

Atolls

– Distribution, Development and Architecture –

Nicole Schulz

TUBAF Institute for Geology

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Abstract

Whether a volcanic island becomes an atoll or a guyot depends on physical conditions like water temperature, erosion, salinity, sedimentation and sinking rate. Reefs occur in different sizes and shapes, resulting from the hydrological and geological conditions that occur in different areas of the tropics. The most common types of reefs are grouped into three categories: atoll, barrier and fringe reef. So the distribution of atolls is not very equal at all. Atolls require strong light and warm waters and are limited in the existing seas to tropical and near-tropical latitudes. A large percentage of the world's atolls are contained in the central and southwestern Pacific and in parts of the Indian Ocean and a number are found, mostly on continental shelves, in the Caribbean area.

1 Introduction

Atolls are annular reefs with deep central lagoons (see fig.5) (e.g. SCOFFIN, 1987, DARWIN, 1842). They are the product of the growth of tropical marine organisms, so these islands are only found in warm tropical waters. Atolls are also a monitor of

eustasy because they provide a subsiding platform of carbonate deposition that preserves a record of sea-level changes (QUINN & MATTHEWS, 1990). Volcanic islands located beyond the warm water temperature requirements of reef building (hermatypic) organisms become guyots as they subside and are eroded away at

the surface. An island that is located where the ocean water temperatures are just sufficiently warm for upward reef growth to keep pace with the rate of subsidence is said to be at the Darwin Point. For the North Pacific this Point is at 28°N on the Hawaiian island chain at Kure Atoll (see fig:4) (SCOFFIN, 1987). North of this point the coral reefs are drowned and cold-water carbonates veneer them while the volcanic island chain is submerging. Islands more polar evolve towards seamounts or guyots; islands more equatorial evolve towards atolls (see Kure Atoll). A lot of geological facts can be explained on the ex-

ample of Enewetak Atoll. Therefore most parts of the chapters Development and Architecture refer to this atoll.

2 Distribution

The distribution of atolls (fig:1) is limited to warm tropical and subtropical waters of oceans and seas and is not uniform. Most of the atolls can be found in the Pacific Ocean (e.g. Marshall Islands, Coral Sea Islands, Kiribati) and the Indian Ocean (e.g. Outer Islands of the Seychelles, Maldives) (PAUL S. KENCH, 2006).



Figure 1: The distribution of some examples of atolls. The distribution of atolls around the globe is instructive: most of the world's atolls are in the Pacific Ocean (with concentrations in the Tuamotu Islands, Caroline Islands, Marshall Islands, Coral Sea Islands, and the island groups of Kiribati and Tuvalu) and Indian Ocean (the Maldives, the Laccadive Islands, the Chagos Archipelago and the Outer Islands of the Seychelles). The Atlantic Ocean has no large groups of atolls, other than eight atolls east of Nicaragua.

Atolls are reduced or absent at the limits of tropical areas (fig:2), such as the west coasts of South America and Africa, because these are areas of upwelling and the existence of cold currents, such as in Peru and South America. The Atlantic Ocean has no

appreciable groups of atolls, only in the region of Bermuda.

The northernmost atoll of the world is Kure Atoll at $28^{\circ}24'\text{N}$, along with other atolls of the Northwestern Hawaiian Islands. The southernmost atoll of the world is Elizabeth

Reef at $29^{\circ}58'S$ in the Tasman Sea, which is part of the Coral Sea Islands Territory. The next southerly atoll is Ducie Island in the Pitcairn Islands Group, at $24^{\circ}40'S$. Bermuda is sometimes claimed as the northernmost atoll at a latitude of $32^{\circ}24'N$. At this latitude coral reefs would not develop without the warming waters of the Gulf Stream. However, Bermuda is what is termed a pseudo-atoll because its general form, while resembling that of an atoll, has a very different mode of formation. The clos-

est atoll to the Equator is Aranuka of Kiribati, with its southern tip just 12 km North of the Equator (DARWIN, 1842).

The largest atolls are found in the Maldives: Huvadhoo Atoll, having an area of 2800 km^2 . Large atolls are also found in the Tuamotu Archipelago. In most cases, the land area of an atoll is very small in comparison to the total area. The largest atoll in the world in terms of 'land area' above sea-level is Kiritimati (321.37 km^2).

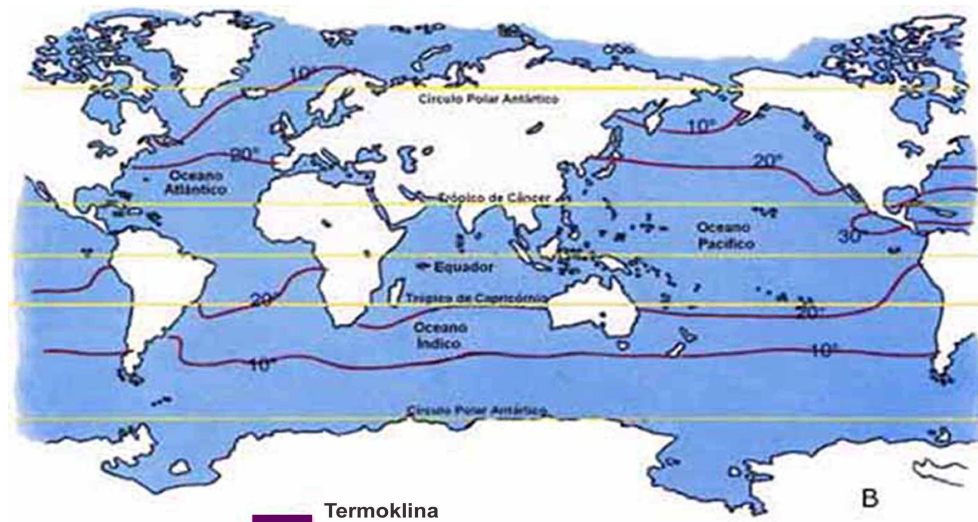


Figure 2: The dynamics of warm currents. Atolls develop exactly between the 20°C thermoclines (modified after www.naturlink.pt).

3 Development

Already Charles Darwin was concerned about the development of atolls. To his subsidence theory (DARWIN, 1842) atolls develop from fringing reefs, which are formed around a volcanic island. When a volcanic island is built on the oceanic crust, the lithosphere starts to sag and a wide (tens of kilometers) moat is created around the island. Any atolls in this zone of depression would

subside more rapidly than normal. Because the lithosphere behaves elastically and the subsidence is accompanied by a much less pronounced peripheral bulging, any atolls in this zone of arching would suffer a vertical movement and maybe raise over sea-level (SCOFFIN, 1987).

The fossils identified in the Enewetak Atoll drill cores throughout the entire reef thickness were varieties characteristic of shallow water only (WIENS, 1959). In reefs rocky sub-

strate areas can be found, where many sessile organisms attach themselves, and areas of sand, which require different forms of adaptation, in the same way that there are zones of strong hydrodynamism and others that are calm, where currents are minimal. This great diversity of habitats is one of the reasons for the great diversity of life on the reefs.

A volcanic island begins to subside in the course of time (fig:3). When the island becomes an atoll, gradually all traces of basalt are submerged beneath the sea surface. Through the process of global warming, glacial melting and/or island subsidence, the level of the sea gradually rises (GUOZHONG, 1998; QUINN & MATTHEWS, 1990) relative to the seabed and water begins to overtake the island. SCOTT & ROTONDO (1983) said that it seemed clear that the life cycle of Bikini and Enewetak Atoll was one of subsidence of

volcanic mounds, reef building, emergence during the Miocene, and erosion and growth during the fluctuating sea level of the Pleistocene. Earliest parts of the reef can be found in depths of 4600 feet below the present surface. This can be explained in two different ways. One is that the island foundation was subsided since the first corals started forming. The other is that the sea-level rose (WIENS, 1959).

If the subsidence does not occur very rapidly, the corals will continue to push upward and outward well after the volcanic island is completely submerged (FAGERSTROM, 1987). Under favorable conditions the reefs grow upwards at a pace equal to that of the foundation subsidence, and as the volcanic cone subsides, become separated from the coast by a progressively deepening lagoon. This is called the barrier reef stage (SCOFFIN, 1987).



Figure 3: The standard theory of atoll formation states that a volcanic island forms in deep tropical waters, giving coral polyps a foundation to grow on. In time, the volcano becomes dormant and the island begins to subside (middle). Coral reefs, originally fringing the edges of the island, become a barrier reef outlining the contour of the original coastline. After the original island slips entirely beneath the waves, all that is left is a coral atoll. (modified after the Images by Robert Simmon, NASA GSFC)

QUINN & MATTHEWS (1990) mentioned that the subsidence rate of the Enewetak Atoll is about 39 meters per million years. SCOFFIN (1987) said that the initial rates of subsidence

(first 2 Ma) of mid-ocean ridges are 0.2 mm per year and for mature ocean crust the rate is 0.02 mm per year. Mid-ocean volcanic islands subside as they cool, and the coral reefs that

fringe the shores develop into atolls.

Where the island used to be, assorted detritus and dead coral will pile up on the inside of the coral ring and fill the void. For SCOFFIN (1987) it is possible that the surface 'dish' morphology was enhanced by fresh-water dissolution when the limestone was exposed to the atmosphere during times of lowered sea-level.

Another theory says that atolls build from cone-shaped reefs, on which the corals in the center die off because of insufficient water supply and only the corals at the border continue growing. So the structure becomes cone-shaped.

3.1 Sedimentation

In PURDY & GISCHLER (2005) the authors describe the lateral filling processes of the lagoon by reef-derived sediment in stages and the aggradation and progradation of carbonate sediments.

The lateral filling is a result of the bilateral progradation that results as waves breaking on a beach with the major return flow of water seaward and the minor short-lived advancement of the strand line shore ward. They named the table reefs of the south seas, which are small coral reef areas without a central island or lagoon, as an example for complete infilling. For some atolls it is evident that the filling process is not necessarily dependent on the area and/or depth of the lagoon. Sand production, wind-induced current transport, leeward and windward rates of reef debris production are equal.

The dominant filling factor is the difference in the production of reef perimeter debris. Since the sea-level only rose to its present level of 3 to

6 ky ago, it follows that the present extent of infilling is minimal because prior to that time, the more rapid rate of sea-level rise would have insured that vertical sediment aggradation exceeded lateral accretion by a wide margin (PURDY & GISCHLER, 2005; WOODROOFE ET AL., 1994). Karst development might be expected to have occurred several times on atolls and limestone shelves during periods of low sea-level in the Pleistocene (SCOFFIN, 1987). The carbonate production would be greatest in interglacial (re-advance of the sea) on the elevated rims and prominent knolls. The remains of an ancient atoll as a hill in a limestone area is called a reef knoll.

3.2 Limiting factors

Reefs are limited by depth and do not develop at depths greater than 50–70 meters, most of them being found above 25 meters (GUOZHONG, 1998). This restriction is related to the need for light in coral development for photosynthesis by zooxanthoma. If this factor was limited, photosynthesis would be reduced and with it the capacity of the corals to secrete calcium carbonate. QUINN & MATTHEWS (1990) used for their model a optimal lag depth of 8 meters. The lag depth is the water depth needed to initiate carbonate sedimentation.

Sedimentation, which is related to fresh water drainage, is also considered as a limiting factor in coral development. Most corals do not support high levels of sediments, not only because these block feeding structures, but because they also reduce water luminosity, making photosynthesis difficult. In general, coral

reef development is greater in areas that are subjected to strong hydrodynamism (wave action), because this is a continual source of oxygen and food, without sedimentation. Continual growth on the outer edge (of the reef) by the coral keeps the reef close to the surface, but in its interior, due to conditions of calm water and higher sedimentation, this is not possible, which causes the development of the lagoon. Sedimentation rates that do not keep pace with sea-level change result in the preservation of additional subaerial exposure surfaces by allowing subsequent intermediate sea-level stillstands to be recorded as depositional events.

Salinity is another factor that restricts reef development. Typical corals are intolerant of salinity levels below 25‰ and above 32‰. On the Atlantic coast of South America, reefs are absent, due to the discharge

of fresh water from the Amazon and Orinoco rivers.

Coral exposure is also important. Mucus secretion can prevent dehydration, but only when exposure occurs for a short period, and corals will not survive being out of the water for more than two hours. Mucus is a viscous, slippery substance that consists chiefly of mucin, water, cells, and inorganic salts and is secreted as a protective lubricant coating by cells and glands of the mucous membranes.

When the plate movement eventually carries the atoll into colder water, where the corals cannot survive, the rate of carbonate deposition may become slower and the coral's growth cannot keep up with the island's subsidence (SCOFFIN, 1987). When the coral dies, only a guyot (a flat-topped submerged seamount) remains of the former high volcanic island (see fig: 4).

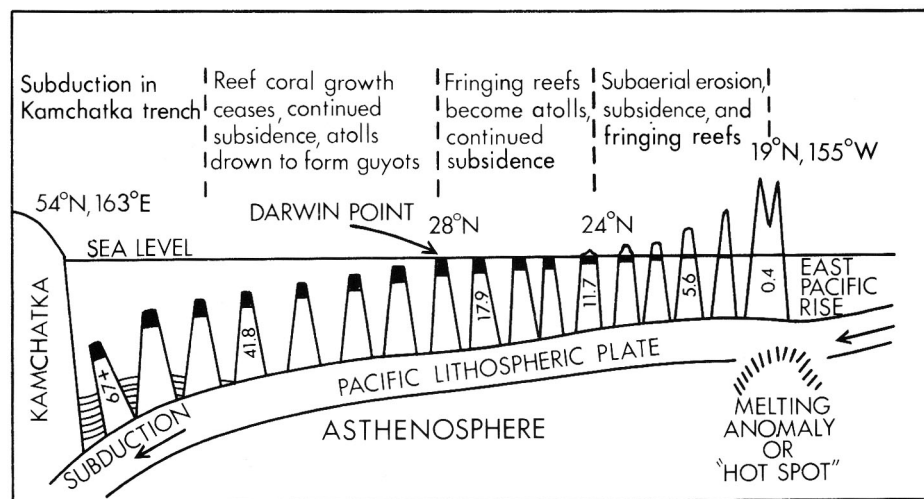


Figure 4: Schematic illustration of the Hawaiian-Emperor chain migrating on the Pacific plate towards the Kamchatka trench. At a latitude of 28°N (the Darwin Point) reef growth slows to a rate that cannot keep up with subsidence, and guyots result (SCOFFIN, 1987).

4 Architecture

WARDLAW ET AL. (1991) describes the Enewetak Atoll (fig. 5) as followed: It is circumscribed by a barrier reef and a chain of small sand islands are bordering an acorn-shaped lagoon. These islands are concentrated on the northeastern, eastern and southern sides of the atoll. The

barrier reef is cut by three passages or channels that lead from the open ocean into the lagoon. But also water spills over the reef into the lagoon because the barrier reef flats are shallow. The reefs of the atoll ring are flat, pavementlike areas, large parts of which, particularly along the seaward margin, may be exposed at times of low tide.

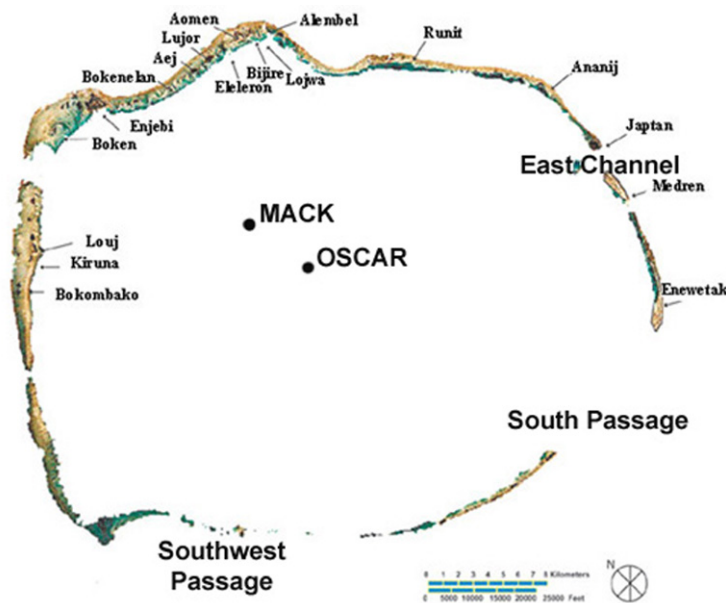


Figure 5: Enewetak Atoll, Republic of the Marshall Islands – with location of main passages and channels, the rim, islands and the coral pinnacles MACK and OSCAR, (modified after <http://eed.llnl.gov/mi/enewetak.php>)

The reefs vary in width from narrow ribbons to broad bulging areas more than a mile (1.6 km) across. The structures form a most effective baffle that robs the incoming waves of much of their destructive power, and at the same time brings a constant supply of refreshing sea water

with oxygen, food, and nutrient salts to wide expanses of the reef (PARKER & PARKER, 1994). Figure 6 shows the effect of water flow around the reef. It points out that the corals on the leeward side of the atoll get less nutrients, grow slower and therefore build a thinner reef.

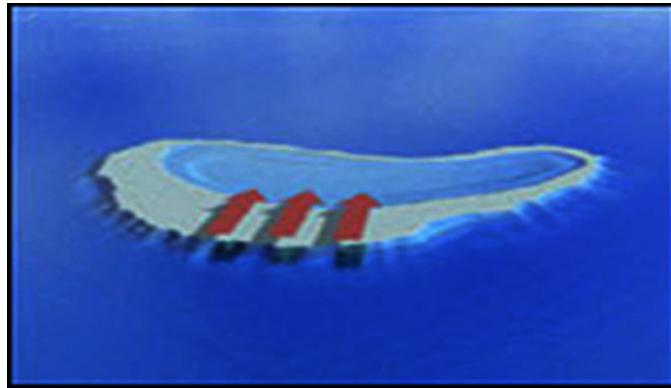


Figure 6: The flow of water around the reefs influencing the growth of atoll. For example, prevailing winds can agitate water on one side of the island, stimulating coral growth. The red arrows in the image indicate the prevailing wind direction. On the lee side of the island the corals do not receive as many nutrients, resulting in slower growth and a thinner reef. (Image by Robert Simmon, NASA GSFC)

EMERY ET AL. (1954) divides the lagoon in four bathymetric features: 1) lagoon terrace, 2) lagoon basin, 3) coral 'knolls' or pinnacle reefs, 4) reef channels or passages.

The rim is formed by the lagoon terrace. The surface of this terrace is pockmarked with scattered, irregular depressions of 3–4 meters and the water depth varies from 15 to 22 meters. The lagoon's water column is isohalin and isotherma and has a salinity of 34.4 parts per thousand. The temperature averages 27 to 29 °C .

The inner slope of the lagoon terrace is less than 1.5 degrees and separates the terrace from the lagoon basin. The floor of the lagoon basin is marked by several thousand coral pinnacle reefs and patch reefs as the terrace and is elliptical, gently undulating. This lagoon basin has a depth of 55 meters. This shows that the Enewetak lagoon is relatively deep in comparison with other Pacific atolls (WIENS, 1962).

The main marine connection on the windward side is the east channel (see fig: 5) and is 1.5 km wide and 55 meters deep. But the subtidal envi-

ronments and biotic communities of the Enewetak lagoon are still poorly known. After COLIN (1986) the subtidal area can be divided into: 1) a lagoon-margin and 2) a deep-lagoon environment.

The benthic samples from the Enewetak Atoll can be subdivided into eight facies: granule, granule-sand, sand-granule, granule-sand-mud, sand, muddy sand, sand-mud, and mud (WARDLAW ET AL., 1991).

5 Discussion

Lot of theories exists for the development of atolls and reefs. For example the Glacial Control Theory or the Murray Theory (more in ENGELN, 1942).

Reef-building corals thrive only where a number of specific environmental conditions are satisfied (ENGELN, 1942). It seemed to be clear that the island-types result primarily from the subsidence of volcanic islands due to the tangential motion of the lithospheric plate (e.g. SCOTT & ROTONDO, 1983). The almost complete absent of atolls north of 28°N

in the Pacific is considered to be due to the combined action of rapid sub-aerial erosion of basalts and this tangential component.

Around the 1950s, bore holes were drilled in the Marshall Islands (Eniwetok atoll), to a depth of 1283 meters, where volcanic rock (olivine basalt) was encountered, thus confirming Darwin's theory, a hundred years later. This theory connects the three types of reef (atoll, barrier and fringe reef) in an evolutionary sequence, but does not explain, however, all the barrier and fringe reefs.

Some of the studies of atolls have been made because of the long-term effects of the radionuclides in the sediments on the food chain and their consequent impact on relocated human populations after nuclear tests (WARDLAW ET AL., 1991 and WARDLAW & HENRY, 1990).

In PAUL S. KENCH (2006) the authors described the effect of tsunamis on the system of atolls as minor. Morphological and sedimentary evidence suggests that although tsunamis do generate both erosional and depositional signatures.

To the actual state of research the structure and development of atolls is already not clear. Alone the fact that nearly every atoll build up in another way because of the different conditions makes the research for a universal model complicate. So a combination of several theories may provide the general answer that is sought for the atoll-reef problem.

References

- Colin, P.L. (1986): Benthic community distribution in the Enewetak Atoll lagoon, Marshall Islnds. *Bulletin of Marine Science*, 38:129–143.
- Darwin, C. (1842): *The structure and Distribution of Coral Reefs*.
- Emery, K.O., Jr., J.I. Tracey and Ladd, H.S. (1954): Geology of Bikini and nearby atolls. *U.S. Geological Survey Professional Paper*, 260-A.
- Engeln, O.D. (1942): *Geomorphology*. The Macmillan Company, New York.
- Fagerstrom, J.A. (1987): The Evolution of Reef Communities. *Palaos*, 3:217–220.
- Guozhong, Wang (1998): Tectonic and monsoonal controls on atolls in the South China Sea. *Reefs and Carbonate Platforms in the Pacific and Indian Oceans*, 25:237–248.
- Parker, S.P. and Parker, S. (1994): *Concise Encyclopedia of Science and Technology*. McGraw-Hill companies, Inc.
- Paul S. Kench, Roger F. McLean, Robert W. Brander Scott G. Smithers Murray R. Ford Kevin E. Pamell Mohamed Aslam (2006): Geological effects of tsunami on mid-ocean atoll islands: The Maledives before and after the Sumatran tsunami. *Geological Society of America*, 34, no.3:177–180.
- Purdy, E.G. and Gischler, E. (2005): The transient nature of the empty bucket model of reef sedimentation. *Sedimentary Geology*, 175:35–47.
- Quinn, T.M. and Matthews, R.K. (1990): Post-Miocene iagenetic and eustatic history of Enewetak Atoll: Model and data comparison. *Geology*, 18:942–945.

- Scoffin, T.P. (1987): *An Introduction to Carbonate Sediments and Rocks*. Chapman & Hall, New York.
- Scott, G.J.A. and Rotondo, G.M. (1983): A model for the development of types of atolls and volcanic islands on the Pacific lithospheric plate. *Atoll Research Bulletin*, 260:1–34.
- Wardlaw, Bruce R. and Henry, Thomas W. (1990): Introduction: Enewetak Atoll and the PEACE Program. *U.S. Geological Survey Professional Paper*, 1513-A:A1–A25.
- Wardlaw, Bruce R., Henry, Thomas W. and Martin, Wayne E. (1991): Sediment Facies of Enewetak Atoll Lagoon. *U.S. Geological Survey Professional Paper*, 1513-B:B1–B30.
- Wiens, H.J. (1959): Atoll development and morphology. *Annals of the Association of American Geographers*, 49:31–54.
- Wiens, H.J. (1962): *Atoll environment and ecology*. Yale University Press, New Haven,.
- Woodroffe, C.D., McLean, R.F. and Wallensky, E. (1994): Geomorphology of the Cocos (Keeling) Islands. *Atoll Research Bulletin*, 402:33.