Transactions, American Geophysical Union Volume 29, Number 6 December 1948

ADJUSTMENT OF BIKINI ATOLL TO OCEAN WAVES

Walter H. Munk and Marston C. Sargent

(Contribution from the Scripps Institution of Oceanography, New Series, No. 392)

Abstract--Atolls in the trade-wind belt withstand a continuous heavy pounding from ocean waves. Against the windward side of Bikini Atoll alone it is estimated that waves dissipate 500,000 hp, one-fourth the power generated at Hoover (Boulder) Dam. To withstand these forces the exposed reefs are moulded into a most effective natural breakwater, consisting of long narrow grooves in the seaward face of the reef, and surge channels on the reef flat. These surge channels are tuned to the prevailing wave periods. Their distribution around the reef conforms to the distribution in wave activity, which in turn is controlled by prevailing winds over the North and South Equatorial Pacific.

Some of the power of the breaking waves is utilized to maintain a water level just inside the surf zone about 1.5 ft above the general sea level. The water flows downhill over the reef into the lagoon, regardless of the stage of the tide, with an average speed of 0.5 to 1.0 knot, but occasionally with speeds up to four knots. The reef as a biological community utilizes this current and maintains thereby a wave-resisting and modifying structure.

Grooves and surge channels--The features to be described here are best developed between Bikini and Amen Islands (see Fig. 1), where the reef is directly exposed to the waves of the prevailing trade winds [EMERY, TRACEY, and LADD, in press]. Grooves cut the seaward face of the reef at fairly regular intervals (see Fig. 2) and give it the appearance of a series of buttresses rising from the debris-covered slope of the atoll.

The grooves commence at a depth of 50 to 75 ft, then run steeply up the reef slope into and through the surf zone. At the inner end, they may end abruptly or be continued as surge channels, or as tunnels, with blowholes, under the reef platform. Just inside the surf zone, around the blowholes and the heads of grooves and channels, nullipores and coral colonies rise about two ft above the general reef level. The upper faces of the buttresses are paved with living nullipores which present an extremely rough surface. The sides of the grooves are covered with projecting, often bracket-like, colonies. The bottoms of the grooves consist of relatively smooth rock and sand.

Between Bikini and Amen Islands the grooves are spaced about 25 ft apart, are about 16 ft deep at their inner ends, and vary in width from three to six ft. The grooves play a vital part in the function of the coral reef as a breakwater. Near their outer ends, which extend to the maximum depth of appreciable wave action (see Appendix 1), they interfere with the normal orbital water motion associated with waves on a sloping bottom, by taking the bottom out from under the waves; at the inner end they pursue a divide and conquer policy. The resulting effect on waves is remarkable. To an observer standing on the platform just inside the surf zone, the breakers appear to come crashing down upon him; two sec later, the wave has virtually disappeared, its momentum converted into a noisy surge which rushes up the channels on each side of the platform. Much of the remaining energy is spent when the surge meets the backrush from the preceding breaker. Wave energy is also dissipated by friction along the sides of the grooves and channels, where an abundant bracket-like growth of organisms is found.

The surge channels are properly tuned to the average wave characteristics (see Fig. 2). An average depth of 15 to 20 ft, and a length of about 200 ft (ℓ_1 in Fig. 2) between the outer end of the platform (Lithothamnion ridge) and the inner ends of the channels correspond to a fundamental period of oscillation of eight sec, which is also the prevailing period of the waves of the trade winds (see Appendix 2). As a result, the uprush of each wave will meet the backrush of the preceding wave at approximately mid-channel.

Distribution of grooves and prevailing wave directions--The dimensions of grooves around the entire reef of Bikini Atoll were estimated from aerial photographs, and are designated by arrows on Figure 1. The spacing s, width w, and outer length ℓ_0 (see Fig. 2) of the grooves are designated by the spacing, width, and length of the arrows. Photographs of the reef to the south of Bikini Island were unsuitable for the determination of the grooves, but it is known that grooves are well developed in that area.

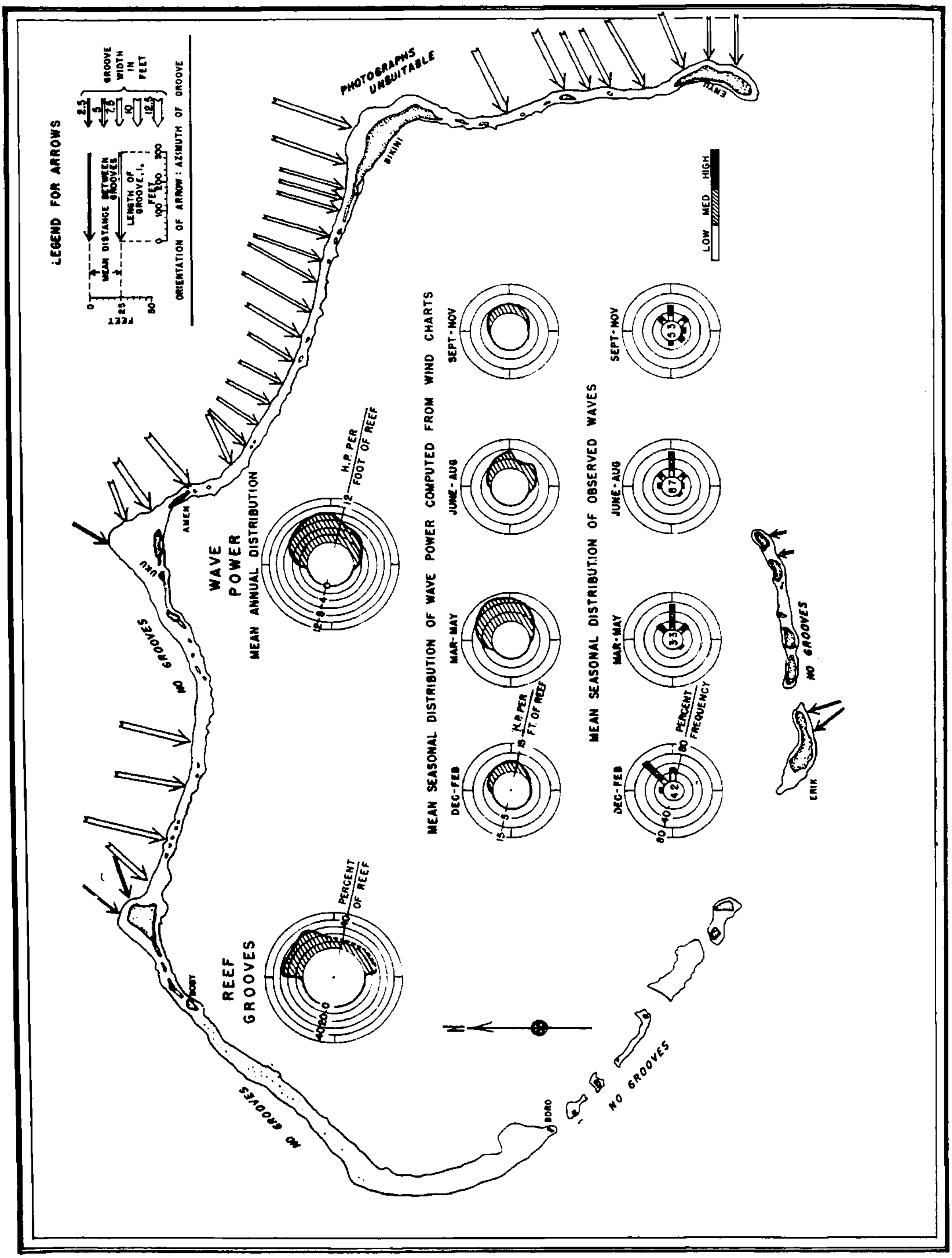

Fig. 1--Distribution of reef grooves and wave power around the reef of Bikini Atoll; the length, width, and spacing of the grooves are proportional to the length, width, and spacing of the arrows drawn against the reef; polar coordinate graph to the left shows per cent of area occupied by grooves as function of their exposure; polar coordinate graphs to the right show mean distribution of computed wave power, and of observed waves

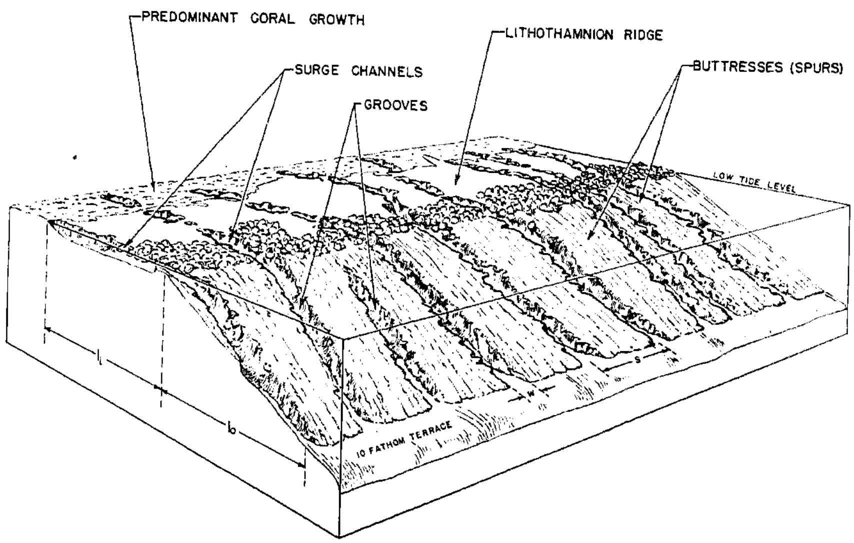

Fig. 2--Generalized sketch of seaward face and top of reef on windward side of Bikini Atoll; original by D. B. Sayner

The greater length of the grooves with northern exposure relative to those with southern exposure is due to the steeper slope of the reef to the south [EMERY, TRACEY, and LADD, in press]. The absolute depth at which the grooves commence appears to be approximately constant, and to extend to the greatest depth for which wave action is appreciable (see Appendix 1).

The per cent of reef area occupied by the grooves equals 100 w/s. This is plotted as a function of the azimuth of the grooves on the polar coordinate graph on the left in Figure 1. No grooves were found where the reef exposure has a westerly component.

The distribution of grooves can be correlated with the distribution of wave power around the Atoll. The polar coordinate graphs to the right in Figure 1 give the average seasonal and annual distribution of wave power plotted against reef exposure and expressed in units of hp per foot length of reef.

Wave power was computed in the following manner. The principal generating areas were determined from the Atlas of Climatic Charts of the Oceans [UNITED STATES WEATHER BUREAU, 1938]; they fall into the trade-wind belts of the North and South Pacific. (Swell from the "roaring forties" may occasionally reach the northern Marshalls, but will be too low to be significant.) The frequencies of the prevailing winds in the two main generating areas, and of winds from other directions, were determined from wind roses on the North and South Pacific Pilot Charts. The height, period, and direction of waves reaching Bikini from all directions were then computed, following the method for forecasting sea and swell from weather maps [SVERDRUP and MUNK, 1946a]. Finally the bending of waves around the Atoll due to refraction was estimated [SVERDRUP and MUNK, 1946b] and the wave power computed (see Appendix 3).

A rough check of the validity of these computations could be obtained from sea and swell observations appearing in the Sea and Swell Charts, Northwestern Pacific (Hydrographic Office 10712C). Averages were formed for each season, taking into account all observations in the area between longitudes 160°E to 170°E, and between latitudes 5°N to 15°N. These are presented by the wave roses in Figure 1. The main features in the observed wave distribution are in agreement with the computed distribution of wave power.

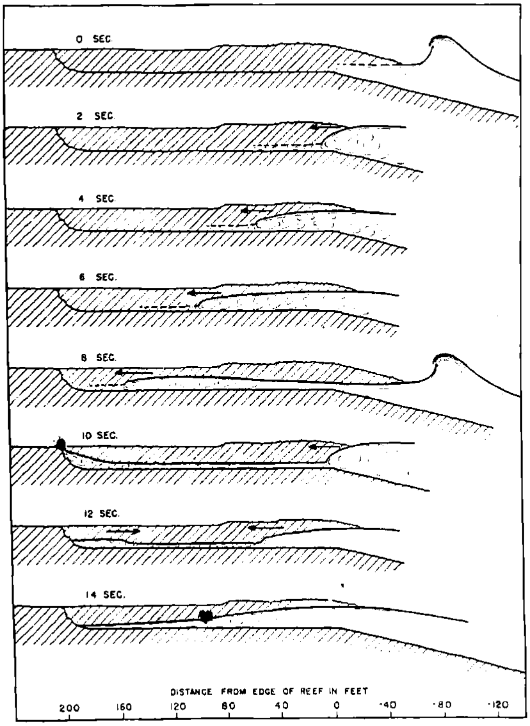

Fig. 3--Breaking wave produces surge which travels up the surge channels, is reflected on the upper end, and meets surge from subsequent breaker midchannel; surge channels are tuned to the period of prevailing waves

The graph of the annual distribution of wave power is based entirely upon the computed rather than the observed wave characteristics, partly because of the small number of observations, but chiefly because the quality of these observations is believed to be inferior to the quality of the computed values.

The diagrams in Figure 1 show a significant correlation between the directional distribution of wave power and of reef grooves. Grooves are restricted to reefs with a component of exposure to the east, the direction from which wave action is pronounced. Due to wave refraction a small portion of the wave power does reach the western sides of the Atoll, but there the power dissipated amounts to only a fractional hp per foot length of reef, and it appears that at least one or two hp is required for the development of grooves. On the eastern half of the reef the average power delivered by the waves equals three hp per foot length of reef, or about 20 hp per groove.

The distribution of grooves reveals a maximum for an east-northeast exposure, and a secondary maximum for southeast exposure. These features are associated with the principal wave-generating areas in the trade-wind belts of the North Pacific and South Pacific, respectively. The distribution of wave power reveals the same features; except during the summer months the effect of the distant South Pacific trade winds is overshadowed by the effect of the local trade winds. For a corresponding location in southern latitudes the reverse should be true, and the distribution should be a mirror image of the one found at Bikini.

The bimodal distribution of grooves points strongly toward a wave origin; if the channels were to be attributed to direct wind action, the development in the southeast quarter would be missing.

Head of water at reef edge--Not all the energy of the incoming waves is dissipated by friction. Some energy is converted into potential energy to maintain a water level at the outer edge of the reef at about two ft above the mean water level of the ocean and lagoon water. If the entire wave energy were to be consumed in lifting the water which flows over the reef, the level of this volume of water could be maintained 42 ft above the mean sea level (see Appendix 3). Therefore only about 5 per cent of the wave's energy is utilized to raise the water level, and 95 per cent is dissipated by friction, a large part of it within the surge channels.

It may be worthwhile to consider the design of artificial breakwaters along the lines of the natural coral reef breakwater, as the present structure of these reefs represents the result of thousands of years of adaptation resulting in a most suitable structure to withstand the wave forces. Artificial surge channels have indeed been employed on the south coast of the Mediterranean in the generation of electricity by means of wave power. These channels were relatively wide at their outer end and converged gradually toward the inner end. In this manner the water level in a reservoir was maintained at an average elevation of 40 ft above the mean sea level.

Wave-driven currents over the reef--From the region of maximum elevation the current flows into the lagoon under the influence of gravity assisted by wind traction. Between Bikini and Amen Islands, the speed is about one ft/sec; except during spring low tides, when the retarding effect of bottom friction is disproportionally large, this speed is remarkably independent of tide. In the presence of obstructions the wave-driven current may give rise to striking features. For example, a few days after the arrival of the USS Bowditch a 100-ft channel broke through the sandspit at the northwest end of Bikini Island, and water flowed through this channel in a steady stream for almost six months.

Currents over the reef were measured by dropping dye bombs from planes, and taking timed photographs of the drifting color patches [VON ARX, 1948]. Between February and April 1946, while the trade winds blew predominantly from the east-northeast, wave-driven currents flowed into the lagoon over the entire eastern and northern reefs, adding 3×10^{14} cm^3 of water, one per cent of the entire lagoon volume, during each 12-hourly interval. During an equal time interval the tidal flow (chiefly through the deep southwesterly passages) amounted to two per cent of the lagoon volume. Although the oscillating tidal current represented the principal component of water exchange between the ocean and the lagoon, the one-directional wave-driven current is of primary importance to the renewal of water in the lagoon. The latter feature was of interest with regard to the flushing of the lagoon of radioactive water.

The wave-driven current is important also for another reason. At noon, expecially during low tide, the water over the reef becomes warmer, more saline, and supersaturated with oxygen. Upon entering the lagoon, this "reef water" may be recognized as a distinct water type. The mixing of this water with the lagoon water provided a method for computing the rate of vertical diffusion [MUNK, EWING, and REVELLE, in press].

Discussion and conclusions--Waves breaking over coral reefs may lead to the formation of grooves and to the flow of currents over the reef. The only other known examples of currents due to wave action are longshore currents and rip currents caused by waves breaking on gently sloping beaches [MUNK and TRAYLOR, 1947]. Since the waves represent an integrated effect of the winds, their energy being accumulated during many hours, and over thousands of miles, a wave-driven current assures a steadier supply of water than a wind-driven current.

The waves and the wave-driven current may be of biological significance in three ways. First, they limit luxuriant growth of Lithothamnion and other encrusting coralline algae to situations exposed to the heaviest wave action, possibly because such action prevents the establishment of sedentary organisms. Secondly, the current maintains a nearly constant supply of mineral nutrients and dissolved gases over the whole width of the reef. Thirdly, as noted above, the current carries water into the lagoon, which at noon is supersaturated with oxygen. Also, on the basis of evidence presented elsewhere [SARGENT and AUSTIN, in press], it is believed that there is a net transport of organic matter into the lagoon which is of importance in the total organic matter budget of the lagoon.

Appendix 1

This work represents results of research carried out for the Hydrographic Office, the Office of Naval Research, and the Bureau of Ships of the Navy Department under contract with the University of California. The original of Figure 2 was drawn by D. B. Sayner.

Depth of wave action--The average speed of water movement along the bottom in water of depth h is given by

$$u = 2\pi H/T \sinh^{-1} (2\pi h/L) \qquad (1)$$

where H and T are the height and period of the wave responsible for the water movement. The wave length is given by

$$L = (gT^2/2\pi) \tanh (2\pi h/L) \qquad (2)$$

where g is the acceleration due to gravity. For a wind speed of 16 knots, blowing over a long fetch and for a long time, the wave height and period equal seven ft and eight sec, respectively [SVERDRUP and MUNK, 1946a]. These figures are in agreement with the observed dimensions of trade-wind waves. Simultaneous solution of (1) and (2) leads to the numerical values shown in Table 1.

Table 1--Mean orbital speed on the ocean bottom

Depth h	Speed u	Size of particles which can be eroded
ft	ft/sec	mm
50	1.2	3
75	0.8	1
100	0.5	0.05
125	0.32	No erosion

The outer ends of the grooves fall into a depth of about 75 ft, where the average speed due to wave action is about 0.8 ft/sec. The third column shows the size of particles which can be eroded by a current of speed u, based upon measurements in rivers by Hjulström [TRASK, 1939, pp. 10-11]. According to Hjulström, "...fine sand, which has a diameter of 0.3 to 0.6 mm, is the easiest to erode, whereas both silt and clay on the one hand and coarse sand and gravel on the other require higher velocities.'' If these conclusions are applicable here, they indicate that no erosion can take place for current speeds less than 0.5 ft/sec, that is, at depths exceeding 100 ft, no matter how small the size of the grains.

Appendix 2

At the depth of 75 ft the reef slope is relatively gentle, forming virtually a terrace [EMERY, TRACEY, and LADD, in press]. One would be tempted to ascribe this "ten-fathom terrace" to wave action, were it not for the fact that it is also found inside the lagoon.

Table 2--Length of channels for maximum interference

Period T	Length l_2
sec	ft
6	130
8	175
10	220

Dimensions of surge channels--The speed of a surge in a channel equals approximately $\sqrt{gh}$, where h is the depth of the water measured from the highest point in the surge. For effective interference the surge must travel a distance of roughly the length of the channel during one wave period (see Fig. 3). The corresponding length of the channel equals approximately $T\sqrt{gh}$. Setting $g = 32.2$ ft/sec^2, $h = 15$ ft, leads to the values shown in Table 2.

Appendix 3

The wave period in the region of the northern Marshalls is remarkably constant and falls within the limits of seven to nine sec, probably more than 90 per cent of the time. Over most ocean areas the period of the significant waves vary between such wide limits (probably six to 14 sec) that resonance for any permanent structure would be achieved only a small fraction of the time.

Wave power--The mean energy dissipated by the waves each sec against a unit width of reef is $(1/32\pi)\,\rho g^2 H^2 T$ where ρ is the density of water. The transport of water per ft width of reef equals $h'V$ where h' is the depth of water over the reef, V the corresponding speed of flow. If the entire wave energy were to be utilized in raising the water flowing over the reef, then

$$(1/32\pi)\rho g^2 H^2 T = \rho g\, h' V s \qquad (3)$$

so that the vertical distance through which the water would be raised is

$$s = gH^2 T/32\pi h' V \qquad (4)$$

Setting $H = 7$ ft, $T = 8$ sec, $h' = 3$ ft, $V = 1$ ft/sec gives $s = 42$ ft.

References

EMERY, K. O.; TRACEY, J. I., JR.; and LADD, H. S., Submarine geology and hydrography in the northern Marshalls, Trans. Amer. Geophys. Union, in press.

MUNK, W. H., and TRAYLOR, M. A., Refraction of ocean waves; a process linking underwater topography to beach erosion, J. Geol., v. 55, pp. 1-26, 1947.

MUNK, W. H.; EWING, G. C.; and REVELLE, R., Diffusion in Bikini Lagoon, Trans. Amer. Geophys. Union, in press.

SARGENT, M. C., and AUSTIN, T. S., Organic productivity of an atoll, Trans. Amer. Geophys. Union, in press.

SVERDRUP, H. U., and MUNK, W. H., Empirical and theoretical relations between wind, sea, and swell, Trans. Amer. Geophys. Union, v. 27, pp. 823-827, 1946a.

SVERDRUP, H. U., and MUNK, W. H., Theoretical and empirical relations in forecasting breakers and surf, Trans. Amer. Geophys. Union, v. 27, pp. 828-836, 1946b.

TRASK, P. D. (Ed.), Recent marine sediments, Tulsa, Amer. Ass. Petrol. Geol., 736 pp., 1939.

UNITED STATES WEATHER BUREAU, Atlas of climatic charts of the oceans, U. S. Govt. Printing Office, 130 charts, 1938.

VON ARX, W. S., The circulation of Bikini and Rongelap Lagoons, Trans. Amer. Geophys. Union, pp. 861-870, 1948.

Scripps Institution of Oceanography,
University of California,
La Jolla, California

(Manuscript received May 13, 1948; presented at the Twenty-Eighth Annual Meeting, Washington, D. C., April 28, 1947; open for formal discussion until May 1, 1949.)