CHAPTER 13

CORAL REEFS; AN INTRODUCTION

13. 1. INTRODUCTION

13. 1. 1. Introduction

From a spacecraft entering earth's atmosphere, the first visible signs of earthly life would be a coral reef. Yet living on a tropical island, it is easy to take our coral reefs for granted. We walk on coral skeletons every day. We may even curse the stones we trip over.

However, in other parts of the world these stones are celebrated as having among the rarest and most striking beauty among life's natural products.

Coral reefs and islands are the piled-up remains of billions of tiny creatures. These parts have been cemented together by other living things over the course of tens of millions of years.

These sturdy structures hide their true nature. They are products of minute and fragile organisms—the reef-building corals and stone-producing algae.

Many of these organisms are not clearly visible to the naked eye. Anyone who has taken along a magnifying glass when snorkeling on a coral reef has certainly been startled and fascinated by the beauty and intricacy of the reef's tiny realms.

In this chapter and the next, we will explore the reef and its fascinating denizens. We will examine the structure of coral reefs and the organisms and processes that have built them. In the next chapter, we will look more closely at the reef as a community. Our final coral reef chapter will focus on the problems facing coral reefs, and the interactions humans have with reefs.

Minute and fragile organisms such as these coral polyps build the coral reefs - the largest natural structures on earth.

13. 1. 2. Appreciating Our Reefs' Importance

Fortunately, here in the Mariana Islands we live literally beside the reef. Many scientists who have devoted their lives to the study of coral reefs live in large cities far from any reef. Their visits are usually brief trips that cost them thousands of dollars.

On the other hand, we are in a far better situation for the study of coral reefs. We can visit the reef daily after school or on weekends. (When you visit the reef, try to make it a point not to harm the corals.)

When you visit the reef, try to make it a point not to harm the corals.

Human activities harm corals and the other organisms of the reef. Human actions can even affect the geology of reefs and reef islands. Micronesian cultures have grown up around coral reefs; Micronesians depend upon the reef for food and for a wide variety of implements and raw materials. Yet traditional Micronesian cultures probably had much less impact on reefs than do our modern cultures.

13. 1. 3. The International Year of the Coral Reef

In the late 20th Century, coral reefs all over the world are experiencing an emergency of potentially grave consequences.

A large number of scientists and interested persons around the world have recognized this. They elected to celebrate 1997 as the "International Year of the Reef." The Northern Mariana Islands also celebrated the Pacific Year of the Coral Reef.

13. 2. WHAT ARE CORAL REEFS?

Before we start our study of coral reefs, we will quote one of the great coral biologists of the 20th Century, John Wells, concerning the nature of coral reefs.

13. 2. 1. Quoting John Wells

"Coral reefs have happened because of a long chain of events. These events have taken place over millions of years in the warm shallow marine waters of the tropics.

"The warmth, light and food in the shallow waters of places like Micronesia provide a perfect environment for reef building. These conditions support the two kinds of organisms that have been building up coral reefs during this long history. The *corals*, which are animals, and *calcareous algae* have built most of the reefs.

Composed of the skeletons of millions or corals, reefs grow very slowly.

"These organisms take in seawater containing food and calcium, and produce from them **Calcium Carbonate**. They attach this to the substrate, the bottom.

"This activity forms a framework, on, in, and around which sediments collect. These sediments come from the organic and physical breakdown of organisms and of the frame itself.

"The sediments mass together in a volume a lot bigger than the frame. The geological history of coral reefs is the story of this biologically-produced calcium carbonate. It interlocks and encrusts on the frame with other material produced by other organisms. These sediments also collect there."

13. 2. 2. Old, Slow and Shallow Growing Structures

This brief quotation will help us draw certain initial observations about coral reefs.

First, we note that it has taken coral reefs millions of years to grow into their present form. Second, coral reefs have only grown in the shallow, marine waters of the tropics, where the environment is ideal for the main coral reef builders: corals and calcareous algae. We are reminded that these organisms take up food and calcium, and produce the stone of the reef, that is calcium carbonate. Finally, we also learn that this stone forms the bulk of the reef, together with other sediments. From this initial vantage point, let us begin our more detailed examination of the coral reef.

Calcareous algae (such as the Halimeda macroloba shown behind the shrimp) play a major role in building the reef.

13. 2. 3. Defining a "Coral Reef"

Coral reefs are geological structures built by corals, calcareous algae, and other organisms. They are complex and intricate structures made up of many interconnected and mutually dependent parts. They are dynamically changing day by day, tide by tide, wave by wave.

A coral reef is a community of thousands of species. However, it is so tightly integrated in function and structure, it might easily be taken to be a **super-organism**. Each coral reef is different from all others; yet all reefs bear certain distinct, underlying similarities or identifying marks. What are these marks?

To arrive at a working definition of a coral reef, let us consider several important aspects of reefs that may enter into our definition. But first, let's start with a very basic definition. We will then build upon this foundation.

As defined by Richard H. Randall, "[A coral reef is] a wave resistant feature built mainly of reef-building corals and red calcareous algae."

13. 3. THE DEFINING FEATURES OF CORAL REEFS

When you think of a coral reef, what do you think about? Most of us would think of the same thing, whether we are from Micronesia, the Caribbean, or somewhere else. What are the features common to all coral reefs?

13. 3. 1. Reefs are Shallow Water Outcrops, Usually Navigational Hazards

The word "reef" originally referred to a navigational hazard. The Newbury House Online Dictionary, for example, defines a reef as "a long bar, made of sand, or coral." Many people think of a reef as an underwater rock structure that is near the surface of the ocean. Sailors think of reefs as hazards to navigation.

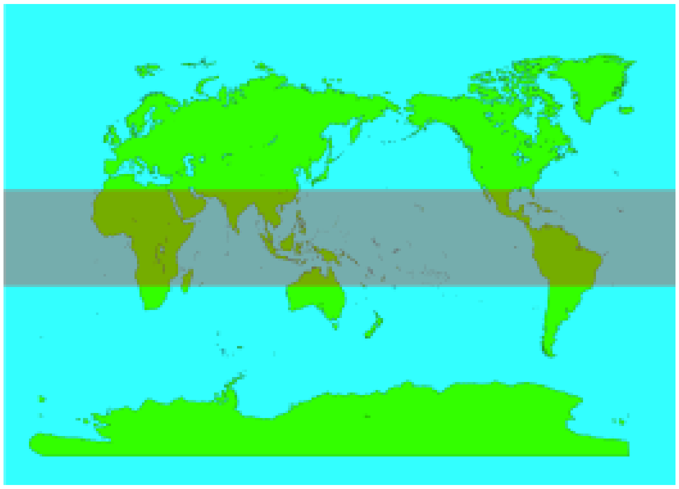
Reefs can pose a navigational hazard.

13. 3. 2. Coral Reefs are Biologically Produced

The name "coral reef" implies a structure that is produced by corals. This is at least partly true; however, **coralline algae** also play important roles in building the reef. The name "coral" reef is thus, to some extent, a misnomer. However, since much of the initial work of reef building is done by corals, we let it stand. Besides, corals are among the most important organisms on the reef.

Both corals and coralline algae produce calcium carbonate. So do many other coral reef organisms, including a number of kinds of algae, mollusks, microscopic protozoans called foraminifera, and echinoderms.

All of these contribute some amount of stony material to the reef. However, it is mainly the reef corals and coralline algae that build reefs. These organisms form a very thin living veneer. This layer is only about one millimeter thick on the very surface of the reef rock.



Coral reefs are found only in the tropics.

13. 3. 3. Coral Reefs are Wave-Resistant Structures, Lying at or Near the Surface of the Ocean

The richest growth and most of the dynamic activity of coral reefs is near the surface. The organisms that form coral reefs can only grow properly in the well-lit, upper 100 meters of the ocean. Waves seem to be beneficial to most corals and coralline algae, which grow very actively in wave-washed waters.

Coral reefs are found in the open ocean where water is clean and transparent. Coral reefs prefer these oceanic environments which offer clear, sediment-free water. Normal oceanic salinities are essential for the growth of corals. Sediments such as sand and silt are detrimental to the growth of corals. In addition, corals will die if they are exposed to air.

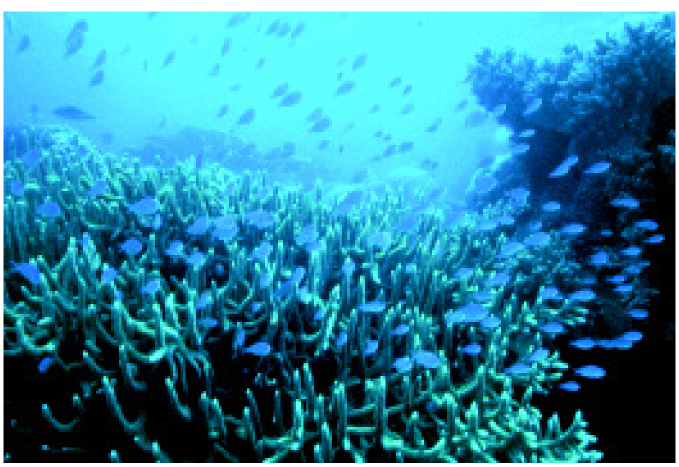
Strong wave motion helps keep sediment off the corals. The wave action also means more oxygen is dissolved in the water. Since corals exchange oxygen and carbon dioxide across their surfaces, active water movement means improved respiration.

Corals cannot grow in water that is diluted very much from normal oceanic water. They cannot live out of water and will immediately die if exposed to air by, for example, an anomalously low tide. Thus, the processes of reef building are restricted to a very thin layer at the surface.

13. 3. 4. Coral Reefs are Found Only in the Tropics

Coral reefs are only found in tropical environments. However, reef corals cannot tolerate temperatures very much higher than 30° Centigrade. A little bit warmer and they will die.

If the water is a little cooler, adult corals can survive; however, they cannot reproduce at temperatures less than about 20° Centigrade.



Reefs require clear water of good quality.

13. 3. 5. Coral Reefs are Complex Systems

Coral reefs are extremely complex ecosystems with thousands of species. Many specific relationships and specialized life styles make for a complex tapestry of inter-dependencies and associations. Like a tapestry, it is hard to tell how other parts of the system might be affected should one thread be snipped.

13. 4. WHERE ARE CORAL REEFS FOUND?

13. 4. 1. Introduction

As stated, coral reefs are produced by living organisms—corals and calcareous algae. Reefs can only develop where these organisms have become established and where they are able to flourish.

Reefs are *not* found where the conditions are unfavorable for these organisms. Neither are they found in places to which corals have not been able to disperse (spread).

We can consider the distribution of organisms globally and locally. In both cases, coral reefs grow only where they can tolerate the conditions. If an environment changes to become unfavorable for the growth of corals, coral reefs will not continue to grow in that environment.

Coral reefs are located in the tropics, in shallow water, where the water is clear and of good quality.

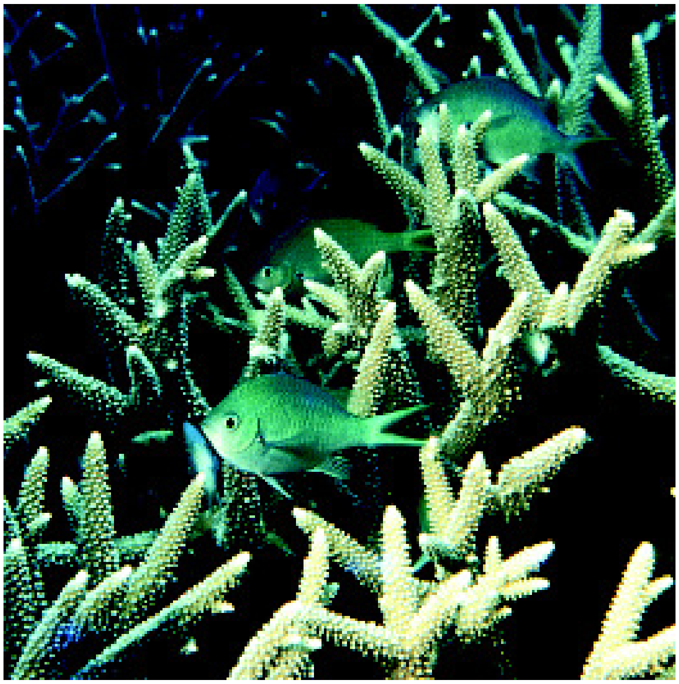
13. 4. 2. Where do Corals Grow Best?

Corals are fussy about their living conditions. A certain species may thrive in an environment. Another environment close to, and very similar to the first, may be intolerable to the same species of coral.

Because of the sensitivity of corals to environmental conditions, coral reefs are vulnerable to human activities which may, even only slightly, change the conditions of reefs.

A given species of coral is usually found within a restricted range of environmental conditions. Each coral has its own place on the reef.

Different zones on the reef are identified by dominant species of corals just as zones on islands are known by a specific, dominant species of plant. Biologists and native Micronesians name different island zones after plants. Micronesians sometimes name specific zones on the reef after certain corals.



Branching corals are often found on the outer reef platform...

Similar patterns seem to be found on reefs everywhere. *Porites spp.* are dominant in nearshore, shallow water environments. On reefs close to mangrove or sea grass environments, *Porites* species may be the dominant or only corals. One may hear mention of a "*Porites* zone."

Thickets of branching *Acropora* species of corals are often found on the outer reef platform inside the reef margin.

Brain corals and other massive corals are generally found in their own places, usually over the edge of the reef, where water is somewhat deeper, such as on the forereef or reef slope.

So-called "foliose corals", with leafy skeletons, are usually found in quiet waters on the sides of drop-offs or on the underside of overhangs where light is diminished.

13. 4. 3. Corals are Adapted for Certain Conditions

Corals are adapted to live where they do. We have mentioned the *Porites* species of corals which are often found close to the shore. Species of *Porites* are also found close to mangroves.

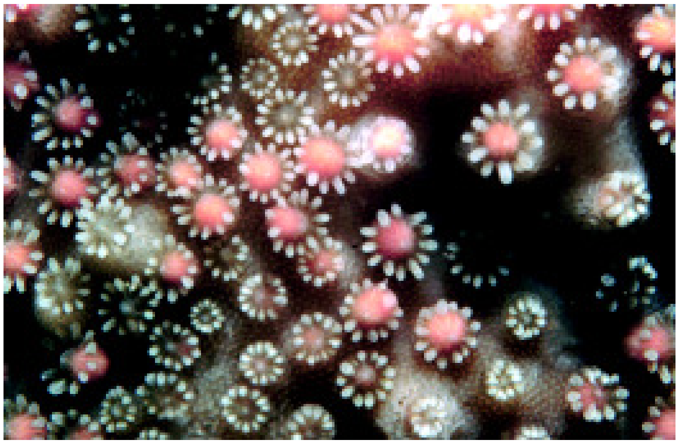
...while Porites species are often found close to the shore.

Because of the large amount of suspended sediments, most corals cannot tolerate this environment. *Porites spp.*, however, are among the most sediment-tolerant of corals.

Adaptation to specific environments helps explain the zonation patterns indicated above.

13. 4. 4. How do Corals Select the Places They Live?

Adults of most corals are cemented to the reef; yet they have nothing to do with selecting their home environments. Larvae of corals, on the other hand, are free-swimming, motile members of the plankton community. It is the young coral larvae that explore the reef and select the best place to settle down.



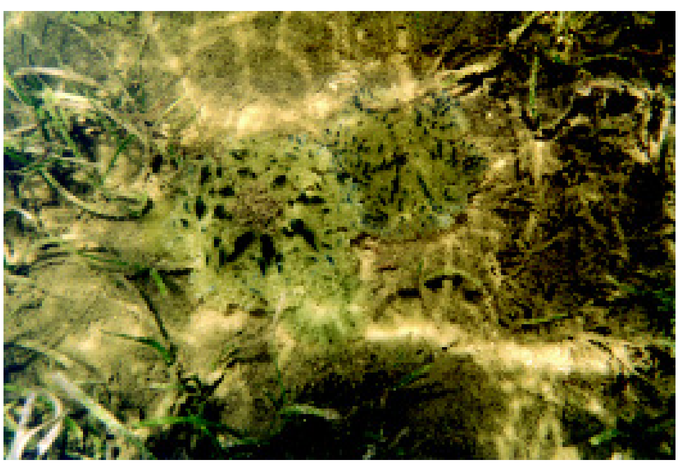
The environmental factors faced by the adult, such as this one spawning here, are determined by the larva's choice of a settling place.

We may imagine at least two possible explanations for the clustering of corals in certain types of environments. Either (1) the larvae is choosing the correct environment for the adult; or (2) the larvae settle in many environments, but only those settling in the best environment survive.

Larvae which settle in the wrong environment do not survive to adulthood so corals are not found in these “wrong environments.” Can you imagine any other explanation? Can both be correct?

The environmental factors faced by the adult are determined by the larva's choice of a settling place. Each larva tests and explores the environment, seeking an ideal situation, largely by chemical cues although other factors are involved. Once the larva has made its decision and has settled, it develops into a polyp. The polyp begins to develop the calcium carbonate skeleton that will later form the colony.

Larvae of the upside-down jellyfish, *Cassiopeia spp.*, have been found to use a combination of cues in determining where to settle initially. The larvae ordinarily are negatively **phototactic** (abhor light) and positively **geotactic** (attracted toward gravity). When the larva has drifted under an overhanging ledge, it is shaded from the sunlight, and shows, under this unique condition, a negatively geotactic response (fleeing from gravity). Thus, the larva almost automatically winds up under an overhang, where the developing medusae are found.



Larvae of the Upside-Down Jellyfish, Cassiopeia sp., have been found to use a combination of cues in determining where to settle initially.

Coral polyps cannot ordinarily decide to move out once the larva has committed to a specific site. However, in some species of corals, the young, developing polyp is able to “bail out” if the new environment is unsuitable. It then returns to a swimming mode of existence in the **water column**. The water column is the water above the bottom where plankton can swim freely. Once there, it searches for another place to set up housekeeping.

Even though the larva determines the site in which the adult colony will live, the environment will also exhibit an effect. The environment selects which of them will survive and which will thrive: if the larva makes a poor choice, the adult will probably not survive.

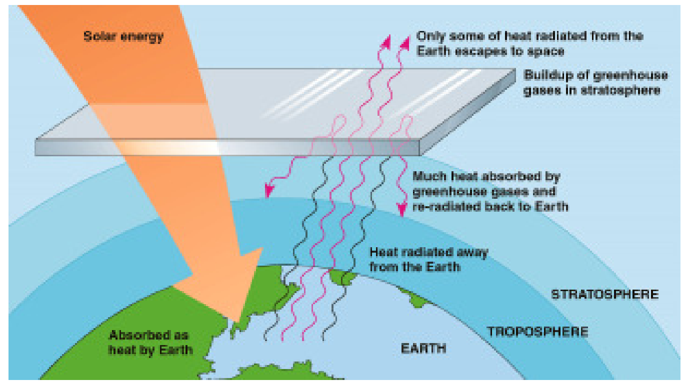
13. 4. 5. Temperature

Corals can live in water colder than 20° Centigrade (68° Fahrenheit). However, coral reefs are restricted to tropical marine environments where the average annual temperature is 20° Centigrade or warmer. This is because corals cannot reproduce in colder temperatures.

If the average temperature is 20° C, then some time during the year the sea water will be warm enough for corals to reproduce successfully.

Saipan's mean sea temperature is about 26-27° Centigrade (80° Fahrenheit). This is well within the range preferred by reef corals. Our Northern Mariana Islands may have at least 200 species of reef corals, and thousands of species of other reef organisms.

Many scientists believe that sea temperatures are now rising as a result of the **greenhouse effect**. The greenhouse effect is due to increased levels of certain gases in the atmosphere. The two most common gases that cause this effect are **carbon dioxide** (**CO_2**) and **methane** (**CH_4**).



The Greenhouse Effect is due to increased levels of certain gases in the atmosphere.

These gases are called greenhouse gases. They trap heat in the atmosphere. This trapped heat ultimately leads to the rise in sea temperatures. The predicted rise in sea temperatures would have two major effects on coral reefs.

The first is a rise in the sea level by several decimeters. This rise would have major effects on coral reefs and human populations in low-lying areas. A rise in sea level would affect numerous communities in Micronesia.

Another major effect would be widespread death of corals, and hence of coral reefs. Corals are not tolerant of excessively warm water. Isolated occurrences of this effect, which have been observed in many reef locales over the past decade, are called **bleaching events**.

13. 5. FUNCTIONS OF CORAL REEFS

Why do coral reefs matter? After all, they are navigational hazards! Well, coral reefs do matter, and if the coral reefs of the Mariana Islands became unhealthy due to mistreatment, we and our islands would suffer in several ways.

First, coral reefs protect the coastline from erosion. Healthy reefs are even able to enhance the coastline, creating natural harbors. Coral reefs produce land. Imagine Saipan without the flatlands of the West Coast: all this land was produced by corals. Managaha is a reef-formed island in Saipan Lagoon. The numerous atolls of the Caroline Islands were all produced exclusively by coral reefs. Coral reefs also provide all the materials for our white sand at the beach.

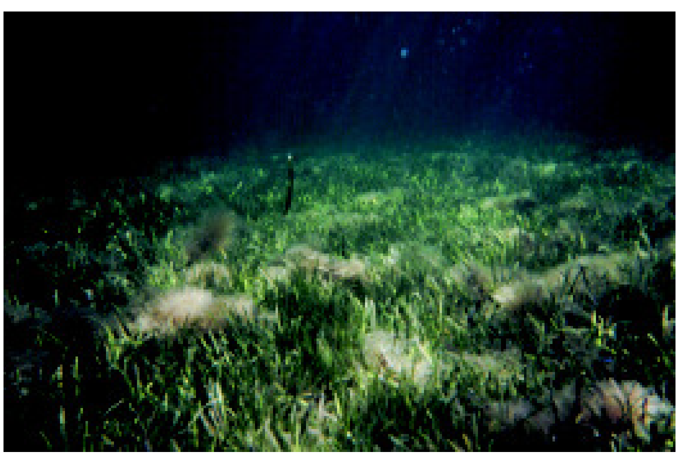

Coral reefs are productive biological communities.

Coral reefs serve as a breakwater against large waves produced by typhoons and other storms. Even very large waves expend most of their energy on the reef and do not harm the beach.

Coral reefs are productive biological communities. They are a food chain with plants using solar energy to produce food that is cycled through the system. It all leads to food for us, too.

Coral reefs are also beautiful. The health of coral reefs is vital to any hopes for a viable tourism industry in the CNMI. The coral reef serves many traditional uses as well, perhaps even providing medicines. Today, scientists hope that coral reef organisms may provide novel chemical substances that may be utilized as drugs for cancer or AIDS, as well as sun-blockers. Coral rock has even been used as a medical bone replacement.

Mud and silt are trapped by mangrove swamps.



Seagrass also serves as a sediment trap.

13. 6. MUTUAL INTERACTIONS BETWEEN REEFS AND OTHER ECOSYSTEMS

13. 6. 1. Mangrove Swamps

Mangrove swamps are very important to coral reefs. Mud and silt from storm runoff are trapped by the mangrove swamp, which stabilizes sediments from terrestrial origins into soil. This process serves to protect the reef from these sediments which are deadly to the corals.

Mangroves may also scrub nutrients from runoff. Mangrove swamps, where they exist, serve a filtering function. Coral reefs, in turn, protect mangroves from strong wave action that would be harmful to them.

13. 6. 2. Seagrass Beds

Seagrasses also serve as sediment traps. Sea grasses serve as baffles and screens, causing the smallest sizes of sediments—silts, clays, and fine sand—to settle from the water column. These are the sediments that would be the most destructive to the reefs.

13. 7. THE ORIGIN AND HISTORY OF CORAL REEFS

Europeans who first visited the tropics brought descriptions home of corals, atolls, and reef islands. They described the wealth and diversity of life associated with them.

Later, scientists traveled to the warm oceans and directly observed coral reefs and atolls. They speculated about their origins. Their reports aroused much interest, and a controversy raged for decades concerning the possible origins and history of coral reefs.

Scientists wondered about the following questions:

Why are atolls shaped as circular reefs surrounding lagoons, with scattered reef islands?

Why are atolls virtually all found exactly at sea level? And, of course,

What is the history and origin of coral reefs?

Visitors to the tropics continued to ask these questions and others. Many published their opinions on the origin of coral reefs. One such visitor was Charles Darwin. Darwin speculated on the origin of coral reefs and atolls in the book, *The Structure and Distribution of Coral Reefs*.

13. 8. ORIGIN OF CORAL REEFS AND ATOLLS

13. 8. 1. Introduction

European explorers visited dozens of atolls and coral reefs and noted similarities in their structures. These odd shaped islands were always right at the level of the ocean’s surface. All were produced by living organisms. Several theories appeared concerning the origin of atolls.

Scientists noted the presence of coral reefs in regions where volcanoes are common. Some scientists suggested that corals settled on the rims of volcanoes that had just come up to the surface of the ocean, and projected no higher.

Other scientists disagreed with this idea. It seemed impossible that hundreds of volcanoes would stop their upward growth precisely at the ocean's surface. These scientists speculated that corals settled on the bottom of the ocean and grew upward toward the surface.

13. 8. 2. Coral Reefs Don't Grow in Deep Water

There was one problem with this second idea: reef corals do not grow in deep water. During his voyage, Charles Darwin spent some time exploring reefs.

His explorations were assisted by a sounding line, with a "bell-shaped lead" weight. A waxy substance, tallow, was packed into the concavity on the bottom of the bell-shaped weight. Sand and small pieces of rock stuck to this tallow, and were cut off at each sounding, to be studied by Darwin. His results indicated a trend of increasing sand cover with depth.

Reef corals do not flourish at depths greater than 20 or 30 fathoms. Other organisms, such as these anenomes and crabs inhabit the depths.

13. 8. 3. Results of Darwin's Soundings

Darwin's impression during this experiment was of a gradual change. He described that change as "from a field of clean coral to a smooth sandy bottom." He concluded, "In ordinary cases, reef building [polyps] do not flourish at greater depths than between 20 and 30 fathoms." [Ed. note: one **fathom** equals 6 feet]

After observation and experimentation, Darwin reasoned that coral reefs do not grow upward from the deepest ocean. They must grow upward on sinking platforms.

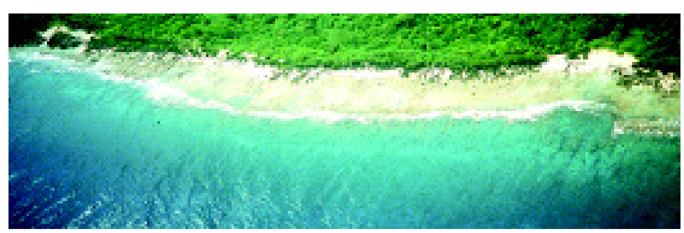
In arriving at this conclusion, one of the lines of reasoning followed by Darwin involved his division of coral reefs into three basic types: **1) fringing reefs**, **2) barrier reefs**, and **3) atolls**. He saw in these three types of reefs, which he observed to be similar wherever he saw them, a continuum. In these three steps, he envisioned a continuum in a dynamic process of reef building.

13. 9. TYPES OF CORAL REEFS

13. 9. 1. Introduction

Darwin was an astute observer. During his visits to coral reefs, he made certain simple observations that enabled him to speculate upon the origin of coral reefs. This is the question that drove scientists of Darwin's day to study reefs: "What are the three basic types of reefs, and what can be inferred from these three in regards to a sequence of the genesis of reefs?"

We will consider each of these types of reefs briefly, in turn. We will describe the physical structure of each. These three types represent a sequence, or progression.



A fringing reef on Saipan

13. 9. 2. Fringing Reef

The fringing reef is, as its name suggests, a reef that is a fringe on the flanks (sides) of an island. The Northern Mariana Islands have many fringing reefs surrounding their flanks.

Darwin reasoned that a fringing reef was the first, or youngest stage in the atoll building sequence.

As we now understand, the larvae of corals can travel thousands of miles across the ocean. They are towed by the currents wherever they may go. Should a few of these larvae encounter a newly formed island—such as a volcano that had only just broken the surface—new corals would begin to grow.

Saipan's barrier reef is a reef separated from land by a lagoon.

Over the course of tens of thousands, or millions of years, an assemblage of corals and other organisms might accumulate in the same way. This leads to the development of a small reef. Darwin reasoned that this new reef would have the form of a fringing reef.

A fringing reef may have a **moat** (a short span of shallow to deep water), but it does not usually have a **lagoon** (a much longer span of shallow to deep water).

Darwin imagined that if an island *subsided* slowly enough, the fringing reef would grow slowly and continuously upward. As the island sunk and the reef grew straight upward, the breadth of the fringing reef would increase. Eventually, a barrier reef might form.

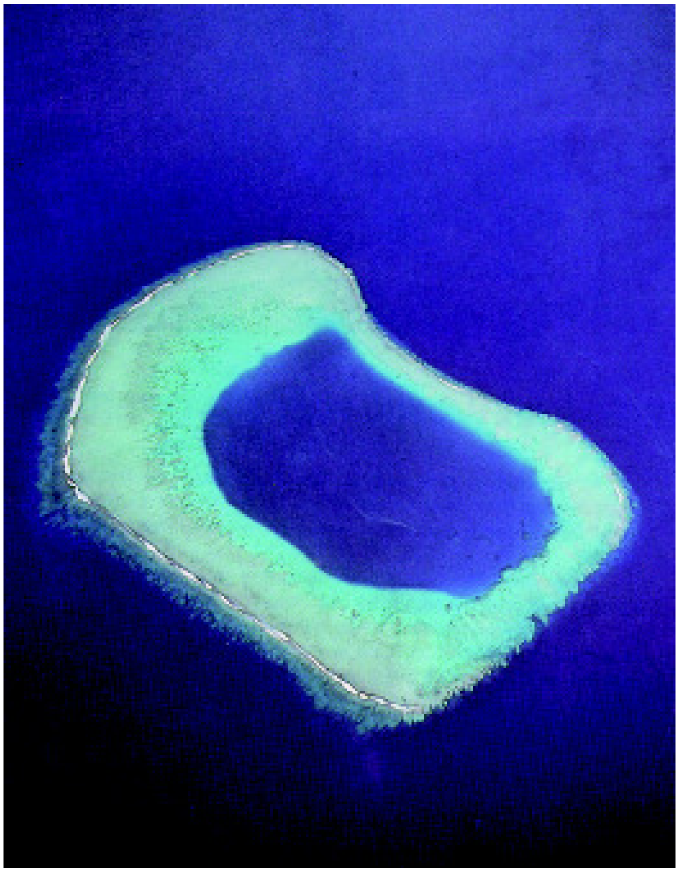
13. 9. 3. Barrier Reefs

A barrier reef is a reef separated from land by a lagoon. Reefs adjacent to the Saipan Lagoon are examples of barrier reefs.

Barrier reefs look a lot like wide fringing reefs with lagoons.

Barrier reefs suggested to Darwin an intermediate stage between a fringing reef and an atoll. As an island continued to subside at a rate slow enough to allow the reef to keep pace with it, the most active growth would take place at the sea's edge. The inner portions would not be able to keep up, and a lagoon would form. It would be carpeted with the sand being transported across the reef by currents and waves.

Tanapag Lagoon is surrounded by a sequence from a simple fringing reef in the north to a well-developed barrier reef in the south.



Atolls are circular reefs with sunken islands within.

13. 9. 4. Atolls

Atolls are the peculiar, circular reefs with islands. Micronesia is renowned for this type of reef. Atolls are now understood as the oldest stage of island coral reef development.

13. 9. 5. Submerged Atolls

Some atolls are submerged, apparently because the corals have not kept up with the subsidence. An example of a partly submerged atoll is the Namwonwuito group. It is northwest of Chuuk Lagoon. It is not known what forces have prevented some of the reefs of this atoll from growing upward normally.

Such a reef serves as a model of what will happen when a coral has been killed and is unable to maintain its normal function. It is also an example of what will happen to atolls if and when sea level rise exceeds the normal rate of upward reef growth.

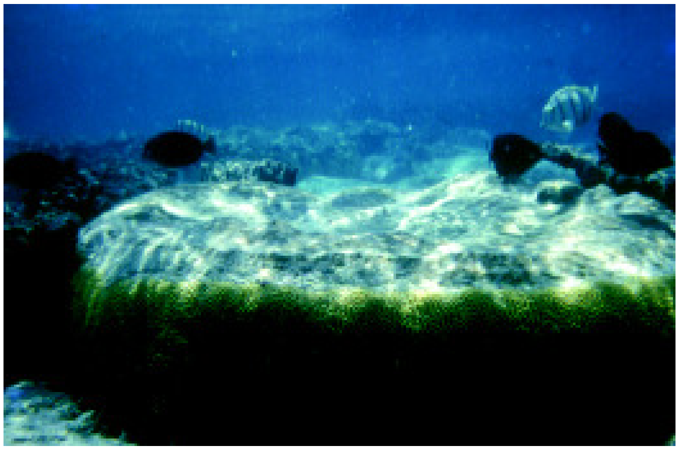
13. 9. 6. Coral Islands

Coral islands are oceanic islands in which there is no lagoon. Typically a coral island is surrounded by a fringing reef. Examples in Micronesia include Nama, Kuria, and Fais.

13. 9. 7. Lagoon Reefs (Patch Reefs)

Another important type of reef is the patch reef. Patch reefs are reefs, often in lagoons, that stand off by themselves.

Saipan Lagoon has several patch reefs just off of Garapan and Tanapag. Tinian has the beautiful Tatchonya Patch Reef, and until recently, Rota had a fantastic patch reef known as the "Coral Gardens". (In 1996, a section of this reef was blown up when W.W.II-era depth charges found in the reef area were detonated by the US Navy as a safety measure at the request of the CNMI Government.)



Patch reefs stand by themselves.

13. 10. REEF ZONATION

13. 10. 1. Introduction

One of the most conspicuous aspects of coral reefs is the presence of distinct physiographic and biologic zones. These zones run parallel with the reef margin. They are maintained by the processes of erosion, calcium carbonate (limestone) deposition, and sedimentation.

Remember that calcium carbonate is deposited by many reef organisms. Some of these organisms are red and green algae, corals, and mollusks.

13. 10. 2. The Intertidal Zone

If you were to swim from the shoreline of a fringing reef in a seaward (towards the open sea) direction, you would first encounter an intertidal zone.

At high tide, this portion of the shore is covered with water, but at low tide, the intertidal zone becomes exposed to the atmosphere. The width of this zone depends on the slope of the shoreline and may be very narrow or wide.

Organisms which live in this zone have to be adapted to the exposure. Many will burrow in sand or find refuge under rocks during dry times.

13. 10. 3. The Reef Flat

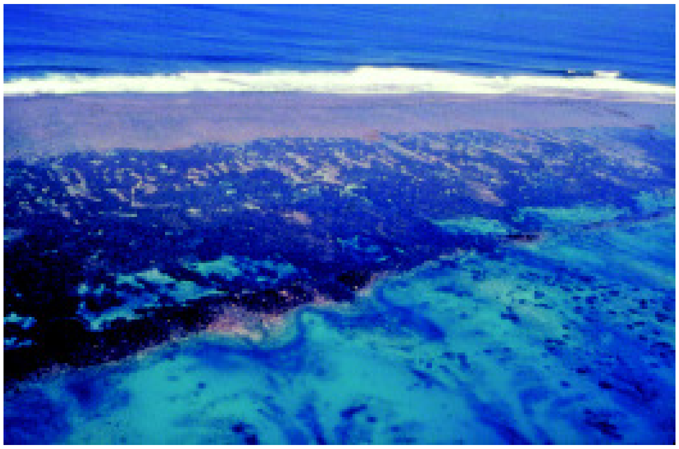
If you continue to swim seaward past the intertidal zone, you will enter the reef flat. The reef flat zone lies between the intertidal zone and the reef margin, and may be up to 2 meters deep during high tide. At low tide, portions of the reef flat platform may be exposed. The reef flat is often divided into sub-zones, depending on the depth and width of the platform.

The reef flat lies between the intertidal zone and the reef margin.

The inner reef flat may be relatively deep with a moat through which water flows. If you were to swim across the inner reef flat, you would probably encounter many types of life. You would see fleshy seaweeds, many sea cucumbers, mollusks, possibly some corals, and a host of fishes.

If the water depth increases in this subzone, there would also be an abundance of sediments. When water flows over the reef margin, it is usually moving fairly fast. As it enters a deeper area, it slows down some.

Because faster flowing water can carry particles farther than slow moving water, sediments and other small materials will fall out of suspension. Therefore, one would expect to find more sediments in water which is deeper and slow moving.



The reef margin, or crest, is the region where the surf breaks.

Seaward of the inner reef flat subzone is the outer reef flat region. The outer reef flat is characterized by low tide exposure, fast current speeds, and generally a hard, consolidated bottom.

One might expect to see small, low coral heads, sea urchins, mollusks, and many fishes. Depending on the amount of atmospheric exposure this area receives, corals may or may not be present.

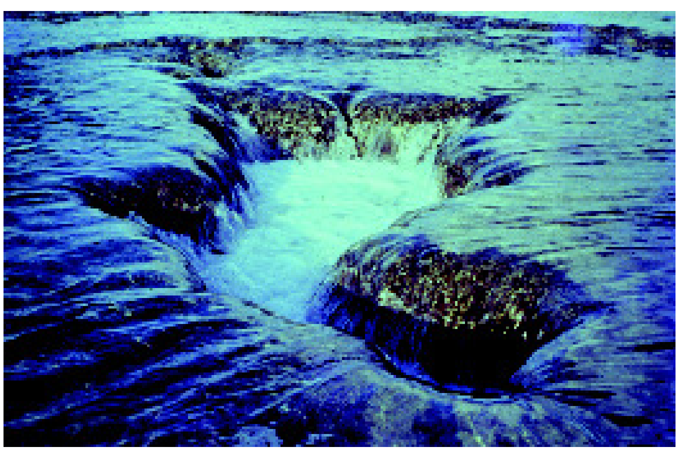
13. 10. 4. The Reef Margin or Reef Crest

The reef flat's shallow seaward edge is known as the reef margin, or the reef crest. This is the region where the surf breaks, and even though it is shallow, it stays awash even at low tide.

The narrow wave-washed margin can be dominated by coralline red algae or it may contain a wide variety of coral and algae. Mollusks, sea urchins, red algae, corals, fishes, and many other reef organisms live in and on the reef margin. Some organisms can live only in these wave-washed environments.

The reef margin's seaward edge may grade into **surge channels** and **buttresses**. Surge channels are channels of varying depths, but are often cuts 4 meters deep and 3 meters wide into the reef margin and reef front. The buttresses are the "hills" in the reef framework separating the channels running perpendicular to the reef margin.

The channel and buttress system is quite effective in displacing wave energy. Much reef growth can be found along the channel walls.



The reef margin's seaward edge may grade into surge channels.

When corals and coralline algae grow towards each other from adjacent channel walls, they may meet at the surface and form caves and tunnels underneath. Many fish, such as TATAGA and HUGUPAU, living in this zone are caught by people.

13. 10. 5. The Reef Front

The reef front zone is an extension of the buttresses and surge channels of the reef margin. This region is always covered with water and is never awash. The location where the features of the channel and buttress system ends seaward marks the boundary of the steeply sloping reef front.

The richest assortment of reef life grows on the reef front and reef margin. For example, more than 200 species of corals grow in the reef front and reef margin; whereas, on the reef flat platform, fewer than 40 species of corals are found.

The reef front often grades into a submarine terrace or bench. In Micronesia, this terrace will vary from island to island, but may be anywhere from 10 to 15 meters in depth. The terrace then grades seawardly into the forereef slope. Lau Lau Bay is a submerged terrace, popular for scuba diving.

The forereef slope is the steeply dipping seaward limit of the reef which extends downward past the lower limit of reef-building corals. Nearly vertical slopes are common here, but the slope may be interrupted by other submarine terraces. The steep upper slopes are rich in coral growth and other marine life.

13. 10. 6. Barrier Reef and Lagoon Zonation

If you examine the images to the right, you will notice the main difference between a fringing reef and a barrier reef. It is that the seaward slope, the reef front, the reef margin, and the reef flat zones are separated from the land by lagoonal zones.

Imagine that you are swimming from the shore in a seaward direction across the lagoon of a barrier reef. You will first encounter a shallow, gently sloping lagoonal reef flat. This region is shallow, sandy-bottomed, and often supports seagrass communities.

The lagoonal reef flat terminates seaward into the lagoon slope which connects the reef flat to the lagoon floor. The lagoon floor varies in depth, but may be 5 to 10 meters in depth. Rising from the sandy lagoon floor are patches of growing reef which form mounds and pinnacles. These small, isolated reef formations are known as patch reefs.

The lagoon floor grades seawardly into the lagoon slope that rises gently up to the barrier reef flat. The zones of the barrier reef are similar to the fringing reef. Both reef formations are exposed to the open sea and its strong waves and currents.

13. 11. ORIGIN OF REEFS

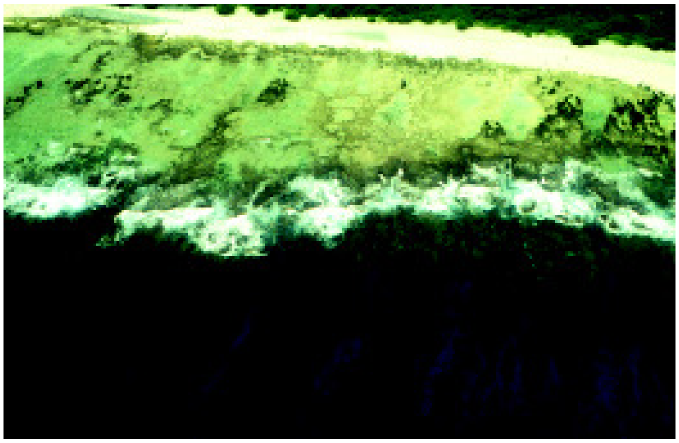
13. 11. 1. Introduction

Reef building corals, called **hermatypic corals**, thrive only in well-lit surface waters. All reef growth takes place in the well-lit waters of the upper 200 meters, and growth is best in the waters closest to the surface. In water deeper than about 200 meters, reef corals do not do well, and in water deeper than 300 meters, there are probably no *reef building* corals at all. However, there may be **ahermatypic**, or deep water corals. As we saw in earlier chapters, the upper 200 meters or so is called the **photic zone** or **euphotic zone**.

Darwin had proposed that subsidence, or sinking, of the earth's crust beneath the sea, was solely responsible for developmental sequence of reefs and atolls. Many fossil reefs had also been observed that were hundreds or thousands of meters thick: clearly these had been formed by growth of corals on a sinking surface.

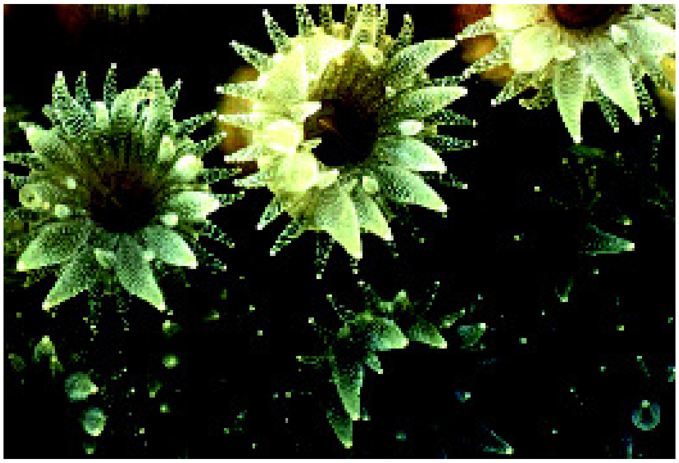
Many years later, geologists realized that sea levels change over time. Darwin could not have known about sea level changes. After sea level changes were better understood, other scientists proposed an alternative theory to that of Darwin: that sea level rise determines the development of coral reefs.

According to this theory, the tops of volcanic oceanic islands are planed by wave action during a low sea level stand; after a slight sea level rise, corals settle and a reef begins to develop. This theory was later proven to be false.



Fringing...

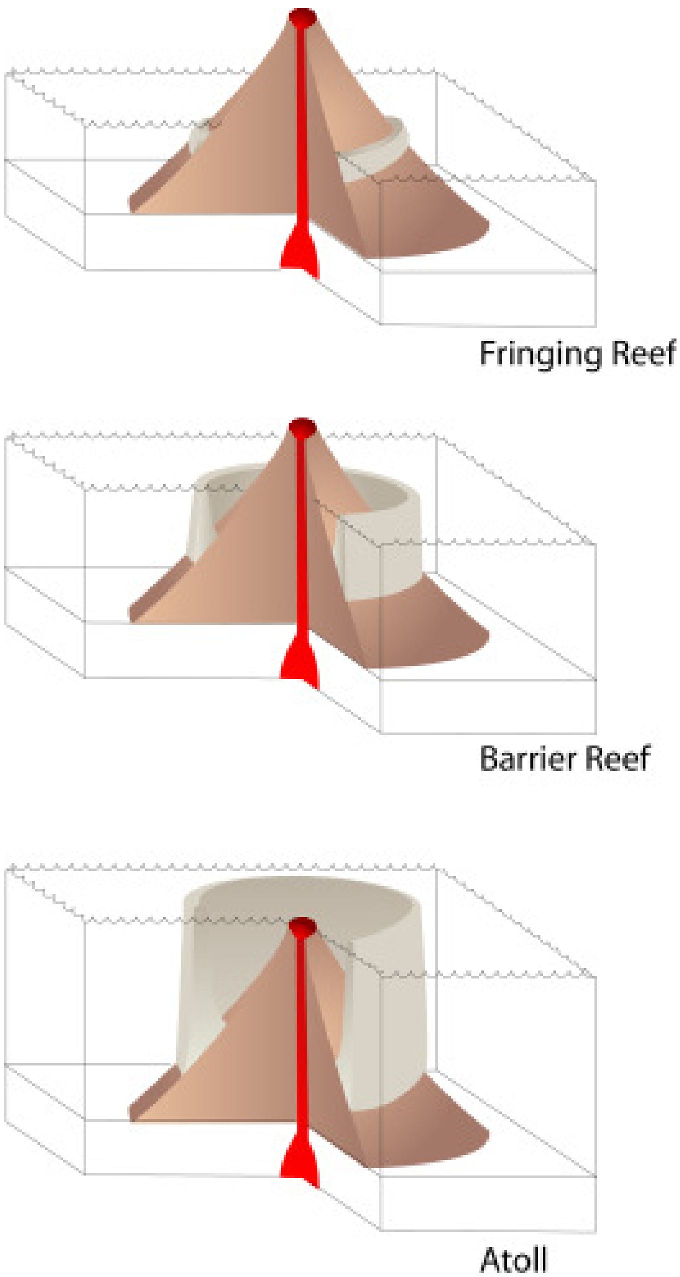
and barrier reefs



Reef building corals, called hermatypic corals, thrive only in well-lit surface waters.

Scientists' boring through reefs at Eniwetok and Bikini Atolls in the Marshall Islands reached volcanic rock after boring to a depth of over 1300 meters, nearly a mile, through coral rock. Some corals at the bottom of these borings were of types that are not now found on the earth. Since corals do not grow in deep water, Darwin's point was neatly proven: only through subsidence could these reefs have grown to such depths.

In the Mariana Islands, land is being uplifted by a combination of tectonic and volcanic action; however, atolls of the Caroline Islands are sinking at a rate of approximately 1 centimeter per year.



Geologic subsidence results in the development of different types of reefs over vast spans of time.

13. 11. 2. Geological History

The coral reefs of Micronesia are tens of millions of years old. Eniwetok, for example, is about 45 million years old. The southernmost CNMI islands are also about 45 million years old.

13. 11. 3. Earlier Types of Coral Reefs

Borings at Eniwetok and Bikini penetrated to a depth of nearly a mile. Evidence suggests that 50 million years have passed since the laying down of the first corals on the flanks of the volcanoes that produced the Marshall Islands.

Cores taken from the borings in the lowest levels of basalt were found to be well-preserved. Even deep in the reef, the coral species can be identified by their skeletal characteristics. The species and community composition change over time in these cores. Skeletons of coral species that are now extinct were found.

13. 11. 4. Extinct Reef Organisms

Stromatoporoids are extinct organisms known only from fossils. *Rugosa* and *Tabulata* are two types of Stromatoporoids that have been found. The evidence from the skeletons of colonies was dug up from the earth. *Tabulata* and *Rugosa* lived and produced reefs millions of years before modern corals made their appearance on our planet.

Even before the *Rugosa* and *Tabulata* appeared, other organisms had produced reefs. The earliest type of biologically-produced build-up was the **Stromatolites**. They are still in evidence in Australia. Stromatolites are **bioherms**. They are produced by the action of bluegreen algae binding sediments together.

13. 12. SO JUST WHAT IS A CORAL?

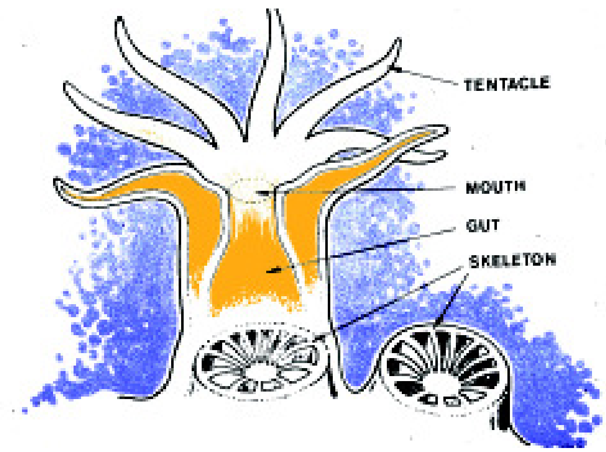
13. 12. 1. Basic Biology; Structure

Though it may come as a surprise, corals are animals, belonging to the **Phylum Cnidaria**. This phylum is also known by another name: **Coelenterata**.

Each of these names describes a different aspect of the structure of these animals. The name Cnidaria, the current name for these animals, comes from the word *cnida* (*pl. cnidae*), meaning something like "stinger". One of the distinguishing characteristics of all these animals is the possession of nematocyst-containing **cnidoblasts**, or "stinging cells." The **nematocysts** are the weapons they use for defense and to capture prey.

Only Cnidaria have stinging cells, but the **Ctenophores**, or comb jellyfishes, have similar though slightly different structures. Many of us have had first hand experiences with nematocysts if we have been stung by a fire coral or a jellyfish. This structure is the hallmark of cnidarians.

Although no longer used, the name Coelenterata is also quite descriptive. It is taken from another structural feature of these organisms. *Coel* is a Greek word meaning "cavity," or hole. *Enteron* means "gut." Taken together, this name Coelenterate means "hole-gut animal". This name reflects the most basic element of the design of these organisms.



Anatomy of a cnidarian

Whether **polyp** or **medusa**, the body of these organisms takes the form of a sac with a mouth at one end. The mouth is surrounded by **tentacles**.

The German name for Cnidaria is *die Höhl Tiere*, meaning "hole animals." It is said that these animals have a "two-way gut": after digestion, wastes pass back out through the mouth.

In fact, these are only two of the most important characteristics of these animals. Here is a more comprehensive list.

Polyps are simple animals with a crown of tentacles surrounding a mouth.

All corals share this basic structural plan. Even those which may superficially look entirely different have this structure.

Polyp or medusa, the body plan is quite similar. The main difference is the development of swimming as a mode of locomotion in most medusae, and the presence of some means of attachment to the substrate for most polyps.

There are exceptions. Some medusae, like the "upside-down jellyfish," *Cassiopeia spp.*, spend most of their lives lying on the substrate. They use their swimming muscles for respiration. Certain unusual sea anemones swim. There is one species of swimming anemone found in our sea grasses here in the Marianas.

As mentioned over 200 species of corals are found on the coral reefs of the Northern Mariana Islands.

13. 13. REEF CORALS

13. 13. 1. Introduction

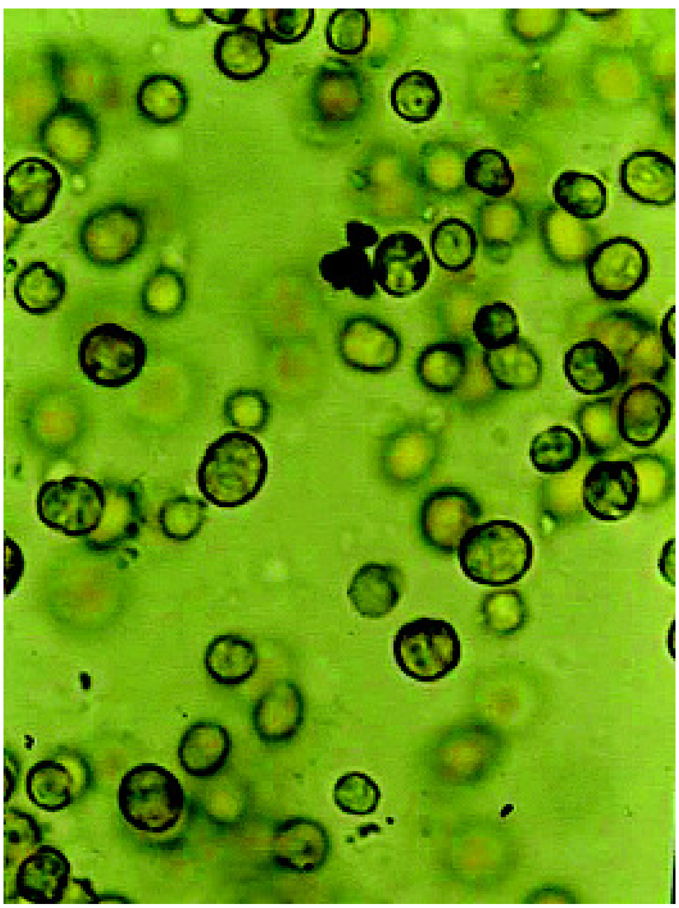
Reef building corals are capable of rapidly building massive skeletons of calcium carbonate, or limestone. Over millions of years, corals, with the help of stone-producing algae, have built entire coral reefs and reef islands. The island of Saipan, which is volcanic in origin, was built up all around by reef limestone. Reef building corals are fast growing hard corals.


The islands of Saipan and Tinian were built up all around by reef limestone.

13. 13. 2. Some Coral Uses

The CNMI is blessed with an extremely diverse assortment of corals and other cnidarians. It is quite easy to take corals for granted. We

Coral is the basis for the pavement on our roads.



Zooxanthellae

walk all over their skeletons almost every day, use their lime as an ingredient of betel nut, or perhaps use coral gravel as aggregate.

Coral is used as the basis for the pavement on our roads, and boonie roads are sometimes called "coral roads." Indeed, the very islands of the CNMI were largely formed by these minute organisms.

It is in our interest to understand coral reefs better. In recent years, we have come to understand that our actions can cause harm to corals. Much of the harm results from commerce and the economical development of the islands. When we damage corals, we harm the reefs that they and their companions produce.

13. 13. 3. Reef Building vs. Non-Reef Building Corals

Have you noticed that corals are most abundant in the shallow waters of the reef? Have you also noticed that fewer corals are present in the slightly deeper waters on the reef slope? In the dark waters deeper than about 50 meters, we might not find reef corals at all, even if we were able to dive that deep.

Other **scleractinian** (rock-forming) corals, that do not build reefs—called ahermatypic corals—are found even in deeper parts of the ocean, but they are not up to the task of producing mountains of robust stone. These facts lead us to an important puzzle: *why can't reef corals live in deeper waters, or in darkness*?

Another interesting observation, one that you may have observed, is also noteworthy: most reef corals close up during the day and open only at night.

13. 13. 4. Efficient Bio-Machines

Corals are efficient machines for the capture of the minute animal plankton upon which they prey. They need no complex nervous system to coordinate visual hunting activities. However, they do have a simple nervous system that can sense vibrations, smells, and light. This nervous system also coordinates the action of their tentacles which capture food as they wave around.

13. 13. 5. Micro-Spearguns

The polyp, like the jellyfish, stuns its prey using poison darts that are fired from thousands of stinging cells each containing spears (nematocysts). The nematocysts shoot powerful venoms into any small prey that ventures too close to the tentacles of the polyp. (Have you ever been stung by a jellyfish or a sea anemone?). The coral tentacles then flex and move the captured prey to the polyp's mouth.

But why do so many species of corals only fish for prey at night? Aren't there any prey around during the day? Here we are faced with another puzzle: *why are corals willing to stop feeding in the daylight*?

13. 13. 6. Zooxanthellae

The answer to both of our puzzles lies in the curious and fascinating association between reef corals and certain organisms. These organisms are **zooxanthellae** (pronounced "zoo-zan-thel-ai"). They are microscopic, single-celled, and plant-like. Zooxanthellae have a similar relationship with many other coral reef animals.

13. 13. 7. Mutualistic Symbiosis

This relationship is called **mutualism**, **mutualistic symbiosis**, or sometimes just **symbiosis**. It is an association between two organisms. Each of the organisms has come to depend upon the other for its needs. This is different from **parasites** which take from their hosts, giving nothing in return.

Each partner of a mutualistic symbiosis benefits from the association. The rewards of the association surpass the costs for each partner. Other examples of mutualism on the coral reef are the *clownfish-sea anemone symbiosis* and the *cleaning symbioses* displayed by several organisms.

Clownfish and sea anemones enjoy a symbiotic relationship.

In many cases of mutualism, at least one of the partners cannot live without the other. This is the case for zooxanthellae and hermatypic reef corals. Each depends upon the other so much that reef corals cannot live for an extended time without zooxanthellae.

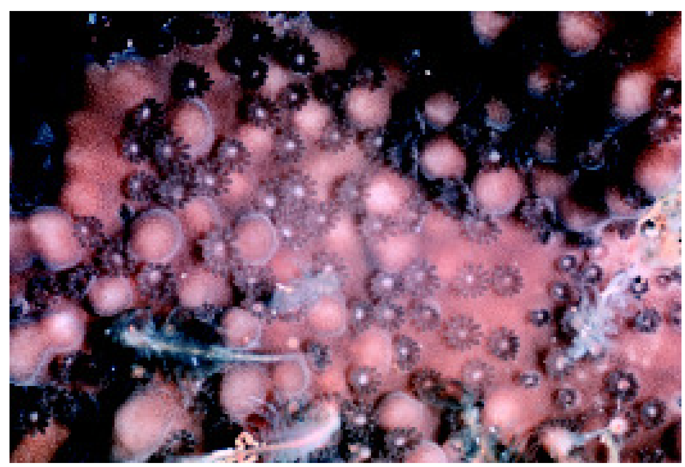
13. 13. 8. Food Exchanged for Shelter and Nutrients

Zooxanthellae, like other plants and plant-like protists, obtain the energy they need from sunlight. However, because corals are animals, they cannot photosynthesize and must obtain their energy from food that they consume.

Zooxanthellae produce their own food substances: sugars. Since they are able to produce more than they need, they give their leftovers to the corals in which they take shelter.

Zooxanthellae are able to gain more than shelter from this association. In exchange for the food the zooxanthellae provide, the corals contribute their nutrient-rich wastes directly to the zooxanthellae. The zooxanthellae need the nutrients in the waste. The waste is something that is not missed by the coral.

Nutrients are not abundant in the warm surface waters of tropical oceans. This linkage of nutrients and food between these two partners solves a serious problem for each. The coral's growth is enhanced. Otherwise, the growth would be limited by the scarcity of food. The zooxanthellae take advantage of the waste nutrients from digestion of the food that is captured by the coral. The amount of food maybe insufficient, but it is useful to the zooxanthellae.



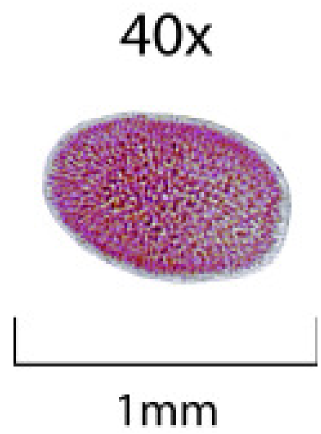
Zooxanthellae take advantage of the waste nutrients from digestion of the food that is captured by the coral.

13. 13. 9. Assistance with Limestone Formation

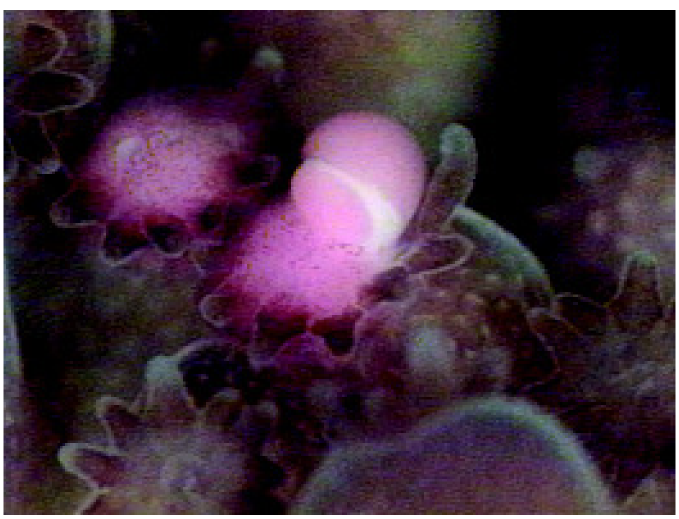
Zooxanthellae also make another extremely important contribution to their animal partner. They help the animal make calcium carbonate stone.

This is actually a crucial contribution. Non-reef building scleractinian corals do indeed produce stony skeletons. These skeletons, however, are fragile and only produced very slowly. They are neither robust nor fast growing like those of reef building corals.

The vital difference is the lack of zooxanthellae in such non-reef building corals. Giant tridacnid clams, which produce the most massive shells of mollusks, also have zooxanthellae in their tissues.



The planula looks like a very tiny piece of rice. It is perhaps less than a millimeter long.



A closeup of coral spawning

13. 14. CORAL REPRODUCTION

13. 14. 1. The Coral Life Cycle

Each coral species has a unique life cycle. Many corals, however, follow a similar pattern. The eggs and sperm (or gametes) are broadcast into the water, all at the exact same time, obviously! They meet there, then the egg is fertilized and it becomes the first cell of a new coral.

Corals are exceptionally fragile organisms. They respond to slight changes in the conditions of their environments.

In addition, the life cycle of corals, like that of other coral reef organisms, is normally fairly complicated. It involves very different young and adult stages. The adults of many species are attached to the reef and cannot move. However, the larvae, **planula**, drift with open ocean currents.

13. 14. 2. Sexual Reproduction

Corals have a remarkable reproductive biology. During several stages of their life cycles, they are vulnerable to environmental effects caused by humans.

There are two times that are most sensitive for the coral. The first time is when they are **spawning**. This is when the eggs and sperm of the corals are shed into the water. The other time is during *settlement*. At this time, the larvae return to the reefs to seek a place for the adult to live.

There are numerous peculiarities of this generalized life cycle. In fact, each species of coral has it's own particular life cycle. These may differ in a number of ways from the life cycles of its neighbors.

Individual species may be either **hermaphroditic** or **dioecious**. Within each of these types, some species spawn, while others **brood** their young for different lengths of time.

13. 14. 3. Mass Spawning

It seems miraculous that for a given species this process always happens on the same night or on the same few consecutive nights. Yet, if it were any other way, the egg wouldn't be fertilized, so perhaps it isn't a miracle at all.

It seems improbable that the spawning of dozens of species of corals would happen at the same time. However, it has been discovered that in the Mariana Islands, the Great Barrier Reef in Australia, and other locations around the tropics, this kind of mass spawning does occur.

Most years in the Northern Mariana Islands, it happens in late June to mid-July during a period of a few days. It sometimes occurs in both months. It usually happens about five to seven days after the full moon of July.

For many species of corals, the eggs and sperm float for a short time on the surface of the ocean at the reef; this fact may increase the probability of fertilization.

As I (this section's author) write this chapter, it is the 21st of July 1997. The full moon was yesterday. Within a few days, it is expected that the CNMI will experience a mass coral spawning event.

Such events are one of the most incredible, dazzling performances in nature. Each year, on certain coral reefs, a large number of species of corals spawn their gametes on the same night, or over a period of only a few nights. This usually happens a few days after the full moon.

The spawning event is exposed to environmental influences. These influences can include human induced pollution. For example, the coral *Pocillopora damicornis* is hermaphroditic. Each polyp produces both sperm and eggs. The gametes are produced in packages. The eggs are on the interior and the sperm is an outer layer.

When spawning occurs, these balls of gametes are broadcast by the polyps. The balls float at the surface for about 20 minutes. After this time, they break apart, and the sperm and eggs separate. After this, the eggs are fertilized by sperm which probably come from another colony.

Oil or pesticides floating on the surface will impede coral fertilization.

13. 14. 4. Free Swimming Larva, Called a "Planula"

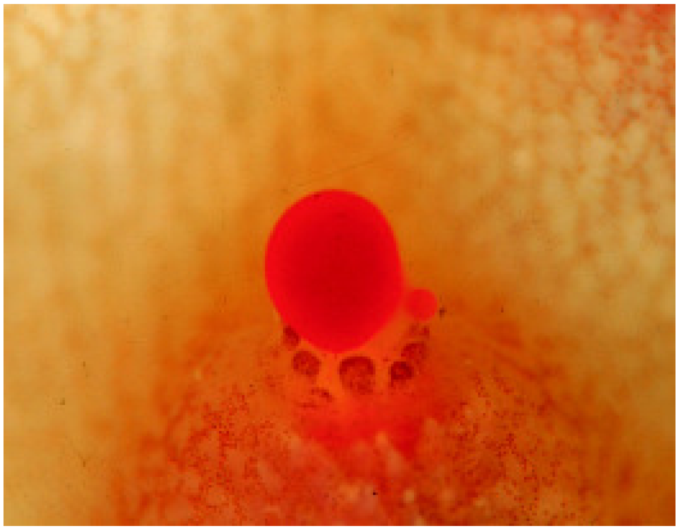
The larvae of corals, unlike the adults, are free swimming, and the larvae of many species go to sea for a period of time.

Such a larva drifts until, if it is fortunate, it reaches an island, quite possibly a different island from that of its parents. Here, the new larva searches for a home where it can settle out of the water and make a home for the adult colony. Larvae of some species can live this way for months.

It is thus the coral larva, and not the adult, that determines where the coral will finally live. This seems quite unusual to us. It is just the opposite of the situation for a butterfly and a caterpillar, in which it is the adult butterfly that is motile.

Like the caterpillar, the coral larva—called a *planula*—differs dramatically from the adult. The planula looks like a very tiny grain of rice. It is perhaps less than a millimeter long.

Once it reaches the reef, the planula crawls around, tasting and touching the reef, until it senses the right place for final settlement. This fact is all the more remarkable, when we consider that adults of a single species often wind up on the same kind of environment on reefs all over the world!



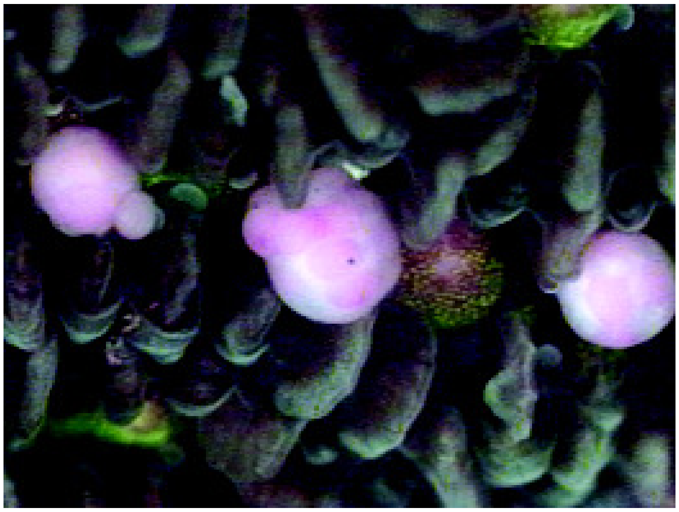
During spawning, the eggs and sperm of coral are released into the water.

13. 14. 5. A Fragile Life Stage

This is a critical time for corals. If there are any organic chemicals, like oil or pesticides, floating on the surface at this time, it is likely that fertilization will be impeded. Fertilization may even fail. The presence of sediments on the reef at this time is also unfavorable to the prospects for settlement. Sediments decrease the chances for the survival of embryos and larvae.

For this reason, some of the CNMI and US Federal resource management agencies issue short term bans during the spawning season for corals. There are restrictions on land clearing activities, dredging, and other activities that may cause organic compounds or sediments to enter the water.

If there are any chemical residues floating on the surface of the ocean at the time of spawning, during this 20 minute period when the gametes are floating, reproduction will not be successful.



During spawning, balls of gametes are broadcast by the polyps.

The gametes are quite fragile and easily harmed by pollution. Gasoline or oil residue can kill the gametes. Even a small amount left over from a can or plastic container carelessly thrown off a boat can kill the gametes.

It has been shown that sediments off the land in southern Guam caused coral larval settlement to fail. See more on sedimentation effects upon coral settlement in our reef problems chapter (Ch. 15) and our water pollution chapter (Ch. 41).

13. 14. 6. Cloning by Fragmentation

Corals are colonial animals. Each individual colony is formed of hundreds or thousands of tiny individuals. Typhoons and other events damaging to reefs can cause corals to fragment.

After a typhoon has swept the Mariana Islands, you will likely find that corals on the reef have been devastated. Even boulders over 15 feet tall may be torn off the face of the reef and thrown up on the reef platform. Large and small colonies are shattered. Their fragments are scattered all over the reef.

Because of the colonial nature of corals, each of these fragments may consist of a viable colony. Each polyp may sustain only a minor trauma, but most polyps may be unharmed. Under these circumstances, each of these fragments can continue to grow. They may **cement** themselves down in new locations.

Fragmentation can enable corals to re-populate the reef rapidly.

In this way, corals are able to begin to repopulate the reef rapidly. As one becomes many, this is a kind of reproduction. Since all the polyps of a colony are derived from a single colonizing individual, all polyps of a colony are genetically identical. They are **clones** of the first polyp, like identical twins. *Fragmentation* is an opportunity for a colony to expand its territory.

13. 15. CORALS ARE COLONIAL ORGANISMS

13. 15. 1. Introduction

As stated earlier, most reef corals are colonial organisms. A single coral polyp is an organism, capable of living on its own, and performing all the functions of a living thing. Yet, corals do not generally live alone, but rather in colonies.

13. 15. 2. After Settlement, Reproduction by Fission

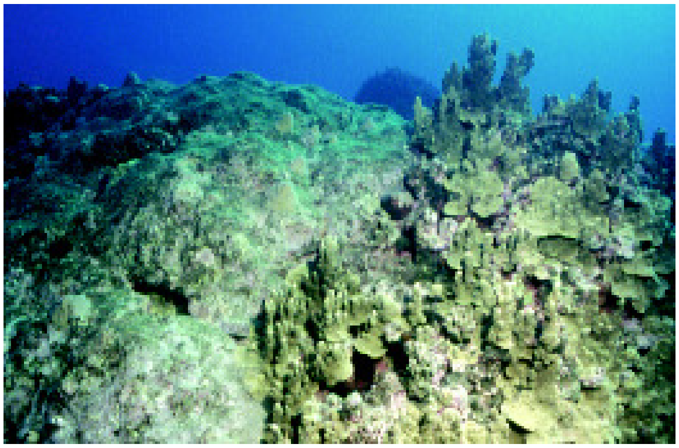
A colony is produced by fission. It begins from the single polyp formed by the planula larva that settles on the reef from the plankton.

After the larva changes its form into a polyp, it begins to grow, depositing the first traces of the limestone skeleton that will become the hallmark of the coral on the reef.

The skeleton of the first polyp is formed into a cup-like structure that supports the polyp and protects it when it contracts. This first cup (called a **calyx**) will be the first of hundreds, or thousands, of cups that form the colony.

13. 15. 3. Growth and Division

After the polyp has fully grown, its cup having taken its mature form, it then divides into two daughter polyps. As each of these daughter polyps matures, they too will divide, and after a period of several months, a small colony will have developed. Biologists refer to this as reproduction by 'budding'. Daughter polyps are often referred to as 'buds'.



Corals build upon the skeletons of previous generations.

13. 15. 4. Coordination and Specialization within the Colony

Corals are simple animals with simple nervous systems and two way guts with single openings. They do not have a head. Yet, the actions of all the individual polyps are coordinated to some extent, and a certain amount of specialization occurs in certain polyps. The nervous systems and digestive systems are colonial.

13. 15. 5. The Colonial Nerve Net

If you gently touch a polyp, it will contract—an obvious defensive movement. If one polyp is touched in a coral colony, other nearby polyps will also contract. This is possible because the nervous system of corals is a simple nerve net. In colonial corals, this net extends all over the colony.

You may investigate the nature of this colonial nervous system by carefully and gently touching a single polyp. The first time you touch the polyp, the polyp you have stimulated and a few neighboring polyps will contract. If you touch the polyp again a few seconds later, equally as gently, more polyps will probably contract. With each stimulation, more polyps will respond, up to a point.

You may carefully try to compare the difference in response between two stimuli. Try to compare one which is intense, and the other which is gentle.

Touching a single polyp will trigger a response in surrounding polyps.

13. 15. 6. The Colonial Digestive System

Coral polyps have simple digestive systems—a two way gut with only one opening. Recall the meaning of the earlier phylum name, Coelenterata—"hole gut".

In a colony, the digestive systems of all the polyps are connected. This happens in a number of different ways in different coelenterates.

13. 16. ENVIRONMENTAL BIOLOGY OF CORALS

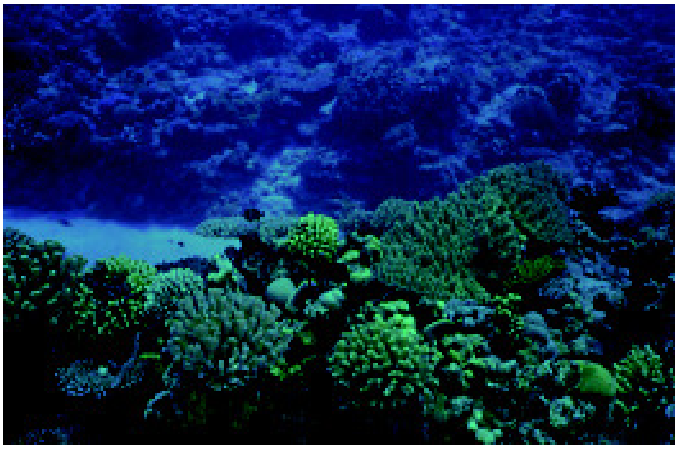
Corals are for the most part minute organisms. In contrast to the sturdy structures they produce, corals are fragile and easily harmed. They can be killed by pollution or sediments of human origin. They are sensitive to temperature; it is feared that global warming may kill many of the earth's coral reefs.

13. 16. 1. Distribution

The **distribution** is the range of environments where an organism is found. The distribution of coral reefs is determined by the tolerances of corals, the primary group of reef building organisms.

All reef corals live only in warm tropical waters. Each species, however, has more particular preferences. Each lives only within narrowly restricted, well-defined environments. Most corals have swimming larvae, while the adult is firmly fastened to the bottom of the ocean, on the reef. Thus, the larva and the adult have distinctly different ecological requirements.

As mentioned, the coral larva decides on a place for the adult coral to live. Larvae make their decisions based on information about the environment provided by their senses.



There are over 200 species of corals in the CNMI.

13. 16. 2. Diversity

There are over 200 species of corals in the CNMI. Each of these species is associated with a particular community. Each species, each community, is associated with specific physical environmental factors. Different zones are recognized by the species of corals that usually grow in them.

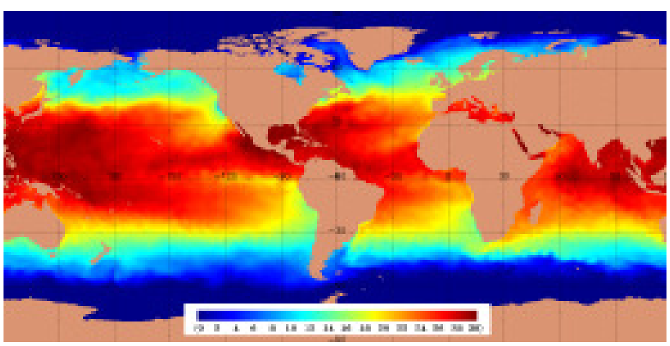
13. 16. 3. Tolerances

The most important environmental factors on the reef are temperature, light, salinity, purity of water, waves, tides, and currents.

The tolerance of reef building corals is quite narrow for some of these environmental factors. For other factors, the range is possibly wider. Each living coral species seems to have a preferred environment. Some of these environments have been named after the most dominant species of corals that are in them.

13. 16. 4. Temperature

The distribution of reef building corals correlates with average sea temperature. No reef building corals can reproduce well at temperatures less than 20° Centigrade (usually noted as 20° C). Reef-building corals flourish where the *average* water temperature is at least 20° C.



Coral reefs are limited to those regions of the world with temperatures above 20 degrees Centigrade.

Some species of corals can live for a while in water colder than this, as some species do in southern Japan. However, it is too cold in these places for corals to reproduce. The larvae of the corals in such places have come with the currents from reefs further to the south.

This situation in S. Japan is unusual because of the very strong Kuroshio Current running from South to North. On most reefs of the world, corals are able to reproduce. The corals in S. Japan, however, do not because the water is too cold. This is a case where the *distribution of an organism is not determined by the temperature at which it is able to reproduce.*

13. 16. 5. Need for light; Depth Limit

Reef corals need light in order to grow and be healthy. It may seem unusual that corals, which we have learned are animals, need light. This is the case because, as mentioned earlier, corals are party to relationships with certain single-celled plants, the zooxanthellae. As you recall, zooxanthellae are dinoflagellates that live within the tissues of the coral. These plant cells are able to photosynthesize, and contribute their excess food production to the coral.

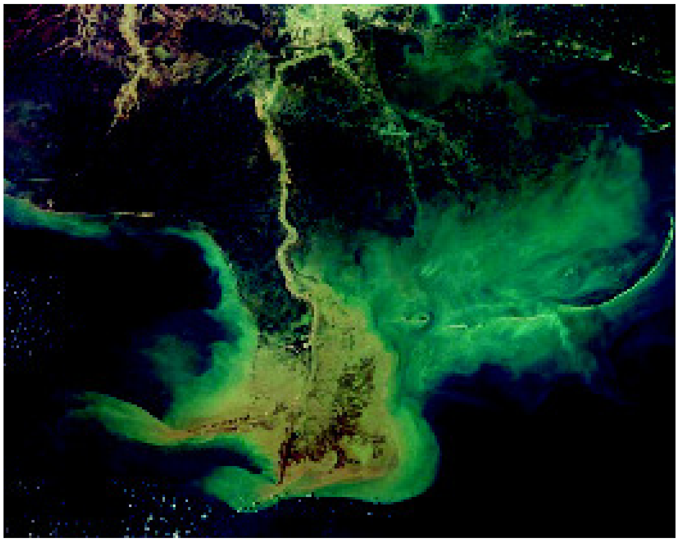
The relationship between the coral and the zooxanthellae is one of mutual dependence. Without the zooxanthellae, reef building corals cannot survive; it is for this reason that reef corals do not grow in water deeper than about 100 meters, a depth at which the zooxanthellae cannot live.

13. 16. 6. Salinity

Corals need water of ordinary oceanic salinity (saltiness). Salty ocean water has a salinity of about 3.5% (35 parts per thousand). Most species of corals are sensitive to even slightly lower or higher salinities.

Higher salinities, for example, are found in tide pools on reef platforms, and any corals that live in such tide pools are tolerant of these salinities. Likewise, few species of corals can tolerate water even slightly less salty than ocean water.

As a result, few corals are found close to river mouths. In fact, reefs themselves are often poorly developed in such places. This is due both to the lowered salinity of water near the rivers, as well as the lack of clarity of the water and the higher amounts of sediment that can settle out and smother the corals.



Lowered salinity of water near rivers, as well as the lack of clarity of the water, and the higher amounts of sediment inhibit coral growth.

Corals of a few species are more tolerant of these circumstances than others. Any long-term freshwater increase, such as after a long, hard rainfall, may damage or kill corals.

13. 16. 7. Water Quality; Sediments

Clear water is necessary for reef growth. Some of the healthiest coral reefs are found on atolls and other oceanic islands where water is the clearest. Sediments block sunlight from the coral's zooxanthellae, which interferes with photosynthesis.

Sediments can also smother coral polyps because they breathe through their delicate body walls. Most corals can tolerate only a small amount of sediment. Some coral species, like *Porites spp.*, are more tolerant of sediments, but even these species can be killed by large amounts. Sediment tolerant species are often found in areas where less tolerant species would be smothered.

13. 16. 8. Water Quality; Nutrients

Corals thrive in clear tropical oceans where nutrients are limited. The symbiosis between coral and zooxanthellae is largely responsible for recycling nutrients. Nitrogen (**N**) and Phosphorus (**P**) are recycled to minimize losses to the environment. Scientists have learned that corals carefully regulate the amount of nutrients they provide to the zooxanthellae.

If the environmental level of **N** and **P** increases, the complex system of exchanges breaks down. Nutrient pollution results when excessive levels of nutrients are exported to the reef. This causes stress to corals. High levels of nutrients have another effect. Algae find a more favorable environment when the nutrient level is elevated.

Human activities that release excess nutrients have a strong effect on the reef. They cause fleshy algae to be favored over corals. The result, when the high nutrient level is maintained over time, is often a reef that is dominated by this green algae. These algae overgrow the corals and kill them.

Nutrient pollution commonly occurs when sewage is leaked or dumped into the ocean near coral reefs, and from agriculture and golf course over-fertilization.

Many corals like waves, as they sweep away sediments and provide oxygenated water.

13. 16. 9. Water Movement

Many corals like waves. This is partly because the waves sweep sediments like sand and mud, which are harmful to the health of corals, off the surface of the corals. Water in wave-swept areas is also well oxygenated. This is a factor in favor of corals, which exchange oxygen with the environment across their body walls.

The distribution of corals is also determined by ocean currents. Coral species whose larvae are able to survive for long periods can reach islands far across the sea.

13. 16. 10. Foundation of the Reef

Most corals can only live on hard surfaces. It has been demonstrated that atolls sit on top of volcanic mountains that are subsiding at a slow enough rate to allow the reef to maintain an equal upward growth.

13. 17. THE DYNAMIC PROCESS OF REEF BUILDING

13. 17. 1. Introduction

Borings at Eniwetok Atoll demonstrated that *basalt* underlies the atolls of the Pacific Ocean. Darwin was right. Coral reefs are build-ups of calcium carbonate. They grow upward during a long history of subsidence of their underlying foundations.

Borings at Eniwetok Atoll demonstrated that basalt underlies the atolls of the Pacific Ocean.

Researchers at Eniwetok bored continuously through almost a mile of reef rock before striking basalt. We know that the corals that were brought up as part of the core of the boring, deep beneath the reef, could only live near the surface of the ocean.

The only way this could happen is by upward growth, and either sea level change or subsidence (sinking down) of the sea bottom. As we now know, the sea level has changed but it has not changed by the depth of a mile.

At least some of the effect we are seeing must have been caused by subsidence. We now know that the majority of the effect is caused by subsidence, and that this subsidence in Micronesia results from sideways and downward movements of the ocean floor. We now wish to ask, “How does this process of reef building happen?”

13. 17. 2. Deposit of Limestone

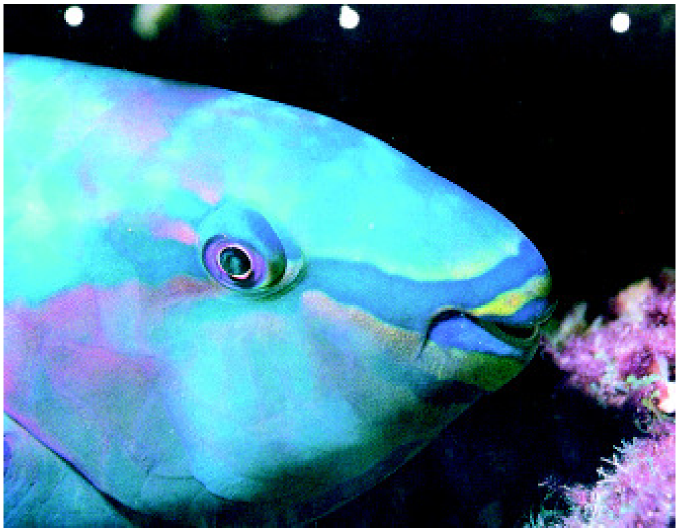
We also know that the main process by which the reef framework is built-up is by the upward growth of corals. This happens over a time-scale of centuries, or thousands, even millions of years.

Corals may grow a centimeter a year, or a few centimeters a year. At such a rate, a coral would grow a meter or two a century. The process of growth is so slow that a coral as big as a pick-up truck would probably be about 600 years old.

Many coral reef organisms produce limestone or other hard parts. All these are involved in some way in building reefs. These organisms, from the lowliest foraminiferan to the shell of the hugest clam, are all somehow incorporated into the reef.

13. 17. 3. Degradation of Limestone Framework

Erosion on coral reefs is both a physical and a biological process. Waves and strong currents break up the reef's framework, especially during typhoons. Waves and currents also abrade and wear away reef material. In addition, there are many organisms which bore, scrape, eat, break, and dissolve the reef framework.



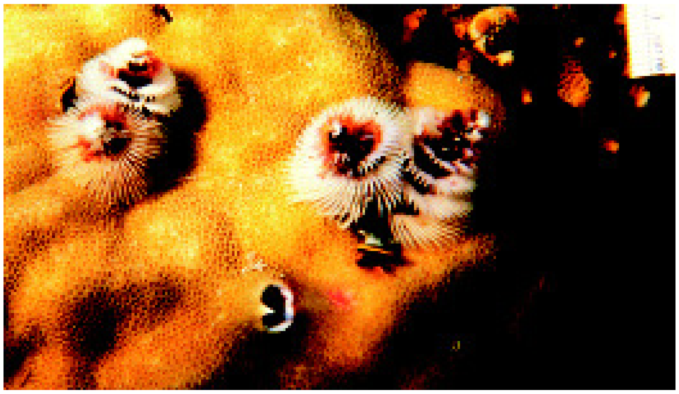
Many organisms, such as this parrotfish, eat the coral framework.

All of these erosion processes remove reef material. The material takes the form of silt, sand, gravel, cobbles, and boulders. The loose material will then be transported and redeposited by currents. Sedimentation is, as described above, part of the erosion process.

Not all sediments on the reef result from erosion. Many organisms secrete hard skeletal parts. These parts become a part of the sediments when the organisms die. Mollusks, soft corals, sponges, sea cucumbers, some red and green algae, and foraminiferans all contribute to the sediments of a coral reef.

At the same time as the coral colony tries to grow, something else is happening. Many organisms are trying to destroy the coral rock. Filaments of algae, for example, work their way into the rock of living corals where they enjoy protection from the living coral. Sufficient light passes through a thin layer of limestone to provide energy for photosynthesis.

Other organisms are busily working at the task of further weakening the structure of the rock. Perhaps they take advantage of the cracks made by the algae. Boring sponges, boring clams, and boring worms riddle the stone with their galleries, leaving behind a weakened matrix of stone.



Boring worms riddle coral rock with their galleries.

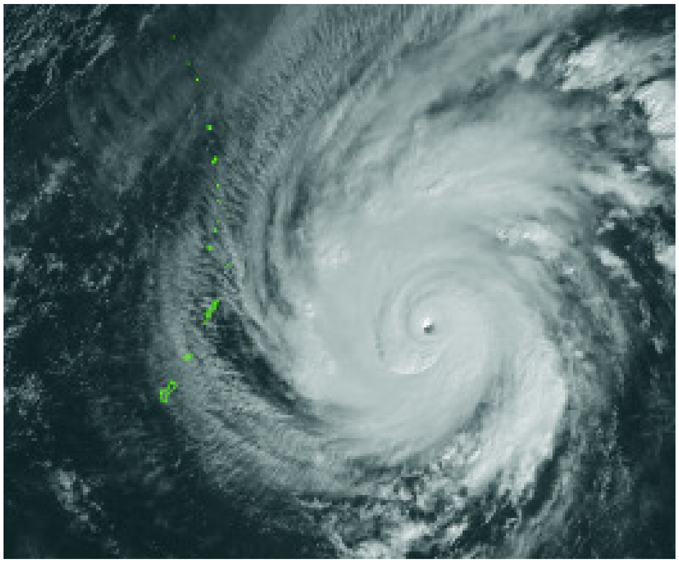
No coral rock can resist this damaging attention for long. Many of the corals on the reef, as strong as they may look, are seriously weakened by the continuing pressure of boring animals. Meanwhile, other animals, and microorganisms like fungi, are attacking the tissues of the coral.

We can see that the reef is like a war zone. Even though they may be survivors, living corals are subjected to all kinds of harm, and their skeleta are being rapidly destroyed from the inside out.

All it takes is a typhoon. Even a relatively small typhoon with its storm-driven waves shatters this weakened matrix. It broadcasts fragments of living corals all over the reef.

Some of these coral colonies will continue to grow, but many will die. The dead coral rocks that remain behind have one thing in common: they have lost their living coral veneer, the living tissue that protected the stone and the little community of organisms inside.

Without the living coral veneer, there is no more limestone being laid down to strengthen the stone of the colonies. The death of corals leads to a sure and rapid acceleration of the degradation of the stone.



A typhoon with its storm-driven waves shatters a weakened reef structure.

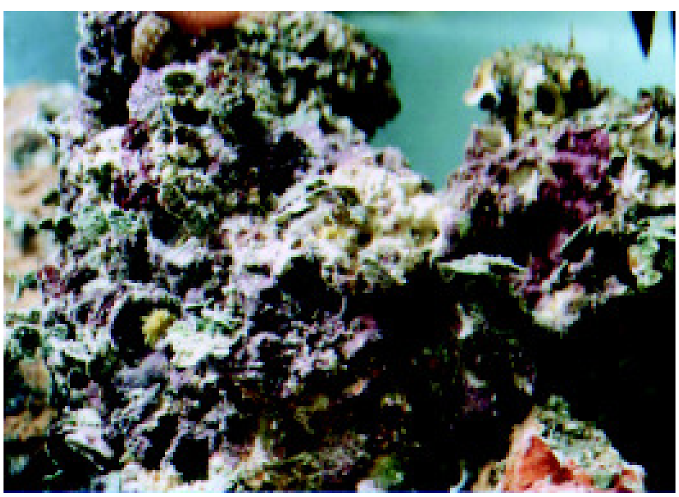
Fish and sea urchins also contribute to the destruction of coral rock. Exposed surfaces are continually eaten and abraded by parrotfishes. Much of the sand on the beach was produced by parrotfishes in just this way. Sea urchins also scrape algal films from on, and in, dead coral rock, taking with them bits and pieces of stone.

As this process of degradation continues, it undermines the efforts of the framework-building corals. The bits and pieces of sand and gravel gradually sift down into the nooks, cracks, and crannies of the reef framework. Over tens of thousands of years, this matrix is steadily packed and tossed and turned by waves, wind, and weathering.

13. 17. 4. Cementation

As the framework builders and degraders busily go about their work, another group of organisms is 'shoring up' the weaknesses in the reef fortress, so to speak. The encrusting *coralline algae* constantly work to cement the sediments and fragments into a stronger composite material.

It is this composite that makes up the growing reef itself. Although some small part of the framework may remain, the sand and fragments that are continually produced by the degraders are cemented into a stronger matrix.



Coralline algae constantly work to cement the sediments and fragments into a stronger composite material.

The most obvious example of this new composite is the reef crest. It is often surfaced with just a pink pavement of corallines. This pavement bonds the packed sand and rock fragment matrix into a stronger material. It is even more solid that the original framework.

13. 17. 5. The Reef Building Cycle; Conclusion

Reef building involves, then, more than just upward growth of corals, one upon the other. Two other important processes are involved: bioerosion and cementation. Without them, there would be no reef.

As we have already seen, reef building corals only thrive near the surface. This observation led Charles Darwin to propose that coral reefs did not grow up to the surface from deep seamounts, but that the mountains themselves had subsided.