELL 21 (fig. 6, *b*) ELEVATION ABOUT 5 FEET

0-4	Coarse gravelly sand grading to sandy gravel; sand matrix has slightly clayey consistency near water line (sample 46)

ELANGALAP ISLAND

WELL 25 ELEVATION ABOUT 5 FEET

0-1	Gravel, coarse, with cobbles
1-2	Gravel, fine, with granules and pebbles, no sand
2-5.7	Gravel, coarse, containing cobbles and boulders, some sand

ELLA ISLAND

WELL 27 (fig. 6, *c*)	ELEVATION ABOUT 8 FEET
0-7.5	Boulder conglomerate, pebble and sand matrix, poorly stratified; some boulders 2 feet in diameter; matrix sand at water level white and clayey, smelling strongly of hydrogen sulfide

WELL 28	ELEVATION ABOUT 8 FEET
0-4.1	Coarse pebble and cobble gravel, sand matrix; two boulder layers
4.1-7.3	Sand, coarse, abundant scattered pebbles, a few cobbles and boulders; roots near bottom of unit

WELL 29	ELEVATION ABOUT 6 FEET
0-1.5	Sand, gravelly, dark to medium brown carbonaceous with rootlets
1.5-5.3	Sand, medium to light brown, some pebbly layers

The lagoon flat, which extends from the north to the south end of the island, ranges in width from 150 to about 400 feet from the lagoon beach to the interior basin. A series of long, low mounds, elongate in a north-south direction, extends along the inner edge of the lagoon flat next to the basin. The mounds are 100 to 500 feet long, 50 to 100 feet wide, and rise only a foot or two above most of the lagoon flat. They are outlined in figure 7 by the auxiliary 5-foot contour. They are formed of gray to black pebble gravel (wells 7 and 8, table 7; sample 46, table 10) similar to that underlying much of the low interior basin. Most of the houses on Ifaluk are built on these mounds. Most of the lagoon flat shoreward of the mounds and between them is formed of medium and fine, well-sorted light-brown sand of unit *Os* (sample 45, table 10). The unusually good sorting of this sand in most places suggests that it is windblown. In some places on the lagoon flat, however, the sand is gravelly, in others it is coarse and unsorted but stratified, typical of the sand deposited on the lagoon beach nearby. In general, the soil appears to correspond to the sandy flats on Arno Atoll, which Stone (1951) correlated with the Shioya Soil Series of Okinawa. The lagoon flat is mostly just above the 3-foot contour, and therefore is less than 2 feet above the highest tides.

The broad, gently sloping lagoon beach of coarse- to medium-grained sand (*Ys*) runs the length of the island. In addition to the lagoon beach, a broad sandy flat 150 to 300 feet wide alongside Falalap Channel is formed of younger sand (*Ys*), as is the bottom of the now filled Maia Channel near the north end of the island. Younger boulders and cobbles (*Yb*), in addition to forming the seaward beach, form the boulder rampart across Maia Channel near well 18 and form a triangular blanket of recent coarse boulders and gravel that laps over the boulder rampart at the south end of the island near wells 4 and 5.

Both the sand flats and the sediment-filled Maia Channel are now coconut groves, but the coarse yellow gravelly sand of unit *Ys* can easily be differentiated from the fine brown carbonaceous sand of unit *Os*. The coconut trees in Maia Channel are much younger and poorer than those planted in older soil. According to the accounts of some of the older men of the atoll, the material of units *Ys* and *Yb* was deposited during the typhoon of 1907, when the island was almost completely covered by the sea. The sandy flats at the south end of Falarik were intertidal boulder flats before the typhoon, and Maia Channel was a shallow rip-channel that separated Falarik and Maia. The sides of old Maia Channel are distinctly marked by boulder ramparts up to 7 feet above datum, covered with black humus and typical ridge vegetation. Large breadfruit trees grow just inside the crest of the boulder ramparts on the rich black humus, but do not grow on the younger sand (*Ys*) in Maia Channel (fig. 20). On the seaward coast the position of the former channel is indicated by the indented shoreline, and on the lagoon coast by the bulging shoreline, a feature which is comparable to the sand shoal that extends lagoonward at the inner end of Falalap Channel.

The first map of the atoll, made by Lütke in 1828 (Damm and Sarfert, 1938), shows Maia as a distinct islet labeled Fararyk, separated from Falarik (labeled Ifalouk) by an open channel. Sarfert calls attention to Lütke's "error" in indicating an islet north of Falarik, but notes that a sandspit called Maje (Maia) was joined to north Falarik during the 1907 typhoon. Lütke's chart appears to be correct in general outline for pre-1907 conditions. The names Moai and Imoai applied to various islets on the atoll by earlier visitors probably apply to the present north tip of Falarik, which is called Maia by the inhabitants.

FALALAP ISLAND

Falalap Island measures about 4,500 by 2,000 feet and is approximately 175 acres in area. The island is a horseshoe-shaped boulder rampart enclosing a large interior basin that includes several ponded swamps, brackish mangrove swamps, and large swampy basins used for the cultivation of taro. The principal ones shown on the geologic map (pl. 1) are traced from aerial photographs. The interior basin is enclosed at the north end near Falalap Channel by sand and gravel flats (*Os*) and by gravel mounds similar to the lagoon flat on Falarik Island. The boulder rampart (*Ob*) was not surveyed in its entirety, but in a few places measured more than 12 feet above the intersection of the reef with the beach (about mean sea level). The rampart is 460 feet wide near well 19, shows two crests where it was measured along cross section E-E′ (pl. 2), and is reported to have two crests along the south end of the island. The outer crest, which is low, is thought to be a relic of the typhoon of 1907. Bedded beach conglomerate (*Ocg*) conformable to the present beach is shown in plate 1. The beach conglomerate on the east coast was found to be 3.8 feet above the base of the present beach (approximately mean sea level) or more than 2 feet above the highest tides. This was the highest exposure of consolidated rock found on the atoll.

A path around the taro pits and swamps of the interior basin follows the base of the backslope of the boulder rampart and is taken as the contact between the older boulder unit (*Ob*), and the older gravel (*Og*). The large swampy areas of the interior basin are covered with thick carbonaceous muck, in places several feet deep (pl. 2, cross section E-E′). Ponded water and muck are reported to be waist deep in the deepest places. Some of the gravel mounds of the north end are more than 7 feet above mean sea level; otherwise they appear to be identical to those bordering the interior basin on Falarik Island. A relatively small sandy flat at the north end of Falalap is comparable to the lagoon flat on Falarik. Younger sand and gravelly sand (*Ys*) forms a narrow low flat bordering Falalap Channel, and younger boulder gravel (*Yb*) forms the beaches around the boulder rampart as well as the outer low crest of the rampart.

ELLA ISLAND

Ella Island is about 2,000 feet by 750 feet and covers about 25 acres. A long, narrow rock bar, partly covered with vegetation, extends about 1,200 feet east of the island along the reef toward Ifaluk Pass (fig. 8, *a*). The seaward side of the island is a wide boulder rampart, 7 feet high near well 27, which grades lagoonward to a hummocky gravel flat (*Og*) that forms the north half of the island. Nothing corresponding to an interior basin was seen. The boulder rampart has a double crest. The inner, wide rampart (*Ob*) is crescent-shaped and forms the backbone of the island. The outer, low, narrow rampart is a continuation of the long boulder bar at the east end of the island. It merges with the main rampart near the middle of the island, but near the west end of the island it diverges to enclose a shallow, brackish pool about 300 feet long, 50 feet wide, and 1 to 2 feet deep, floored with coarse sandy gravel covered with thin carbonaceous silty ooze (sample 47, table 10). According to the islanders, the rock bar and the outer rampart were built during the typhoon of 1907, at which time numerous large blocks, including one 18 feet in diameter, were thrown up on the narrow reef flat south of Ella Island (fig. 8, *b*). This unit is, therefore, mapped as younger boulders (*Yb*). Natives report that at the time of the typhoon a large wave visible from Falarik Island washed completely over Ella and was "taller than the trees on Ella." Coarse rubble and gravel carried over the rampart by this wave may have filled any former interior basin that existed, and this would explain the coarse gravel overlying sand in wells 28 and 29 (table 7).

ELANGALAP ISLAND

Elangalap Island is a small, vegetated, double mound of boulders, each part of which is roughly 75 by 100 feet across. Well 25 was dug to 5.7 feet through the boulder pile (table 7). The island is not mentioned by any of the people who visited the atoll prior to Sarfert's two-week stay in 1909 (Damm and Sarfert, 1938). It was Sarfert's opinion that the islet was built by the typhoon of 1907 two years earlier, although he fails to mention any confirmation by the natives. While on Ifaluk, he apparently did not recognize the possibility of island construction by the typhoon, but later discovered that no previous accounts or charts showed an islet at this location. Sarfert's hypothesis appears reasonable, and we have mapped the island as younger boulders (*Yb*). The island name, literally translated, means "big boulder flat." Elangalap Island sits in the middle of a boulder flat (*bf*) that consists of unconsolidated rubble 1 to 2 feet higher than the reef flat (fig. 8, *c*). There is no lithification to indicate that the rubble foundation is old.

ISLAND BUILDING

The geologic evidence from all the islands, coupled with consistent information from the native population, shows conclusively that major additions to the atoll and to each island were made by the single large storm in 1907. (The pre-1907 and post-1907 geology are differentiated in figure 7 and plate 1.) On Falarik Island the addition amounts to 8 acres in 150, or about 5 percent.

The apparent pattern of building of the islands is (1) the construction on the reef of a crescent-shaped or horseshoe-shaped ridge of boulders, the convex side facing the sea, and (2) gravel bars, piled up on the lagoon side of the boulder ridge by swells across the lagoon, forming the gravel mounds that bound the interior basin. The gravel bars evidently formed a locus of deposition for fine sand and gravel that built out to form the present lagoon flat bounded by the lagoon beach.

Consolidated conglomeratic rock on Falalap Island 2 feet above high tide and relatively conformable with the present beach indicates that the islands had formed when the sea stood a few feet higher—possibly at the time of the 0.5- to 1-meter stand of Kuenen (1933) and others. No lithified rock has been found inside the seaward beach on any island; and no hard rock was struck in any of the dug wells. None of the wells were dug below mean lower low water level, but lithified conglomerate is found on the reef flat as high as mean sea level and the top of the old "reef remnant" at the south end of Falarik Island (fig. 17) is at mean higher high water, more than 2 feet above the bottom of the wells. Therefore, the island sediments were deposited before the reef was lithified.

No beachrock was found on any of the lagoon beaches; and it evidently is not forming at present, although a few slabs of bedded sandstone used as markers or corner posts for canoe houses suggest that lagoon beach rock once existed.

The only evidence of present-day island lithification is the fine material of silt or clay size that binds the gravel at water level in several wells. This may be a precipitate of carbonate dissolved at the surface by rainwater, or it may result from the settling of fine material washed down from the surface by rainwater.

The pattern of growth of the islands is essentially the same as that postulated for Arno Atoll by Wells (1951, p. 3) and by Cox (1951), for Onotoa Atoll by Cloud (1952), and for Bikini by Emery and others (1954). The evidence for Ifaluk is less complicated than any of these and appears to correspond almost identically with the idealized scheme figured by Cloud (1954, fig. 7). Although the building of the islands may have taken place in several episodes of construction and destruction, only the simplest pattern of formation can be deduced.

The present island regimen in normal times appears to be a slow retreat or erosion of the seaward shoreline, as evidenced in places by remnant beachrock ridges 50 to 150 feet from shore, accompanied by a comparably slow accretion of beach sand on the lagoon beaches. The lagoon beaches of the islands all project a hundred feet or so into the lagoon. The only record of a departure from this regimen is that left by the typhoon of 1907, wherein material was added to all the islands, as well as to the rubble tracts on the reef. There is no clear evidence that the islands ever occupied much more area than they do now, although the wide lithified boulder flat seaward of Falarik and Falalap Islands and extending some 3,000 feet westward of Falarik along the northern reef may represent the truncated foundation of an ancient island.

The islands of Ifaluk appear to be more stable than those of atolls such as Funafuti (David and Sweet, 1904, pls. 2-19), the cross sections of which show a very complicated history; or of Arno (Wells, 1951, p. 5), where a typhoon destroyed large parts of Ine Island in 1905. There is no way of telling whether another typhoon would build or destroy Ifaluk, just as there is no way of foretelling how relatively slight changes in the normal regimen might affect the growth or destruction of the islands.

HYDROLOGY[3]

The only source of fresh water on any island of Ifaluk Atoll is the rain that falls directly on that island. Part of the rainfall evaporates or is transpired

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[3] A preliminary report on the hydrology of Ifaluk was published by Arnow (1955).

by plants, and the remainder, because of the high permeability of the island sediments, seeps directly into the ground. There is no significant surface runoff.

GROUND WATER

The porous rock below the islands is permeated by the sea. Fresh-water seepage, being only about 40/41 as heavy as sea water, accumulates and floats on the surface of the subterranean salt water. The fresh water displaces a volume of salt water equal to its own weight and depresses the fresh-salt water interface below sea level, forming an underground reservoir which is roughly the shape of a biconvex lens. The edges of the lens coincide approximately with the edges of the island. Because of the 40/41 weight relationship of fresh to salt water, for every foot the water table is above sea level the interface is about 40 feet below sea level under ideal conditions in an island of homogeneous texture. Actually, the shape of the fresh-water body varies, depending upon local geologic conditions and variations in rainfall, and the 40 to 1 depth ratio is modified by a transition zone of variable thickness in which there is a mixture of fresh and salt water. This fresh-water body floating on sea water is known as the Ghyben-Herzberg lens. It is the only source of potable ground water in Ifaluk and is tapped by means of shallow dug wells.

Fresh water is miscible with salt water, and the Ghyben-Herzberg lens will not form or will be destroyed unless there is a favorable balance of four factors that affect the lens (Wentworth, 1947; Arnow, 1954). The first controlling factor is precipitation. In order to build up a fresh-water lens, the annual precipitation must be great enough to provide adequate recharge to the lens in spite of the small infiltration area offered by the islands in Ifaluk Atoll, and in spite of high evapotranspiration losses which may dispose of a large part of the precipitation. Furthermore, the precipitation cannot be concentrated wholly in one short season, lest the fresh-water lens degenerate during the ensuing dry season. An average annual rainfall at Ifaluk of 100 to 120 inches provides enough recharge to maintain the Ghyben-Herzberg lens. On Onotoa Atoll in the Gilbert Islands, where the annual rainfall averages about 40 inches, Cloud (1952) found a fresh ground-water lens.

No data are available concerning the seasonable distribution of precipitation on Ifaluk. An analysis of the rainfall distribution on Guam, Yap, and Truk, however, indicates that the average total precipitation at Ifaluk during the dry season from January to May is about 25 inches. On Falarik, Falalap, and part of Ella this amount has proved to be enough to prevent the degeneration of the fresh-water lens during the dry season.

A second factor affecting the ground-water lens is the permeability of rocks and unconsolidated deposits that form the island. This permeability must be sufficiently high to allow infiltration of a substantial portion of fresh water from rain, but not so high as to allow free mixing of fresh and salt water. The islands of Ifaluk Atoll consist mainly of coarse sand and gravel overlying a reef platform, and both the sand and gravel and the reef platform in general have a degree of permeability that is conducive to the formation of a Ghyben-Herzberg lens. Exceptions are noted below.

A third factor affecting the ground-water lens is the magnitude of tidal and seasonal fluctuations of the water table which serve to increase the rate of diffusion between the fresh and salt water and, thereby, to enlarge the zone of transition and reduce the zone of fresh water. If the fluctuations are large enough the transition zone will grow until it encompasses the entire lens, in effect destroying it as a source of potable water. The magnitude of the tidal fluctuations in the ground-water lens at any given point is directly proportional to the permeability of the rocks between that point and the shoreline and is inversely proportional to the distance from the shoreline. On very small islands such as Elangalap, the ocean tides pass through the island practically undamped, resulting in such free mixing of fresh and salt water that a fresh-water lens does not form. No data are available concerning the magnitude of seasonal or annual fluctuations of the fresh-water lens on the islands of Ifaluk Atoll.

A fourth factor affecting the ground-water lens is the size and shape of the island. The island must be wide enough to damp the effects of tidal fluctuations sufficiently so that the fresh-water lens is not prevented from forming. It must also be large enough to catch sufficient rainfall to build up a lens of such magnitude as to survive through the dry seasons of the year. Ella, with an area of 0.04 square mile, was the smallest island on Ifaluk in which a fresh-water lens was found. The lens was well developed along a line where the island is approximately 700 feet wide, but was not present where the island was only about 350 feet wide.

The ground-water lens is not a static body, nor does it represent a closed system. It is in a state of dynamic equilibrium in which the controlling factors all function simultaneously and continuously either to destroy or to build up the lens. When the balance of the controlling factors is unfavorable the lens will be nonexistent or, at best, will contain potable water only during the rainy season. When conditions are favorable the lens will contain potable water throughout the year.

Three lines of wells for ground-water observation were established on Falarik Island: the Fan Nap line, the Fan ni Wa line, and the Maia Channel line (fig. 7). Benchmarks for determination of altitude of water levels at the 15 wells were tied in with mean sea level as determined by the tide gage. The largest vertical error on any surveyed loop was 1.5 feet in a 6,000-foot traverse, resulting in a correction of 0.025 feet per 100. Because of difficulty with the level bubble of the alidade, however, some of the well elevations may possibly be in error with respect to adjacent wells in the line by as much as 0.1 foot. Furthermore, any of the well lines may possibly be in error relative to the primary benchmark by several tenths of a foot. Water-level measurements were made on Falarik Island only. Wells on the other islands were used only for sampling.

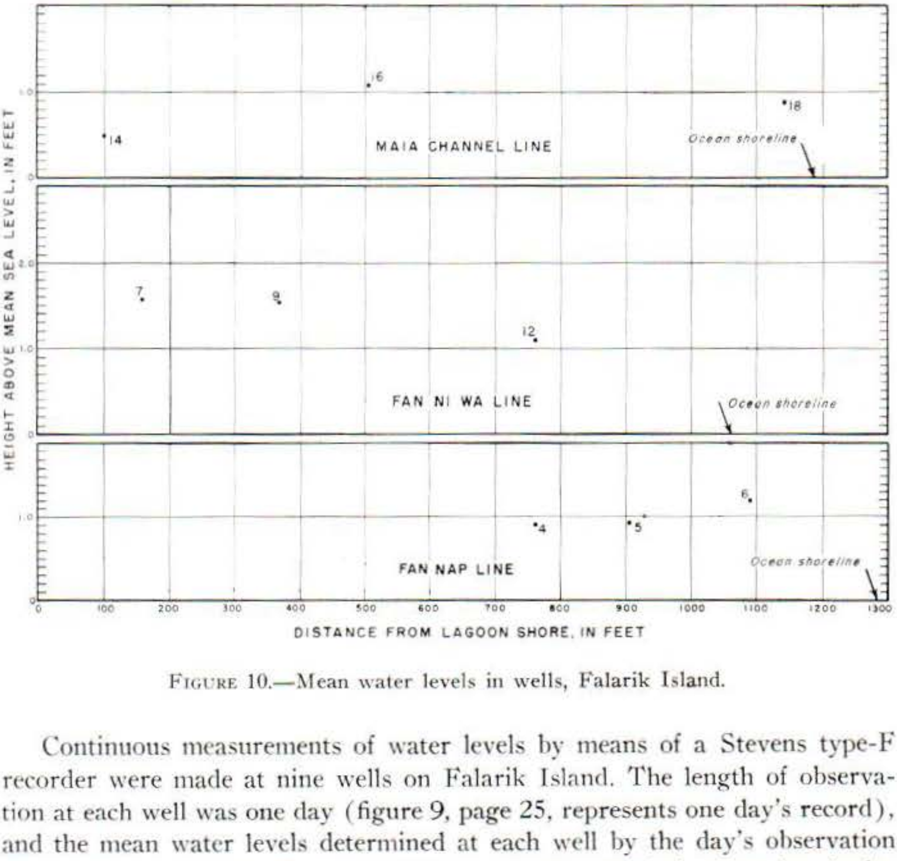


FIGURE 10.—Mean water levels in wells, Falarik Island.

Continuous measurements of water levels by means of a Stevens type-F recorder were made at nine wells on Falarik Island. The length of observation at each well was one day (figure 9, page 25, represents one day's record), and the mean water levels determined at each well by the day's observation are shown in figure 10. The value of the mean water levels is somewhat doubtful, for records of water levels in the wells were obtained on separate days during the rainy season over a period of 11 days, during which more than 7 inches of rain fell. The effect of rainfall on the water level in each well was variable and depended on the day during the 11-day period on which the well was measured. The mean water levels, therefore, are not completely comparable and probably are not representative of the means that would be determined if measurements were made over a period long enough to determine average seasonal fluctuations. The configuration of the ground-water body as determined by water-level measurements does not agree with the configuration suggested by chloride determinations, which are discussed in the next section of this report. The chloride data are believed to be more reliable.

Mean water levels, however, do give an indication of the thickness of the Ghyben-Herzberg lens on Falarik. Allowing for errors due to surveying and shortness of record, the lens on Ifaluk undoubtedly attains a head of at least 1 foot and possibly 1.25 feet above mean sea level. Therefore, the depth to salt water below mean sea level probably is 40 feet or more. The area of maximum thickness in general is in the center of the island or on the lagoon side of the center, and from there the thickness of the lens diminishes to zero at both shorelines. The 40-foot figure is a wet-season estimate, and the depth undoubtedly decreases during normal dry seasons and during extended periods of drought. Native informants have no recollection or legend of a drought on Ifaluk (Burrows and Spiro, 1953). The lenses on Falarik and Falalap, therefore, may be assumed never to have shrunk to a point where food plants or well-water supply were noticeably affected.

The amount of damping and lag of the tides as they move through Falarik Island is shown in figures 11 and 12 by a comparison of the tidal curve obtained in the lagoon and the tidal fluctuations of the water table observed in wells on Falarik. The data for each well were obtained by means of continuous

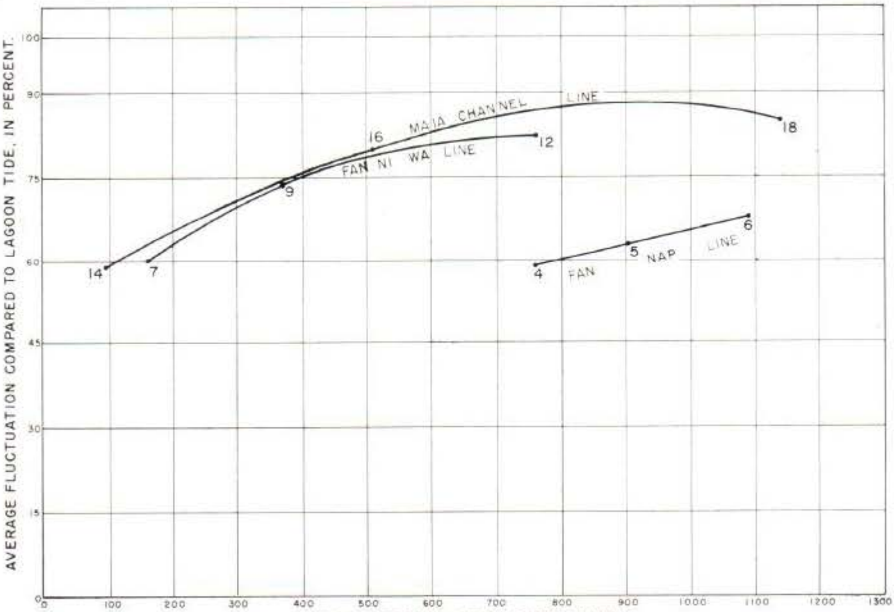


FIGURE 11.—Relation of damping of tidal fluctuations in wells to distance of wells from shoreline, Falarik Island.

observations over a period of one day. Both damping and lag increase progressively from the lagoon shore toward the ocean shore. The full significance of this progressive change cannot be completely explained because of the lack of tidal data from the ocean side of the island. If such data were integrated with the tidal data obtained in the lagoon, a significant change might result in the slope of the curves shown in figures 11 and 12.

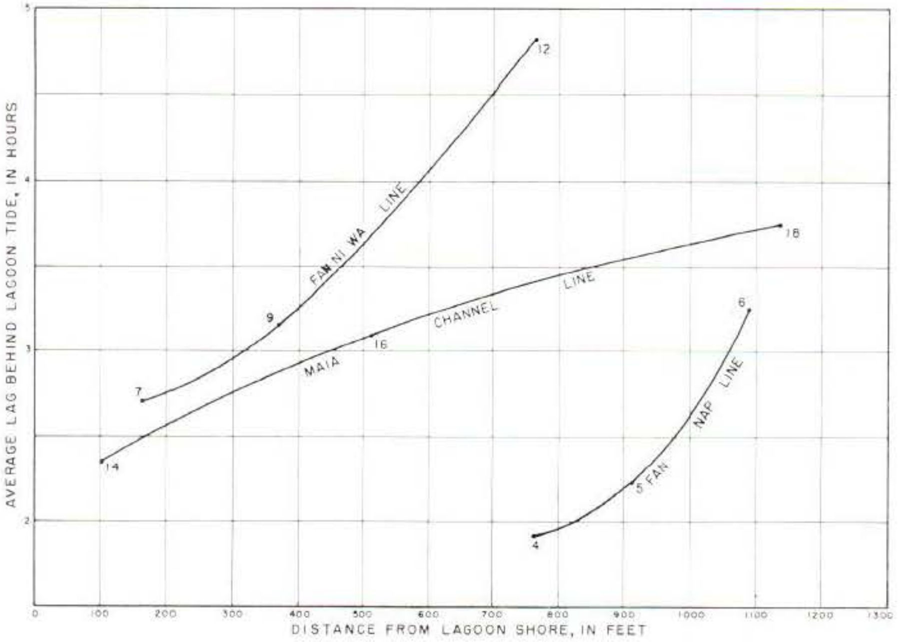


FIGURE 12.—Relation of lag of tidal fluctuations in wells to distance of wells from shoreline, Falarik Island.

The Ghyben-Herzberg lens is not completely developed on Ella Island and apparently is not developed at all on Elangalap Island. These islands are discussed more fully in connection with quality of water.

The extent of development of the Ghyben-Herzberg lens controls the quality of the ground water in the islands of Ifaluk Atoll. The three lines of wells on Falarik Island were sampled on September 21 and during the period November 1 to 3. Partial chemical analyses were made of all samples (table 8). The relation of chloride content to distance from the shore is shown in figure 13 for the samples obtained on September 21, and in figure 14 for the samples obtained from November 1 to 3. The chloride content of the water along the Fan Nap and Maia Channel lines is greatest near the ocean shore, decreases to a minimum about two-thirds of the way across the island, and rises again near the lagoon shore. These relationships suggest that the Ghyben-Herzberg lens has its thickest development about one-third of the way inland from the lagoon shore, and from there thins toward both shores. The displacement of the point of maximum development of the lens from the center of the island toward the lagoon shore may be the result of high permeability in the rocks on the ocean side. The chloride content of the water along the Fan ni Wa line of wells suggests that the maximum development of the lens along this line may be nearer the ocean side of the island than it is along the other two lines. If this is so, it may be due in this particular place to the presence along the ocean shore of well-cemented beachrock (*Ocg*) which acts as a relatively impermeable barrier, retarding the mixing of fresh and salt water that results from tidal fluctuations. The beachrock is not exposed throughout (fig. 7), but it probably extends along most of the northeast coast of Falarik. It terminates, however, before reaching the Fan Nap and Maia Channel well lines.

The chloride content of the ground water throughout Falarik Island rose slightly between the two periods of sampling, but the only significant change was at well 18, where the chloride content rose from 68 to 1,160 p.p.m. This sharp rise indicates that the lens is thinner in the vicinity of well 18 than elsewhere along the three lines of wells. The former channel now marked by the

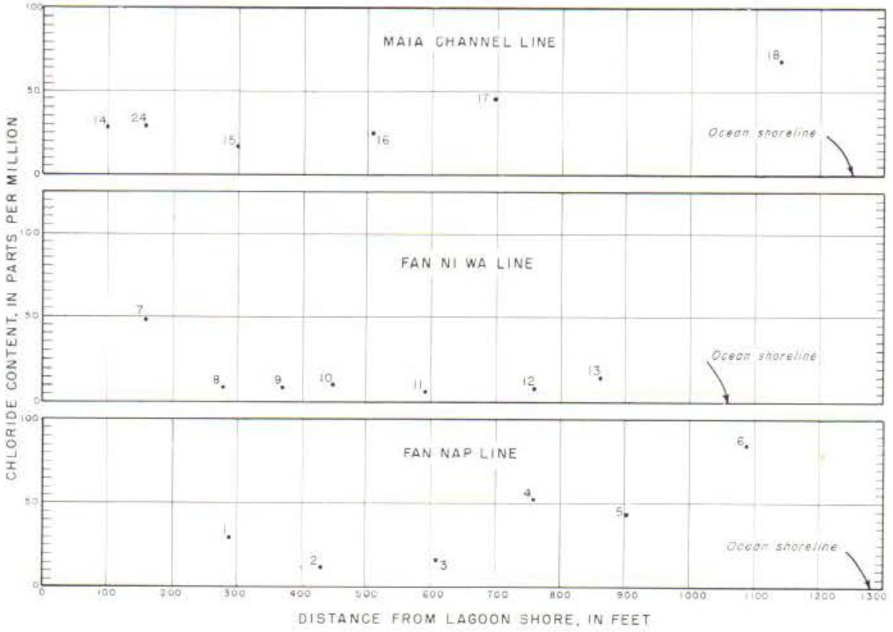


FIGURE 13.—Relation of chloride content of ground water to distance from shore, Falarik Island, September 21, 1953.

Maia Channel line of wells was filled during the typhoon of 1907. Well 18, however, is east of the filled channel which curves toward the northwest north of well 17 (fig. 7). Well 18 is in the bedded sands and gravels that are typical of beach deposits. These deposits are very permeable and permit free movement of water during the tidal cycle. The high permeability coupled with the fact that the shoreline is only 110 feet away may explain the poor development of the fresh-water lens in the vicinity of well 18.

The relation of total hardness of the ground water to distance from the shoreline for the three lines of wells on Falarik follows, in general, the same pattern observed for the chloride data (fig. 15). Because of the acid environment created by decaying vegetation, sampling points 2 and 24, a small taro pit and a coconut retting pit, yield water harder than that of nearby wells.

In addition to the partial analyses discussed above, a set of water samples from the Fan ni Wa line was analyzed for all major dissolved constituents (table 9). The results, in general, agree with those discussed above. The silica content in four of the six wells exceeds that of sea water. The excess silica probably results from solution of detritus of Foraminifera and algae which concentrate silica (Emery *et al.*, 1954, p. 67).

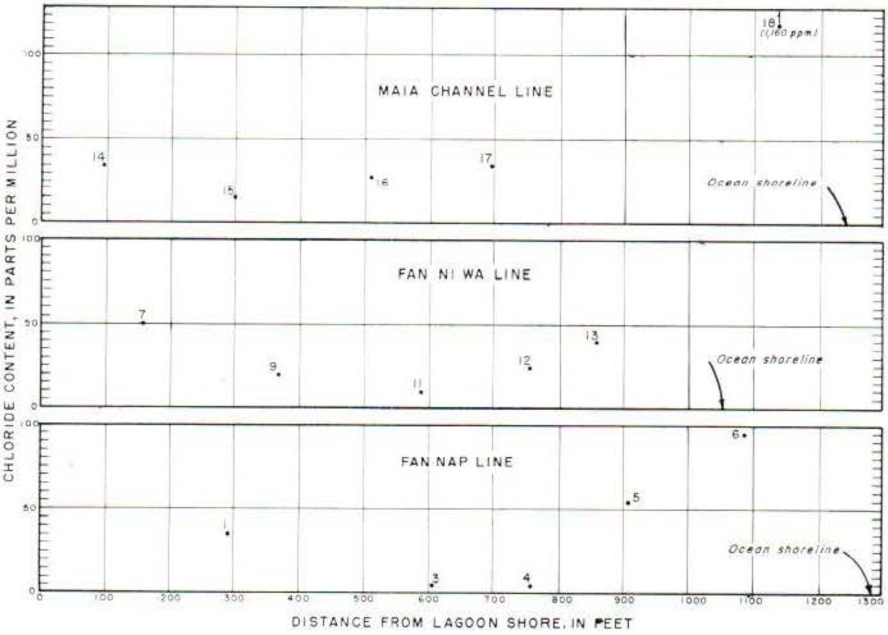


FIGURE 14.—Relation of chloride content of ground water to distance from shore, Falarik Island, November 1-3, 1953.

Analyses of water samples from Falalap Island indicate that the Ghyben-Herzberg lens is as well developed there as it is on Falarik Island. Much of the central part of the island is a fresh-water swamp (pls. 1 and 2; samples 20 and 22 in table 8), but closer to the coasts where boulder ramparts exist the ground water becomes more saline as the lens becomes thinner (sample 19 in table 8). The northwest coast of Falalap, however, is formed by finer grained sediments which are conducive to the formation of a well-developed Ghyben-Herzberg lens. Samples from wells 30 to 34, which are 125 to 180 feet from the coast, all showed less than 50 p.p.m. of chloride. The fresh-water lens in Falalap Island is disrupted along the ocean shore by brackish or saline areas in which mangrove trees grow. A ground-water sample obtained from one such mangrove swamp (sample 23 in table 8) had a saline content approximately one-third that of sea water.

Three wells were dug on Ella Island along a line where the island is approximately 700 feet wide (pl. 1). The two outer wells (numbers 27 and 29), which are about 140 feet from the ocean and lagoon shores respectively, contain fresh water, whereas the middle well (number 28) contains water averaging about 2,000 p.p.m. in chloride (table 8). A similar situation is discussed for Falalop Island, Ulithi Atoll, by Schlanger and Brookhart (1955, p. 572). The higher salinity at well 28 may be due to the presence of a section of underlying reef which has a more permeable matrix or a larger number

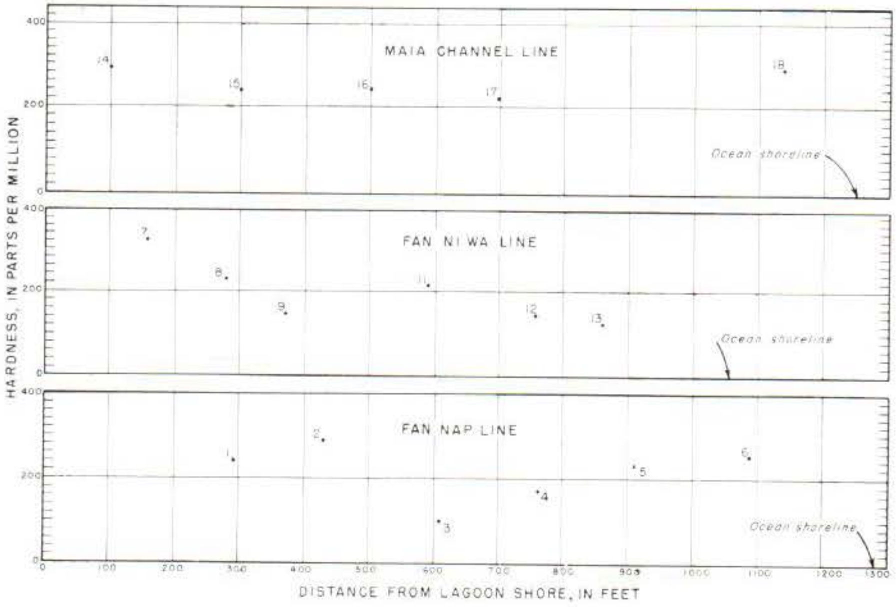


FIGURE 15.—Relation of hardness of ground water to distance from shore, Falarik Island, September 21, 1953.

Table 8.—Partial chemical analyses (parts per million) and temperature (°F.) of water from various sources (field determinations by Arnow)

No. of sampling point	Source	Date (1953)	Chloride	Total hardness as CaCO$_3$	Calcium hardness as CaCO$_3$	Temperature
	FALARIK					
1	Shallow pond, diam. 30 ft.	Sept. 21	28	240	132	79.5
		Nov. 1	35	210	129	....
2	Taro pit	Sept. 21	12	290	242	79.5
3	Dug well	Sept. 21	16	100	71	77.5
		Nov. 1	5	170	88	....
4	Dug well	Sept. 21	52	170	132	79
		Nov. 3	5	100	82	....
5	Dug well	Sept. 21	44	230	181	....
		Nov. 1	55	190	132	....
6	Dug well	Sept. 21	84	250	132	79
		Nov. 1	95	210	66	....
7	Dug well	Sept. 21	48	320	275	79
		Nov. 1	50	320	269	....
8	Dug well	Sept. 21	8	220	170	76
9	Dug well	Sept. 21	8	140	132	77
		Nov. 1	20	220	170	....
10	Taro pit	Sept. 21	10	......	......	79
11	Dug well	Sept. 21	6	210	93	78
		Nov. 1	10	120	104	....
12	Dug well	Sept. 18	8	140	93	78
		Nov. 1	25	170	132	....
13	Dug well	Sept. 21	14	120	93	79
		Nov. 3	40	340	286	....
14	Dug well	Sept. 21	28	290	192	79.5
		Nov. 1	35	190	104	....
15	Dug well	Sept. 21	16	240	187	80
		Nov. 1	15	210	176	....
16	Dug well	Sept. 21	24	240	105	81
		Nov. 1	27	160	124	....
17	Dug well	Sept. 21	44	220	165	79
		Nov. 1	35	230	165	....
18	Dug well	Sept. 21	68	290	132	80
		Nov. 1	1,160	660	242	....
24	Coconut retting pit	Sept. 21	28	340	302	....
....	Rain sample from canvas	Sept. 18	10	10	7	....
....	Rain sample from palm tree	Sept. 26	52	36	17	....
....	Rain sample from rain gage	Sept. 26	5	12	9	....
	FALALAP					
19	Dug well	Sept. 21	252	390	215	....
		Nov. 3	445	400	247	....
20	Taro swamp	Sept. 21	12	170	148	....
21	Dug well	Sept. 21	40	180	121	....
		Nov. 3	10	110	104	....

22	Taro swamp	Sept. 21	16	140	71	....
23	Mangrove swamp	Sept. 21	5,500	2,020	462	....
30	Shallow pond, 12 by 25 ft.	Sept. 21	24	200	132	....
31	Dug well	Sept. 23	44	320	247	....
32	Dug well	Sept. 23	32	270	198	....
33	Dug well	Sept. 23	20	280	264	....
34	Dug well	Sept. 23	48	280	214	81
	ELLA					
26	Shallow pond, 50 by 300 ft.	Sept. 20	10,200	4,100	660	....
27	Dug well	Sept. 20	108	230	170	....
		Nov. 4	80	210	165	....
28	Dug well	Sept. 20	1,090	1,090	330	....
		Nov. 4	3,060	1,270	407	....
29	Dug well	Sept. 20	204	280	181	79
		Nov. 4	180	250	176	....
	ELANGALAP					
25	Dug well	Sept. 20	10,900	3,920	616	....
		Nov. 4	15,000	3,800	616	....

of cracks than the sections of reef underlying wells 27 and 29. The greater tidal mixing would permit the development of a thicker zone of mixture within the Ghyben-Herzberg lens. Presumably, at well 28 the edges of the zone of mixture extend to the water table. The lens is practically undeveloped on the southwest end of Ella Island where the land is only about 350 feet wide. There a shallow ground-water pond about 50 by 300 feet has a salinity greater than half that of sea water (sample 26, table 8).

Elangalap Island is divided into two roughly equal segments which are independent hydrologic units. The larger segment has maximum dimensions of about 75 by 150 feet and an area of 0.0004 square mile. It does not support a fresh-water lens. Two samples obtained from a well in the center of that segment ranged in chloride content from 60 to 80 percent that of sea water (sample 25, table 8).

The temperature of the ground water at Ifaluk ranged from 76° to 81°F. and averaged 79°F.

RAINWATER

Three samples of rainwater were obtained for analysis, one from the rain gage, the second from catchment on the roof of a canvas tent, and the third from a drum fed by catchment on a palm tree. Results of partial analyses are shown in table 8 (samples without numbers, from Falarik Island). The sample from the drum had a higher salt content than the other samples because, in the course of running through the crown of the tree and down the trunk, the water presumably had a greater opportunity to dissolve salt crystals blown in by the wind from the ocean.

Table 9.—Chemical analyses (p.p.m.) of water samples from the Fan ni Wa well line, Falarik Island, taken September 23, 1953 (analyses by U. S. Geological Survey, Quality of Water Branch)

Well number	7	8	9	11	12	13
Dissolved solids	446	271	232	157	233	174
Specific conductance (micromhos at 25° C.)	748	467	290	272	399	311
Hardness (as $CaCO_3$)	331	242	204	134	172	132
Noncarbonate hardness (as $CaCO_3$)	0	0	10	8	13	0
Silica (SiO_2)	15	8.8	13	4.0	9.5	3.6
Iron (Fe)	0.17	0.37	0.06	0.03	0.07	0.03
Calcium (Ca)	103	82	68	47	59	44
Magnesium (Mg)	18	9.2	8.3	4.1	6.0	5.4
Sodium (Na)	29	4.7	5.8	3.9	15	12
Potassium (K)	8.3	1.7	3.0	0.4	1.7	2.5
Bicarbonate (HCO_3)	408	298	237	154	194	163
Carbonate (CO_3)	0	0	0	0	0	0
Sulfate (SO_4)	5.8	3.5	4.1	2.6	8.7	7.7
Chloride (Cl)	47	6	10	5	26	14
Fluoride (F)	0.2	0.3	0.4	0.5	0.5	0.2
Nitrate (NO_3)	0.6	0.5	0.2	3.8	0.3	0.6

REEFS AND LAGOON

Reef Traverses

The reefs of Ifaluk range in width from less than 600 feet at the east end of Ella Island to more than 2,000 feet at Falalap Channel. Where there are no islands the reef is 1,000 to 1,700 feet wide. Parts of the reefs fringing the islands are narrow, ranging from 600 feet at the north end of Falarik Island to less than 50 feet at the east end of Ella Island. The reefs show well-defined zones that are more or less continuous around the atoll although they vary considerably in width and in degree of development from place to place, depending upon their position relative to islands and to prevailing wind, surf, and currents. The zones and the names used to designate them agree generally with those listed by Tracey, Cloud, and Emery (1955). Three traverses are described, two at Falarik Island and one on the west reef. Locations are shown on plate 1; cross sections, on plate 2. All measured sections are related to mean sea level and to diurnal tide ranges, as computed by the U. S. Coast and Geodetic Survey on the basis of data from the lagoon tide gage.

TRAVERSE 1

Traverse 1 is at the south end of Falarik Island (pl. 1, A-A′; fig. 16). The reef front was not examined but it was estimated from aerial photos taken during a heavy surf to be about 100 feet wide. Well-developed grooves and spurs show on aerial photographs and occasional grooves extend into the reef margin as shallow surge channels.

The seaward reef margin is about 40 feet wide, with a low algal margin rarely exposed at lowest tides. By its similarity to traverse 2 (pl. 2, C-C′), which was surveyed with alidade, the margin is estimated to be a little above mean lower low water. It is exposed as much as a foot only on extreme low tides if there is no surf. A colored reproduction of a photograph of the reef margin at this traverse is shown by Bates (1956, p. 556).

The outer reef flat is 180 feet wide (based on photographs). The outer part of the flat is about at the level of the crest of the margin and supports abundant small coral colonies. It is covered by an inch or two of water during extreme low tides. The main part of the flat is a truncated rock pavement, bearing scattered coral colonies and veneered in places by a feltlike mat of algae 1 to 2 mm. thick, supporting such reef Foraminifera as *Calcarina spengleri, Baculogypsina sphaerulata, Amphistegina madagascariensis,* and *Marginopora vertebralis,* the tests of which are among the principal sedimentary products of the reef (fig. 25,*c*).

The inner reef flat is 150 feet wide. The outer reef flat terminates at a line of relict coral-algal rock which we interpret to be an old eroded reef flat (fig. 17). The rock is composed of tightly packed coral, red algae, and encrusting Foraminifera. Space between the larger skeletal organisms is filled with a firmly lithified detrital matrix. The remnants of reef rock south of the line of traverse are pinnacle-like, 3 to 10 feet long, about 2 feet wide, and as much as 2.0 feet above the reef level, or about mean higher high water level. The top of the rock is thinly encrusted with calcareous algae although it is covered with water only at highest tides. Inside the thin line of relict reef the inner reef flat is a rock pavement containing numerous solution pools a few inches deep (fig. 16). The pavement is covered by soft algae and sand 1 to 3 inches deep. About 100 feet south of the traverse the inner reef flat is covered by boulders piled up to mean water level, about the same elevation as the beach line.

The seaward beach is 28 feet wide. The outer part of the beach, or foreshore, is lined with boulders, above which the beach is sandy back to the vegetation line.

TRAVERSE 2

Traverse 2, Maia Channel line (pl. 2, C-C′), was surveyed with plane table and alidade. The reef front was not measured, but it is about 100 feet wide. Well-formed spurs and grooves show in aerial photographs.

The seaward reef margin is 40 feet wide. The broad, gently crested margin is coated with pink encrusting calcareous algae (mostly *Porolithon onkodes*), with a few scattered corals and numerous slate-pencil sea urchins (*Heterocentrotus trigonarius*). The top of the crest rises only a few inches higher than

FIGURE 16.—Panorama of reef flat and shoreline, traverse 1, south end of Falarik Island (pl. 1), cross section A-A′: exposed inner reef flat, covered by shallow solution basins, is bounded by "old reef line"; beyond is outer reef flat covered by water. Seaward reef margin is marked by line of surf. Falarik-Falalap Channel and northeastern tip of Falalap Island at far right. (Photographs by Abbott; photomosaic retouched by W. H. Elliott.)

the inner edge of the zone. It is a smoothly arched zone that is washed even by small waves at low tide. The top of the crest is 1.2 feet below mean tide level, or about 0.3 feet above mean lower low water. On extreme low tides the algal ridge rises a foot above the water when there is no surf. The grooves of the reef front do not cut the seaward reef margin to form surge channels.

The outer reef flat, which is 90 feet wide, is mostly truncated pavement 0.2 to 0.5 foot below the crest of the algal ridge, and covered with a few inches of water at lowest tides. Corals are found here and there (10 percent), but the zone is mostly a felted, smooth surface with algal filaments binding Foraminifera.

The inner reef (boulder) flat is 500 feet wide, with solution basins, or tidal pools. The greater part of the zone is a low lithified conglomerate platform with a veneer of loose boulders and cobbles on top. Numerous interconnecting tidal pools are cut about 0.5 foot into the conglomerate, and the bottoms of successive pools form a uniform, extremely gentle gradient from the beach line at mean tide level to the outer reef flat at about mean lower low water level. Individual pools, which range from a few feet to 100 feet across, contain an inch or two of water at low tide. The actual level of water on the outer reef flat at the time the traverse was surveyed was half a foot higher than the water level in the lagoon, measured on the tide gage. Confirmation of this difference in levels is provided at Bikini, where the water level on the windward reef was repeatedly measured at 1.5 feet above the lagoon level, owing to the piling of water on the reef by the trade-wind waves that averaged about

7 feet (Munk and Sargent, 1954). The 0.5-foot difference at Ifaluk is, therefore, about what one should expect with the 3-foot waves that prevailed at the time of observation.

TRAVERSE 3

Traverse 3, the western reef, is shown in plate 2, D-D′. The reef front was not measured, but was estimated from photos to be about 100 feet wide. It has a gently to steeply sloping convex front with abundant coral growth. A few scattered grooves, widely spaced and poorly developed, show in photographs. The presence of a terrace is not definitely established at this point, although photographs show a terrace at several places along the western rim of the atoll at a depth of 35 to 50 feet.

The seaward reef margin is 150 feet wide. A broad, very gently crested coral and algal zone rises slightly from the reef front and drops only slightly to the reef flat. The extreme flatness of the zone and the fact that it rises above the reef flat are shown by the following measurements: from the point arbitrarily selected as the contact between reef front and seaward reef margin to the crest of the algal ridge the slope is 0.35 foot in a distance of 42 feet. This gentle seaward slope is 50 percent smooth barren rock; 25 percent stubby coral, mostly *Pocillopora;* and 25 percent smooth red encrusting algae (*Porolithon*) with minor branching coralline algae. The crest of the ridge is predominantly smooth encrusting algae. The contact with the outer reef flat, a distance of 117 feet behind the crest, is only 0.1 foot lower. The backslope of the algal ridge is about 20 percent coral, mostly *Pocillopora;* less than 5 percent branching or encrusting calcareous algae; and 75 percent smoothly truncated rock, felted with filamentous algae.

The outer reef flat is 225 feet wide. The smooth but irregular rock floor of the preceding zone becomes a more regular floor of packed debris, mostly coral and algal fragments, covered by a thin felt of soft algae and Foraminifera. Lagoonward the floor is more irregular and slightly deeper (covered by 1 foot of water at a moderately low tide). Corals, about half of which are *Porites*, are common, but cover less than 10 percent of the surface. Some boulders and blocks are scattered on the surface.

FIGURE 17.—Old reef line: lithified coral and algal limestone, as much as 2 feet above present reef level, separates inner and outer reef flat on traverse 1 (fig. 16). (Photograph by Abbott.)

The inner reef flat is 1,275 feet wide. The boundary with the outer reef flat just described is arbitrarily placed where large blocks (1 to 2 feet) and boulders of coral are abundant. Corals form about 20 percent of the surface, but they are in small masses or microatolls separated by the deeper sandy floor. Living red algae such as *Porolithon* are common, but form only a small proportion of the surface. *Heliopora*, the blue alcyonarian, is rare on the seaward part of the inner reef flat; at 900 feet in from the outer margin, colonies are 3 to 5 feet across and 1 foot above the sandy floor of the flat. *Heliopora* colonies increase lagoonward in size and abundance until they become the dominant feature of the zone.

The lagoon reef margin, 80 feet wide, is a zone dominated by large, anastomosing *Heliopora* colonies 2 to 3 feet above the floor and 10 to 100 feet in diameter which are separated by connecting pool areas. Both inner and outer boundaries of this zone are more or less arbitrary. The colonies all grow to low-tide level, and their tops form a flat, barren surface. The inner edge or lagoon edge is considered to be the point where the colonies become scattered on the sandy floor instead of being more or less contiguous.

The lagoon shelf is 500 feet wide. The sand floor deepens lagoonward from 3 feet below mean lower low water level, or 3 feet below the top of the *Heliopora* colonies, at the lagoon reef margin to about 6 feet at the edge of the lagoon slope. Scattered *Heliopora* colonies 5 to 50 feet across are common near the lagoon reef margin, but are absent near the lagoon slope. The floor of the shelf is mostly covered with medium-grained to coarse-grained sand.

The lagoon slope is about 60 feet wide. The steeply dipping edge of the sandy lagoon shelf drops abruptly to the lagoon floor, about 30 feet in a horizontal distance of 60 feet, at the line of traverse. This is a 50 percent slope, or about 25 degrees. At the line of traverse no corals grow on the sand slope to depths of 40 feet.

ZONATION

From the three detailed traverses; from observations at several other places around the atoll, especially between Elangalap and Ella Islands; and from a study of aerial photographs of the atoll the entire atoll may be divided into the reef, lagoon, and island zones shown in figure 18 and described below. The zoning is based partly on the composition of the reefs and lagoon, as determined from the traverses and from scattered samplings and observations in the lagoon, partly from the linear zones apparent in photographs, and partly from topographic relations observed and sketched stereoscopically from photographs.

SUBMARINE TERRACE

Outside the atoll the submarine terrace is delineated approximately by the 60-foot contour (pl. 1; fig. 18). A broad bank extends about 1,500 feet south of Falalap Island. It is shallow enough near the reef (25 to 35 feet) that natives can dive to it. Near the outer margin it is shoal enough to see from a boat, but too deep for diving (about 50 to 60 feet deep). A terrace can be seen in aerial photographs at the south end of Falarik Island, and also at several places along the western reefs. The outer edge of the terrace south of Ella Island is reported by Rofen to have a ridge covered with coral growth at a depth of 60 feet (fig. 19). The ridge is broken here and there by irregular clefts, or notches, that appear to be erosional, probably the result of storm waves despite the depth. Inside the ridge is a broad moat, or hollow, several feet lower than the ridge. The terrace floor is covered here and there with living coral and with blocks of debris. The floor rises to the reef front, which also is covered with coral. Irregular cracks or grooves in the reef front do not extend onto the terrace.

REEF FRONT

This zone is shown on plate 1 between the seaward reef margin and the outer, approximately 12-foot, contour. Generally the reef front meets the terrace at depths of 25 to 30 feet, and in some places at 40 to 50 feet. On the windward side the reef front contains grooves that appear to be 6 to 8 feet deep and 2 to 5 feet wide (fig. 20). The longest grooves measured in aerial photographs are 150 to 300 feet long, and most of them fork downslope so that the grooves average 40 feet apart at the surface and 20 feet apart at depth. As the well-grooved windward reef was not examined directly, we do not know whether the front is cut into the terrace or grows onto it; but the grooves do not appear to continue onto the terrace. On leeward reefs the front is poorly grooved or ungrooved (fig. 21), and in places it has been eroded by storms to depths of 40 feet (fig. 22).

SEAWARD REEF MARGIN

On the windward side of the atoll the reef margins have broad, low crests formed of calcareous red algae and abundant corals of genera such as *Pocillopora* and *Millepora*. The crest is, at most, only a few tenths of a foot above the reef flat. Only a few small surge channels cut the margin. Two colored photographs of part of this zone are shown by Bates (1956, p. 554). The leeward margin of Elangalap Island (traverse 3) is a low zone that differs from windward zones mostly in having a poorer development of red algae. Its crest is only about 0.1 foot higher than the reef flat, and it is not cut by any surge channels.

The reefs of Ifaluk are subdivided by means of a classification similar to that proposed for the reefs of Bikini Atoll (Tracey, Ladd, and Hoffmeister, 1948, p. 810), based on the development of the seaward reef margin. The classification is shown on figure 18 as follows:

Type I-A: Strongly grooved reef front; algal margin low, uncut by the grooves.
Type II-A: Grooves weak or absent; reef margin somewhat lobate or scalloped.
Type II-B-1: Irregular reef margin with broken reentrants.
Type II-B-2: Irregular reef margin with long, narrow submerged channels or small grooves.

Examples of each type are seen in figures 20 and 21. Windward reefs at Ifaluk all fall into the category I-A, which predominates at Bikini although it is restricted to the long arcs of reef between islands, concave to the sea. Crests at Bikini were mostly 0.5 to 1 foot higher than the reef flat and better developed than at Ifaluk.

The most striking difference between the seaward reef margins of the two atolls is seen in comparing the surveyed profile of a normal windward reef margin at Ifaluk (pl. 2, C-C′) with the massive algal ridge of type I-B at Bikini (pl. 2, *F*). The surveyed profile at Bikini was made across the highest living algal margin observed, 3.5 feet above the reef flat.

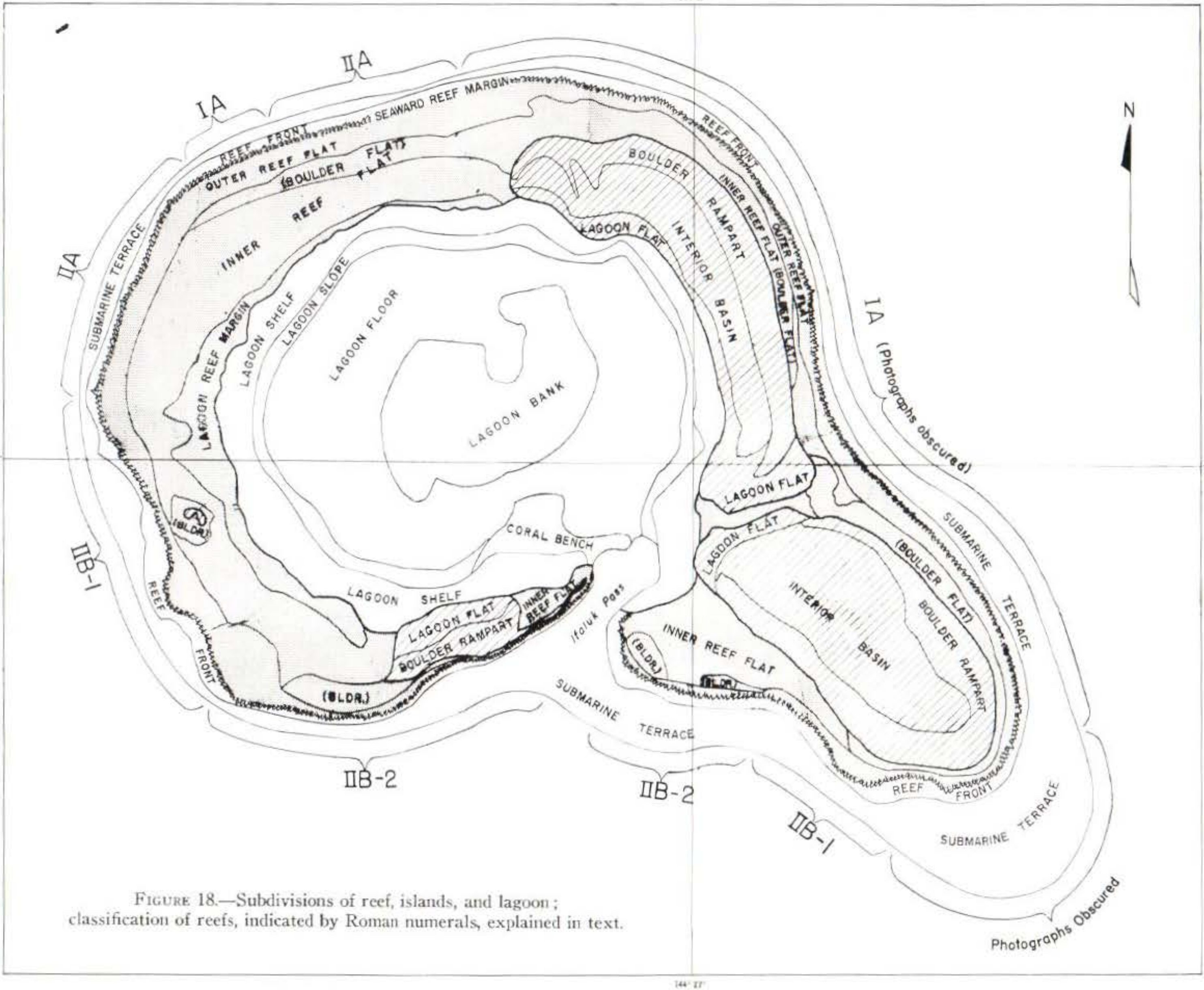


FIGURE 18.—Subdivisions of reef, islands, and lagoon; classification of reefs, indicated by Roman numerals, explained in text.

The leeward reef at Ifaluk shows on the southwest-facing parts irregular, broken reentrants (II-B-1, fig. 21, *b*) and on the south-facing parts the smaller, jagged grooves that are similar to the "comb tooth" margin of type II-B-2 at Bikini. Both types are thought to be caused by storm waves. The western reef margin shows only in a few places the steep, smoothly scalloped edges of type II-A (fig. 21, *a*) common on the western reefs of Bikini. Several distinctive types at Bikini, such as type I-B (massive algal cuesta), type I-B-1 ("room-and-pillar" structure), and type I-B-2 (roofed-over surge channels and blow holes), are not found on Ifaluk. The scale of development of the reef margin at Ifaluk is small compared to that at Bikini. Grooves are smaller and less well developed; crests are low and poorly formed; surge channels are either absent or sparse and weakly developed. Likewise, erosional effects are not on the same scale, and though a similar classification may be applied in both places, distinctions between types at Ifaluk are not nearly so clear. These differences reflect the comparative climatic and oceanographic regimes at Ifaluk and Bikini. The diurnal tidal range at Bikini is 5.2 feet, whereas at Ifaluk it is 2.5 feet. The wind and swell at Bikini are predominantly from the northeast to southeast for most of the year and are moderate to heavy, averaging 16-knot winds and 7-foot waves over much of the year. Munk and Sargent (1954) show that an azimuthal diagram of the grooves at Bikini has the same

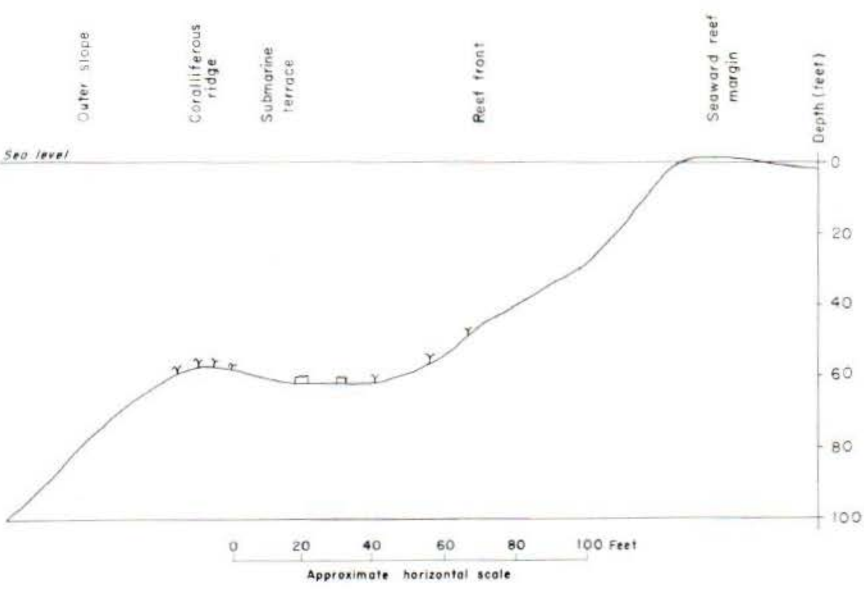


FIGURE 19.—Submarine terrace near Ella Island.

FIGURE 20.—Falarik Island and windward reef, Ifaluk Atoll: well-grooved reef front (type I-A) at north end of island. Former Maia Channel shows as a line of coconut trees across Falarik Island in right center of photograph, connecting slight indentation in outer shoreline with shallow bulge in lagoon shore; Ella Island in background. (Photograph by U. S. Navy.)

bilobed pattern as a rose diagram showing the annual swell pattern. Both patterns show maxima in the northeast and southeast quadrants, indicating that the reefs at Bikini reflect the effects of wave power integrated over the entire year. Conditions at Ifaluk are not so well known quantitatively, but moderate easterly wind and surf prevail only from December to March and are low or irregular in direction for most of the year. Calms are usual in August and September, and brisk west winds blow for several days at a time during this period. The annual wave pattern for Ifaluk, therefore, would show less marked maxima than that for Bikini.

The classification devised for Bikini, or modifications of it, have been applied to a number of reefs in various places. Arno Atoll in the southern Marshall Islands contains reefs dominantly of type I-A, although type I-B is common on the northeast reefs (Wells, 1951, p. 8). The reefs of Raroia Atoll in the Tuamotus are grooved (comparable to type I-A) on all sides

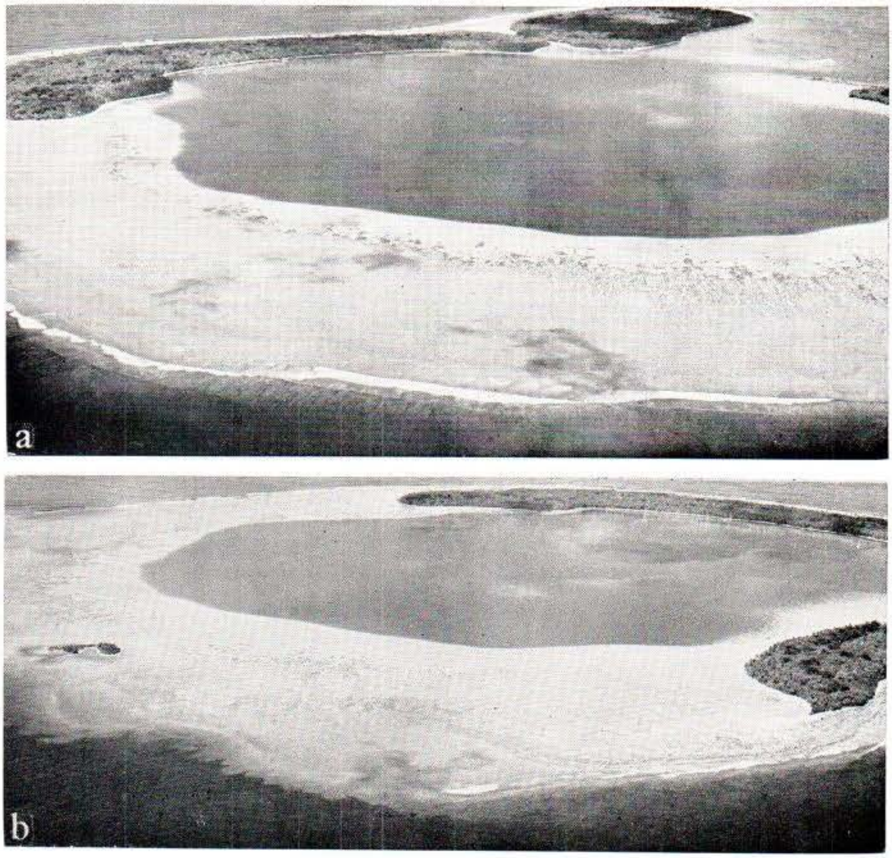


FIGURE 21.—Leeward reefs: **a**, leeward reef margin from west; west-facing reef margin on right side of photograph is comparatively smooth type II-A, whereas north-facing reef on left shows moderately well-developed grooves of type I-A; poorly defined dark *Heliopora* zone on lagoon shelf marks lagoon reef margin; parts of lagoon bank 33 to 40 feet deep show as light patches in middle of lagoon; Falarik, Falalap, and Ella Islands in background. **b**, leeward reef from southwest, Elangalap Island on far left: southwest-facing leeward reef in left foreground is irregular (type II-B-1) and contains large reentrants broken by storms; south-facing reef in right foreground near Ella Island contains narrow irregular erosional grooves similar to type II-B-2 on Bikini Atoll. An extensive boulder flat extends from Ella Island toward Elangalap Island. (Photographs by U. S. Navy.)

(Newell, 1956, p. 345). At Ulithi Atoll in the western Carolines Schlanger and Brookhart (1955, p. 570) found that northerly and easterly reefs were mostly well-grooved (their type A) and that the southerly and westerly reefs were mostly lobate and poorly grooved (type B). Guilcher (1955) states that the reefs of Banc Farson in the Red Sea are grooved on the east and smooth on the west, similar to those of Bikini, but he says also that this pattern is apparently unrelated to the prevailing wind and surf which comes from the northwest. The reefs from Cap Voilava to Cap San Sebastian, northwest of Madagascar, however, are apparently adjusted to prevailing conditions (Guilcher, 1956, p. 89).

A marked differentiation of reef margins in different quadrants is not to be expected unless the swell conditions integrated over the year show distinct maxima. Of all the reefs mentioned, those of Bikini are certainly subject to the most uniformly strong easterly swells. Most of the other reefs lie closer to the equator where the trades are not so regular, and those described by Guilcher (1955, 1956) are subject to varying influences from continental environments. Raroia Atoll, 16 degrees south, should be far enough south so that a "mirror image" of conditions at Bikini might be expected. The trades at Raroia are dominantly easterly. Newell (1956, p. 328) points out, however, that strong swell from the south results from the prevalent southwesterly gales of the high southern latitudes according to "Sailing directions for the Pacific." The prevalence of heavy swells on all sides of the atoll may be the cause of the well-developed grooves on all reefs of Raroia.

REEF FLAT

The outer reef flat on windward reefs is a truncated rock floor; on leeward reefs, a floor of packed debris. It is covered in both places with a thin, feltlike mat of algae and spiny Foraminifera (*Calcarina*). Small corals and heads of coralline algae are abundant near the margin, and patches of encrusting red calcareous algae and of soft green algae are common. The outer reef flat is a little above lowest tide levels, but because of the gently crested margin and because of the usual presence of waves at the reef edge, an inch or more of water almost always covers the flat.

The inner reef flat on the north and east reefs, particularly near the islands, is a truncated rock pavement exposed at low tide. Large shallow solution pools an inch or two deep cover most of the flat (fig. 16). Over most of the windward reef, however, the inner reef flat is covered by coral rubble that forms a loose to poorly consolidated boulder flat—the "coral shingle" of British and Australian geologists. On western and southern reefs the inner reef flat is generally formed of sand or packed debris on which scattered living coral colonies are common. Areas labeled *bf* for boulder flat on these reefs (pl. 1) are mostly concentrations of scattered rubble and large coral blocks (fig. 8). On the western reef the coral colonies increase in size lagoonward and grow on a sand floor that deepens lagoonward.

LAGOON REEF MARGIN

On leeward or western reefs the lagoon edge is marked by the coalescing of large *Heliopora* colonies that form a continuous zone of active growth. On other reefs the lagoon beach of the island forms the margin of the lagoon.

LAGOON SHELF

A shallow shelf 100 to 500 feet wide lies between the lagoon reef margin, or the lagoon beach of the islands, and the steep lagoon slope. The shelf is only a few feet deep near shore, and drops gently to 1 to 2 fathoms at the edge of the slope. Near islands, beds and patches of coral grow thickly enough in some places to be called "lagoon reefs." On the western reef the broad shelf forms a continuation of the sandy reef floor and is generally an area of sedimentation. Scattered large areas of *Heliopora* grow on the shelf beyond the coalesced colonies of the lagoon reef margin. As these separate colonies enlarge and grow together on the sandy shelf they cause the lagoon reef margin to grow lagoonward.

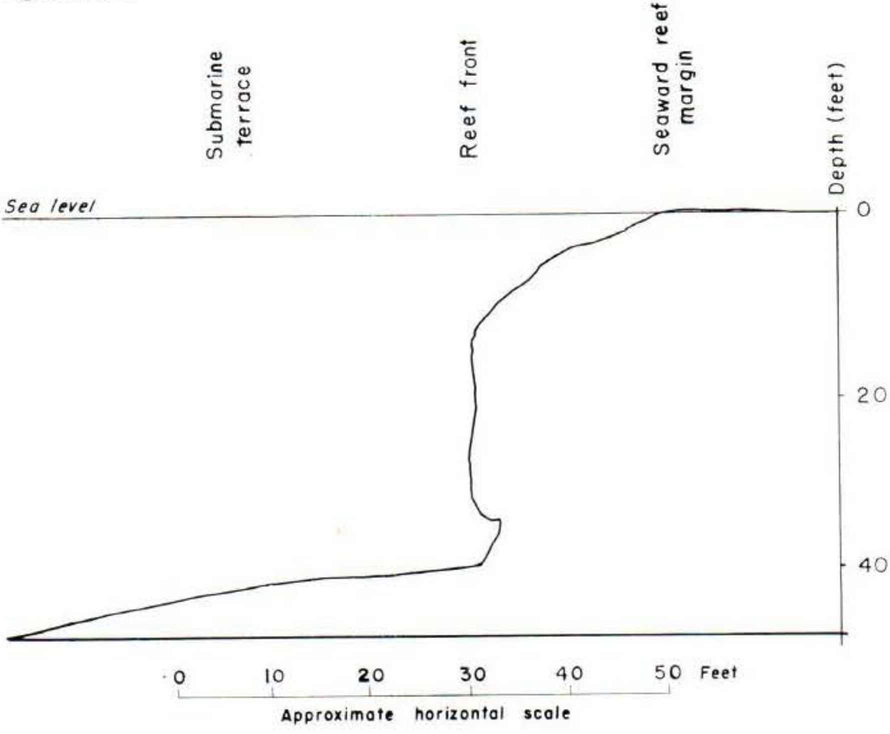


FIGURE 22.—Submarine terrace near Elangalap Island.

LAGOON SLOPE

In most places the slopes drop steeply; the angle from the horizontal averages perhaps 20 degrees but exceeds 35 degrees in some places. Coral colonies are uncommon on western slopes at depths of less than 30 feet, probably because of the amount of sand carried down the slopes. Colonies are more common on the slopes near islands because the islands protect the slopes from

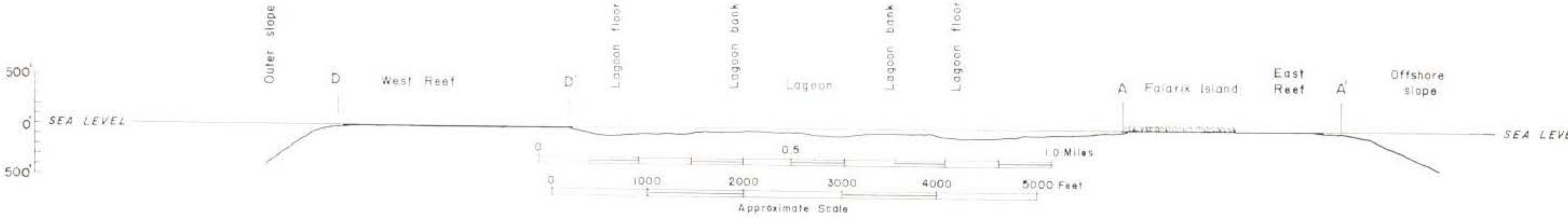


Figure 23.—Cross section of Ifaluk Atoll, taken along lines D-D′ and A-A′ shown in plate 1.

sedimentation. At depths below 30 feet, however, corals are more abundant along the western reefs than they are near islands on the south and east sides, according to the observations of Rofen, who collected at numerous stations over the lagoon.

LAGOON FLOOR

The lagoon floor at the base of the lagoon slope is a flat, relatively featureless surface at a depth of 50 to 66 feet. This is the deepest part of the lagoon, and it forms a broad ringlike moat around a prominent low mound in the center of the lagoon which we shall call the lagoon bank. The numerous scattered coral colonies at the base of the lagoon slopes extend only a short distance onto the lagoon floor, according to Rofen. The greater part of the floor that he observed was a monotonous expanse covered only by seaweed, and crisscrossed by straight paths of fine white mud about a foot in width. He saw schools of parrot fish swimming above these trails, apparently following them, and suggests that the trails result from the clouds of ground-up calcareous debris ejected by the parrot fish. Rofen also noticed that the sediments on the bottom were so fine that they were easily disturbed by swimming over them and that they remained in milky suspension.

No sediment samples were taken from the deepest parts of the lagoon, but the fine mud of sample 40 (table 10) from a depth of 48 feet is believed to be representative of much of the material of the lagoon floor. It is probable that *Halimeda* debris also forms a major constituent.

The lagoon bank (fig. 23) can be seen easily from a boat or in aerial photographs. It is about 3,500 by 2,000 feet in size and irregular in shape; and its nearly flat top, 33 to 40 feet below the surface of the water, contains broad swells and hollows. Large areas of the bank are carpeted with the green alga *Halimeda stuposa,* and the hollows and sides of the bank are largely formed of *Halimeda* debris (table 10, samples 41-44). Parts of the periphery of the lagoon bank and some of its low mounds are exposed flat ledges and knolls of dead coral limestone, generally covered with a thick growth of dark-green *Microdictyon.* The limestone ledges bear small heads and a few large colonies of scattered living coral, chiefly *Porites.* Fine calcareous mud was noted by Rofen, particularly in cavities in the limestone and mixed with coarse debris on the sides of the bank. Though largely covered by sediments at present, it seems likely that at some time in the past the lagoon bank was a large living coral knoll.

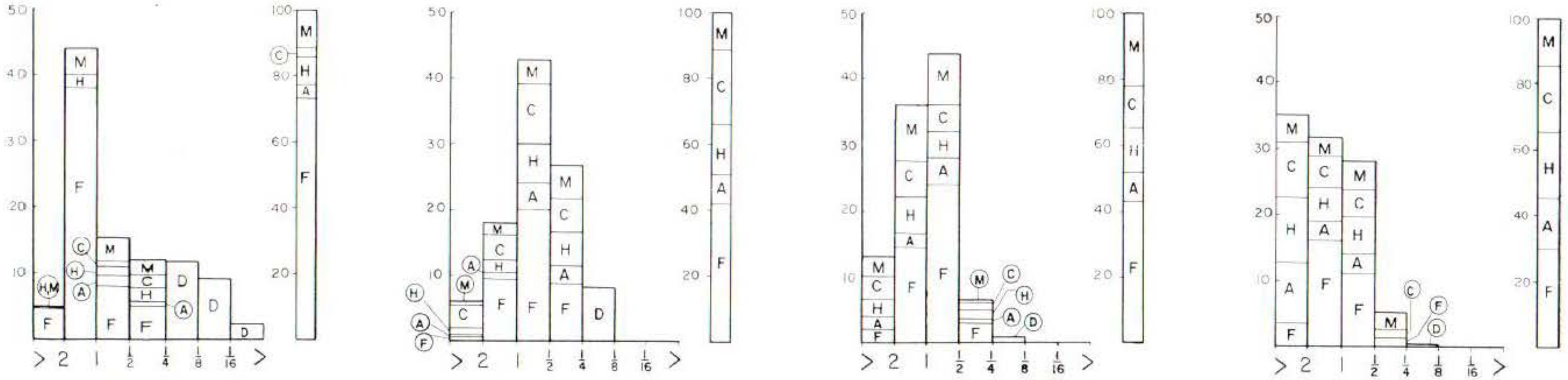
SEDIMENTS

Sand samples from a number of reef, beach, and lagoon localities were studied to determine a pattern for the sediments of the atoll. Location and description for each sample are given in table 10. Localities are shown on the geologic map (pl. 1). Samples finer than 4 mm. were dry-sieved in Wentworth grades and weighed. Each fraction larger than 0.25 mm. was examined under the binocular microscope and visual estimates were made of the proportion of each grade size formed by Foraminifera (F), coralline algae (A), *Halimeda* (H), coral (C), and miscellaneous (M). The miscellaneous category is dominantly molluscan shells, but it includes in the coarser grades crustacean and echinoid fragments and in the finer grades pteropods and siliceous or calcareous spicules. The medium fraction (0.5 to 0.25 mm.) was boiled in Meigen's solution (dilute cobalt nitrate) to stain the aragonite fragments, providing a means of estimating roughly the aragonite-calcite ratio for that grade as well as permitting easier identification and estimates of the constituents. Undifferentiated fine sand (under 0.25 mm.) and silt was grouped as detritus (D). Results of estimates for each sample are shown in the histograms (fig. 24).

Table 10.—Proportions of rock-forming constituents in sediments from Ifaluk Atoll

		DEPTH BELOW M.S.L.		CONSTITUENTS (PERCENT)						
NO.	LOCATION	(FEET)	DESCRIPTION	A	C	F	H	M	D	SORTING
35	Inner reef flat, S.E. end Falarik Island	1	Foraminiferal sand	4	4	54	6	9	23	P
36	Lagoon edge Falalap Channel	3	coarse reef sand	8	21	39	14	10	8	F–
37	Falarik lagoon beach	M.S.L.	coarse sand	9	13	43	13	22	0	F
38	Inner reef flat, S.W. reef	3	coarse reef sand	15	19	32	21	13	0	F
39	Coral bench, N. of Ella Island	20	medium and coarse sand	5	16	18	20	20	21	F–
40	Lagoon floor, E. side	48	fine sand and silt	0	0	5	3	7	85	F–
41	Sloping side of lagoon bank	48	Halimeda sand	0	0	5	60	5	30	P–
42	Sloping side of lagoon bank	50	Halimeda sand	0	0	4	55	4	37	P–
43	Lagoon bank, top	36	Halimeda sand	Halimeda (by inspection only)						
44	Lagoon bank, top	39	Halimeda sand	Halimeda (by inspection only)						
45	Lagoon sand flat, Falarik Island		medium and fine sand	0	0	2	0	1	97*	G
46	Well 21, Falalap Island		coarse gravel	12	16	23	14	7	28*	P
47	Brackish pool, Ella Island	1	coarse gravel	14	40	4	12	15	15*	P–

* In samples 45, 46, and 47 constituents were estimated for coarse fractions only (greater than 0.5 mm.). D here includes both medium and finer fractions.

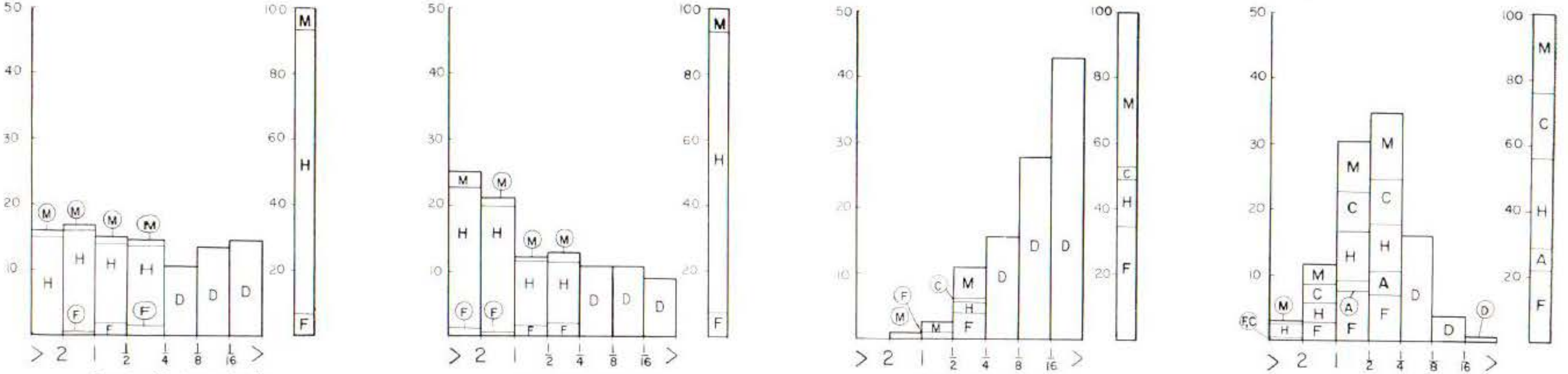


Sample 35, reef flat

Sample 36, lagoon shelf

Sample 37, lagoon beach

Sample 38, Inner reef flat



Sample 42, lagoon bank

Sample 41, lagoon bank

Sample 40, lagoon floor

Sample 39, coral bench

FIGURE 24.—Histograms of sediments from Ifaluk Atoll. Estimated proportions (percent) of major constituents are shown for each grain size and for total sample greater than 0.25 mm. Symbols: *F*, Foraminifera; *A*, red coralline algae; *H*, *Halimeda*; *C*, coral; *M*, mollusks and miscellaneous; *D*, fine sand and silt less than 0.25 mm. (Locations of samples are shown in plate 1, and data are tabulated in table 10.)

At the right of each histogram is a scale showing the estimated proportion of that sample formed by each category of organism, disregarding the fraction of fines (D). The sorting shown in table 10 is according to the Payne scale: good (G), 90 percent falls into one or two grades; fair (F), 90 percent falls into three or four grades; poor (P), 90 percent falls into five or six grades. The essentially coarse nature of the reef-associated sediments (samples 35-39) contrasts with the dominantly fine material of the lagoon bank (samples 41 and 42). The contrasts are shown in photographs (figs. 25, 26). Histograms of island materials are shown in figure 27, which contrasts the unsorted gravel of the older gravel unit (*Og*) from well 21 (sample 46) and younger boulders and gravel (*Yb*) from the salt-water pool on Ella Island (sample 47) with well-sorted, wind-blown sand (*Os*) from the lagoon flat on Falarik Island (sample 45).

Plate 3 is an interpretation of the sedimentary pattern of Ifaluk Atoll, based on the zones of the atoll as defined in figure 18, on the geologic units of the islands (pl. 1), and on the sediment samples (table 10), which are broadly representative of many of the zones of reef, lagoon, and islands. Zones of the atoll are grouped into zones of production or of deposition of sediment. Parts of zones dominantly of one type may include significant areas of the other type. Areas principally productive of sediment are the following.

1a: The terrace, reef front, seaward reef margin, and outer reef flat produce mostly coral, calcareous red algae, and Foraminifera. Except in times of storm, all of the products of the reef front and terrace and part of the products of the reef margin are carried down the outer slopes of the atoll. Only the Foraminifera and finer coral and algal detritus of the reef margin and outer reef flat are carried lagoonward over the reef flat. In times of storm, however, coarser coral and algal debris from the reef margin and from the reef front is carried across the reef flat, and in times of the rare great storms large blocks and corals from the reef front and even from the submarine terrace are carried up onto the reef.

1b: The inner reef flat (excluding boulder flats, *2b*), and the lagoon reef margin produce coral, Foraminifera, and in places *Halimeda* (samples 35 and 38). As the inner reef flat, for the most part, is at low-water level and cannot be raised any higher by growth, most of the material produced is rapidly transported lagoonward to the lagoon shelf or slope. Large debris carried from outer zones onto the inner reef flat remains until broken down by organic disintegration, solution, or erosion into material fine enough to be carried away. The lagoon reef margin produces living coral, mostly the alcyonarian *Heliopora*. Isolated areas of *Heliopora* on the shelf, as well as fairly numerous areas of coral on the lagoon slope, probably add significant amounts of coral, but these are small compared to contributions of the reef areas already mentioned.

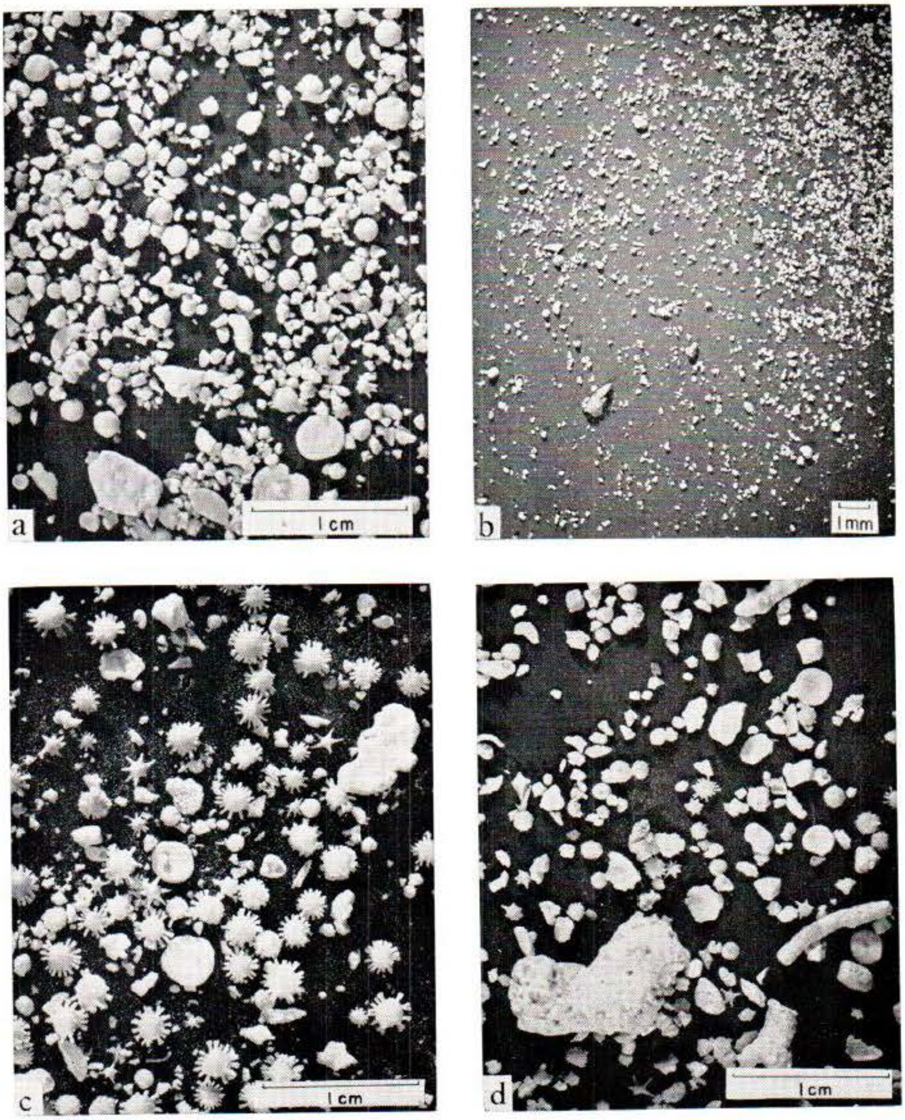


FIGURE 25.—Beach and reef sands: **a**, beach sand from lagoon beach at south end of Falarik Island (sample 37); most Foraminifera worn (see *c*). **b**, fine, well-sorted sand from lagoon flat of Falarik Island near benchmark (sample 45). **c**, coarse foraminiferal sand from reef flat near cross section A-A′ shown in plate 1 (sample 35), contains abundant *Calcarina spengleri* (numerous spines), *Baculogypsina* (few spines), and *Marginopora* (disks). **d**, sand from lagoon reef margin between Ella and Elangalap Islands (sample 38).

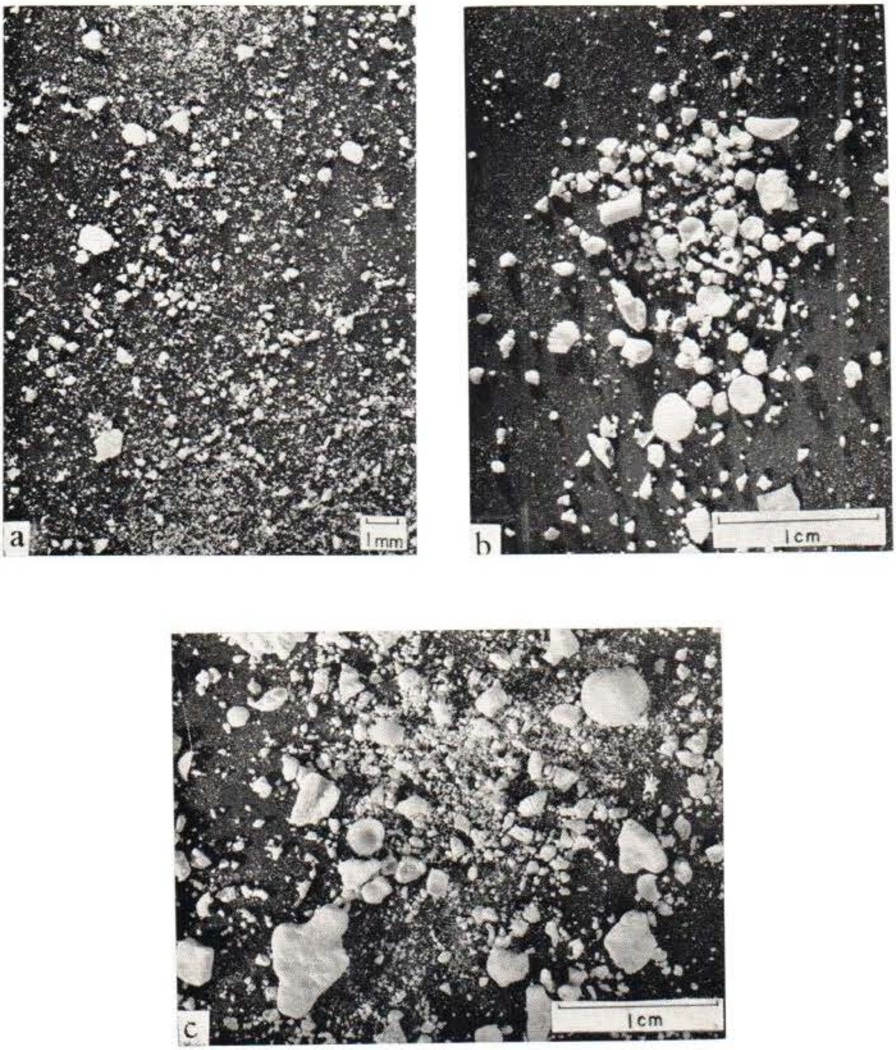


FIGURE 26.—Lagoon sands: **a**, fine sand and silt from lagoon floor (sample 40); **b**, coarse sand from coral bench north of Ella Island (sample 39); **c**, *Halimeda* sand from side of lagoon bank (sample 42).

1c: The lagoon bank produces mostly *Halimeda* (samples 41 and 42). Since this area is completely segregated from the reef by the deep moat of the lagoon floor, it receives none but the finest detritus. The sediment on the lagoon bank is, therefore, characteristically pure.

Zones primarily of deposition are the following:

2a, islands: Boulder ramparts and gravel mounds are composed primarily of coral and coralline algae, with shells and Foraminifera contributing to the sand-sized detritus of the matrix (sample 46, table 10). Sand of the lagoon flat and lagoon beaches is principally foraminiferal (samples 37 and 45).

2b: Boulder flats of the inner reef flat contain mostly coral rubble, but blocks of coralline algae are abundant in places along the windward reef.

2c: The lagoon shelf and lagoon slope inside the reef comprise a zone mostly of deposition, although they contain numerous areas where scattered coral colonies are common. Samples 36 and 38 are more or less representative of these zones. Much of the material on the shelf passes down the slope to the floor; but some remains on the shelf, building it up to low-tide level, and the rest remains on the slope, building it lagoonward.

2d: The lagoon floor is the ultimate basin of deposition within the atoll. The strip of floor near the foot of the lagoon slope receives medium-grade detritus from the reef, and parts of the floor near the lagoon bank receive medium- and coarse-grained *Halimeda* debris from the bank. Most of the floor, however, gets only the finest material carried in suspension (sample 40).

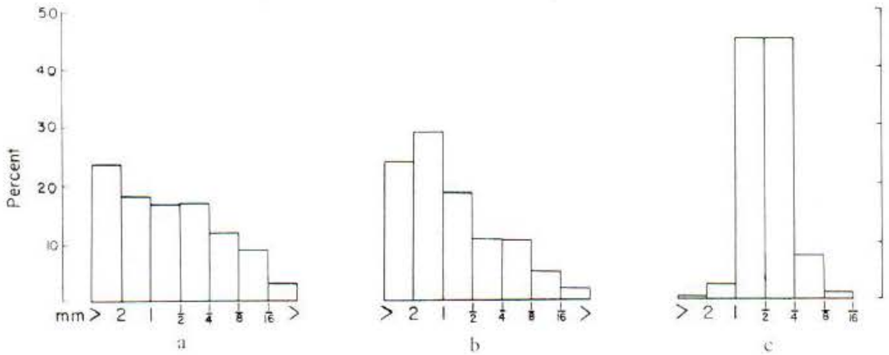


FIGURE 27.—Histograms showing distribution of grain sizes in island sediments: **a**, gravel from brackish pool on Ella Island (sample 47); **b**, gravel from well 21, Falalap Island (sample 46); **c**, sand from lagoon flat, Falarik Island (sample 45). (Locations of samples shown on plate 1; data, in table 10.)

The source of the fine material is of particular interest inasmuch as all reef-associated limestones contain significant amounts of silt and clay-size carbonate "mud." The two modes of origin most commonly considered by geologists are by disintegration of calcareous skeletons of animals or plants and by chemical precipitation. The grinding up of coral and algae by browsing fishes has also been considered as a source of sediment.

The ratio of aragonite to calcite for the medium and coarse fractions of five samples was estimated from table 10 by comparing the total Foraminifera and coralline algae (calcite) with *Halimeda*, coral, and miscellaneous portions (aragonite). The results are shown in table 11, column A. For comparison, the finest fraction (less than 1/16 mm.) of each sample was analyzed by Paul D. Blackmon of the U. S. Geological Survey, using the X-ray diffractometer. His results are shown in table 11, column B, and his estimates for the composition of the calcite are shown in column C. High magnesium calcite in the samples contains approximately 17 molecular percent (14.8 weight percent) magnesium carbonate.

Sample 42 from the lagoon bank consists almost entirely of aragonitic *Halimeda* debris (95 percent). Moreover, the gradual breakdown of the *Halimeda* segments to fines is strongly indicated not only by the comparable volumes of each grade size in the histogram (fig. 24), but by the constant ratio of *Halimeda*, Foraminifera, and miscellaneous debris in each grade size. In addition, specimens of the finest (less than 1/16 mm.) fractions of samples 40 and 42 were examined by Dr. Heinz Lowenstam, who reports (written communication, 1957) that they contain aragonite needles one to several microns in largest dimension similar to those he has isolated from living *Halimeda* and other green algae from lagoon environments (Lowenstam, 1955; Lowenstam and Epstein, 1957, p. 364). The finest fraction of sample 42 contains, however, nearly 30 percent calcite, most of which is high-magnesium calcite containing 17 molecular percent $MgCO_3$ in the calcite structure (table 11, B). This calcite might be derived from a selective breakdown of the five percent of Foraminifera in the coarser fractions of the sample, although it seems more likely that the high proportion of fine calcite was carried in from some other environment; for example, finely ground coralline algae from the reef margin.

Table 11.—Proportions of calcite and aragonite in fine fractions of sediments from Ifaluk Atoll

No.	Location	Ratio of aragonite to calcite, in percent: Particles more than ¼ mm. A	Ratio of aragonite to calcite, in percent: Particles less than 1/16 mm. B	Composition of calcite in column B (percent of high-magnesium-type calcite) C
35	Reef flat	25:75	58:42	more than 95
39	Coral bench	70:30	70:30	more than 90
40	Lagoon floor	65:35	75:25	more than 90
42	Lagoon bank	95:5	72:28	more than 90
46	Well 21	50:50	35:65	70

Column A: Aragonite to calcite ratio of medium and coarse fractions estimated from table 10.

Columns B and C: Analyses by P. D. Blackmon. High magnesium type calcite contains about 17 mol. percent (14.8 weight percent) magnesium carbonate in the calcite structure. Low-magnesium calcite contains 0 to 4 percent magnesium carbonate.

Sample 35 from the reef contains 75 percent calcite in the medium and coarse fractions, but the finest fraction contains only 42 percent calcite. Here again the predominance of aragonite in the fine fraction might be explained by a selective breaking down of aragonitic organisms relative to calcitic ones. Indeed, the medium fraction contains about 50 percent aragonitic debris compared to the coarser fractions which are predominantly calcitic. A second possible source of the aragonite in the finest fraction may also be fine needles from soft green algae that produce no coarse particles. It may also be interpreted as a result of precipitation on the reef flat of calcium carbonate caused by the daily changes in chemistry and temperature of water over the reef (Emery, 1946; Revelle and Emery, 1958).

The relatively large proportion of silt and clay-size material in sample 40 from the lagoon floor, possibly representative of large areas of the lagoon floor, may have originated from the breakdown of *Halimeda* debris close at hand; from the breakdown of both aragonitic and calcitic organisms at some distance away on the reef; or from precipitation of aragonitic needles on the reef flat. Silt and clay-size material derived from the reef can be carried to any part of the lagoon by strong currents across the reef.

The possibility suggested by Darwin that browsing fishes may have contributed considerable sediment to limestone has been investigated by Cloud (1952) and others. Emery (1956, table 2) has examined the sands in the intestines of several kinds of browsing fishes from Johnston Island. Rofen's observations of white trails crossing the weed-covered lagoon bottom indicate that quantitatively significant amounts are contributed by fishes to the fine sediments of Ifaluk lagoon.

In summary, we do not know the principal mode of origin of the fine sediments of Ifaluk Atoll. From the data at hand it appears that each mode of origin considered—mechanical disintegration, decomposition of soft algae, precipitation on the reef flat, and grinding by browsing fishes—could have resulted in a significant proportion of the fine sediments of the atoll.

A rough quantitative estimate may be made of the organic composition of the atoll by combining traverse observations of the products or deposits of each subzone of the atoll (pl. 3) with estimates of constituents in samples selected as representative of that subzone. The samples represent only the smaller grain sizes of the deposits and the traverse observations are necessary for appraising cobble and boulder deposits and, especially, for estimating constituents of growing parts of the reef. Each subzone must be weighted by areas, and zones are totaled to show the constituents for reef, lagoon, and islands (table 12). These, in turn, are weighted and combined to give the constituents for the whole atoll. Emery's results for lagoons of Bikini Atoll, Cocos Lagoon (Guam), and Johnston Island (1956, table 1) are given for comparison.

Table 12.—Proportions of rock-forming constituents

	A	C	F	H	M	D	PERCENT OF TOTAL AREA
Lagoon	4	10	19	22	10	35	44
Reef	21	33	21	9	8	8	36
Islands	11	48	18	6	8	9	20
Average for atoll	11	26	20	14	9	20	100
Comparison with other lagoons (Emery, 11, table 1)							
Johnston Island (average of all samples)	51	20	2	1	10	16	....
Guam (Cocos Lagoon) Samples weighted by depth zones	18	45	3	11	15	8	....
Bikini Samples weighted by depth zones	1	13	11	43	7	25	....

A = coralline algae, C = coral, F = Foraminifera, H = *Halimeda*, M = miscellaneous, D = detritus (fine material under 0.25 mm.). While estimates for Ifaluk are based on few samples, the sample density is relatively high because of the small area of the atoll. Although any one individual estimate may be in error by ± 5, the computed estimates are expressed to two significant figures to show the most probable value of each constituent relative to other constituents.

CIRCULATION

No systematic observations were made to determine the general pattern of water circulation of the atoll; but a few scattered measurements indicate that under ordinary conditions the water of the lagoon is renewed rapidly, in comparison with large lagoons such as Bikini.

Observations were made on dye packs tied near the top, bottom, and middle of a sounding line in the 33-foot-deep Ifaluk Pass over a period of two hours of the flood tide and on a day of moderate northwest winds. The outward current from lagoon to ocean slackened considerably about a half hour past low water, but did not stop or reverse. The outward current then increased considerably as the tide rose in the ocean, and crude measurements for the next 1.5 hours showed a range in velocity of 0.3 to 1 foot per second. The outward current was still increasing on the flood tide two hours past low water when observations had to be stopped. An average outflow of 0.5 foot per second over the tidal cycle under these conditions is probably a reasonable estimate.

A few current measurements were made on the west reef at places along cross section D-D′ (pls. 1, 2) on a day of light to moderate northwest winds that resulted in waves about 3 feet high on the reef margin. A steady lagoonward flow was continuous for the observation period of two hours after low water. By timing the rate of movement of floats over a paced distance in water of measured depths, the flow over a foot-wide strip was found to range from 1 to 4 cubic feet per second and to average 2 cubic feet per second over the first two hours of flood tide. This lagoonward flow results from the head of water piled up by wave energy at the seaward reef margin. The rate of flow normally increases during the flood tide because the frictional drag of the reef on the sheet of water is proportionally less as the depth of water increases.

Therefore, the measured flow of about 2 cubic feet per second per linear foot of reef should be a conservative figure to use over a complete tidal cycle in computing the daily flow, assuming a constant moderate wind and waves from the northwest. The total reef length facing northwest is about 5,000 feet. The total inward flow into the lagoon is then 10,000 cubic feet per second, or 924,000,000 cubic feet per day.

With a northeast to northwest wind, the flow over southwest reefs is generally oceanward, as was the flow observed through Ifaluk Pass. The outward flow through Ifaluk Pass can be computed by assuming an average of 0.5 feet per second over the tidal cycle. The cross-sectional area of the channel is about 10,000 square feet (500 feet wide by approximately 20 feet average depth). The volume of flow of 5,000 cubic feet per second amounts to half the flow over the north and west reefs into the lagoon, which means that outflow over the southwest reefs approximately equals outflow through the channel.

These figures are crude, and hold only for a specific set of conditions that cannot be considered normal over the year, but they show that the daily flow with a light to moderate wind is about equal to the total volume of the lagoon. The area of the lagoon inside the lagoon reef margin is 1.1 square miles, and inside the lagoon shelf (12-foot contour) it is 0.8 square mile. Since the average depth inside the shelf is about 50 feet, the total volume of the lagoon inside the shelf is 1.1 billion cubic feet. This is little more than the daily inflow calculated for the northern reef.

Northwesterly winds are not normal during a large part of the year, and the more general northeasterly to southeasterly winds, even though moderate to strong, might not put a comparable volume of water into the lagoon because of the island barriers. Nevertheless, the time necessary to replenish the lagoon water under most conditions should range from a day to a week. This is much less than the 39-day period calculated for Bikini Atoll (von Arx, 1954), where about 4 percent of the lagoon volume exchanges in each tidal cycle during the spring trade season. Periods of stagnation sufficient to affect plant and animal life of the lagoon are unlikely at Ifaluk. On the other hand, the diurnal variation in oxygen and carbon dioxide and in temperature of water on the reef flat may cause comparable variations in the characteristics of the lagoon water because the daily volume of water passing over the reefs is comparable to the total volume of the lagoon.

EARLIER STANDS OF THE SEA

Observations indicate several levels at which the sea stood long enough to leave a recognizable trace. The submarine terrace, about 60 feet deep, and the broad 60-foot deep lagoon floor is the deepest recognizable level. This may have been caused by a eustatic stand of the sea, for 50- to 60-foot terraces have been reported from widespread places over the Pacific (Emery *et al.,* 1954).

The sill depth in the main channel of Ifaluk Pass is about 33 feet, the minimum depth of the broad lagoon bank is about the same (fig. 23), and the coral bench north of Ella Island is about 30 feet deep. The flat profile of the limestone ledges on top of the lagoon bank, when considered together with the pass depth, suggests a truncation to this depth, which in turn implies that the surrounding reefs had grown close to their present level before the sea dropped to the 33-foot level. The wide extent of the submarine terrace south of the atoll is evidence that the 60-foot level antedates both the near-present level and the 33-foot level.

Only one former level is evident above present sea level. The "old reef" remnant on profile A-A′ (fig. 17) is at mean high water, indicating that the reef grew at least to this height and then was truncated more than 2 feet higher than corals and coralline algae now grow. Also, the highest known lithification of rubble, 3.8 feet above approximate mean sea level on Falalap Island, is about 2.5 feet above high tide. Both of these occurrences may relate to the 0.5- to 1-meter stand of Kuenen (1933), or to the closely related 6-foot (2-meter) stand. No higher stands have left a recognizable trace on Ifaluk.

SUMMARY OF GEOLOGIC HISTORY

The probable sequence of events at Ifaluk, then, are growth of a reef or bank and subsequent truncation at the 60-foot level, probably during a late glacial stage. Then the reefs grew to near the present level, following which the sea dropped, or the island rose, to the 33-foot level for a period long enough for the lagoon bank to grow to, or be truncated at, that level and for the notch to be cut at Ifaluk Pass. With the return of the sea to and above its present level, the reefs again flourished until the sea dropped in Recent time to the + 1-meter level, resulting in truncation of the reef and piling of rubble on the reef to form the island ramparts. The principal lithification of the island beaches, of the reef surfaces, and of the rubble tracts on the reef flat probably occurred at this time. Comparatively little has happened since. Continued dropping of the sea to present level has resulted in solution and erosion of the lithified flats and truncation of beaches and reefs to their present form.

Islands have migrated lagoonward an average of about 150 feet because of the erosion of seaward beaches and the addition of sand to the lagoon beaches. At least 500 feet of sand shelf has been added to the lagoon reef edge of the western reefs, and the lagoon reef margin continues to grow lagoonward on this shelf. It is doubtful that any erosion has reduced the seaward reef margins comparably. Fifty years ago a great storm added about 5 percent to the area of the islands; closed off one channel, thereby joining two islands; added large rubble tracts to the reef flat; and built one small island. Other equally severe storms may have hit the atoll in the more distant past, but no traces of them were noted.

Ifaluk Atoll is small and very simple in its structure, compared to most other atolls that have been recently studied. Three periods of development of the atoll have been shown. The most recent of these, the catastrophic typhoon of 1907, left well-defined and mappable traces whose sequence is clearly shown. An earlier period of formation, lithification, and erosion of the present reefs and islands can be assumed to date from a 1-meter stand of the sea only a few thousand years ago, but the sequence of events is much less clear. The earliest period of formation that can be deduced includes growth of the atoll mass to near the present level and truncation at two different submarine levels. Both the dating of this period and the sequence of events are uncertain. It cannot be surely demonstrated whether the traces of former levels relate to eustatic shifts of the sea, to local movements, or to both.

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