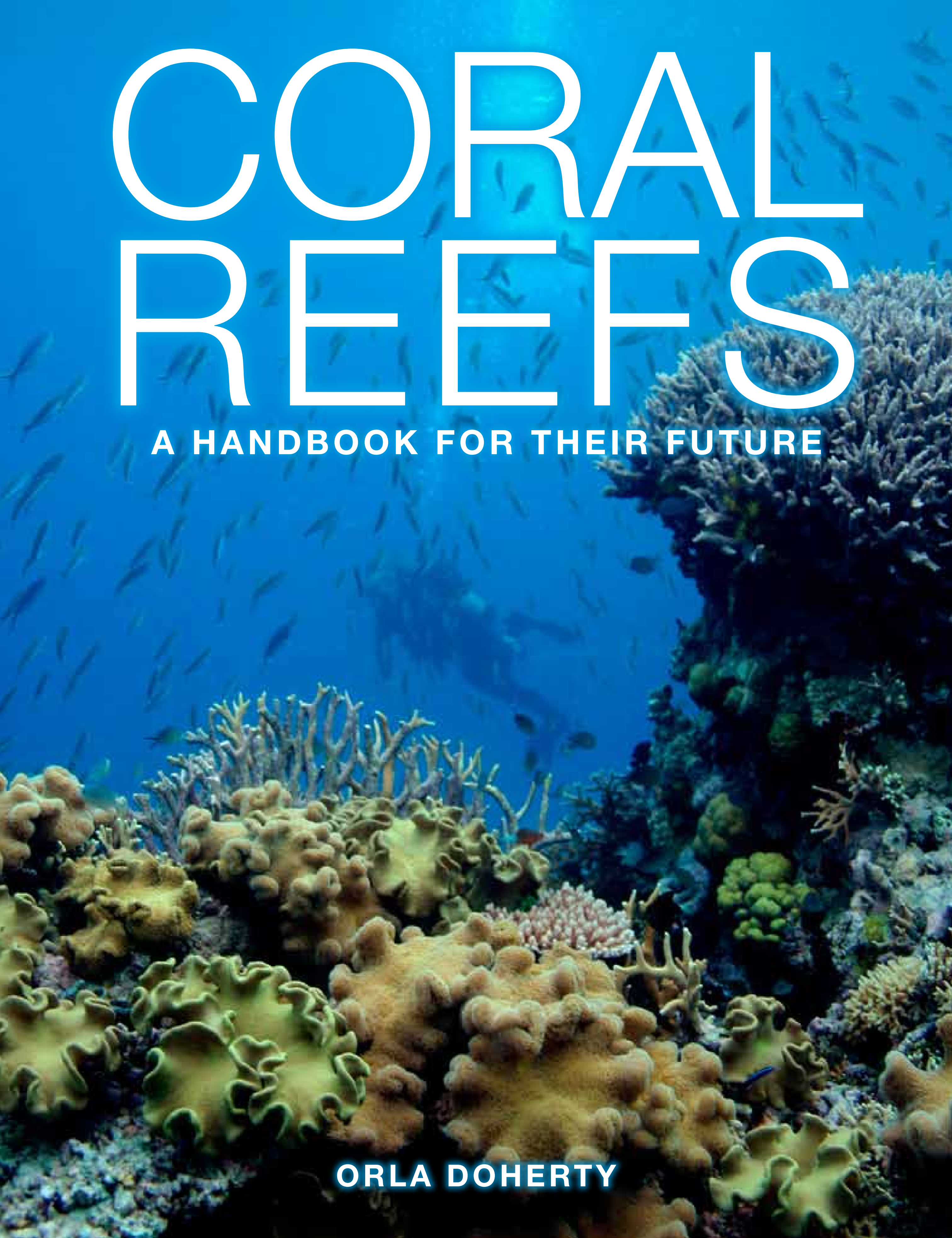
CORAL REEFS

A HANDBOOK FOR THEIR FUTURE



ORLA DOHERTY

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ORLA DOHERTY

BIOSPHERE
FOUNDATION

Marshall Cavendish
Editions

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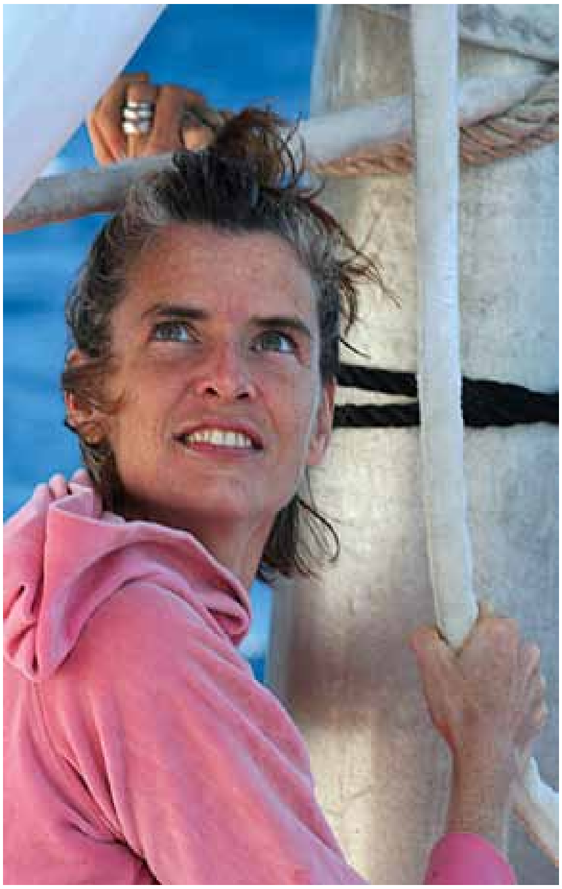
This book was written by a woman who sailed the world's oceans for over a decade on an expedition dedicated to furthering knowledge about coral reefs. During these years, Orla lived on an 82' Chinese junk rig sailing ship named "Heraclitus," after the Greek philosopher who was known for many things including a saying that those who wish to know about the world must learn about it in its particular details. She applied this idea to knowledge about coral reefs and headed up 49 coral reef science studies while diving nearly every day in the Pacific Ocean, Indian Ocean and Southeast Asian Seas. All of the data, reports, and films about the voyage can be found at Planetary Coral Reef Foundation (*www.pcrf.org*).

As part of this expedition and during a four and a half month journey across the North Pacific, she began to draft this book from her small bunk while tossing in the high seas. It was her desire to write a guide to the reef - a book about coral reefs for students and island people that was scientific but easy to read. It was a labor of love and an expression of her desire to bring this underwater realm to the very people who needed to learn about reefs the most. And thus it was her hope that one day the book would be translated into Bahasa Indonesia.

Over 17,000 inhabited and uninhabited islands make up the unchartered biodiverse coral reef country of Indonesia; a land where people fish daily; remove reef substrate for roads and walls; and in some cases eat turtles, dugongs and whales. Reefs at Risk (2011) has estimated that 95% of these reefs are threatened due to over-fishing, destructive fishing (dynamite & cyanide), inorganic and organic pollution, sedimentation from industry & deforestation, excessive tourism, plastic pollution and climate change. This percent is accelerating and is devastating for people who's livelihood depends on healthy reefs. Yet most people living alongside these reefs do not know how to dive, nor do they have a guide to inform them about the ecology of the reef and how to restore its health.

Coral Reefs: A Handbook for their Future gives a view into this underwater world with the aim to educate each of us to become intelligent stewards of our reefs. It is a tribute to the expedition that inspired its purpose; a culmination of the work of many who made it possible; as well as a gift for people living close to coral seas who wish to learn more.

Abigail Alling
Biosphere Foundation



I hold a double-edged sword in my hand – the privilege of having studied the world's coral reefs for a decade and the responsibility of sharing what they taught me.

In my journey around this aqua planet, I have explored the reefs and cultures of the South Pacific, Melanesia and South East Asia. I have glided over psychedelic fields of corals, glowing with technicolour fish. I have found myself in waters so crowded that nearby divers disappeared behind walls of life. I have engaged with dolphins in crystal clear seas. I have watched green turtles make love a few feet from me.

I have also seen the worst of the world's oceans, experiencing first hand the demise of coral reefs on a planetary scale. In the Philippines and Indonesia, I have recoiled from the bomb blasts of dynamite fishermen while diving on the remnants of their once thriving coral reefs. In Papua New Guinea, I have snorkeled with lifeless fish, spiraling in a dance of death, killed by cyanide, which kills the corals too. There I have also watched as fins were severed from dead sharks while the living ones become a rare sighting. In the central Pacific Ocean, a thousand miles from anywhere, I have witnessed the incontrovertible effects of climate change. In the Solomon Islands, I have returned to a reef that I knew like the back of my hand to find it unrecognisably destroyed by an earthquake and tsunami. It seems that whichever way I turn, there is trouble at sea.

There is still so much that we don't know about our seas, both good and bad. While a new species of giant manta ray has only just been discovered on Africa's reefs, so too has the fact that climate change could wipe out coral reefs as we know them by the end of this century. In this uncertain world, I have asked myself many times – do coral reefs stand a chance of survival, given how fast I have seen them disappear with my own eyes? With so much still unknown about our oceans, there is no clear answer.

In this book, I will outline the basic principles of why coral reefs are important to our biosphere. An understanding of how something works has always enhanced the amount of attention I have paid to it. So I am including the science of how a coral reef functions, but in an easily understood manner. I dwell on the corals themselves since they are the fundamental building blocks to the ecosystem. I give an overview of the different organisms on the reef, from the other invertebrates to the fish, turtles etc. I then launch into a description of the many-faceted problems facing coral reefs around the planet today, illustrated by my own first-hand experiences in a decade of studying and photographing them. I hope to provide inspiration as to what each of us can do to make a difference for their future.

I have spent ten years with a mask on my face and a tank on my back. I had not realised, until very recently that what actually happens when a coral bleaches is not common knowledge, nor is the fact that many fishermen around the world use dynamite instead of fishing hooks, or that sharks are disappearing from our seas for the sake of a soup. My hope is that this book will help to lift the reefs from beneath the layer of salt-water that denies them the global attention that they, and we, so desperately need, both in English and bahasa Indonesia.

Orla Doherty

CORAL REEF ECOLOGY & BIOLOGY

chapter 1

THE PAST AND PRESENT OF CORAL REEFS

1.1 WHAT IS A CORAL REEF?

The biological definition of a reef is a structure created by living organisms that rises to the surface of the sea and is capable of resisting hydrodynamic stress. On a *coral reef*, the structure is made up of calcium carbonate, or *limestone*, and the living organisms depositing it are, for the most part, corals.

As in any *ecosystem*, a balance is required to ensure the continued livelihood of the coral reef. The measure of that continued livelihood is the progressive build up of a calcium carbonate bed beneath the living layer of corals and the other animals and plants that depend on them. This *calcification* process continues for years and years, sometimes millions of years, creating a massive network of skeletons, sometimes even creating new islands. When we talk about the 'coral reef', we are referring to this entire system: the highly colorful 'skin' of living plants and animals and what lies beneath, a giant mesh of limestone deposits, the remains of the plants and animals that went before.

Figure 1 : A healthy and protected coral reef on the world's largest organic structure, the Great Barrier Reef!

Figure 2 : A small reef patch inside a shallow lagoon

In slightly looser terms, a coral reef is many things. It is a complex underwater *biome*, a vital component of the oceanic realm, a slow and determined construction by plants and animals that live together in close dependency, a testament to the power of nature, a historical record of our past, a teaching in the fragility of ecological balance, but above all, a healthy coral reef is a declaration of the beauty of our planet's biodiversity.

1.2 HOW DID WE DISCOVER THEM?

The relationship between man and coral reefs is an ancient one. In Papua New Guinea, archaeologists have found fish bones and shells gathered by humans from the reef and the nearby mangroves dating back 32,000 years. But it was not until relatively recently that we understood how coral reefs are formed or how they function.

Sir Joseph Banks was a great scientist who sailed the world with a great explorer, Captain James Cook, for three years from 1768 to 1771. Until his voyages, coral reefs were known mostly for the danger they threatened to the safe passage of ships in tropical oceans. Banks and Cook were not immune to these dangers and their ship *Endeavour* ran aground on the Great Barrier Reef in Australia. However, Banks made some of the first scientific observations of coral reefs and discoveries of how they work.

Charles Darwin was the next to make major contributions to our knowledge of coral reefs. In 1835, he set sail on the famous expedition ship, the *Beagle*. By this time most of the world's major coral reefs were known. During his voyages from the Galapagos to Tahiti, he made many observations on coral islands which appeared to him as 'curious rings of coral land, just rising above the water's edge.... These low hollow coral islands bear no proportion to the vast ocean out of which they abruptly arise; and it seems wonderful that such weak invaders are not overwhelmed by the all-powerful and never-tiring waves of that great sea, miscalled the Pacific.'

In 1842, he published 'The Structure and Distribution of Coral Reefs' in which he put forward theories of their development that still stand scientifically today, suggesting that coral animals were responsible for creating enormous structures that went deep beneath the ocean's surface.

While in Chile, he had constructed the notion that the earth's crust could be depressed as well as elevated and he proposed that while the Andes had been rising, the Pacific seafloor had been sinking. He called this phenomenon *subsidence*. Darwin was convinced that he could prove that coral polyps had built up reefs to keep pace with sinking ocean floors.

At Cocos-Keeling Island, an island just south of Indonesia but belonging to Australia, he went out in a small boat to the outer reef and carefully took many samples from the steep outer slope of the atoll. He found living corals up to 40 metres deep. Deeper than that, there were few living corals. Darwin suggested that these *atolls* were the results of a series of events and that, at different points in time in the sequence, different types of reef would occur.

1. A volcanic action underwater creates a landmass above the sea's surface.
2. Coral polyps take position on the underwater slopes of this landmass, creating a *fringing reef*.
3. The land itself falls or subsides into the sea, slowly enough to allow the corals to grow upwards at roughly the same rate as the island is sinking.
4. As the reef grows upwards, the outer slopes of the reef receive more nutrients from the seawater around it and grow faster than the inner parts of the reef.
5. Eventually, the inner reef dies and the coral skeletons crumble to sand, creating a lagoon between the slowly sinking island and the outer reef, which can now be described as a *barrier reef*.
6. When the central island has completely submerged, only the outer reef is left encircling an empty lagoon. In some places, the outer reef may have reached the sea's surface and some coral rocks pushed up to form small islands on top of the reef. This is an atoll.

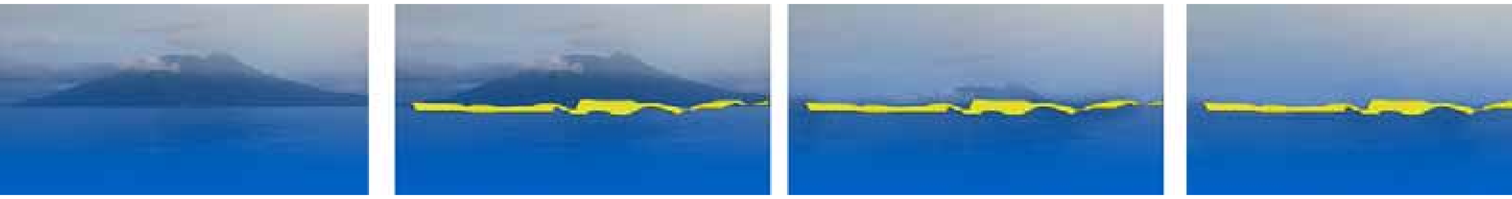


Figure 3 : Darwin's theory of atoll formation

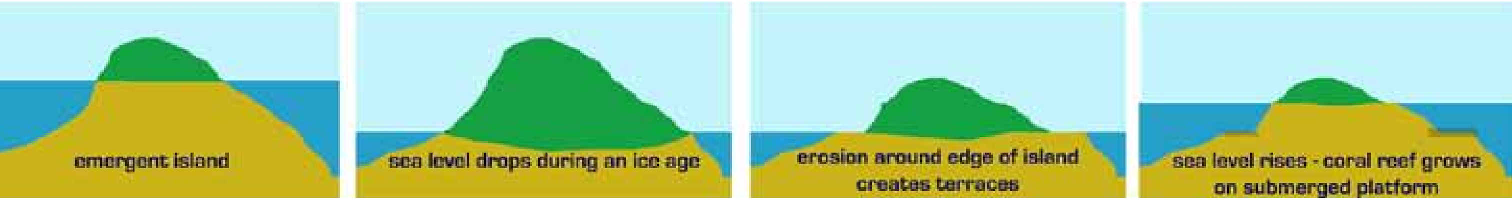


Figure 4 : Daly's glacial control theory

Darwin reckoned that it took at least a million years for an atoll to be created. He called them 'mountains of stone accumulated by the agency of various minute and tender animals.'

In 1872 James Dana, an eminent American geologist who sailed the South Seas for four years on an American expedition, published 'Corals and Coral Islands' which corroborated Darwin's theories.

However, in 1919, the Canadian geologist Reginald Daly came up with a different set of ideas when he presented his glacial control theory after an expedition to the Samoan Islands. At least four times in the last two million years, huge glaciers have been created with ice sheets up to a mile thick. During these ice ages, sea levels dropped by at least 60 metres, seawater temperatures fell and corals were killed, either by the cold water or by being exposed to the air. This left landmasses, previously protected by coral reefs, now exposed to the impact of waves. Waves carved away these shorelines to create platforms in the rock. When the climate warmed again, the glaciers melted, the sea levels rose and corals began to flourish again, merrily settling on the wave-cut platforms. As sea levels continued to rise, the outer edges of the reefs survived better than the landward side. Only the corals on the seaward side could keep up with the rising water level. This is how Daly proposed that barrier reefs were created.

So Darwin's theory was based on land subsidence, a continuous process converting fringing reefs to barrier reefs to atolls. Daly on the other hand believed in changing sea levels and saw no relation between atolls and barrier reefs. Darwin predicted finding massive coral deposits under barrier reefs and atolls. Daly predicted finding a flat platform of rock.

Darwin's hypotheses were corroborated by an expedition to the Pacific atoll of Funafuti, in the country of Tuvalu, in 1904. Here, reef-building coral skeletons were found to a depth of 330 metres with no evidence of wave-cut shelves. In other words, here Darwin was right. In 1931, another team in Samoa where Daly had explored, discovered a wave-cut platform underneath a fringing reef. In other words, here Daly was right! The actuality is that both men are right. Some reefs have evolved around subsiding land and others have evolved because of the effects of glaciation.

Just after World War II when the United States Navy drilled a series of deep holes at two atolls, Enewetak and Bikini Atolls, in the central Pacific Ocean. At Bikini, the coral rock reached 767 metres deep. At Enewetak Atoll, they drilled through more than 1,267 metres of coral

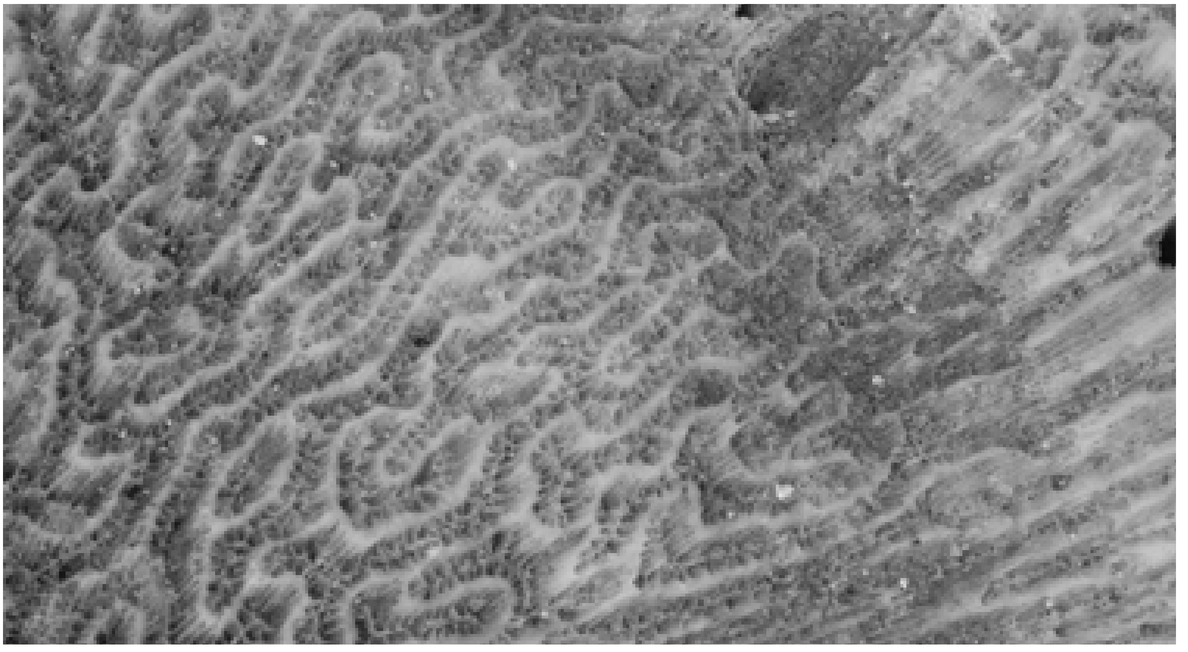


Figure 5 : The skeleton of previous incarnations of coral reefs have helped to deduce their history

reef materials and related carbonate deposits before they reached the volcanic rock beneath. Darwin's ideas were right here. The scientists had found Enewetak to be a mountain of coral reef remains, built up over millions of years, with a living layer of coral reefs at the surface.

On a side note, this important work was not the major mission of the military. Their main purpose was to conduct tests on atomic and hydrogen bombs on these remote atolls. Howard and Eugene Odum, the stars of the science of ecology at the time, were part of the team sent to study the effects of radiation before and after the bomb blasts. In the process, they made a lot of discoveries about how reefs work, including piecing together the puzzle of how such rich ecosystems could exist in such nutrient-poor waters as the tropical seas and discovering the presence of algae within the tissues of the coral animal.

1.3 HOW HAVE CORAL REEFS EVOLVED?

Reefs are the oldest ecosystem in the world. Marine organisms have been forming them in one form or another for at least 3.5 billion years, which is pretty amazing given that Planet Earth was only formed 4.5 billion years ago and life only began about 4 billion years ago.

The first reefs were made up of *stromatolites*, structures formed by *cyanobacteria*. Stromatolites were the first *macroscopic* life form. They are credited with creating the oxygen-rich atmosphere which encouraged the evolution of higher life forms. In other words, stromatolites were fundamental to the creation of our biosphere as we know it.

The first corals appeared over 400 million years ago but began to construct reefs in earnest around 250 million years ago.

Extinctions are part of the evolutionary process but what is interesting is that coral reefs and other systems based on plant-animal symbiosis are especially sensitive to climate changes and, in the past, reefs have always vanished about a million years before all other types of organism feel the effects of change. The positioning of reef-building organisms in the ocean's warm shallows has placed them at the mercy of global climatic change and they have suffered with every shift in sea level, temperature and current patterns that has occurred.

There have been five global extinction events since the first appearance or reefs on Earth. With each extinction, coral reefs disappeared from the planet for at least four million years.

There are remnants all over the world of reefs formed millions of years ago. Way up in the Alps, layers of rock over half a mile thick are composed mainly of coral limestone. In Texas, Capitan Reef was formed by primitive corals about 250 million years ago. It's more than 350 metres thick and more than 600 km long. In Timor, coral reefs have been found 1,200 metres up a mountain. These coral rocks found at high altitudes prove that their locations were once under water and have helped to back theories in sea level changes that have occurred over the last two million years.

What follows is a condensed geological history of reefs.

Figure 6 : Stromatolite reefs still existing today at Hamelin Pool in Shark Bay, Australia.,

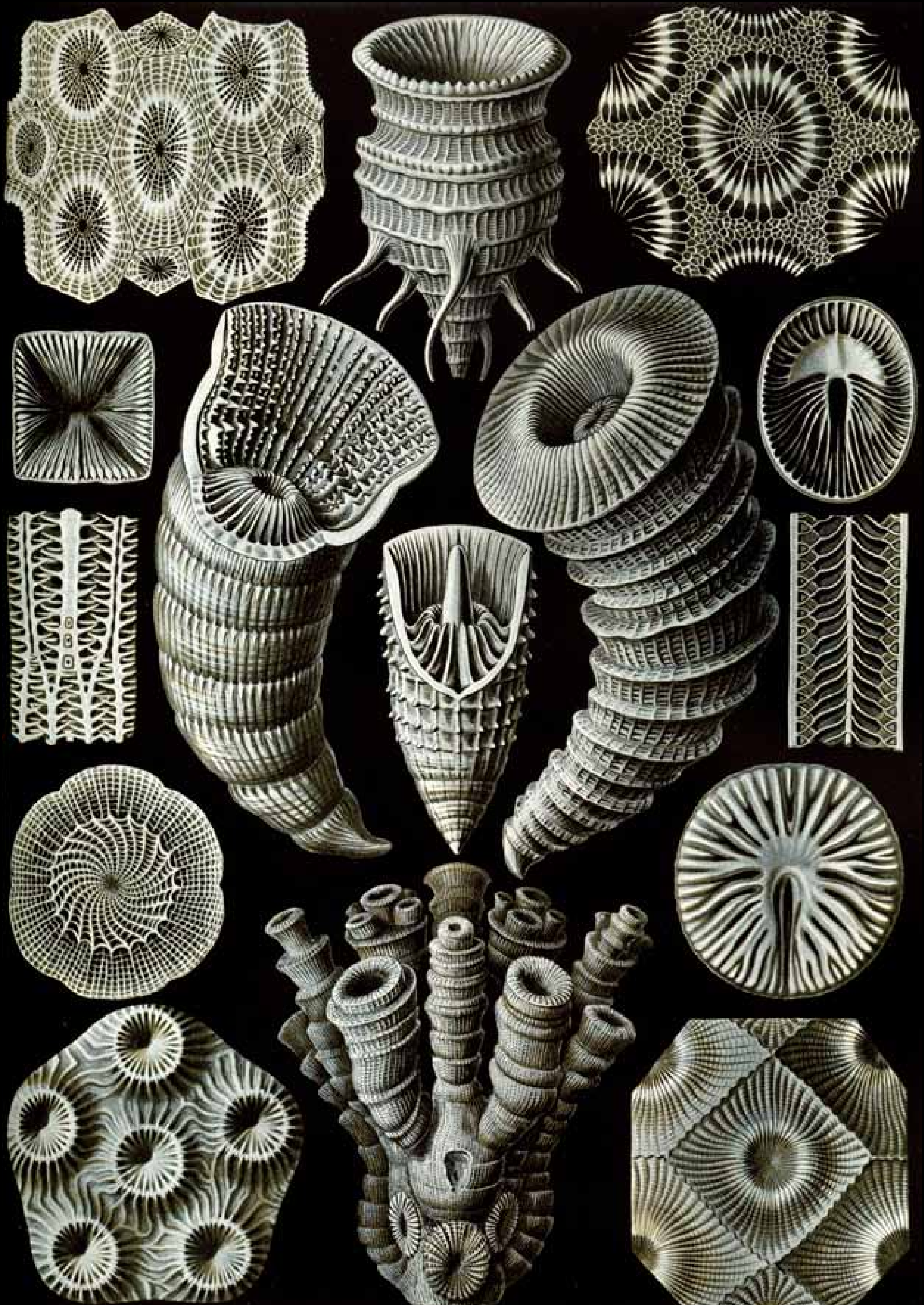


Figure 7 : Rugose coral fossils in a lithograph by Enrst Haeckel who gave us the word ‘phylum’

3,500 - 2,000 MILLION YEARS AGO

Stromatolite reefs were the first form of reef on this planet. Cyanobacteria, or blue-green algae, trapped sediment in calm and shallow waters to make mats on the seabed. Calcium carbonate was then extracted from the seawater, which cemented the mats into what are known as stromatolites, a name derived from the Greek words for flat and stone. A very recent discovery of a fossilised stromatolite reef system in the Pilbara Region of western Australia dates back to three and a half billion years ago. Stromatolites are still being formed today, but only in three places around the world, the most famous being Shark's Bay, also in western Australia. Modern stromatolites grow at a rate of about 5 centimetres a year, which is very slowly compared to either their geological ancestors or to modern-day coral reefs.

530 MILLION YEARS AGO

Animals and plants did not appear on this planet until 600 million years ago. The first reef-building animals to appear were called archaeocyaths, a type of sponge. Their name comes from the Greek words for ancient and cup. The most common type of archaeocyath formed an upside-down cone shape with two-layered walls. However, there was a large diversity in growth forms, from solitary tubes and cups to branching colonies. They were only capable of building a reef with the help of calcified cyanobacteria. The first archaeocyath reef formed in what is now Siberia, 530 million years ago. However, just 10 million years after the archaeocyaths appeared, they were no more. After their demise, cyanobacteria continued to build reefs but, without the aid of their animal partners, they could deposit calcium carbonate only very slowly.

480 MILLION YEARS AGO

Around 480 million years ago, the first type of corals, the tabulate corals, appeared. After a while, a second type of primitive corals, the rugose corals, evolved. They were also called horn corals because of their shape. Both types of coral created relationships with cyanobacteria, which increased the speed at which they could lay down calcium carbonate skeletons. Meanwhile, certain sponges, bryozoans and coralline algae were also forming reefs. Combinations of all these calcifying organisms were the reef builders for the next 150 million years.

434 MILLION YEARS AGO – THE FIRST MASS EXTINCTION

In the first mass extinction event, tabulate and rugose corals became almost insignificant in what they contributed to reef structures, leaving reefs struggling to survive against erosion, storm damage and other attacks. It was mainly stromatolites that survived this extinction.

360 MILLION YEARS AGO – THE SECOND MASS EXTINCTION

A prolonged series of extinctions took place, lasting up to 20 million years. Tabulate and rugose corals were completely wiped out this time, as was half of life on earth at the time. Reef building became very limited for the next 100 million years.

251 MILLION YEARS AGO – THE THIRD MASS EXTINCTION

251 million years ago, the third and most severe

extinction event to date occurred in the history of our planet. It is estimated that around 80-95% of marine species were eradicated. Reefs did not reappear for about 10 million years after this event.

230 TO 245 MILLION YEARS AGO

Scleractinian corals, what we know as today's reef-building hard corals, first appeared on Earth around this time, but it took them about 20-25 million years to start building coral reefs. This is possibly because at the beginning they had not established a symbiotic relationship with algae.

225 MILLION YEARS AGO

The landmasses on Earth merged to form one massive supercontinent called *Pangaea* which was surrounded by a shallow shelf, perfect for reefs to grow on. The newly evolved scleractinian corals immediately began a symbiotic relationship with microscopic algae, the *zooxanthellae*, which still exists in today's hard corals. As a result, corals were suddenly able to deposit calcium carbonate ten times faster than any of their ancestors and so they bloomed. For the next hundred million years, the families of corals that we know today evolved. In fact, at one stage there were even more types of scleractinian coral than there are now.

205 MILLION YEARS AGO – THE FOURTH MASS EXTINCTION

The fourth extinction event occurred in which a third of all scleractinian families went extinct and reefs were almost absent from the planet for about 6-8 million years. About 25 million years later, a high proportion of the families of today's corals evolved and scleractinian corals were in a period of expansive reef construction up to about 140 million years ago.

65 MILLION YEARS AGO – THE FIFTH MASS EXTINCTION

The fifth and most recent mass extinction, the one that removed the dinosaurs, known as the K-T Extinction, took place 65 million years ago. Some theories suggest an asteroid struck Earth which created a dust layer in the upper atmosphere, blocking out sunlight and causing temperatures to fall drastically. There is evidence of a massive impact site on the Yucatan Peninsula in Mexico. Another proposed cause of the extinction is an extensive volcanic episode. Some scientists believe the extinction was caused by dramatic changes in sea level and climate. Regardless of the cause, the effects on our planet's biodiversity were enormous, including wiping out a third of all coral families. Coral reefs disappeared abruptly from the fossil record, vanishing without a trace for 10 million years.

In fact, so did nearly all the organisms that had until this time been producing calcium carbonate in shallow tropical waters, including bacteria, algae and animals. Luckily, some of the scleractinian corals had just migrated to deeper waters to either get away from competing rudists or to avoid the high temperature and salinity in the shallows. As a result, a few species survived the extinction event.

In the next 20 million years, calcification was mainly performed by single-celled organisms called *foraminifera* and the form of algae known

Figure 8 : The Great Pyramids at Giza in Egypt were made from the remains of reefs constructed by foraminifera

as *coralline red algae*. The most famous remains of reefs from this period are the pyramids of Egypt, built from limestone deposited by foraminifera.

50 MILLION YEARS AGO

50 million years ago scleractinian corals became the dominant reef builders with the help of their associated zooxanthellae.

To summarise the evolution of the genera of corals that are on our reefs today, a few of these appeared around 170 million years ago. By 33 million years ago, nearly a quarter of today's reefs had evolved, and by 24 million years ago, nearly half.

2 MILLION YEARS AGO

During the last 2 million years, the Earth has been subjected to a series of rapid climatic changes. Glacial ice periodically covered large areas of North America and the northern parts of Europe and Asia. The alternate growth and decay of these ice sheets had the effect of causing a worldwide change in sea level. Water forming the glaciers came from the oceans, and the buildup of ice during periods of glaciation lowered the sea level. During the interglacial periods the glaciers melted, returning the water to the oceans and causing the sea level to rise again. It is thought that 2 million years ago the sea level was more than 100 metres below its present level. If this is true, then most

Figure 9 : A fringing reef with individual coral colonies discernible

of the present day continental shelves were exposed at that time. Between then and now, there have been four major lowerings of sea level produced by four glaciation events, three of them within the last 100,000 years.

5,000 YEARS AGO

Today's sea level was only reached during the last 5,000 years and scientists generally agree that the reefs we now live with must have formed between now and then.

In summary, through evolutionary history, reefs have been formed from many different types of organism from cyanobacteria and microbes to sponges, bivalves and the early ancestors of today's scleractinian corals. Modern reefs can also be formed by organisms other than coral, from coralline algae to modern day stromatolites. However, the most common form of reef, at least for now, is the coral reef, built mostly by scleractinian corals that first emerged 245 million years ago.

Another lesson from history is that conditions for coral reefs today are changing 100 to 1,000 times faster than any change in the last 420,000, in other words way faster than anything experienced in the last half a million years of ice ages. Hence, the grave concerns for the ability of corals to survive.

1.4 WHAT DETERMINES WHERE CORAL REEFS GROW?

Environmental conditions dictate where coral reefs are found on our planet today. Corals as individual animals can be found in all waters from tropical equatorial seas to freezing

polar regions, but coral reefs can only be constructed under very specific conditions.

In fact, only one per cent of the ocean volume of the planet satisfies the conditions required by corals for their growth, and within that volume of ocean much less has a suitable bottom for coral settlement. Coral reefs cover 250,000 km^2. This gives a total percentage of earth's surface area actually covered by coral reefs of a meager 0.05%, or put another way, if all the coral reefs of the world were clumped together, they would amount to an area less than half the size of the island of Madagascar.

The factors which control whether or not a reef will grow are explained below. Rarely is just one of these factors at play. It is usually a complex combination of many of them that dictates where we find reefs on our planet today.

TEMPERATURE

The ideal temperature range for healthy and diverse coral reefs is around 25-28 °C. This is why most corals are found in the seas on either side of the equator, generally in a band from 30°N to 30°S. The further away from the equator you are, the colder the water becomes.

However, individual corals can exist well outside this, for example, in areas of Japan where the sea temperature regularly falls to 14°C, approximately half of all coral species have been found to occur. Even where the temperature drops to 11°C, still approximately a quarter of all coral species are found. However, the important fact is that they do not form reefs here.

Figure 10 : *Porites* fingers fighting off the competition - green algae and a branching soft coral

The lower temperature threshold of a coral is really defined by the saturation level of calcium carbonate which varies with seawater temperature. When a coral creates calcium carbonate in colder waters, it immediately dissolves into the surrounding sea because the saturation level is lower here. When the temperature is lower than 18-20°C, growth either slows down or stops completely. Most corals cannot survive below 16-18 °C for even a few weeks.

The upper temperature threshold is defined by the relationship between the reef-building coral and the microscopic algae, the zooxanthellae, that dwell in its tissues. Most corals today appear to be living only 1-2°C below the maximum temperatures that they can withstand, a fact extremely pertinent to the threat of climate change and mass coral bleaching events.

OCEAN CURRENTS

Currents have a strong influence on seawater temperature, and have created areas outside of the zone between 30 °N – 30 °S where coral reefs can flourish. For example, the Leeuwin current in western Australia, the East Australian current, the Kuroshio current off Japan and the Gulf Stream all bring warm water year round from the tropics to higher latitudes. As a result, coral reefs are found off Japan and Bermuda in the northern hemisphere at 35°N and 32°N respectively, and Lord Howe Island, east of Australia, in the southern hemisphere at 32°S.

There are also currents that prevent coral growth in what seems otherwise like the perfect latitude. For example, cold upwellings along the coast of northeast Somalia, southern Arabia, the western coastlines of the Americas and west Africa prohibit the growth of reefs.

In general, there are very few reefs along the western shores of the Americas and one of the suggested reasons for this is the occasional high temperatures associated with El Niño events.

COMPETITION WITH ALGAE

Corals are in constant competition with other organisms on the reef but in particular, they compete for with algae space and light. There are many types of algae underwater, the largest types being called *macroalgae* which can grow very fast. In the tropics and subtropics, macroalgae crops are kept under control by the fact that plenty of reef fish eat them. Like cows in a field of grass, the fish graze on the macroalgae, and so the macroalgae does not have the chance to overgrow corals. But further from the equator, these types of fish are rare so macroalgae tends to spread very quickly and grow over the top of corals. Temperature is therefore not the only factor in determining the latitudes at which we find corals.

SALINITY

Salinity is the measurement of the amount of salt in seawater. Reefs do best in waters with salinity between 3.4 and 3.7% but they can survive in salinity of 2.5 to 4.2%. In bays and gulfs, salinity may be too high because of trapped water evaporating. Conversely, at river mouths, where fresh water is constantly running out to the sea, the salinity may be too low. This is the reason why there are no reefs around the mouths of the huge Amazon and Orinoco rivers of South America and the Zaire system in Africa.

Figure 11 : In these turbid waters surrounded by mangrove trees, the reef is present but not very diverse

TURBIDITY

Turbidity is a measurement of the concentration of particles floating in the water and therefore of the water quality. If the water is very turbid, then the particles will stop some of the light at the sea's surface from reaching the corals that lie beneath. This makes life more difficult for the corals because of their dependency on successful *photosynthesis* in the zooxanthellae inside their tissue.

SEDIMENTATION

Sedimentation describes the process of particles in the water column settling down onto the sea floor. If there is a lot of sedimentation, then corals are choked by the particles that land on them. Sedimentation is also bad for reefs because it can have a negative effect on the amount of successful reproduction that can occur on a reef. Coral larvae are very fussy about the substrate they can attach to when they first land on the reef and loose particles are their least favourite landing pad.

NUTRIENTS

A nutrient is a chemical compound which provides nourishment to the organisms that consume it. Many of the nutrients that corals need are found in the plankton of the sea. As a result, coral reefs grow best where the currents and waves wash in the highest concentration of fresh supplies of plankton. However, the higher the concentration of nutrients, the more food also for the corals' competitors like algae and sponges and there is, therefore, a fine line between too little and too much.

Eutrophication occurs when a body of water receives too many nutrients, most commonly when fertilisers and other nutrient-loaded chemicals used on the land are run-off by rain into the sea. Eutrophication can have a disastrous effect on coral reefs. Plant life explodes and animal life suffocates.

OXYGEN

Corals are animals, and like us, need oxygen. Wave action stirs up seawater, increasing the amount of oxygen it contains. This is another reason why coral reefs grow very well where there is plenty of wave action.

LIGHT

Light has a huge influence on where corals grow because most hard corals are dependent for their survival on photosynthesis occurring within zooxanthellae, the microscopic algae that live inside their cells. In general, less than a quarter of the light at the ocean's surface will reach below 10 metres deep and at 100 metres, there is only about 0.5% light left. Having said that, the different wavelengths that make up light waves reach different depths. Red light waves, which have a longer wavelength, are the first to be absorbed by the water molecules. Blue waves, with shorter wavelengths, penetrate more deeply. Red wavelengths are the most readily used by plants in photosynthesis. Therefore, coral growth tends to occur best in the shallower zones where there is more red light. Few hard corals which depend on this symbiotic relationship with algae will grow much below 55 metres.

EXPOSURE TO AIR

Exposure to air affects corals adversely because of contact with both air and rainwater.

Figure 12 : As this Acropora fell to one side, new growth took a new angle to maximise the light it receives

Figure 13 : Reefs in different parts of the world can have very different levels of biodiversity

Waters which are too shallow or which have too extreme a tidal range, the difference in sea level between high tide and low tide, are not very encouraging to coral growth.

ARAGONITE SATURATION

These words will mean very little until some basic chemistry has been tackled, explaining how the concentrations of different ions in the sea affect the ability of a coral to create its skeleton.

1.5 WHERE ARE CORAL REEFS FOUND TODAY?

Biogeography is the study of the distribution of biodiversity, over space and time, and the reasoning for that distribution. Today the western Atlantic has 62 species of coral and 1,400 of fish as compared to the Indo-Pacific which has 719 species of coral and 4,000 species of fish.

The reasons for this great difference in diversity on different sides of the planet can be explained by events that happened hundreds of millions of years ago. Pangaea emerged as a supercontinent about 200 million years ago, then, to oversimplify geological events, split into Gondwana, the southern supercontinent, and Laurasia, the northern supercontinent. By about 60 million years ago, Gondwana had further divided to form the four landmasses of South America, Africa, India and Australia-Antarctica. Meanwhile Laurasia was beginning to divide into Eurasia and North America. As these continents broke up, barriers were created across the oceans, which resulted in some species becoming geographically isolated.

One such barrier is the East Pacific Barrier, which is in fact a vast 5,400 km stretch of open ocean with a deep sea floor. Only coral that have larvae capable of surviving for a long time at the sea's surface have ever made it eastwards across the Pacific, which means against the currents. However, six species of shark did because of their incredible swimming strengths. All these migrations occurred from west to east, hitching a ride on the very narrow equatorial counter-current.

Another is the Isthmus of Panama, formed by volcanic activities around 3 million years ago. This was the first landmass border-line within the oceans. The sea on the eastern side of it became the Atlantic, the sea on the west became the Pacific and they would never mix again, making it impossible for species to cross from one to the other. In fact, only seven types of coral have survived to exist in both the Atlantic and Pacific today.

Once these oceans were separated, corals evolved differently within each, faring much better in the Pacific. As the world's climate went through the traumas of repeated glaciation and melting of ice caps, the Atlantic suffered much more than the Pacific. This is because the large number of islands in the Pacific provided plenty of shallow waters where corals were able to sit out the rapid environmental changes.

BIOGEOGRAPHY TODAY

There are four groups of coral reefs spread across the world.

1 THE INDO-PACIFIC contains 92% of the world's coral reefs. It stretches from the Red Sea and the eastern African coast all the way through the Indian Ocean, southeast Asia, Australia and Melanesia to eastern

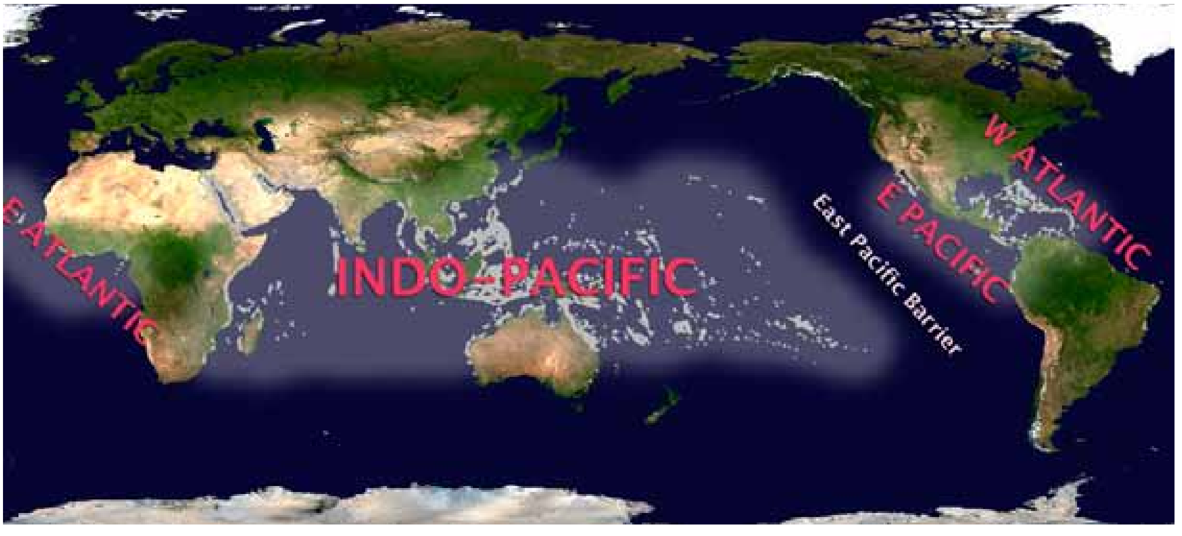


Figure 14 : Map showing the four major areas where coral reefs are found today and the East Pacific Barrier

Polynesia including Hawaii, the Line Islands, the Marquesas and Easter Island. East of this lies the East Pacific Barrier across which few corals have travelled.

Southeast Asia holds almost 34% of the world's coral reefs. Reefs are common in or dominate much of the Indo-Pacific although in some places, such as along the southern Asian coastline from Pakistan to Bangladesh, they are rare. Practically all tropical oceanic islands in the Indo-Pacific are encircled by coral reefs and many were even built by corals. Diversity tails off from more than 700 species of coral in the western end of the Indo-Pacific to just over 100 in French Polynesia.

2 THE EASTERN PACIFIC covers the tropical western American coastline as well as nearby offshore islands, including the Revillagigedo, Clipperton, Cocos and Galapagos Islands. There are generally very few reefs growing here because upwellings and strong cold coastal currents reduce seawater temperatures below the reef-building range. Clipperton is an atoll which was built by the vigorous growth of only 8 or 9 species of coral, compared to reefs of the Indo-Pacific which may have been formed by up to 150 species of coral. All eastern Pacific reefs are constructed from fewer than 10 dominant coral species.

3 THE WESTERN ATLANTIC covers the tropical eastern American coast in the Atlantic Ocean, neighbouring islands in the Caribbean and off Brazil, and Bermuda. This is the second largest reef region and reefs are found in most shallow waters, especially around islands. We commonly call this geographical region the Caribbean and it contains less than 8% of the world's reefs.

4 THE EASTERN ATLANTIC includes the tropical coast of western Africa and neighbouring island groups including the Cape Verde Islands and islands in the Gulf of Guinea. There are very few reefs here.
In terms of biogeography, some of the most significant differences in levels of biodiversity are best illustrated between reefs of the western Atlantic and the Indo-Pacific, the two major reef areas of the world.

1. Scientists have found more coral species around a single island in southeast Asia than have been identified for the entire Caribbean.
2. Western Atlantic reefs are, for the most part, dominated by just two species of corals, Acropora palmata near the reef crest and Acropora cervicornis in slightly deeper water. Indo-Pacific reef fronts have a much more varied collection of coral species and growth form, probably because of the greater species diversity in this ocean in general.
3. The Indo-Pacific has over 700 species of soft coral, whereas there are hardly any in the western Atlantic.
4. The richer species pool in general in the Indo-Pacific has created predators here that have no equivalent in the western Atlantic. For example, the crown-of-thorns starfish, giant clams, anemone fish (clownfish) and sea snakes do not

Figure 15 (right): The riches of the Indo-Pacific coral reefs

exist in the Caribbean.

5 In the Indo-Pacific there are more mutualistic relationships between different organisms compared to the other ocean areas. For example, the relationships between giant clams and zooxanthellae or anemones and anemone fish only occur here.

6 There are 175 species of butterflyfish and angelfish in the Indo-Pacific but only 15 in the western Atlantic.

The differences in biodiversity between the different parts of the world's oceans is well represented by the levels of biodiversity in hard corals.

1.6 WHAT IS THE CORAL TRIANGLE?

Biodiversity is a term used to describe the variety of species in an ecosystem. In the world of coral reefs, biodiversity reaches a peak in what has become known as The Coral Triangle, an area of the Indo-Pacific that holds 35% of the world's coral reefs across the Philippines, central and eastern Indonesia, Timor Leste, part of Malaysia, Papua New Guinea and the Solomon Islands. Although it represents just 1% of the Earth's surface area, the triangle is home to more than 600 of the nearly 800 species of reef-building coral found worldwide. It hosts 3,000 species of fish and the largest area of mangrove forests in the world. It is truly the coral reef epicentre on planet Earth. This richness has also made it a major nursery and migratory route for tuna, billfish, turtles, whales, dolphins, manta rays, whalesharks, dugongs and many other marine megafauna. These creatures come to breed and feed in these nourishing and sheltered waters.

There are many factors that created this magical underwater triangle.

1 Because it contains a large number of

Figure 17 : Map showing the bounds of the region known as the 'Coral Triangle'

Figure 16 (left) : Marine biodiversity peaks in the heart of the 'Coral Triangle' islands with shallow shelves, the reefs in this region were the least affected by the repeated glaciations that caused such chaos in the rest of the world's oceans.

2 It is also possible that the region actually became geographically isolated during glaciation, which would have allowed independent evolution of new species.

3 Currents may also have played a major role in creating this area of high diversity. Where currents meet, there is a higher chance of species meeting other species and new species forming from their interaction. Again, the high number of island groups and the currents that run around them and meet between them may have increased the chances of new species forming. The major currents in the equatorial regions of the Pacific Ocean flow westward towards the Coral Triangle area, therefore most planula larvae head west towards it.

4 Currents have had another effect on the Indo-Malayan area. Most of the winds, storms and currents that reach this area come from the east continually bringing species to this area from other parts of the Pacific. In this way, the triangle has possibly become some kind of living museum for species that have since become extinct in their place of origin.

5 The prevailing conditions within this triangle, including salinity, turbidity, sea level, wave exposure and temperature, for the most part, continue to encourage a wide range of coral reef species to thrive.

Indonesia is the world's largest archipelago, with an enormous 18% of the world's coral reefs spread across 17,504 islands, at the last count. It was Indonesia's President, Susilo Bambang Yudhoyono, who spearheaded the Coral Triangle Initiative in 2006, asking for concerted international efforts to increase the chances of survival of the resources in this area. Many of the 120 million people in the zone depend almost entirely on these resources. The Coral Triangle is of huge economic importance to its host countries, valued at US$2.3 billion a year from fisheries, nature-based tourism and coastline protection by reefs and mangroves.