Chapter 1 — Geography

INTRODUCTION TO THE GEOGRAPHY OF ATOLLS

by E. H. Bryan, Jr.

The study of atolls, being sponsored by the Pacific Science Board of the National Research Council, has two broad objectives. The first is to investigate total environmental interrelationships on atolls. The second is to apply the knowledge gained from such studies to improve the wellbeing of persons living upon atolls. At its best, an atoll presents a harsh environment in which to live. Numerous atolls are inhabited, and several, particularly in the Gilbert Islands Colony, are overpopulated, which adds to the difficulty. These atoll studies are being made in cooperation with a project of the South Pacific Commission to improve human conditions on atolls.

This handbook presents suggestions for various types of investigation on atolls. By way of introduction, I have been asked to summarize some general aspects of the subject: What is an atoll? What is the range of physical form? Where are atolls found? What are some of the theories of their formation? What general observations are needed concerning atolls?

WHAT IS AN ATOLL?

A "coral reef" is an accumulation of limestone principally derived from skeletons of marine animals and plants, especially corals, foraminifera, mollusks, echinoderms, and red and green algae. These may or may not be in their original location or position of growth. The structure extends from the sea bottom near or quite to the surface. Changes in sea level or elevation of the sea bottom may cause it to protrude above the present level of the ocean.

Reefs occur chiefly as fringing reefs, barrier reefs, and atolls. In addition, there may be reef structures which do not fall into any one of these categories.

Fringing reefs are platforms of reef which extend out a relatively short distance from the shores of both high and low islands, even continents. Such reefs are not at uniform depths below sea level and may be cut by channels, especially opposite the mouths of streams, for reef organisms do not develop in fresh or silty water.

Barrier reefs lie at a greater distance from shore, with relatively deep water between. The Great Barrier Reef, for example, lies up to 90 miles off the coast of Australia, with soundings of 20 fathoms in the intervening channel. Barrier reefs may be cut by channels, and there may be islets upon them, but the proximity to other land, which usually is high, distinguishes them from atolls. The barrier reef around the Truk group illustrates this point. Although the reef resembles an atoll rim, Truk is <u>not</u> an atoll because of the high islands within its lagoon.

An atoll is a physiographic structure, composed of reef, broken reef rock, and sand, rising abruptly from the ocean, and typically enclosing a shallow lagoon, which does not contain "high" islands. The popular conception is that an atoll rim is circular. This seldom is the case. More frequently it is angular or elliptical. There is great range of size, shape, and form. Some atolls are completely submerged, with no dry land. At the other extreme we find "raised atolls", the reef rim of which is raised to a considerable height above sea level, enclosing a dry lagoon basin. Every intermediate form can be found. Some atolls have a great number of distinct islets (Kwajalein has about 95), and numerous entrances or channels. On some atolls the islets may be connected by ridges of sand, with few lagoon entrances. The next form in this sequence (which I call the "doughnut") has a continuous ring of land surrounding the lagoon, which may vary from very salt (Sydney Island) to quite fresh (Swains Island), depending chiefly upon the rainfall and the permeability of the material of which the atoll is composed. The size of the enclosed lagoon becomes smaller and smaller, in our series, until we reach the "pancake" with no lagoon. On the "pancake" island the marginal rim and enclosed basin may be distinct (as in Baker or Jarvis Islands) or the island may be quite flat (Howland), or so covered with trees that the basin is not apparent (Vostok or Flint). The highest part of such islands generally is just behind the windward beach, and rarely exceeds about 20 to 30 feet, usually much less. Any greater height would require an uplift of the land, as is the case on Fais, Nauru, and Ocean Islands.

The question is, when does an atoll cease to be one? The point is academic. One has to make his own definition, depending upon the circumstances. It was decided at an atoll symposium, held in Washington, D. C. and Honolulu, in 1951, that, for the purpose of our studies, we would include non-elevated limestone structures, with dry land, with or without a lagoon, which were not associated with high land. We would exclude elevated atolls (reaching a height of more than 20 feet or so), sunken atolls (without dry land), barrier reefs surrounding high islands (such as Truk), and reef structures on fringing shelves or platforms adjacent to land masses (such as the Great Barrier Reef, the islands in the Bay of Batavia, Java, and the like.)

DISTRIBUTION OF ATOLLS

The writer has undertaken to compile a list of known atolls for the Pacific Science Board. To date these number about 400. They are located chiefly in the Pacific and Indian oceans, most of them between the Tropics. The ones furthest north are Kure and Midway, at the northwestern end of the Hawaiian chain (28° 25' North). Those furthest south (excepting Pelsart Island and Middleton and Elizabeth Reefs) are Oeno and Ducie (24°40' S.). The greatest concentration is in the Central Pacific: Equatorial, Northern Cook, Tokelau and Phoenix (together 35); Ellice (9), Gilbert (16), Marshall (33), Caroline (40), and isolated in the Northwest Pacific (3), a total of 136. The Tuamotu archipelago contains 75, with 4 more to the east and 7 to the west of it. There are 5 in the Hawaiian chain; 8 in Fiji (not counting a host of small circular reefs without land); 27 between Fiji and Australia, chiefly in the Coral Sea; 6 north of the Solomon Islands; 6 in the Louisiades; 20 near the Admiralty Islands; 9 northwest of Australia; 15 in Indonesia; 41 in the central Indian Ocean (Laccadive 13, Maldive 22, and Chagos 6); and 26 in the western Indian Ocean. Only one has been recognized in the Atlantic (Rocas Reef, off Brazil). There are 25 potential atolls in the Caribbean Sea, but whether or not they are comparable with those in the Pacific and Indian Ocean is in dispute.

If we follow the custom of the taxonomist, the type locality of atolls would be the Maldive Islands, where the native name atollon is used to designate the reef rings found there. These differ in structural detail from "typical" atolls in the Pacific.

ACCEPTED IDEAS REGARDING REEFS AND ATOLLS

Harold T. Stearns (1946) has listed various factors which now are generally accepted by geologists. They are:

"1. Reef building corals thrive only at moderate depths, usually less than 200 feet below sea level in warm, fairly clear ocean water.

2. Nullipores [coralline algae] bind corals together and make a reef possible. In some places nullipore reefs exist nearly free of corals.

3. Sea level was lowered about 300 feet during the Pleistocene by the abstraction of water for the ice caps. If all the ice on earth were melted today, sea water would rise about 150 feet.

4. Changes in the configuration of the ocean basins and consequent changes of sea level have occured since Miocene time to an undetermined extent.

5. The Sialic (continental) islands bordering Australasia [including Melanesia and western Micronesia] are underlain by folded rocks.

6. No folded rocks are exposed in the Simatic (oceanic) islands [Polynesia, except perhaps Tonga and New Zealand] except for slight warping which occurs locally, usually in calderas.

7. Emerged reefs of Tertiary age are exposed in many islands.

8. Coral atolls are not generally formed by growth upward from crater and caldera rims.

9. Coral atolls rest on basements of volcanic or other non-coralliferous rock.

10. Barrier and fringing reefs require shelves built with their own talus, antecedent platforms or shelves of some other origin, or gently shelving shores of any origin.

11. The growth of corals is relatively rapid under favorable conditions, variously reported from 20 to 90 feet in 1,000 years.

12. Very rapid submergence may drown a reef.

13. Reefs at sea level are killed by emergence.

14. Coral reefs grow most rapidly at their outer edges in the breaker zone where the food and oxygen supply is greatest.

15. The lagoons of atolls are not caused by submarine solution."

[Evidence for some solution of limestone in the intertidal zone recently has been pointed out.]

Dr. Stearns proceeds to examine the various theories which have been proposed to explain the formation of reefs and atolls, and to develop some modifications of his own. He points out that the shelves and platforms upon which reefs have grown have been built by volcanism, sedimentation, or diastrophism, or out by marine or subaerial erosion. Examples of all can be found, he says, and "the origin of many shelves can be determined by study of the geology of the adjacent land, but much drilling and geophysical work is needed to determine the origin of submerged platforms."

THEORIES FOR THE FORMATION OF ATOLLS

It is not the object of this summary to discuss the relative merits of the various theories for the formation of atolls which have been proposed. A brief listing of the principal theories is given chiefly to suggest the kinds of observations which need to be made.

In 1928, William M. Davis' monumental work on coral reefs was published. This summarized the theories for reefs and atolls to that date. Many detailed observations on the subject have been made since then, and the resulting ideas should be outlined to bring the subject up to date. One of the more recent summaries, which presents a relatively unprejudiced comparison, is "The problem of coral reefs," by Harry S. Ladd and J. I. Tracey, Jr., (1949). Another recent summary is given by Ph. H. Kuenen in his "Marine geology," (1950). During the past 20 years, several other valuable contributions have been published (see bibliography, below.). Contributions are being made at an accelerated rate.

In order of presentation, the principal theories have been:

1. In 1821, A. von Chamisso proposed a theory for atolls based on the natural growth of corals around the edge of submerged banks, observing that massive corals grow best around the seaward edge of reefs, while those within are killed or stunted.

2. Charles Darwin's famous "subsidence theory" was published in 1842. It suggested that fringing reefs growing around a sinking volcanic island would build up around their outer edge to form a barrier reef, and that an atoll would result when the enclosed island had sunk entirely and its summit, probably buried by coral debris, was submerged beneath the lagoon. This theory was supported and expanded by James D. Dana and favored by Davis.

3. Carl Semper (1863), working in Palau, suggested that reefs were formed by outgrowth on a rising foundation, and that the lagoon of an atoll was formed by solution of the enclosed living reef.

4. Discovery of submerged elevations in the sea prompted Sir John Murray (1880) to go back to von Chamisso's original idea that atolls formed by the upgrowth of corals around the edge of still-standing, aggraded submarine banks. Similar ideas were held by J. J. Rein, H. B. Guppy, and F. Wood Jones. W. J. L. Wharton suggested that the foundations could have been completely truncated by erosion, or incompletely truncated.

5. In 1910 (and later), R. A. Daly developed his "glacial control theory," which supposed that during the glacial period, when sea level was lowered by the removal of sea water to form glaciers, platforms were formed, around the edges of which reefs were built up in the warmer seas as sealevel rose, following the melting of the glaciers. Up growth kept pace with rise of sealevel, forming the present barrier reefs and atolls.

6. In 1928, W. M. Davis amassed a tremendous amount of evidence in support of a combined subsidence and glacial control theory, in which inhibition of coral growth by lowered temperatures in the marginal belts of the coral seas during glacial times played a great part. He favored a modified subsidence theory which did not involve regional subsidence of the sea bottom but individual subsidence of islands separately.

7. J. F. F. Umbgrove (1939 and 1947), unable to find evidence to support the glacial control theory in his studies of the reefs of Indonesia, described evidence for crustal movements during the Pleistocene. He stated that elevated reefs in that area were formed in late Tertiary or early Pleistocene, then uplifted and eroded. He noted that other reefs could be explained by Darwin's subsidence theory.

8. J. E. Hoffmeister and H. S. Ladd (1944) presented evidence for the antecedent-platform theory. This was based chiefly on studies in Tonga and Fiji, where there is land movement due to folding. It suggests that volcanic cinder cones are eroded to a depth of about 150 feet below sea level, and then the resulting platforms are built up by non-coralliferous deposits until reef-building corals can commence their growth, chiefly around the periphery. This theory obviates both subsidence and glacial control. Later studies in Micronesia, particularly as a result of deep drilling on Bikini atoll, have caused these authors to modify or broaden their ideas.

9. In 1945 and 1946, Harold T. Stearns suggested that great eustatic shifts of sea level occured during Pliocene and Pleistocene time, as a result of changes in the configuration of ocean basins. On sialic (continental) islands, he said, reefs formed on rising foundations, caused by folds. On simatic (oceanic) islands of the central Pacific block, they developed on subsiding islands. The appropriate hypothesis was used in each case.

10. In 1947, Ph. H. Kuenen, elaborating Davis' ideas, combined the two chief theories into a "glacially controlled subsidence theory," suggesting that preglacial reefs were cut down to glacial sea level by chemical means, and that reefs grew around the edge of such platforms.

Summary: It will be noted that the important theories fall into two main groups: those that involve a relative change of level between land and sea, and those which do not. Of the former group, some favor a rising foundation, others a sinking foundation, and others a sinking and later rising sea. The chief argument in the other camp seems to be how the foundation was formed and how it became a suitable habitat for the growth of reef organisms. There is good evidence that the sea shifted its level during the glacial period, and doubtless in previous eras. It is also known that oceanic islands can settle as well as be built up, and that other islands, which are remnants of a more ancient land mass, can move up and down with the folding of their foundations.

The trend seems to be for geologists to cease their feuding and to agree that one theory can account for the formation of reefs and atolls in one region, while those in another region may have another explanation, even a combination of theories. Professor Kuenen states that he is in complete agreement with the statement of Hoffmeister and Ladd (1935) that "Probably no single reef theory will explain all reefs. Certainly, recognition of the complexity of the problem is essential to its solution. It does not belong within the realm of any one subject, but requires the attention of scientists of many fields, each contributing his share."

DETAILED FEATURES OF ATOLLS

Careful studies of atolls, such as those recently made at Bikini, are much needed. They show that "an atoll is a composite reef made up of a number of distinctive reef types - windward reefs, leeward reefs, and lagoon reefs. Most of these are zoned relative to prevailing winds and currents. Organic growth, erosion, and deposition of sediment influence each of these zones, but in each the balance of forces operating at the present time may be roughly appraised. Some reef zones appear to be making headway against the sea, others appear to be essentially in a state of equilibrium, while still others are being eroded. Organic growth is the source of all the materials that make up an atoll. Some of the skeletons of the reef-building organisms remain in position of growth after death, but a much larger proportion are broken up by physical and organic agencies to form sediments that are deposited on the seaward slopes or in the lagoons. So long as organisms live on an atoll, it continues to grow, but it grows mainly by the accumulation of classic sediments." (Ladd, Tracey, Wells, and Emery, 1950.)

The above abstract summarizes the kind of study needed for more atolls. It scrutinizes an atoll zone by zone: the Lithothamnion ridge, the coral-algal zone, the reef flat, the beach; submarine cliffs, eroded edge, boulder ramparts; various parts of the lagoon, including the coral knolls. It attempts to evaluate the balance of forces operating on an atoll, which have produced these formations.

TYPES OF INVESTIGATIONS NEEDED

Ladd and Tracey (1949) suggest the following promising fields in atoll investigation.

1. "Island geology. Reef-encircled islands of all types should be mapped geologically." This raised the need for adequate base maps of convenient scale and considerable accuracy. In cataloging the known atolls, the writer has noted that but few atolls, outside of Micronesia, are mapped or charted in any detail, or with any accuracy. The use of the aerial photograph, so widely used in the Pacific during World War II, should be of tremendous value in this connection.

2. "Reef studies. Additional ecological studies such as those carried out on the Great Barrier and at Bikini on organic productivity of reefs are needed."

3. "Lagoon studies. Mapping and coring of lagoon sediments yield data that are of great value in the interpretation of elevated limestones and of the cores and cuttings obtained from drilling. When such information is combined with data obtained from dredging on the outer reef slopes, it is possible to make sound paleoecological interpretations and to determine the significance of the several types of limestone that occur in reef areas." Study is needed also of the internal constitution of the numerous coral knolls rising from the lagoon floor.

4. Submarine geology. More details are needed regarding the structure of seamounts, discovered in considerable number in the Pacific. "Dredging and additional coring of these structures should give more clues to their origin and, perhaps, their age. Specifically, it is essential to learn if they have a hard rim with a central depression now filled with sediment; to determine if the coating of recent sediments is thick, and if it contains pebbles of hard rock suggesting an origin of wave erosion."

"Studies of isolated banks in the coral seas at 300 - 1,000 feet below sea level would give needed data on the types of sediments that accumulate and the kinds of organisms that live in reef areas at depths below the limit of reef coral growth."

5. Island foundations. More drilling and geophysical investigations are needed.

\- - - - - -

Other subjects in need of investigation include:

How do climatic factors tend to modify atolls? These include wind direction and velocity, force of tropical storms, temperature, and rainfall.

What is the effect upon reefs and atolls of ocean currents, tsunami and other large waves, water temperature and salinity?

What are the geographic names in use by the native inhabitants for islets and localities on atolls?

How has man modified atolls? He is known to have removed sand and guano, dredged reefs and cut channels into lagoon basins. What has been the effect of these? He has made large withdrawals of ground water, dug pits for cultivation, removed the natural vegetation.

Items to note regarding human inhabitants include: the number of persons and their areal distribution; land utilization, including areas used for residences, crops, exploitation of the lagoon, and the like.

The general observations, listed above, together with the specific directions presented in the pages which follow, should help to make possible a study of total environmental interrelations on atolls, and result in improved conditions for those who make atolls and reef islands their home.

BIBLIOGRAPHY: Recent summaries of data on Atolls and their formation.

Davis, W. M., The coral reef problem. American Geographical Society, Pub. 9, 1928. [Presents a very complete summary of theories prior to date.]

Gardiner, J. S., Coral reefs and atolls. Macmillan, 1931. [Detailed study].

Kuenen, Ph.H., Geology of coral reefs. Snellius Expedition, Geological results, 2, 1933. [Indonesian region.]

Hoffmeister, J. E. & Ladd, H.S., The antecedent-platform theory. Journal of Geology, 52: 388-402, 1944.

— The foundation of atolls: a discussion. Journal of Geology, 43: 653-665, 1945.

Stearns, H. T., An integration of coral-reef hypotheses. American Journal of Science, 244: 245-262, April 1946.

Umbgrove, J. H. F., Coral reefs of the East Indies. Geological Society of America, Bulletin 58: 727-778, 1947.

Kuenen, Ph. H., Two problems of marine geology: atolls and canyons. Verhandlingen der Koninklijke Nederlandsche Akademie van Wetenschappen, Afd. Natuurkinde, Tweede Sectie, 43 (3): 68 pp., 1947.

Daly, R. A., Coral reefs - a review. American Journal of Science, 246:193-207, 1948.

Emery, K. O., Submarine geology of Bikini atoll. Geological Society of America, Bulletin 59: 855-860, 1948.

Ladd, H. S. and Tracey, J. I., Jr., The problem of coral reefs. Scientific Monthly, 69 (5), 1949.

Sargent, M. C. & Austin, T. S., Organic productivity of an atoll. American Geophysical Union Transactions, 30: 245-249, 1949.

Kuenen, Ph.H., Marine geology. N.Y., John Wiley & Sons, 1950. [Chapter 6: 414-479, gives a detailed account of reef theories.]

Ladd, H. S., Tracey, J. I., Jr., Wells, J. W., and Emery, K. O., Organic growth and sedimentation on an atoll, Journal of Geology, 58 (4): 410-425, 1950.