Geomorphology of Coral Reefs

To study the geomorphology of coral reefs is to examine their physical shape and size. In this chapter we will discuss not only the shape of a typical coral reef, but also the various zones into which it can be divided. We'll also define the terms that are used to describe the various physical aspects of reefs, and will look at the distribution of different types of coral reefs around the world. To better understand the origin of these reefs, we will examine the history of reef development in different areas. Finally we will explain how to go about measuring a coral reef in the field and producing a useable map.

What is a coral reef?

Coral reefs are frequently defined as "wave-resistant biogenic structures." A simpler, but more complete definition would be that a coral reef is an underwater formation built out of calcium carbonate by marine animals and plants, and which is strong enough to stand up to the force of ocean waves. Coral reefs are formed *in-situ* (in place) unlike many geological deposits which are the product of materials which are transported from one place to another and then cemented together.

Structurally a coral reef is primarily composed of a framework made by hermatypic (reef-building) corals and a host of carbonate particles contributed by mollusks, bryozoans, sponges, echinoderms, and foraminifera, all bound together by encrusting coralline algae. The importance of the calcareous algae should not be underestimated as on many reefs corals themselves may make up only about half of the actual structure. As a result coral reefs are now often referred to as "coral-algal" reefs, which is sometimes contracted to "coralgal". Furthermore, all hermatypic corals have internal symbiotic algal known as zooxanthallae. It is thought that the high rates of precipitation of calcium carbonate achieved by hermatypic corals are the result of this symbiosis.

Ecological Requirements of Corals Reefs

Like all plants, both coralline algae and zooxanthallae require enough light for photosynthesis in order to grow and are therefore restricted to the photic zone. In even the clearest waters sunlight decreases rapidly with depth, consequently coral reefs occur in only the top 100 m or so of the ocean. Increased amounts of sediment, plankton or particulate organic matter in the water raise turbidity and will therefore decrease light penetration reducing the depth to which reefs can grow. Because different species of corals and coralline algae have varying light requirements there is a change in species composition with depth. Even within the same species of coral the growth morphology may change with depth in order to better adapt to changing light levels. There are, of course, species of corals which grow at much greater depths than 100 m, but these do not form reefs.

High turbidity not only decreases light penetration to the reef but can also damage reef building organisms. High rates of sedimentation may prove lethal to corals by actually smothering them. Different coral species have varying abilities to resist damage from sediment through the secretion of mucus and by cleansing themselves with cilia, but heavy sedimentation will ultimately destroy a coral reef. Furthermore, once destroyed a reef may never reestablish itself in an area of heavy sedimentation because the coral larvae will only grow on a firm substrate and cannot recolonize the area once it has a soft sediment bottom.

The diversity of corals and coralline algae also decreases with depth on a reef, the number of species decreasing by as much as 50% at 50 m and 95% at 100 m. Furthermore the areal coverage of reef building organisms decreases with depth as does the overall growth rate and rate of precipitation of calcium carbonate. This is not only due to a decrease in light with depth but also to a decrease in water movement (termed "hydraulic energy"), as wave and current motion is both weaker and less frequent at greater depths. This reduction in water motion reduces the supply of plankton carried to corals and the nutrients available for coralline algae.

Corals are also sensitive to salinity and normally grow best in waters between 30^{o}/oo and 40^{o}/oo. Low salinities from coastal run-off and river discharge may damage reefs or prevent reef growth altogether. Even a seasonal drop in salinity due to flooding from a single major storms can cause severe damage to corals. For example, in 1974 a tropical cyclone reduced salinities on the Great Barrier Reef (GBR) near Brisbane, Australia from 32.5^{o}/oo to 24^{o}/oo. The effect of reduced salinity is particularly severe on the shallower parts of a reef because of the concentration of low salinity water at the surface due to density stratification. A 1918 cyclone caused widespread death of corals on the GBR to a depth of 3 meters as a result of fresh water flooding. Such large storms also increase sedimentation, further damaging reefs and limiting their ability to recover.

As mentioned earlier the depth to which reefs can form is mainly limited by light penetration. The upper limit is set by sea level. Corals do not survive exposure to air very well and as a result will dehydrate and die. High levels of wave energy can keep corals wet with the splashes from breaking waves and may permit the growth or some corals and particularly coralline algae up to a meter or so above local sea level. The local water level, of course, regularly fluctuates with the tides. Both the tidal range and the type of tide have an important effect on the upper limit to which reefs can develop and on the types of organisms present on the upper parts of a reef. Reefs in areas with large tidal ranges and especially those with diurnal (daily) tides face the greatest restriction on growth at the surface. On these reefs exposure is greater due to the large tidal range and lasts for a longer period of time due to the extended period of low water characteristic of diurnal tides.

Ultraviolet (UV) radiation is another danger corals must contend with as they grow upward. Sea water effectively filters out UV shielding corals beneath the surface from the harmful effects of the radiation, but corals exposed at low water are not protected. As a result of our damaged ozone layer, levels of UV penetration of the atmosphere are increasing. The UV radiation striking corals at the surface is therefore also increasing. The effects of this heightened UV bombardment on reefs are as yet unknown but the prognosis is not particularly good.

High oxygen concentrations and warm water temperatures are also essential for coral reef formation but these factors change little over the depth range to which coral reefs are restricted by light requirements. Temperature does, however, have a major (often dominant) influence on the geographic distribution of coral reefs as we will see next.

Geographic Distribution of Coral Reefs

Coral reefs are practically synonymous with warm, clear, tropical seas, so it is not surprising that temperature should be the most important factor controlling the global distribution of coral reef ecosystems. In fact, coral reefs do not develop where the water temperatures drops below 18°C and optimum reef growth usually occurs between about 23°C and 27°C. As a result most coral reefs are found within the tropics (23.5°N to 23.5°S latitude). They do, however, occur outside the topics where warm ocean currents extend the proper temperature conditions to higher latitudes, generally along on the western sides of ocean basins. Within the tropics coral reefs are not found where cold currents or upwelling of cold deep water restricts their growth. Their development is also limited by the low salinities and heavy sediment loads of major river systems. For example, in the Atlantic most coral reefs are confined to western parts of the ocean, especially the Caribbean Sea and nearby parts of Florida and the Bahamas (Bermuda at 32°N is an exceptional case.) There is little reef development in the tropics off west Africa due to coastal upwelling of cool water and the cold Guinea Current. In addition, the Niger, Congo and many smaller rivers transport large amounts of sediment which increases the turbidity of coastal waters further limiting coral growth. The development of coral reefs off tropical South America is restricted to north of 5°N latitude by the huge amounts of sediment carried into the Atlantic by the Amazon and Orinoco Rivers.

In the Indian Ocean coral reefs are found in the Red Sea, parts of east Africa and around some tropical oceanic islands. Reefs are not found off Somalia and most of Arabia due to upwelling of cool water. High rates of sedimentation and low salinities restrict the development of reefs off the Ganges and Irrawaddy Rivers in India and off the Malay peninsula.

Coral reefs are well-developed throughout most of the central and western Pacific extending as far north as the Hawaiian Islands and as far south as Rapa in the Austral Islands. The western Pacific also boasts the largest coral reef system on earth, the famous Great Barrier Reef off eastern Australia, which is nearly 2,000 km long. Reef development in the eastern Pacific, however, is limited by the cool California and Humboldt Currents and by coastal upwelling.

As mentioned earlier, water motion is an important factor affecting coral growth. The development of reefs and their particular morphologies in different parts of the world is strongly influenced by the wave direction and energy of each area. This so-called "wave climate" is made up of a combination of the waves produced by prevailing winds (such as Trade Winds), strong seasonal swells from major high latitude storm belts, and the storm waves and surges produced by periodic tropical cyclones (hurricanes and typhoons). For example, in the southern hemisphere waves from the southeast trades and swells from the Antarctic storm belt create the highest energy conditions along the southern coasts of most islands. The western Atlantic, on the other hand receives waves from the northeast trade winds and the northern temperate storm belt. The northern Indian Ocean receives southerly swell from the Antarctic reinforced by waves from the southwest monsoon during the summer but is impacted by waves from the northeast monsoon during the winter. The equatorial regions (between about 10°N and 10°S) of the three major oceans have light, variable wind patterns and are rarely affected by tropical cyclones. These climatic conditions produce relatively low energy reef environments.

Finally, the actual pattern of reef development in a particular area is related to variations in the pattern of settlement of the coral larvae. Local factors such as substrate type and depth affect larval success. Larval dispersal patterns are controlled by ocean circulation which is in turn influenced by global factors such as climate change and the motion of continents and islands resulting from plate tectonics.

Global Variation in Coral Reefs

Coral reefs in the Atlantic, Indian and Pacific Oceans are remarkably similar in their basic structure, habitats, and species interactions, however there are some fundamental differences which have resulted in a general distinction between Caribbean (including Florida and the Bahamas) and Indo-Pacific reefs (stretching from east Africa to western central America). Perhaps the biggest difference in the two areas lies in the diversity of corals. Their are as many as 700 species of corals recognized in the Indo-Pacific region versus only about 60 species in the Caribbean. In fact, only six genera of scleractinian corals and one hydrozoan make up over 90% of the total coral cover in the Caribbean. This lack of diversity is partly made up for by the fact that many of the Caribbean species are capable of adopting a variety of different growth forms depending on water conditions. There are two possible explanations for this lack of diversity on Caribbean reefs. First of all the length of coastline where corals can successfully grow in the Indo-Pacific is much greater than in the Caribbean. The greater area simply allows more room for diversification. Secondly, the Caribbean suffered greater temperature changes during the Pleistocene ice ages than did most of the tropical Pacific. The greater cooling of the Caribbean would have resulted in fewer species of coral surviving into the current post-glacial Holocene epoch.

Many other comparisons can be made between Caribbean and Indo-Pacific coral reefs as well as comparisons between reefs in different parts of the Indo-Pacific region, but first we need to try to categorize types of reefs and begin looking at their respective morphologies.

Types of Coral Reefs

There have been many attempts to categorize or classify coral reefs based on their morphology and/or history of development, but interestingly the scheme first proposed by Charles Darwin in 1842 is still widely used. Darwin's classification recognized three main types of coral reefs: fringing reefs, barrier reefs, and atolls. Because of its wide acceptance by so many coral reef workers we will employee this scheme, though with a few minor modifications. Each category is defined and briefly discussed below:

1. ***fringing reefs*** - These are coral reefs which lie close to shore. They may grow directly out from the shoreline or have a narrow, shallow lagoon between the reef and shore. Fringing reefs are most often found attached to a mainland continental landmass or to high islands[1]. Fringing reefs are found around most Caribbean high islands and are common around high islands in French Polynesia. They are also well-developed in the Red Sea, off east Africa, and around the Seychelles in the Indian Ocean. The reef in Hanauma Bay, Oahu, in the Hawaiian Islands is a classic example of a fringing reef. It extends out from shore in an extinct volcanic crater which was breached by rising sea level. The reef has grown up during the past 7,000 years at the rate of about 3.3 cm. (1.3 in.) per century.

Due to their position close to the mainland or high islands, fringing reefs tend to be those most affected by sedimentation and freshwater runoff. Human activities such as clearing coastal forests or intensive agriculture such as sugar cane have intensified the negative impact on fringing reefs by increasing soil erosion and promoting more rapid runoff and higher sedimentation rates.

In many areas fringing reefs tend to be subjected to lower wave energy because they grow up on a shallow sea floor. Large storm waves may have already lost much of their energy by the time they reach the shallow water where fringing reefs grow. On the other hand, fringing reefs around continents tend to suffer from storm surge produced by tropical cyclones because such surges are most strongly developed over large, shallow continental shelf areas.

2. ***barrier reefs*** - These are reefs which develop at a greater distance from shore and have a more extensive lagoon than fringing reefs. Very large barrier reefs on continental shelves such

[1]The terminology for "high islands" dates back to Captain Cook and means islands of volcanic or continental formation, whereas "low" islands are those made up of material from coral reefs.

as the Great Barrier Reef are often called "shelf barrier reefs" to distinguish them from the barrier reefs surrounding islands such as Bora-Bora in the Society Islands. The lagoons of shelf barrier reefs can be quite extensive. For example, the GBR lies as far as 100 km offshore from mainland Australia in some places. At the other extreme are some barrier reefs in French Polynesia where the lagoons are narrow, the reefs wide, and in places actually grade into fringing reefs. Only two true barrier reefs occur in the Atlantic, the larger off Belize extends some 220 km from near the Mexican border to the Gulf of Honduras and is the largest barrier reef in the northern hemisphere. The smaller barrier reef is found in the southwest Caribbean north of Providencia Island. In the Indian Ocean a barrier reef occurs off the Comoros Islands.

3. ***atolls*** - These are round, oval or horseshoe-shaped reefs which surround a lagoon. The word "atoll" comes from the Maldive Island[2] word "atolu." All together there are over 300 atolls in the Indo-Pacific region, making them the most common type of open ocean reef. They are, however, rare in the Caribbean, where only about 10 atolls have been recognized.

Atolls may be quite large with some as big as 70 km in diameter and have lagoons covering over 2000 km^2. The reefs making up an atoll tend to be most extensively developed in the direction facing the highest wave energy.

4. Other types of reefs - The main reef types discussed above can be recognized throughout the world, but certain areas have also given rise to a few additional names to describe specific types of reefs.

Though having only one major barrier reef and few atolls the Caribbean boasts a fourth type of reef, the "bank" reef. Bank reefs are surrounded by relatively deep water (>20 m), display no linear trend, and have no associated lagoon. They are common on the Mosquito Bank off Central America and on the Yucatan Shelf of Mexico.

The Great Barrier Reef system is made up of numerous smaller reefs, a few of which have been given special names because of their characteristic shapes. Much of the northern GBR is made up of long, narrow reefs called "ribbon reefs." They tend to rise steeply from linear foundations at a depth of at least 50 meters and occur exclusively along the edge of the continental shelf. The longest ribbon reef[3] is more than 35 km long, but the average is 6 to 8 km in length with an average width of only 600 - 800 meters.

Small compact reefs that occur in the lagoons of barrier reefs or atolls are known as "patch reefs." Unfortunately the term "patch" reef has also been used by some workers to describe large, open ocean reefs not shaped like atolls. Many other names such as, knob reef, pinnacle reef, prong reef, plug reef, platform reef, mesa reef, cellular reef and cuspate reef, are found in the literature on coral reefs. Most of these are descriptive, of only local application, and should probably be forgotten. Other names that have been applied to reefs imply a certain history of development and include remnant reef and resorbed reef. It is not advisable to use

[2]This is an appropriate choice as the Maldive Islands are entirely made up of atolls, totaling some 19 in all.

[3]Conveniently called Ribbon Reef.

these terms unless the evolution of a particular reef is thoroughly understood. As we will see the history of reef development can be far from simple.

Reef Development

Not only did Darwin propose a classification of coral reefs based on their morphology but he also suggested these as a series of stages in reef development linking the three types of reefs in a continuous sequence. According to Darwin, the first stage in reef development is the formation of a narrow fringing reef along the shore of an oceanic volcanic island. Subsidence of the island and seaward reef growth would cause the reef to gradually become separated from the island shore by a lagoon eventually leading to the barrier reef stage. If the island continued to sink and the corals continued to grow up and outward the central volcanic island would finally disappear leaving behind a ring-shaped coral reef with a central lagoon - an atoll. Darwin's scheme was not the only hypothesis suggested for the development of different types of coral reefs. In 1910 geologist Reginald Daly proposed that most of the reefs we see today have grown up only during the post-glacial Holocene epoch. He reasoned that during the ice-age cold water would have prevented coral growth and that low sea level would have allowed waves to erode old reefs leaving behind flat planned-off surfaces on which the modern post-glacial reefs have grown. Thus according to Daly, the up and down movement of sea level was the main factor shaping modern reef development and not the sinking of islands as Darwin claimed. In fact, both of their hypotheses are partly correct. The uniform depth of many lagoons is a result of wave erosion during Pleistocene low sea levels and most reef growth visible today has indeed occurred during the Holocene. Darwin on the other hand was correct in that most atolls have developed as a result of the subsidence of volcanic islands. Drilling on numerous atolls has discovered their volcanic basements under hundreds of meters of coral. Darwin did, however, greatly oversimplify. Even the classic fringing reef in Hanauma Bay began forming over a relatively wide band of sea floor growing primarily upward with rising sea level. Only later when it reached the surface did significant seaward reef growth begin. Modern reef development has been strongly influenced by the depth and shape of the ancient pre-Holocene reef surface. The pattern of sea level rise following the retreat of the ice sheets and the net rate of coral reef growth are other critical factors controlling reef formation and evolution. And as previously mentioned, waves, tides, and ocean currents strongly influence reef development.

Recent studies of the evolution of reefs in various areas has given us a pretty good basic idea of the process of reef development. In general the process goes something like this:

juvenile phase - The sea floor is colonized by coral larvae. If larvae settle on a bottom that is exposed to high wave energy, they will be washed away by the next storm, consequently only those that initially colonize areas of low wave activity will be successful in establishing a coral colony. The corals may start off on cobbles, boulder or even shells, but will eventually become their own substrate for growth.

Coral growth continues and additional larvae settle on this now attractive substrate growing up from the shallow sea floor. Upward growth elevates the corals above any unstable bottom sediments and into water with higher light intensity and greater water motion further enhancing growth. Coral colonies are as yet still beneath the zone of high wave energy, consequently the corals are not damaged by breaking waves and little sediment is formed from the reef itself. The actual placement of the coral colonies appears more or less random at this point, being related to the vagaries of larval transport and settlement as affected by neighboring ocean currents and local water turbulence. However, the overall site of reef development is strongly controlled by the shape of the substrate available for colonization, therefore the pre-Holocene foundation will largely determine the initial shape of the reef. As long as the reef has not reached the surface or if sea level rises faster than the reef can grow then much of the reef growth will be in an upward direction and will enhance the shape of the preexisting reef platform.

mature phase - The colonies begin to grow together and approach the surface. If sea level stabilizes or the reef finally catches up and reaches the surface, coral growth becomes directed horizontally. The living coral reef front may begin to migrate seaward. Reef flats begin to develop to leeward, smoothing over the preexisting topography. Now exposed to the full power of waves, corals are broken and fragmented during storms producing carbonate reef sediments. These sediments are washed toward shore by waves but restricted in moving back seaward by the reef itself, hence sediments begin accumulating in a lagoon thereby restricting coral growth toward shore. There is now a division between living coral seaward and sand in the leeward direction.

The lagoon water itself may also have a negative impact on reef growth. The waters in shallow lagoons are more likely to suffer from extremes in temperature, salinity, and turbidity than the ocean water seaward of the reef. Prolonged contact with such lagoon waters can prove lethal to corals. Some researchers have referred to reefs where growth is restricted by harmful lagoon water or sedimentation as being "shot in the back by their own lagoons."

Carbonate sediments produced by the reef continue to build up behind the reef until they reach such a level that they begin to spill out between passes or smaller gaps in the reef forming fans of reef-derived sediment sloping down into deep water.

As noted earlier, the extent of lagoon development is a major feature used in reef classification. The size, shape and extent of a lagoon is in turn strongly influenced by the nature of its pre-Holocene reef foundation.

senile or regressive phase - Some reef workers recognize a senile phase which may occur if sea level stops rising or drops. Enhanced sediment production results in filling of the lagoon. Outer areas of the reef acquire a cover of reef rubble and become dominated by algae. As the lagoon floor approaches sea level sediments will be redistributed and on atolls may advance down-current burying the leeward reefs.

From the discussion above it is obvious that the exact nature of sea level rise or fall is one of the most important factors controlling reef development. Whether sea level rises, falls, or remains stable in any particular location is determined by local tectonism (rising or sinking of the land) and eustatic changes in sea level (global changes related to the volume of water in the oceans). At the height of the last ice-age, around 18,000 years ago, sea level was as much as 90 meters lower than at present. All reefs were severely impacted by this lower sea level and living corals would have only been found near the edge of the continental shelf or on the steep sides of volcanic islands and atolls. As mentioned earlier cooling of ocean water would have further restricted coral growth, though studies indicate that the cooling effect was much less uniform than the effect of sea level lowering. Another effect of glaciation, one with different regional impacts on coral reefs, was caused by cold, sediment-laden water flowing off the melting fronts of ice sheets and ultimately into the sea. Fringing reefs on the continental shelf off Florida were particularly affected by this cold melt water. Mountain glaciers even formed on very large high islands, such as the Island of Hawaii, where melt water would have had a strong negative impact on ice-age reef growth.

With the waning of the ice-age, sea level began to rise. The affect of rising sea level also varied from place to place because of differences in local and regional tectonics, and variations in the topography of the ocean surface related to wind patterns and ocean currents. In the Caribbean, north Pacific and northern Indian Oceans we see sea level rising rapidly until between 5,000 and 6,000 years ago. Since then sea level appears to have continued to rise more slowly until the present. In the Marshall, Caroline and Phoenix Islands and in most of the southern Pacific and Indian Ocean, modern sea level may have been attained as early as 6,000 years ago. Since then sea levels between 1 and 4 meters higher than at present may have occurred followed by a gradual lowering to present sea level.

The impact of changing sea level on coral reefs has lead some workers to divide reefs into those that can "catch-up", or "keep-up", with changing sea level, or those that "give-up" and die. To further complicate the effect of eustatic sea level changes, tectonism related to plate tectonics causes islands moving away from midocean ridges or hot spots to subside, whereas island arcs adjacent to subduction zones may experience uplift and still other islands will subside as they are subducted into trenches. Reef growth is further influenced by plate tectonics as some islands like Midway (28°N) are being carried out of reef forming areas and others such as Pitcairn (24°S) are moving into reef seas as a result of plate motion.

In summary, the main factors affecting the development of modern reefs in any particular area are the shape of the pre-Holocene reef platform and the nature of sea level change. Add to these the wave-climate and we have named the main factors which determine the internal morphology of a coral reef.

Intra-reef Morphology

As coral reefs grow upward in the water column toward sea level they go from a relatively stable deeper environment into a shallow zone with strong daily and seasonal environmental changes and great variability in the energy of water motion. Not only does wave energy tend to increase from deep to shallow water, but also increases going from leeward to windward across a reef, and from less exposed to more exposed reef edges depending on the pattern of refracted waves. These fluctuations in the environment, especially in water motion have created a series of horizontal and to a lesser extent vertical zones into which a coral reef may be divided. Though numerous schemes exist for subdividing coral reefs into different zones, we will apply a four-part division for our discussion of intra-reef morphology. These zones are depicted in Figure 1(below) as they would occur on a typical atoll cross section. Going from windward to leeward they are: the windward reef front, the reef flat, the lagoon zone, and the leeward margin. By definition fringing reefs lack a lagoon zone and the leeward margin zone is generally only applicable to oceanic atolls, consequently not all coral reefs throughout the world possess all these zones. The clearest zonations tend to be found on those reefs receiving the highest wave energies.