CORAL REEF SEDIMENTOLOGY

Though coral reefs are recognized as structures built by animals and plants, it is rarely appreciated that over half of the material in most coral reef complexes is actually made up of sediments. In fact the entire reef itself could actually be considered as one big sedimentary rock. Therefore in this chapter on reef sedimentology we will discuss not just sedimentary particles, but rather the entire reef, both its framework and its particulate fill. Another aspect of reef sedimentology is the important impact sediment can have on reef biota. Sedimentation can damage or kill corals and other reef organisms and the presence of unconsolidated sediments can prevent the successful settlement of larvae of many hermatypic corals. Hence, the sedimentology of a reef is an essential aspect of any thorough coral reef study. We will begin our discussion by looking at where reef sediments come from, proceed to the processes of transportation and deposition, and then look at cementation and diagenesis in a coral reef system.

We have already seen that coral reefs are unique environments biologically, but they are also unique with respect to their sedimentology. They differ from virtually all other benthic marine sedimentary environments in that they produce most of their own sediment. Most benthic marine environments accumulate sediments transported from elsewhere which are known as *exogenous* sediments. These may be land-derived materials transported by rivers, wind or icebergs, or sediments of biological origin such as the skeletons of plankton which have settled from surface waters to the sea floor. On coral reefs, however, well over 90% of the sediments come from the reef itself (*endogenous* sediments). In fact, most reefs produce far more sediment than they can accommodate internally. The excess is carried throughout the reef system and any remaining surplus transported out of the reef environment and even into the deep sea. Therefore, not only do coral reefs not import much in the way of exogenous sediments, they are actually important exporters of carbonate sediments to other marine environments. Where does this supply of sediment come from and how is it produced?

SEDIMENT PRODUCTION ON CORAL REEFS

The source of sediments produced on a coral reef are the reef organisms themselves, consequently the sediments are almost entirely carbonate. Their mineralogy reflects that of their source organisms, hence aragonite produced by corals accounts for more than half of the carbonate, high-magnesium calcite from calcareous algae is the next most abundant mineral phase, and low-magnesium calcite is the least abundant major carbonate mineral. Only on fringing reefs do silicate mineral grains from weathered and eroded rocks (i.e. quartz and feldspar sand) constitute a significant part of the sedimentary material.

The carbonate sediment particles themselves are produced by the destruction of reef organisms and preexisting reef rock through physical, chemical and biological erosion.

Erosion of coral reefs resulting from physical processes

We consider here the erosion of coral reefs resulting from physical processes in a very broad sense to include mechanisms ranging from the mechanical destruction of reefs as a result of storm waves to death and disintegration of reef organisms resulting from changes in their physical environment such as variations in temperature. It is interesting to note that the effect of erosion by physical processes is almost always greatest on the shallow reef front and reef flat zones, precisely those zones which have the highest overall productivity of calcium carbonate. As a result these zones should generate proportionately more reef sedimentary material than other reef zones.

Mechanical destruction of coral reefs is one of the most obvious of all of the erosion processes that affect reefs. Even the most cursory survey of a reef following a major storm will usually reveal obvious damage as a result of the forces of breaking waves and surging currents. A hurricane at Belize in

1961 destroyed virtually the entire reef over an area greater than 300 square kilometers. Entire coral colonies were broken in place forming *in-situ* rubble mounds. Other coral colonies were washed ashore building boulder ramparts and yet other reef material was transported seaward forming debris fans. Organisms left in place showed signs of damage caused by the abrasion of moving reef debris. Studies on the Great Barrier Reef (GBR) have shown damage to coral at depths in excess of 20 meters as a result of tropical cyclones and studies in Hawaii have shown storm damage to corals to a depth of 27 meters. Storm damage can, however, be quite variable depending upon which part of the reef is most exposed to the waves. Storm waves striking the leeward side of an atoll, for example, will be very destructive as the reef organisms there are normally adapted to calm, protected sea conditions. In general the most exposed, smallest, and most fragile organisms are those most affected. Storm waves also move preexisting sediment and rubble. The transportation of this material not only results in additional abrasion but its deposition in new areas can smother and kill reef organisms. Even the ordinary day-to-day mechanical erosion produced by normal breaking waves is important. Portions of coral skeletons are broken off and ground against other skeletons producing particles from pebble to sand size. Sand and gravel are constantly moving around the reef forming bars and spits and accumulating in any depression or other area of lower energy on the reef flat. Even minor changes in swell direction can produce a readjustment in sediment movement. The normal bimonthly changes in tide height and tidal current velocity also result in a readjustment of sediment motion, especially in areas with large tide ranges such as the GBR. All this sediment motion produces additional abrasion to the reef and further breaks down and rounds the sediment particles.

The most spectacular mechanical damage to coral reefs is that produced by tsunamis. Though relatively rare in the Atlantic Ocean, destructive tsunami waves occur every few years in the Pacific Ocean basin. The presence of a well-developed coral reef off a shoreline appears to have a strong effect on tsunami waves. A reef may serve to absorb a significant amount of the wave energy, reducing the height and intensity of the wave impact on the shoreline itself. Though the impact of tsunamis on reefs is not well documented it can be quite dramatic. The 1883 tsunami caused by the explosion of Krakatoa is reported to have cast large blocks from the reef front onto the reef flat. The 1946 tsunami which originated in the Aleutian trench reportedly wrenched five-foot wide pieces of coral from the reef outside Hilo Bay, Hawaii and tossed them on the shore to heights more than 15 feet above sea level. Even more impressive is geologic evidence of an ancient landslide-generated tsunami which occurred in Hawaii about 100,000 years ago. Reef debris from this tsunami has been found deposited more than 1000 feet above sea level on the island of Lanai.

Earthquakes can also damage coral reefs. Though there are few accounts in the literature, off Central American an earthquake of Richter magnitude 7.1 is reported to have caused great damage to massive corals such as *Porities*, some of which disintegrated in place, while others were broken from their foundations and rolled or slid down slope. Foliaceous corals and branching corals such as *Acropora* were broken and fragmented because of their resistance to water motion. Earthquakes can also result in sudden changes in elevation, moving a reef up or down relative to sea level. A 1975 earthquake off the south coast of the island of Hawaii resulted in subsidence of more than three meters in the small cove at Halape. Corals and other reef organisms suddenly found themselves in a new environment. The sudden uplift of a reef area would obviously have a more disastrous impact on reef organisms by leaving them exposed above water. Periodic exposure due to normal tides is a regular physical occurrence on reefs, especially in areas with high tidal ranges. However, if very low spring tides happen to coincide with heavy rainfall or extremely hot weather, widespread mortality of reef organisms may occur. Such coincidences may occur as the "negative storm surge" of a tropical cyclone is combined with heavy storm rainfall. Likewise, the changes in sea level associated with El Niño/Southern Oscillation (ENSO) events are accompanied in many areas by unusually warm temperatures. The narrow temperatures and salinity limits to which most reef organisms are adapted make them especially vulnerable to changes in these properties. Fringing reefs tend to be those most affected as they are closest to coastal runoff with its potential for perturbing reef water temperature and especially salinity. Moreover, the high sedimentation resulting from coastal runoff as a result of tropical cyclones has been identified as the cause of most short-term reef destruction.

In recent years a phenomenon known as "coral bleaching" has been recognized as a special case of catastrophic coral mortality. In coral bleaching the corals lose their symbiotic algae and become white. If the event lasts for weeks or months the corals may actually die. Coinciding with the severe 1983 ENSO, a bleaching event occurred in the eastern Pacific killing between 70% and 95% of corals. The exact causes of bleaching are presently under study, but explanations include elevated water temperature, increased ultraviolet radiation, and disease.

Perhaps the most insulting physical causes of high coral reef mortality are those which result directly from human activities. Ironically, boats carrying coral reef enthusiasts to snorkel or scuba dive account for significant damage to corals through careless anchoring practices. Fishing trawls near coral reefs stir up fine bottom sediments which are in themselves detrimental to corals. These same fine sediments may also have high organic contents which results in an increased oxygen demand in reef waters producing a further adverse impact on the reef. But pollution may be the human impact which most threatens coral reef systems. Oil and chemical pollution and nuclear weapons testing are the obvious cases which come to mind but dredging, mining, land clearance and intensive coastal agriculture can have devastating impacts. Every year sugar refiners wash hundreds of tons of cane leaves and pulp into the ocean around islands in the Caribbean Sea and Indian Ocean. Though ocean dumping of cane wastes has long been prohibited in Hawaii, until recently sugar companies continued to dump wastewater loaded with fine sediment into coastal waters. Fertilizer-rich runoff from coastal agriculture and such seemingly innocuous activities as seaside golf courses may contribute to nutrient overload of coral reef environments. These excess nutrients may cause an increase in coral competitors such as fleshy algae and stimulate phytoplankton productivity. Increased phytoplankton densities not only reduce light intensity levels but may cause subsequent increases in zooplankton and possibly cause overfeeding of corals resulting in excess production which is shed as coral mucus. This mucus can serve as an attractive substrate for bacteria which may result in the death of the coral. Furthermore, some researchers believe that population explosions of the crown-of-thorns seastar (*Acanthaster planci*), which are important grazers on corals, may be directly related to phytoplankton blooms.

An instructive example of adverse human impact on coral reefs is offered by the case of Kaneohe Bay, Hawaii. This bay was once the site of an extensive, well-developed system of coral reefs. Small areas of the reef system were destroyed by dredging during World War II, but a post-war population boom had a much greater impact. Land clearing and urbanization so altered the retention capacity of the coastal watershed that by 1965 heavy runoff from storm rainfall resulted in mortality to corals to a depth of 1.5 m near streams and to a depth of 30 cm throughout the entire bay. A sewage outfall entering the bay resulted in intense eutrophication producing additional coral mortality. The combined effect was the overall destruction of some 70% of the former reef over a period of less than 30 years.

All of these physical causes of reef mortality make coral reef organisms more susceptible to mechanical disintegration and to bioerosion, a type of erosion produced by organisms themselves. Though bioerosion is not as dramatic or easily observed as the physical destruction of a coral reef, it is pervasive, persistent, and over the long term may produce even greater affects than physical erosion.

Bioerosion of Coral Reefs

Organisms erode coral reefs through various chemical and mechanical processes. This bioerosion has two major effects: (1) it creates new cavities in the reef and (2) it produces new sediment through excavation of these cavities. We will discuss bioerosion by first looking at the organisms and their activities which produce bioerosion and then at the resulting effects to the reef. We will also include in our discussion the effects of those organisms which alter preexisting sediments on the reef. Though various schemes have been used by different workers, we will divide the bioeroders into grazers, borers, and sediment burrowers.

Grazers

These are organisms which feed on live coral, encrusting coralline algae, and on tufted, filamentous and endolithic algae growing on dead reef substrate. Perhaps most dramatic of the grazers are those which attack the coral itself. Live coral is eaten by various worms, gastropods, sponges, nudibranchs, crabs, starfish and some 12 families of fishes. Though pufferfish (Tetradontids) are known to bite off and swallow the tips of growing coral, and surgeonfish (Acanthurids) to scrap the coral surface with their teeth, it is the activities of the parrotfish (Scarids) which have attracted the most attention from coral reef researchers. It was none other than Charles Darwin during his voyage on the *Beagle* who, after examining the gut contents of several parrotfish, recognized their role as agents of bioerosion. Parrotfish are now known to feed mainly on soft algae growing on dead coral substrates and less frequently on live corals. But even when feeding on the encrusting layer on dead coral they remove part of the substrate beneath it producing new sediment. Some species have been observed to ingest mostly sand and it has been suggested that they merely recycle old reef sediment. However, the pharyngeal mill of parrotfish, like the gizzard of surgeonfish, is very effective at grinding fragments of calcium carbonate into smaller sizes. Also it is likely that some fine $CaCO_3$ sediment particles dissolve while passing through the parrotfish gut. Parrotfish can therefore be considered as significant bioeroders by producing new sediment as a result of grazing on both living and dead coral substrates and by reducing the size of preexisting sediments they ingest.

Most of the grazing activities on live coral do not result in the death of the coral colony, there is however one major exception, the crown-of-thorns seastar. These asteroids feed on live coral polyps by everting and spreading their stomachs over an area nearly equal to their own diameter. They then secrete digestive enzymes onto the coral tissue, absorb the digested tissue as they withdraw their stomach, and leave behind the white skeleton of a dead coral colony. Population explosions of *Acanthaster* produced widespread mortality on the GBR in the late 1960's and early 1980's. These dead coral skeletons are then readily infested with algae which is in-turn grazed producing additional bioerosion.

Sea turtles have been observed grazing on algae covering dead coral and in so doing to leave characteristic scratches in the substrate. Gastropods also contribute to bioerosion on coral reefs through their grazing activities. In scraping off epilithic algae (which grows on the surface of the substrate), and shallow endolithic algae (which grows just beneath the surface of the substrate) with their radula they erode the substrate. The radula can scrap and scar the coral substrate because it is made of low-magnesium calcite which is harder than the aragonite of corals or the high-magnesium calcite of coralline algae. Even more abrasive are the teeth of chitons, some of which are composed of the mineral magnetite, which readily cuts into the softer reef rock.

Among all of the grazing bioeroders, it is probably the activities of the echinoids (urchins) which are most easily observed. In many areas, especially in the Caribbean and eastern Pacific, they are considered the major agents of bioerosion. *Diadema antillarum* feeds on living algae and possibly to a minor extent coral. They rapidly erode the substrate by scraping with the articulated plates of their Aristotle's lantern (their teeth) leaving behind characteristic star-shaped marks. On some reef areas it is thought that bioerosion by *Diadema* may be equal to or greater than carbonate production. The "mushroom" shape of many older coral heads is thought to be the result of the grazing activities of *Diadema* around their bases. It has also been suggested that the "halo" of bare sand that is often found separating reef from sea grass areas is produced by the grazing activities of *Diadema*. Like parrotfish, these urchins also ingest preexisting sediment but it is thought that some 65% of the sediment they excrete is new sediment formed from coral and coralline algae. In addition to being surface grazers on the reef, some echinoids may bore into the reef for protection hence overlapping with our next group of bioeroders.

Borers

These are organisms that bore holes into the reef substrate. A wide range of different organisms including both plants and animals are involved and produce holes ranging in size from a few microns to several centimeters in diameter. The smallest holes, only 1 - 5µm in diameter (1µm = 1 millionth of a meter), are thought to be produced by bacteria and fungi. Better documented is the boring activity of endolithic algae. Green, red, and blue-green algae (cyanophyta bacteria) are all known to be capable of eroding carbonate substrates. A greenish band, called the "Ostreobium band", visible just beneath the surface of the coral substrate, indicates the presence of live endolithic algae. The blue-green algae are known to possess special boring filaments which produce cavities between 5 and 15µm in diameter. The micro-boring activity of algae, bacteria and fungi is believed to be accomplished through biochemical dissolution of the $CaCO_3$. As the boring front advances downward into the rock it leaves behind a highly porous weakened rind. Experiments in the Caribbean with a boring green algae, *Phaeophila engleri*, indicate a boring rate of about 20-30 µm/year. Because all boring algae are photosynthetic, their distribution is largely controlled by sunlight which usually limits their abundance to waters less than 15 m deep.

As the activity of boring algae decreases with depth the importance of boring sponges as agents of bioerosion becomes more important. Boring sponges are found world-wide, occurring on both Caribbean and Indo-Pacific reefs, those of the clonid family being the most important. *Cliona* may form large chambers with smaller galleries branching off. The walls have pitted surfaces and the diameter of the galleries varies in size. These sponges bore by chemically etching around a small chip of substrate. The chip is then mechanically removed and conveyed out of the sponge through an exhalent canal. The chips range in size from 15 to 80µm, making them mostly silt size and therefore easily transported off the reef. Boring rates for sponges have been reported ranging from 1mm to as much as 1.4 cm/yr. Sediment production by sponges in Barbados has been estimated at 5-10 metric tons per hectare per year.

The activities of boring bivalves are also important agents of bioerosion on coral reefs. The mussel, *Lithophaga*, bores into both living and dead coral by a combination of chemical dissolution and mechanical action. They apparently secrete acid which softens the coral substrate and then remove pieces mechanically by a rocking motion of their shell. The borings may be as large as 2 cm in diameter, more or less straight, and have smooth interior walls. Some workers believe that bivalves may dissolve as much as 40% of some corals with their boring activities.

Various marine worms including sipunculids (peanut worms) and polychaetes (segmented worms) also bore into coral reefs. Polychaetes produce "U"-shaped tubes from 0.3 to 0.5 mm in diameter and are thought to bore by first chemically weakening the substrate and then mechanically removing the grains. Sipunculids, which may grow up to 2 cm in length, produce simple, blind, straight or gently curved tubes.

There are also boring gastropods, barnacles, zoanthids, bryozoans and crustaceans. Boring eunicids are believed to chew their way through the reef substrate using their sharp spade-like lower mandibles. The organisms which produce by far the largest holes are echinoids. Their boring success is thought to be achieved by the rotary action of their teeth and possibly spines. The urchin *Echinometra lucunter*, in particular, has been shown to produce significant quantities of fine sediment through its boring activities. They typically produce numerous closely-spaced, circular cavities, separated by sharp ridges. The surface of these cavities are usually smooth and barren and they apparently feed on endolithic algae and pieces of seaweed that drift into their holes.

Sediment Burrowers

Reef sediments, whether produced by physical erosion or bioerosion, may be further altered by the activities of organisms that burrow in or browse on sediment particles. Holothurians and herbivorous gastropods have acidic intestinal tracks which may result in significant dissolution of carbonate sediments that pass through their guts. As has already been mentioned, parrotfish and some urchins may also alter the grain size of sediment particles as they pass through their alimentary track. Goatfish (Mullids) accidentally ingest sediment while searching for invertebrates on the bottom. This activity along with the burrowing of worms, eels, and crustaceans may have little direct effect on the sediment itself but by moving the particles may produce additional sediment transport and certainly alter the structure of the sedimentary deposit. The effects of this "bioturbation" will be discussed in more detail later.

Variations in Rates of Bioerosion

The effects of bioerosion are highly variable on a coral reef. They vary by area, depth, substrate, organism, season and in many other ways. For example, on newly exposed substrates the types of boring activity vary with time showing a succession beginning with fungi and bacteria, and followed by algae, all within a few days. Within a few weeks sponges, and then polychaetes may arrive and commence their boring activity. Finally bivalves, barnacles and sipunculans will establish themselves. Each individual organism may excavate only a few millimeters but in so doing prepare the surface for the invasion of other organisms. However, major differences in this pattern of succession have been observed between the Caribbean and the GBR. In fact, there are major differences in bioerosion between many different geographic areas. Sponges appear to be more important as agents of bioerosion in the Caribbean than on the GBR. Also echinoids are important bioeroders on most Caribbean reefs but have little impact on the GBR. In general, there is a poorer bioeroding fauna on the GBR than in many other areas and this is thought to be due to the large tidal range which leaves much of the substrate exposed above water for extended periods of time. Plankton productivity has also been considered as another possible explanation for some geographic variations in rates of bioerosion. The number of boring bivalves infesting coral heads has been found to be highly correlated with regional plankton productivity, the eastern Pacific having the highest densities of boring bivalves, followed by the western Atlantic, the Indian Ocean, and finally the western Pacific with the lowest densities of boring bivalves per coral head. It has been hypothesized that growth of these filter-feeding bivalves are stimulated by the increased abundance of plankton.

Bioeroding communities also show variations within a reef system. A recent study revealed a cross-shelf trend in bioerosion on the GBR, where the density of boring organisms in *Porites lobata* was found to decrease with distance from shore. This is possibly the result of a decrease in the occurrence of bioeroding bivalves and sponges with distance from shore and/or the result of an increase in benthic grazing fish offshore. Other studies have shown that sheltered areas tend to have more diverse boring communities than fore-reef areas. In general, however, the intensity of bioerosion appears to be depth related, being most intense nearest the surface. Indeed, many of the major bioeroders such as endolithic algae and echinoids are restricted to the shallower parts of reefs. Clonid sponges have also shown a relationship between rates of bioerosion and water depth. In one study their sediment production ranged from 217 gm/m^2 per year at 40 meters to 1,806 gm/m^2 per year at 15 meters depth. However, their overall effect may be relatively greater at depth due to the decrease in biomass of coral and calcareous algae with depth.

One generalization, which gives an idea of the importance of this erosion process, is that bioerosion is capable of reducing a one meter high colony of *M. annularis* to sediment in only 150 years. Various coral reef researchers have attempted to rank the impact of different bioeroding agents by calculating their rates of bioerosion. However, these data should be treated with caution. Not only are the data from studies of limited areas but it should also be noted that bioeroding organisms show annual and seasonal variations in recruitment success. Furthermore larval recruitment of boring organisms may be heavily dependent on circulation and orientation of the available substrates on which they can settle.

In addition, most bioeroding organisms, especially borers, cannot infest a substrate as long as there is a layer of living coral tissue. Mortality to the corals can occur as a result of physical destruction or predation at any time of year. Opportunities for bioerosion are therefore greatly increased following a storm or a population explosion of *Acanthaster*. Obviously the timing of coral mortality and seasonal recruitment of bioeroding organisms will have a major impact on rates of bioerosion. In spite of the wide variations in rates, many coral reef workers agree that bioerosion is probably the most important agent of destruction in many reef systems. Because bioeroding organisms preferentially attack the exposed coral skeleton, their penetration is often concentrated around the edges and underneath coral colonies. Thus the foundation of a colony may be gradually weakened by bioerosion until it can no longer resist the shock of breaking waves and therefore succumbs to physical erosion. Skeletal surfaces freshly exposed due to physical breakage are attractive targets for new bioerosion, producing a vicious circle of physical and bioerosion. Next, we will examine in more detail these important feedback loops between physical and bioerosion in a coral reef system.

Feedback Processes in Coral Reefs Erosion

Feedback from erosion processes can operate to further increase rates of erosion (positive feedback) or to inhibit erosion (negative feedback). An example of a positive feedback loop between physical and bioerosion is the increase in surfaces available for bioerosion produced by fragmentation of corals due to storm waves. This same physical breakage of coral colonies also has negative feedback loops which help strengthen the reef structure. For example, freshly broken surfaces may be colonized not only by bioeroders but also by larvae of reef building organisms, including corals. Furthermore, a study of storm damage to staghorn coral *(Acropora cervicornis*) in Jamaica found that many broken and toppled colonies had become re-anchored and rapidly regrew. In addition, it is thought that the main means of propagation of this species is through fragmentation and not sexual reproduction. Hence, its dominance of Jamaican reefs may be attributable to storm damage.

Another example of negative feedback between physical processes and bioerosion was reported in a study of the grazing effects of *Diadema* on Caribbean coral reefs. These large urchins can be dislodged from the reef surface by heavy surf, hence they tend to avoid exposed areas during periods of storm wave activity. As a result bioerosion by *Diadema* is reduced on the exposed reef front during periods of heavy physical erosion there. The more protected backreef, however, maintains a high population of urchins and therefore experiences more constant high rates of urchin bioerosion. Also, increased bioerosion due to urchins is thought to result from reduced predation on the urchins by reef fish. Human exploitation of certain reef fish has consequently been implicated as the cause of increased bioerosion on some reefs.

Grazing by fish has it owns positive and negative feedback loops. Fish feeding on live coral produce a surface upon which boring larvae can settle without being preyed upon by coral polyps, thereby further increasing bioerosion (positive feedback). However, a study in Hawaii indicated that areas that were heavily grazed by parrotfish had higher recruitment of coral and coralline algae than areas of low fish grazing activity. This is thought to be the result of parrotfish reducing the abundance of algae which might successfully compete with corals for space. Damselfish (pomacentrids), on the other hand, kill corals in their territories in order to cultivate algae which they consume.

Fish grazing also affects the activities of borers which in turn affect the susceptibility of corals to physical destruction. A study of bivalve boring activity on coral reefs off of Costa Rica revealed that trigger fish frequently bite off pieces of live *Porites lobata* in order to feed on boring mussels underneath. Once the fish expose the bivalves they spit out the coral fragments, some of which are thought to serve as nuclei forming new colonies, i.e. both positive and negative feedback. The effect of the boring bivalves (*Lithophaga*) is, however, purely positive feedback. A strong relationship was found between the abundance of *Lithophaga* and the strength of *P. lobata*, with the weakest coral colonies having the highest numbers of boring bivalves. Bioerosion tended to be concentrated near the dead bases of corals, areas often killed by sedimentation. It is the coral bases where the stress from water motion is also concentrated, hence the combined effects of sedimentation, bioerosion and physical erosion all act in concert to produce broken colonies of *P. lobata*. As previously mentioned the abundance of boring bivalves appears to be greatest on reefs in areas with high plankton productivity. There are often areas where successful coral growth is already marginal due to high levels of nutrient enrichment and increased turbidity due to high plankton densities.

Boring bivalves are not without their minor negative feedback loops as many secrete calcium carbonate linings to their tubes which help cement the reef substrate. Some endolithic algae also secrete a high-magnesium calcite cement which helps bind the reef together. Bioerosion further promotes reef cementation by creating fine sediment particles which are then trapped in the highly porous structure created by bioerosion. The increase in porosity and permeability facilitates the circulation of fluids through the reef substrate further increasing cementation of the reef.

Even the sediment itself is subject to feedback processes. Once sediment particles are permanently buried most micro-boring on them ceases. However, organisms which re-suspended sediment, such as shrimp of the genus *Callianassa*, keep grains near the surface where micro-boring activity is vigorous thereby increasing bioerosion. On the other hand, thick sediment deposits laid down during storms may be subject to relatively little bioerosion, i.e. negative feedback.

Of course, the most important positive feedback loop is that between bioerosion and mechanical breakage of corals. Not only do heads of *P. lobata* become more susceptible to physical breakage as a result of bioerosion, a study of the *Acropora palmata* graphically illustrates the impact of bioerosion. Stems of *A. palmata* averaging 13 cm in diameter required a force of up to 60 kg to break, whereas stems of the same diameter weakened by bioerosion broke at forces between 23 and 35 kg, well within the range of forces found in waves from major storms.

Bioerosion versus the Sorby Principle

Before dispensing with the processes of sediment production we should mention the importance of the size and shape of the sediment particles produced on a coral reef. It is their size, shape and density which determine their hydrodynamic properties and hence the extent to which they will be transported both on and off the reef. The size and shape of sediment particles produced on coral reefs is thought by many researchers to be largely the result of the size and skeletal structure of the contributing organisms. This relationship between the shape and size of grains and the micro-architecture and skeletal structure of the organism is known as the *Sorby Principle*. For example, some researchers believe that the coral, *Acropora cervicornis*, first fractures into pieces of gravel whose size is determined by the dimensions of the branches, and then further degrades into 250 µm sand, whose diameter is controlled by the size of the aragonite crystal packets. *Halimeda* plates generally contribute to 1 to 2mm size part of the sediment, but upon disintegration to their aragonite micro-crystals add to the less than 64µm carbonate silt-size sediments. Whole foraminifer tests are an important component of many reef sediments, especially on beaches, lagoons and reef flats. Their initial size obviously controls their grain size as a sediment particle, with very large foraminifers such as *Marginopora* adding to the gravel fraction and smaller *Aphistegina* contributing to reef sands.

The origin of sediment particles smaller than 64µm, however, is very difficult to determine. Certainly the morphology of many smaller grains is strongly influenced by the crystal structure and mineralogy of the original skeleton, but the tiny chips ejected by sponges and the many other products of bioerosion also represent an important component of fine reef sediments. In fact, some researchers believe that the breakdown of organic skeletons into particles on both the macro- and micro-scales is controlled primarily by bioerosion and wave sorting of the particles and that purely mechanical fracturing and abrasion are not important factors under normal wave conditions. Storm waves can, however, in a few hours do the work of years of "normal" mechanical erosion. The Sorby Principle is, no doubt, a valid concept when considering the mechanical breakdown of reef substrates especially in regard to certain particular skeletal components of reef sediments. Bioerosion, on the other hand, should not be underrated as a factor contributing to the size and shape of reef sediment particles.

SEDIMENT TRANSPORTATION AND DEPOSITION ON CORAL REEFS

Earlier we indicated that sediments may actually control the growth and distribution of coral reefs. The preceding discussion on erosion has given you an idea of the numerous ways in which reef sediments are produced. It has been estimated that between 50% and 90% of the annual production of calcium carbonate by coral reefs is reduced to sediment. This may amount to anywhere between 5 and 20 Kg/m^2 per year. With such large amounts of sediment being produced, why are reefs not buried in their own debris? Actually, some do become buried and cease to be actively growing reefs, but most manage to redistribute and/or rid themselves of much of this sediment. Knowledge of the processes of sediment transport and deposition are important if we are to understand reef morphology and development. To better understand sediment accumulation and transport on coral reefs sedimentologists have developed the concept of a reef sediment budget. This can be expressed by the simple equation: $P_G - P_N = T_S$, where P_G stands for the gross carbonate productivity, derived by multiplying the standing crop of reef-building organisms times their production rate, and P_N is the net carbonate productivity, or in other words the carbonate ultimately incorporated in the reef. The difference, $P_G - P_N$, is "excess" carbonate production and may be considered to be equal to T_S, the sediment transported away from the reef. In fact, the excess carbonate ($P_G - P_N$) must be transported off the reef as sediments (T_S) or the reef will ultimately be buried. However, studies of some reefs have shown that under normal conditions $P_G - P_N$ may exceed T_S on an annual basis, yet these reefs appear to be healthy and not in the process of being buried by their own sediments. The important question is when and how are these excess sediments removed. Before solving this paradox we need to take a more in-depth look at the actual processes of sediment transportation and deposition.

Not only do erosion processes on coral reefs differ from those of virtually all other sedimentary systems, but so do the processes of sediment transport and deposition. Terrigenous sediments usually travel large distances from the places where they are eroded before finally being deposited. During this long transport process, the composition, sorting, shape, and size of the original grains is often radically altered, with the end product often reflecting more the transport and deposition processes than the source material. The processes of transportation and deposition are almost exclusively physical and dominated by water turbulence. The carbonate sediments of biological origin which dominate coral reefs are in contrast almost exclusively produced on the reef itself (endogenous). Much of the reef sedimentary carbonate is deposited *in-situ* or very near its point of origin, hence the distribution of sediment-producing organisms has a major impact on the distribution of reef sediments. Furthermore, though wave turbulence may dominant sediment transport and deposition processes on coral reefs, organisms strongly modify sediment deposits and in some cases actually transport sediments.

On most reefs only a tiny percentage of sediment particles are exogenous. These include bits of pumice and volcanic sand near areas of recent volcanism, the remains of planktonic organisms such as diatom frustules, *Globigerinoid* foraminifer tests and coccoliths, and a small amount of aeolian (windblown) dust, which occurs in the finest size fractions.

The biogenic origin and short transport distances of endogenous reef sediments gives these particles a much greater range of density and morphology than typically found in clastic sediments of terrigenous origin. Most grain size and transport relationships are based on studies of terrigenous sediments assumed to be quartz sand grains of spherical shape. Reef sediments have shapes ranging from the thin plates of *Halimeda*, through the blocky shapes of coral fragments, to the spheres and discs of many foraminiferal tests, (clearly demonstrating the importance of the Sorby Principle). Particle shape and microstructure has a strong influence on particle settling rates. Spherical and blocky particles tend to settle in a straight path, whereas thin plates and discs are inclined to oscillate while settling. Settling rates are also affected by particle density. Though the specific gravities of calcite (2.72) and aragonite (2.95) are greater than quartz (2.65), the micro-architecture of many reef sediments results in particles with a high percentage of pore space and hence a lower bulk density than quartz sand grains. At large sizes, density may be more important than particle shape, causing, for example, *Halimeda* plates to settle faster than more compact but less dense *Marginopora* tests. The result is that relationships between grain size, shape, and sorting are far more complex on coral reefs than in most other sedimentary environments.

In general sediment transport on coral reefs is dominated by three often interrelated processes: 1) currents generated by waves and tides; 2) gravitational settling; and 3) biological processes.

Physical Processes of Sediment Transport

Under the heading of physical processes which transport sediment we will consider gravitational settling as well as sediment transport by waves, tides and ocean currents. All particles which settle through the water column do so in response to gravity which pulls them vertically down toward the bottom. Lateral transport only takes place when some other mechanism, whether physical or biological, has displaced sediment particles horizontally. However, gravity alone rarely acts to produce sediment transport except on steep gradients where particles may slip or slide down slope primarily in response to gravity. This may produce sediment "creep", where the grains on the bottom are pushed down slope by the impact of other grains striking the bottom, and "slump", where an entire body of sediment moves down slope en masse. It should be noted that a small amount of horizontal transport over steep slopes can produce a large movement along the bottom as a result of settling in response to gravity. Furthermore, even after striking the bottom grains may roll some distance down slope in response to gravity before finally coming to rest. Consequently the impact of gravitational settling will have a greater impact on sediment along the steep slopes of a fore-reef than those of a flat lagoon floor.

Sediment transport produced by the motion of the ocean can be divided into that which operates under normal everyday conditions and that produced by short-term but extreme events, such as hurricanes and other violent storms. Under normal conditions water motion produced as waves pass over a reef will put some grains into suspension and move others along the bottom by bouncing, rolling and sliding. As particles are rolled back and forth across the reef, they are abraded and become more rounded, but little net displacement may take place as a result of the oscillatory motion of the waves. However, once this oscillatory motion has put the smaller particles in suspension, water movement due to tides or background currents are capable of producing net sediment transport, therefore water motion due to passing waves is extremely important. The instantaneous velocities produced by waves decrease dramatically with depth. For example, a 1.8 m high wave (7 second period) would produce an instantaneous maximum velocity of 1.52 m/sec at a depth of 3 m, a velocity of 0.43 m/sec at a depth of 15 m, and a velocity of only 0.13 m/sec at a depth of 30 m, so obviously wave-induced sediment transport is most effective on the shallower parts of the reef.

The maximum movement of sediment due to waves takes place just seaward of where the waves break, usually on the edge of the windward reef. Waves may lose more than half their energy here which often results in the formation of a coarse sediment deposit. Waves may then reform and travel across the reef flat. Shoaling of these reformed waves produces additional lose of energy resulting in further sediment deposition. These reef flat deposits may ultimately form a cay upon which the reformed waves may break. The importance of water depth in determining both maximum velocity of oscillatory currents from waves and the wave break point means that changes of water depth due to tides will have an important modulating influence on sediment motion caused by waves. At high tide, small waves may pass over the edge of the reef causing very little disturbance to bottom sediments, whereas these same waves are very effective at putting sediment in motion at low tide. Large storm waves, however, will produce maximum sediment transport with minimum energy loss during high tide. Wave set-up itself will increase water depth further influencing sediment transport efficiency. The bores formed as waves break may cause sediments put into suspension by oscillatory waves motion to move lagoonward across the reef flat and up surge channels.

Tidal currents may move already suspended sediment toward the lagoon during flood tide and out through reef passes in a seaward direction during the ebb. Tidal effects will naturally be greater in areas with macro-tidal ranges such as the GBR, but even in microtidal areas such as the Caribbean, tides may play an important role in both net sediment transport and in modulating wave-induced sediment transport. Sediment transport due to other types of water motion has also been suggested. Water motion of major ocean currents surrounding reefs may produce a background net transport of suspended sediments on reefs. Space photography of the Leeward Hawaiian Islands has clearly shown masses of white, cloudy water moving out of atoll lagoons and joining the background flow. Currents produced by density-driven circulation resulting from differences in temperature and salinity have also been proposed, as has water motion due to trapped or resonant long period waves with wavelengths of approximately 20 km, but little actual data is available on these potential sediment transport mechanisms.

The efficiency of waves transporting sediments is not only influenced by the depth of water but also by the size of the waves. Wave energy increases as the square of wave height, thus high-amplitude, long-period storm waves may have orders of magnitude more energy than everyday wind-generated waves. Most really large pieces of reef debris, such as reef blocks and boulders can obviously only be moved by very high energy storm waves, but the impact of storm waves on smaller sediment particles has only recently begun to be appreciated. It is now known that storms may move enormous volumes of sediment in a very short time. Studies in the U. S. Virgin Islands indicate that as much as half of annual sediment transport there may take place during as little as two weeks of intense storm activity. Large waves produce high velocity water motion capable of putting and keeping large quantities of sediment in suspension. Wave set-up produced during storms may permit waves to travel across even normally shallow reef flats. Water piled up in lagoons or in estuaries flows out through reef channels and passes transporting huge quantities of sediment off the reef into deeper water. Velocities of such strong seaward flow of water off a reef system have been estimated at 0.5-0.8 m/sec and their power was dramatically demonstrated in 1979, when water flushed out of the estuary off St. Croix in the U.S. Virgin Islands moved the 65-ton Hydrolab. It has been estimated that major tropical storms may remove the sediment stored on a reef during as much as 5 to 10 years. Following a major storm, sediments will be redistributed by the normal processes discussed previously. Particles too large to be transported by normal conditions will be left in place as so-called "lag" deposits. Finer sediments will be transported to areas of lower energy such as lagoons and the deeper water of the seaward slope where they will be deposited to await eventual incorporation into reef rock or remobilization by the next major storm.

A final sediment transport mechanism which operates on coral reefs is sediment movement by the wind. Since most reef studies concentrate on submarine processes wind transport of sediment is often neglected, furthermore it may be difficult to differentiate between wind and wave deposited materials. Obviously coarse debris such as gravel can only be transported by waves and currents, but fine sand and silt is undoubtedly transported from exposed cays into protected lagoons by wind action. The effects of wind transport are, perhaps, most obvious on reef cays where boulders and vegetation interfere with and dissipate wind energy resulting in deposits of fine and medium-size wind-blown sand which in some cases may eventually form dunes. Hurricane force winds are capable of transporting even coarse sand and granules, but such strong winds are usually accompanied by rain which tends to at least temporarily stabilize subaerially exposed sediments.

Biologically Mediated Sediment Transport

Disturbance of sediments by the activity of animals is common in many benthic marine environments including coral reefs. The process of sediment mixing called **bioturbation** is generally caused by animals which burrow in the sediments in search of food. It is important because it permits buried organic matter to reenter the reef food chain. Moreover, bioturbation also has a major impact on reef sediments. Burrowing organisms such worms and *Holothurians* take in fresh sediment at one end and expel the processed sediment at the other. As the sediment passes through their gut not only is organic matter removed but in some cases the sediment particles are also reduced in size due to chemical solution or abrasion. Some organisms appear to segregate sediments according to size, moving fine-grained material toward the surface. Stirring of sediments tends to undermine and bury larger particles such as empty shells and pebbles. This is important because once buried these particles are largely protected from both physical and bioerosion. Experiments have also shown that stirring of sediments by organisms tends to leave shells such as those of pelycepods in a concave-up position, whereas wave and current action tend to leave shells in a more-hydraulically stable concave-down orientation. The greatest overall effect on the sediment strata, however, is to destroy any internal layered structure by mixing the sediments.

Not only is the internal structure of the sediment altered but the sediment surface is often radically modified. In many sedimentary environments physical processes control the nature of surface features such as ripple marks, which are known as "bedforms." On coral reefs, however, it is biological activity which often dominates the configuration of the sediment surface. Many echinoids and gastropods disrupt the sediment surface by crawling over it. Some herbivorous fish graze on surface algae and eject ingested sediment via their gills, whereas goatfish push sediment aside in their search for infaunal invertebrates. These types of crawling and feeding activities are mostly nondirectional processes in that on their own they do not transport sediment in any particular direction. However as already mentioned, sediments can be transported significant distances by water currents too weak to initially suspend the sediments. Organisms that throw sediments into suspension may thereby induce significant sediment transport via weak currents. This may be especially significant on deeper parts of the reef where water motion due to waves rarely attains sufficiently high velocities to put sediments into suspension. So-called mound building organisms, which include various polychaete worms, garden eels, and shrimp are among the most important. In the normally low-energy backreef lagoon environments of the U.S. Virgin Islands the dominant mound builder is the thalassinid shrimp, *Callianassa*. Here mound densities in excess of 10 individuals per square meter have been measured. These tiny shrimp eject sediment 5 - 10 cm up into the water column. Studies have shown that the activity *of Callianassa* may suspend as much as 3.9 kg of sediment per square meter per day, which once suspended is then wafted along by bottom currents. Obviously, in areas of low wave energy this is significant in inducing sediment transport. Mound-building organisms may actually produce a local change in the bottom topography which then affects the response of the substrate to physical processes. *Callianassa* mounds may be as high as 30 centimeters and have steep side slopes near the angle of repose of the sediments (i.e. the steepest slope at which the sediment will remain stationary without sliding down slope). This activity may reduce by as much as 50% the current velocity necessary to suspend and transport sediments.

Bottom slope and gravitational settling can further enhance biologically-induced sediment transport. The plumes of sediment erupted by mound building organisms are generally ejected perpendicular to the bottom. On a sloping bottom gravitational settling will therefore result in net sediment displacement down slope. In fact, any biological disturbance of sediments on a steep slope may result in some down slope motion contributing to sediment creep. Even corals may contribute to down slope sediment transport. Most corals have some mechanism for ridding themselves of sediment particles. These include action by tentacles, entangling in mucus, distension of polyps by absorption of water in order to shed the unwanted particles, and ciliary action. As corals randomly reject sediment which falls on them, a net downward transport is produced and particles are moved from living coral toward sediment floored areas.

Also important on coral reefs is directional transport of sediment by organisms. Octopods, for example, prey on mollusks whose shells accumulate around their lairs thereby concentrating these coarse sediment particles. The sand tilefish, *Malacanthus plumieri*, lives in burrows on sand flats adjacent to coral reefs. They construct roofs for their homes from coarse coral debris which they carry from the reef to the sand flats, producing net transport of coarse debris away from the reef.

In summary, sediment transport in coral reefs systems is accomplished by a combination of physical and biological processes. Sediments are put into suspension by the rapid oscillation of water over the bottom as waves pass and by the activities of a variety of organisms. Suspended sediments are laterally transported primarily by wave surge, and tidal and background currents. Particles settle in response to gravity, which may produce some net sediment transport especially on steep slopes. Under normal, everyday conditions some reefs may accumulate more sediment than they lose due to transport. However, violent storms have shown that they are capable of removing enormous quantities of sediments from reefs systems, thereby keeping coral reefs from becoming buried in their own sediments.

Deposition of Sediment on Coral Reefs

Before a sediment grain is finally deposited to become a more or less permanent part of the structure of a reef system, it may have taken a very circuitous route around and through a coral reef. A sediment particle may originate as a fragment of coral is broken by wave action at the fore-reef and then be transported shoreward across the reef flat. It may be repeatedly transported and temporarily redeposited on the reef flat before making its way to the calm waters of the lagoon or another low energy area. It may become a permanent part of lagoon fill or be finally transported seaward off the reef into deep water by storm action. Those sediment particles that do become a more or less permanent part of the reef structure require two conditions before final deposition. First, the energy keeping the particles in suspension must be reduced enough to permit gravitational settling of the particles to the reef surface, and secondly, the sediment particles must be held in position and stabilized against further transport.

As discussed above the energy of water motion on a reef system varies enormously between prevailing conditions and storm events. In addition to varying with time it also varies spatially with large energy gradients in different directions over surprisingly short distances. In general, wave energy decreases going from shallow to deep water, and from windward to leeward across a reef. In addition there is a more variable decrease in wave energy going from more exposed to less exposed reef edges depending on the pattern of refracted waves. As already mentioned, physical and bioerosion of reef material initially produces a large range of different particles sizes. Large particles normally require high energy water motion to stay in suspension, whereas small particles remain in suspension with much lower water motion. The overall reef energy gradient should therefore produce a decrease in grain size from shallow to deep water and from windward to leeward on a reef system. However, the effects of bioerosion and the original micro-architecture of biogenic reef sediment particles produces a wide range of different particle densities. This results in hydrodynamic properties that deviate from a simple size:energy relationship as is often found in clastic sediments of terrigenous origin. Furthermore, the complex, irregular topography of a typical coral reef results in important local energy gradients. In fact, many of the particles of diverse sizes and shapes produced by the breakdown of reef skeletal material fall directly into cavities within the reef structure. These cavities, even those just below the high-energy fore-reef margin, are low-energy micro-environments. Sediments deposited *in-situ* like this are sometimes referred to as "internal" sediments, in contrast to "external" sediments which have been transported from another part of the reef system, and "exogenous" sediments which come from outside the reef system all together.

In addition to internal sediments deposited in cavities in the reef, the irregular surface of coral reefs also produces a reduction of water motion known as baffling. Baffling involves deflecting, absorbing and dispersing the energy of waves and currents. Baffles range in size from the entire reef, which serves as a baffle producing the overall leeward gradient in reduction of wave and current energy, to individual organisms. In fact any upright structure or object can serve as a baffle. Spurs and grooves, sand cays, patch reefs, coral heads, and a variety of other organisms may all have baffling effects. Baffling structures may cause lateral depressions in the sediment as a result of scouring along their sides, but the overall impact is a reduction in current velocity producing increased sediment deposition.

To keep a sediment particle from being re-suspended and transported by an increase in energy due to waves and currents it must somehow become stabilized. Once again we find that coral reef environments are unusual in regard to the impact of organisms on sedimentary processes as they can play a major role in the stabilization of sediment particles. On sand cays sediment deposits may be stabilized by terrestrial vegetation. Underwater the process is more varied. In some areas the roots of mangroves and *Thalassia* bind sediments on the reef flat. On flat bottomed areas with fine sediment, the mucus secretions of deposit feeders may serve to hold sediment particles in place. In many areas of sediment accumulation on a reef, benthic diatoms, fungi and most importantly mats of filamentous algae serve to bind sediment grains. A study in Cane Bay, St. Croix, U.S.V.I. indicated that sediment movement on the fore-reef was largely controlled by the algally-bound surface sediment layer. The algae was so efficient at inhibiting sediment transport that a critical energy velocity sufficient to rip up the algal mat was required in order to expose sediment grains and permit their suspension. The effectiveness of algal mats is, of course, dependent on the continuity of the cover, the type of algae and the smoothness of the mat. Bioturbating organisms may, however, locally disrupt the mat decreasing its efficiency. Some bioturbating organisms, on the other hand, tend to be sediment stabilizers themselves. For example, chaetopterid polychaete tube worms, common on central Pacific and eastern Australian reefs, stabilize sand in constructing their tubes. In some areas of Hawaii these worms are found at densities of thousands per square meter and may have a significant influence on sediment stabilization. Finally, encrusting algae and some sponges may give a protective coating to parts of the reef surface, thereby sealing off sediments from future suspension and transport.

The initial stabilization of sediment particles by biologic or other means allows time for long-term stabilization through chemical or biochemical cementation which ultimately produces a solid, sedimentary reef rock. Before examining cementation processes, however, let's look at the typical distribution of sediments on a coral reef and at variations in sediment distribution among coral reefs in different parts of the world.

SEDIMENT DISTRIBUTION ON CORAL REEFS

Earlier we stated that the entire coral reef could be considered a sedimentary rock. We should, however, distinguish between two distinct types of deposits which make up a reef: the rigid framework, and the sediments. The framework is usually composed of interlocking colonies of hermatypic corals and encrusting calcareous algae buried *in-situ*. Loose sediments which become part of the reef are deposited within this framework. Geologists consider the framework as a type of sedimentary rock, however, here we are mainly concerned with the loose sediments and their distribution.

We'll begin by looking at how sediment grain size and sorting vary on a coral reef system. In general there is a correlation between particle grain size and the prevailing hydraulic energy of the sedimentary environment. Thus we could expect to find the coarsest sediments in those areas with the highest energy of turbulent water motion and the finest sediments in those areas with the calmest prevailing conditions. As an approximation this is true on most coral reefs. Most other sedimentary environments also have a strong correlation between turbulent energy and degree of sorting of sediments, with high energy beaches, for example, having a high degree of sorting. In spite of the generally high levels of turbulent energy found on coral reef systems, they are notable for their poorly sorted sediments. This can be explained by the fact that most reef sediments are organic skeletons which come in a variety of shapes and sizes, and many sediments are rapidly deposited near their point of origin without having the opportunity to be sorted by turbulent water motion.

A useful way of conceptualizing reef sediment sorting is to divide the sedimentary deposits into three classes: (1) immature, (2) mature, and (3) lag sediments:

(1) Immature sediments are basically "death assemblages" made up of organic skeletons near their source of origin and have their size, shape and sorting determined by that of the original organism (i.e. the Sorby Principle). These are generally poorly sorted, unless strongly dominated by the remains of a particular type of organism.

(2) Mature sediments are those that have been transported from one part of the reef to another and have been deposited in energy equilibrium with prevailing conditions of turbulent water motion. These sediments tend to have the highest sorting found among reef sediments.

(3) Lag deposits are normally made up of sediments transported to the site of deposition under high-energy storm conditions, and which are too large and/or dense to be further transported by the normal, prevailing hydraulic energy of the environment. They may also include coarse sediment formed in place by large organisms.

Most reef sediments are mixtures of these three sediment classes. The proportions of the sedimentary mixture are partly determined by the energy of the environment and partly by the ecology of the environment. Areas with low hydraulic energy may not have enough turbulence to remove even fine particles and produce significant sorting, hence they may be dominated by immature sediments with additional fine sediments transported to and settling out at the site. Areas with high turbulent energy may be dominated by coarse sediments of local origin as well as those transported to the site. Fine sediments will generally be absent and sorting will be better than for many low energy areas. The reason it is so difficult to make firm rules governing reef sedimentary processes is that reefs are subject to quite dramatic variations in energy conditions. A storm may quickly change the sediment grain size and degree of sorting of a particular site. Following a storm, prevailing conditions will begin to redistribute the sediments but leave lag deposits behind. Lag deposits will produce poor sorting in a normally well-sorted area of moderately low energy. Calm weather conditions and their low energy levels will permit locally produced fine sediments to remain in normally high energy environments producing poor sorting there.

To further complicate matters, the important process of bioerosion normally produces sediments with a bimodal grain size distribution. The smaller particles are made up of tiny fragments such as minute sponge chips excavated by bioeroders. The larger particles are fragments of coral skeletons so weakened by bioerosion as to collapse. Bioerosion therefore has a strong influence and in some cases may even control sediment sorting.

Reef Zones

In spite of the complexity described above, it is still possible to recognize sedimentary assemblages characteristic of particular zones of a coral reef. This is true because the relative importance of sediment formation, transportation and deposition processes vary between zones. Wave sorting will dominate in some areas, whereas gravitation settling will be significant in others, and still others will be largely dominated by biological processes. As we discuss each reef zone, bear in mind that hydraulic energy usually decreases in both landward (lagoonward on atolls) and seaward directions from the edge of the fore-reef zone.

Reef Front zone

As you will recall the reef front zone extends seaward from the algal ridge, through a system of spurs and grooves, and often terminates with steep seaward slopes in relatively deep water. Because of the change in depth from algal ridge to the deep seaward edge of the reef front, there is a wide range in available hydraulic energy. This often produces a bathymetric gradient in grain size going from large blocks and boulders below the reef crest, through coarse fragments of coral and *Halimeda* sand at intermediate depths, to fine sand and silt near the deep water boundary of the reef. Much of the fine sediment may have been transported from the lagoon by currents during periods of increased wave activity to settle out in the calm waters at the base of the reef front. The seaward-most area of fine sediment may also contain a minor amount of fine pelagic particles such as tests of globigerinoid foraminifers and coccoliths, as well as siliceous sponge spicules of reef origin. In some areas the fine-grained sediments may be poorly oxygenated and partially anaerobic, containing a relatively high amount of organic matter.

There is also a general decrease in sediment transport rates with depth across the reef front as the energy of water motion decreases. However where steep seaward slopes occur, gravitational and biologically-induced gravitational transport processes are intensified. Finally on the deepest parts of the reef front biologically-induced processes may completely dominate sediment transport.

Particle sorting also tends to decrease with depth in response to decreasing hydraulic energy and addition of immature sediments which add larger particles to the fine sediments accumulating in low energy areas. In contrast, there is almost no net accumulation of fine material in the shallowest areas, where sediments typically form coarse-grained coral-Halimeda conglomerates. The floors of grooves along the reef front buttress zone are usually covered with a mixture of poorly sorted coarse sand and pieces of larger rubble.

A comprehensive study of sedimentation on a Caribbean coral reef showed the expected decrease in grain size going from shallow to deep water in the reef front zone with three distinct modes occurring: granules, sand, and silt. Each mode had its own distinct composition. The granules were almost exclusively *Halimeda* plates. The sand was composed of fragments of coral, coralline algae, mollusks, and benthic and pelagic foraminifers, and the silt was made up of fine carbonate particles with an abundance of sponge chips.

Some studies have attempted to identify sediments from different zones of a reef by using special indicators. In some areas deep reef front sediments have been distinguished from shallow reef sediments through the dominance of deeper growing species of *Halimeda* in the sand fraction. A study at Moorea in French Polynesia found that different species of foraminifera could be useful in differentiating shallow reef front sediments from lagoon sands and sediments occurring on the reef flat. The shallow reef front assemblages of foraminifers were dominated by large (> 500µ), hermatypic species such as *Amphistegina*, whereas assemblages in reef flat and lagoon sand areas were dominated by small, agglutinated species living embedded in cavities hollowed in sediment particles.

Reef Flat

The reef flat zones extends from the algal pavement through the an area of boulders, rubble and shingle to a sub-zone of coral, and finally to the sanded reef flat adjacent to the lagoon. In general, the reef flat has mixed assemblages of mature and immature sediments, though on some reef flats a concentric zonal arrangement in grain size can be found going from coarse behind the high turbulence algal ridge to fine nearest the lagoon. Gravity and bio-induced gravity transport are negligible on the reef flat because it is normally almost horizontal.

In shallow grooves on the pavement and extending across the boulder zone are found very coarse sediments consisting of coral fragments, gastropod shells, and whole tests of foraminifers, such as *Homotrema*. Sands occurring in the coral and sanded reef flat areas are frequently composed of smaller fragments of coral and coralline algae, *Halimeda* plates, broken echinoid spines and plates, and foraminifers, such as *Gypsina*. Where low turbulent energy allows the deposition of silt, sponge chips and other fine carbonate debris dominate. On some reefs there is a tendency for sands nearest the algal ridge to be composed largely of tests of foraminifers because of the abundance of these organisms living in this zone. The composition gradually changes through the coral zone to sands dominated by *Halimeda* plates as the abundance of living *Halimeda* increases in this area.

Sediments from the reef front and seaward parts of the reef flat may move leeward and accumulate in bars which may develop into sand cays. These cays are highly unstable and migrate across the reef flat ultimately delivering their sediment to the lagoon. In the meantime they serve as repositories of surplus reef sediment and under some conditions, with sufficient vegetation and cementation, may become at least temporarily stabilized. These reef flat cays and their beaches are composed almost entirely of transported assemblages of mature sediments and totally dominated by wave-induced physical processes. Though some subaerial cay sediments may be transported by the wind, almost all beach sediments are lifted into turbulent suspension by breaking waves and transported laterally by beach drift and longshore currents.

Coral reef beaches are usually very steep and composed of large size particles. Windward beaches may be made of boulders or shingle, and even leeward reef beaches are no finer than coarse to medium sand. It is the large grain size which is responsible for the steep beach slopes due to the high rates of percolation into coarse sediments. This produces a weaker wave backwash than up rushing swash which gradually carries sediments further and further up the beach face until a steep angle is achieved. During storms some beach material may be pushed over the beach berm toward the lagoon as overwash deposits or held in turbulent suspension and lost from the reef to deep water. Since coral reef beaches are composed of carbonate sands which are less resistant to abrasion than silica sands, the grains undergo a significant mechanical reduction in size even under normal wave conditions. Eventually the particles become small enough that they will remain in suspension and be transported into the lagoon or carried out of the reef system entirely.

On many coral reefs the reef flat has the most complex sedimentology of all the zones. The energy regime is constantly changing in response to minor variations in the size and direction of ocean swell and local wind-generated waves. Tidal changes often further complicate the picture. On parts of the GBR for example, the highest winds and hence strongest locally-generated waves usually occur at the same time each day, however, the timing of high and low tide is continually changing. At low tide small waves are efficient at putting sediments into suspension and washing them toward the lagoon. By contrast during very high water refracted waves may bend by as much as 180° and actually break on thte lee side of some reefs and cays. In spite of their high variability, reef flats do serve as important energy buffers in the reef system by absorbing wave energy and leaving a relatively calm lagoon in their lee.

Lagoon Zone

For virtually all reefs which have lagoons, they serve as the most important sediment sink. Lagoons collect sediment washed from the neighboring reef flat as well as from patch reefs within the lagoon itself. On some reefs prograding sheets of sand can be seen sloping down into the lagoon from the adjacent sanded reef flat. Not only do sediments move from windward reef areas into the lagoon but in some lagoons may continue moving across the lagoon toward leeward reef areas.

Lagoon sediments are typically medium size sands but may show a grain size zonation by depth with finer sediments in deeper water. Only the very deepest lagoons however accumulate sediments as fine as silt. Sorting tends to be poor often showing a bimodal grain size distribution due to the mixing of mature, fine sediments transported into the lagoon with coarse, immature sediments produced on local patch reefs. In fact, local production of sediment within some lagoons actually produces a zonation depending as much on the abundance of contributing organisms as on water depth.

The sedimentary environment of the deep reef front zone and the lagoon are similar in a number of ways. Both have less hydraulic energy and are deeper than the reef flat and both may have large amounts of fine sediments which, due to low water motion, may become poorly ventilated and partially anaerobic with high concentrations of organic matter, thereby supporting a dense population of infaunal deposit feeders. Both zones also have lower ambient light levels than other parts of the reef. This is due to water depth on the deep reef front and, in the lagoon, is a result of high turbidity from suspended material. Biologically-induced sediment transport processes are also extremely important in the lagoon. Currents in most lagoons are insufficient to erode sediment particles, however, high rates of sediment suspension may be produced by mound builders and other organisms. The normally weak bottom currents may be capable of transporting these suspended sediments for significant distances before they settle out again. Baffling by sea grasses also occurs in some lagoons which is important in stabilizing sediments.

The general windward to leeward decrease in grain size found in some lagoons may be largely the result of short-term high-energy storm events such as hurricanes and typhoons, which are capable of producing high hydraulic energy even in protected lagoon environments.

The occurrence of patch reefs in many lagoons has a major impact on lagoon sediment distribution. They do this in two ways. First patch reefs modify the circulation in lagoons by serving as obstacles to current flow. The protected down-current side usually builds up a tail of deposited sediments. Secondly, patch reefs add immature sediments to the lagoon thereby introducing coarse material. Some researchers believe that the accumulation of coarse reef debris in the energy shadows of patch reefs permits colonization and growth of corals and results in the leeward propagation of these reefs. Others argue that the accumulation and shifting of these sediments restricts the substrate suitable for coral colonization and reef growth.

Even the accepted role of lagoons as the reef's most important sediment sink has been questioned by researchers. It may be in some cases that as a lagoon becomes filled up it changes from being a sediment sink to a sediment source, with fine material actively winnowed and transported out of the lagoon and off of the reef system into deep water.

Geographic variations in Coral Reef Sedimentology

The sedimentology of coral reefs in different geographic areas varies due to differences in the importance of physical and biological processes and in the availability of various sediments. One of the most fundamental differences in reef sediments is found between oceanic reefs far from land and coral reefs that lie adjacent to continents, subcontinents, or large volcanic islands. In general, the sediments on oceanic reefs are almost entirely composed of calcium carbonate of local origin with only a very minor addition of pelagic carbonates, siliceous sponge spicules and diatom frustules, and aeolian dust of terrigenous origin. However, reefs near continents such as Australia and Africa or subcontinents like New Guinea and Madagascar may have a significant amount of terrigenous input. In the giant lagoon of the GBR, for example, the carbonate to non-carbonate ratio is probably the most important parameter in explaining sediment distribution. There tends to be a very abrupt change from carbonate-poor to carbonate-rich sediments going from shore toward the barrier reef. This is not only due to the location of the source areas but also no doubt largely due to the ineffectiveness of physical processes in redistributing sediments through the deep water of the lagoon. The picture is, however, complicated by the occurrence of relict sediments and by the effects of rising sea level since the last ice age.

The influence of volcanic islands is demonstrated in studies of coral reef sedimentology in French Polynesia. Inside the barrier reefs in Tahiti sediments off the mouths of rivers contain more than 75% terrigenous material whereas near the reef the lagoon sediments are more than 60% calcium carbonate. Where the central island is much smaller, such as at Bora-Bora, the lagoon sediments are 98-100% calcium carbonate in spite of the remanent volcanic structure, and in atoll lagoons sediments are >99% carbonate. These sediments are dominated by fragments of coral and coralline algae, foraminifers, bryozoans and *Halimeda*.

On the GBR even the distribution of carbonate-rich sediments is related more to source than physical processes. One study found that the distribution of the five most abundant sediment components, which together made up more than 90% of the reef sediments, was controlled primarily by the distribution of organisms which produced the particles and only secondarily by sediment transport due to wave and tidal currents. For example, echinoderms make a significant contribution to sediments only in the muddy areas which echinoids favor. *Halimeda* flakes, on the other hand, are a significant component of sediments only near the reef and decline to <1% on the shelf away from the reef. The distribution of sediments from encrusting coralline algae are similar to that of *Halimeda* only more restricted. This is probably because the encrusting coralline algae are thought to be more resistant to erosion than either coral or *Halimeda* and on the GBR may furnish a smaller supply of sediment than less erosion-resistant corals. In other reef areas, however, encrusting calcareous algae contribute large amounts of sediment due to their high growth and turnover rates in spite of a sometimes deceptively small standing crop. The distribution of the coral component of the sediments on the GBR is remarkably similar to that of *Halimeda*. It has even been suggested that the abundance of *Halimeda* sediments could be used as an index of reef influence on the overall sedimentology. *Halimeda* is, in fact, one of the most important sediments on many reefs worldwide and as such merits a closer look.

There are three genera of codiacean green algae which are of special importance in modern reef sediments. *Penicillus*, called the merman's shaving brush, produces extensive meadows in the Caribbean and may also make a significant contribution to sediments on the GBR. *Tydemania* has been found growing abundantly in shallow areas of Indonesian reefs and was found to be common at depths below 8 meters in the lagoon at Enewetak in the northwest Pacific. Though once thought to be rare, this genus is now believed to be an important sand former on some Indo-Pacific reefs. Only *Halimeda*, however, has truly global importance in tropical seas. This genus, which superficially resembles a tiny cactus, appears to be able to colonize most zones of a coral reef due to its ability to survive in shallow, high energy environments as well as in deep, low light regimes. There are, however, three reef areas where *Halimeda* populations tend to be especially large: in sand areas of the reef flat and lagoon, in the area just behind the algal ridge, and in the reef front zone. On the seaward fore-reef slope at Enewetak, living *Halimeda* was found to cover from between 10% and 50% of the substrate down to depths greater than 110 meters, before finally disappearing at 140 meters. It has been observed growing as deep as 150 meters in the Bahamas, much deeper than hermatypic corals.

On many reefs *Halimeda* sediments are quite abundant even though the standing crop of living *Halimeda* appears to be relatively small. This is because of the high growth and turnover rate of *Halimeda* as compared to coral and encrusting coralline algae. *Halimeda* can shed and regrow fronds at an astonishing rate, with an individual plant producing a new segment every three or four days. In the central GBR it has been estimated that *Halimeda* biomass can double in only 15 days, with an average production of 7 grams of $CaCO_3$ produced per meter square each day. Calculations have shown that this rate of production could equate to a lagoon sedimentation rate for *Halimeda* flakes of as high as 14 cm per 1,000 years.

Halimeda forms both coarse sand and fine silt size sediment grains in the following manner. Breakdown of the plant's binding organic matter causes the shedding of individual lobes. The lobes may then separate along the axial void into two halves of approximately equal size. Pores, called “utricles,” which occur perpendicular to the surface of the segments, permit breakdown into fine sand and eventually silt-sized needles of aragonite.

The importance of *Halimeda* in Caribbean and Bermuda coral reef sediments cannot be overstated. In many West Indies sediments most sand larger than 1mm is produced by *Halimeda* and in many areas it constitutes more than 50% of all sediment. Other common constituents to the coarse sand fraction of Caribbean reef sediments are coral and molluscan shell fragments, coralline algae, and the red sessile foraminifera *Homotrema rubrum*. The fine fraction contains much unidentifiable carbonate silt, as well as sponge chips, sponge, holothurian and gorgonia spicules, and aragonite needles from *Halimeda* and *Penicillus*. Aragonite needles in different areas of the Caribbean may have different origins. In Florida Bay and the Bahamas they are produced by the codiacean green algae, whereas off Andros Island they appear to be produced by inorganic precipitation. Other non-skeletal carbonates such as oöids and pellets are found in the Caribbean.

On many reefs in Jamaica, *Halimeda* is the largest single component of the total carbonate produced, accounting for up to 80% of the sediment! Jamaican reefs are of the fringing type, and like all fringing reefs most of the sediments must be transported seaward to keep from burying the reef from behind. Here many reefs contain v-shaped chutes through which dammed-up sediments pour out onto the fore-reef producing detritus cones on the seaward slope. These sediments are highly unsorted with large amounts of fine material. Sediment transport through these chutes is thought to be most active during major storms.

As a gross generalization, we can say that we generally find *Halimeda* and coral fragments to be more important in Caribbean reef sediments than in those of Indo-Pacific reefs, where encrusting coralline algae fragments and benthic foraminifers may dominate sediments.

CEMENTATION, DIAGENESIS, AND BEACHROCK

The internal structure of a coral reef is composed of the skeletons of in-place primary and secondary frame-building organisms, of loose sediments, and of cavities ranging from large voids beneath organisms to small pores in the skeletons of organisms. With time this structure may be changed into a firm sedimentary rock, known as reef rock, and eventually into a dense, solid limestone. This transition from reef skeletons to limestone can be divided into phases of binding, cementation, and finally diagenesis.

Cementation

The first phase in the consolidation of the reef material is binding of the corals and other primary frame building organisms together by so-called secondary frame builders. The encrusting calcareous algae are perhaps the most important group of organism in binding the underlying reef material, as they cover the coral framework with a tough resistant calcareous skin. On those parts of the reef most exposed to wave energy, lithothamnoid algae are important binding organisms especially on Indo-Pacific reefs. In the Caribbean, *Milleporina* may play a major role as a reef binder on the reef crest and outer reef flat. On the deeper fore-reef the colonial foraminifera *Gypsina* and encrusting red algae are important in contributing to binding and initial cementation.

Bioeroding organisms also contribute to initial cementation and binding by boring holes into the reef substrate which fill with sediments that then may become cemented in-place. In this manner some of the primary framework is gradually replaced by cemented sediments.

Cements are also precipitated in cavities within skeletons, between loose sediments, and within sediment particles. This process may begin very early with inorganic crystal growth having been observed just beneath the surface of living coral and calcareous algae. Cements vary widely in composition and crystal form from pore to pore within the reef. The most common cements are aragonite and magnesium calcites, which show diverse textures and fabrics (i.e. crystal orientation and packing), and may be present in both voids between skeletons and in internal skeletal pores. A detailed study of cementation on the GBR found a significant cross-reef trend with the degree of cementation increasing from the inner to the outer shelf. Seaward reef margins were reasonably well cemented whereas leeward areas showed little inter-skeleton cementation and only rare cementation of unconsolidated sediments. This was related to two other cross-shelf trends on the GBR: (1) the percentage of loose sediment, and (2) the level of hydraulic energy. Reefs near the outer edge are 80-90% primary or secondary framework as opposed to reef along the inner edge which are only 18-30% framework, the remainder being unconsolidated sediments. Submarine cements were only rarely found within the pores of loose sediments, which is thought to be related to their high porosity and permeability. It is possible then that the decrease in cementation from outer to inner shelf is related to the increase in loose sediment. The distribution pattern of sediments is, of course, related to the hydraulic energy, but the formation of submarine cements has also been directly related to the hydraulic energy of the environment. It is believed that large volumes of seawater must be pumped through a coral reef in order to precipitate substantial amounts of carbonate cements. Efficient pumping may be the result of pressure gradients produced by the build up of oceanic water against the seaward edge of the reef. This could be accomplished by tidal processes and/or by wave action. Tides could renew pore fluids with each tide cycle and on reefs with restricted lagoonal circulation, tides could also produce a hydraulic head between the outer reef and the lagoon. Large surf would produce a hydraulic head with each breaking wave and as a result of overall wave set-up.

A trend in degree of cementation similar to that of the GBR has been reported in Belize. Other reef studies in the Caribbean have, however, found no clear zonation in degree of cementation and much work remains to be done to clarify reef cementation processes. To further complicate matters, on fringing reefs and barrier reefs adjacent to continents or large islands, cementation may be related to ground water diffusing through subtidal portions of the reef. It has also been suggested that the daily change in pH produced as a result of daytime photosynthesis and the night-time surplus of CO_2 from respiration could result in cycles of dissolution and precipitation of cement in some reef micro-environments.

Diagenesis

Binding and initial cementation result in a highly porous, poorly consolidated, partially cemented, reef rock. The process of **diagenesis** produces a more compacted, less porous, better cemented limestone. This occurs mainly through repeated solution and reprecipitation of the reef carbonates. Much of this is believed to be related to exposure to meteoritic waters (i.e. of rain water origin) and thought to take place in the vadose and phreatic environments. The **vadose** zone lies above the water table and is characterized by slowly percolating fresh water. The **phreatic** zone lies beneath the water table and though processes here are poorly understood it is thought to be an area of rapid chemical solution and reprecipitation. Reefs may be exposed to meteoritic waters at present as the fresh water table is known to extend below sea level beneath many reef islands. But probably more significantly, most reefs have been exposed to meteoritic waters as a result of the lowering of sea level during the Pleistocene ice ages.

The overall process of reef rock diagenesis is one of solution of the original skeletal carbonates and precipitation of low-magnesium calcite, but is much more complicated in its details. For example, the carbonate mineral deposited by foraminifers and coralline algae is usually high-magnesium calcite. It is more soluble than the aragonite of corals and mollusks and is therefore more rapidly replaced by low-magnesium calcite. The chemical replacement of corals is generally slower but can occur at varying rates which have different results. Slow movement of fresh water through the reef rock can cause solution and reprecipitation on a small scale which preserves much of the fine structure of the original skeleton. Rapid movement of fresh water, on the other hand, may quickly dissolve the entire coral structure leaving a void which will only later be filled with coarse calcite crystals. To further complicate matters, different species of coral have different rates of alteration.

Beach Rock

Another type of sedimentary rock commonly found associated with but not unique to coral reef environments is beach rock. The term has been used rather loosely to describe limestones with different morphologies, structures and cements, but of which all form in the intertidal zone. The sediments which make up the rock are dominantly carbonate, but can range in size from boulders to fine sand. It was once thought that beach rock was formed by meteoritic waters percolating through carbonate beach deposits, but the presence of beach rock on arid atolls with no fresh water indicate that there may be a variety of different mechanisms and cementation processes, including aragonite cements forming from seawater. Whatever the process or processes they appear to be related to tidal wetting during high water and drying during low tide which produces partial dissolution and reprecipitation of enough calcium carbonate to cement the beach deposits in place. The thickness of the cemented strata tends to correspond to the tidal range, with only very thin deposits occurring in microtidal areas and deposits up to 3 meters thick found on the GBR. In some areas beach rock appears to form quite rapidly, with soft drink cans and World War II artifacts having been found surrounded by deposits. More precisely, beach rock has been reported to have formed within two years at Dry Tortugas in the Caribbean and in only six months at a site on the GBR. In spite of the apparent rapid rate of formation, it is usually absent from highly mobile beach areas such as spits on the ends of cays. It has been suggested that vegetation may play a role in temporarily stabilizing cays long enough for beach rock to form. Once formed, however, the beach rock armors sand cays and helps them resist erosion. The presence of beach rock has been used in coral reef studies to indicate recent changes in the trend of the coastline and to mark the positions of older sea levels.

Like other reef substrates beach rock is subject to both physical and bioerosion. Regional differences in beach rock bioerosion can be found. In the Caribbean there is a rich and varied fauna of bioeroders made up of large numbers of boring and grazing organisms. These organisms show a vertical zonation, with grazing species occupying the higher tidal positions. Studies of the vertical zonation of bioerosion on raised beach rock have been used to estimate levels of ancient tides. On the GBR, however, few boring organisms are present and grazing forms dominate bioerosion processes on beach rock. This is thought to be related to the much greater tidal range of the GBR, which would leave less mobile boring fauna stranded for long periods.

Beach rock, reef rock, and even well-consolidated reef limestones are all subject to erosion processes when raised above sea level. The results of this erosion in a coral reef environment are rather unique and merit discussion. One such product, called simply "guano", has been of important economic value for use as fertilizer. It is, in fact, a deposit of calcium phosphate rock and was collected extensively from coral atolls during the last century. One scenario for its formation is as follows: Humus accumulating under trees is very acidic. Bird dropping have a pH ranging from 6 - 7, and rain water is also slightly acidic. As bird guano is washed by rain water and acidified by humus any phosphate goes into solution. As this acidic solution seeps through the calcium carbonate reef rock, the calcium carbonate is dissolved and replaced by calcium phosphate, leaving behind a deposit of phosphate rock.

In general emerged islands of reef limestone tend to be readily corroded by both rain and sea water. The deeply etched, topography is termed "karst" by geologists and on land is characterized by solution features such as caves and sink holes. A study of the shores of reef islands reveals three board categories of geomorphic features as you pass through the intertidal zone:

(1) A **supralittoral** zone which is marked by pits, pans, pinnacles and honeycomb structures. These are formed by both rain water and the chemical effects of the expansion of salt crystals from sea spray. In addition, lichen roots, algae, grazers and mobile borers leave their impact.

(2) A **mesolittoral** zone, which corresponds to the site of maximum wave action, is marked by overhangs with one or more undercut notches. Erosion is both physical and biological, including mechanical abrasion by sand, hydraulic pressure from waves, chemical solution, and bioerosion.

(3) An **infralittoral** zone lies just below the low tide line and may be marked by submerged undercut notches. These features may be the result of abrasion by sand confined to narrow channels or simply be karst features inherited from a low stand of sea level.