**Figure 10:** *Stromatolite reefs still existing today at Hamelin Pool (from Paul J Morris, Flickr)*

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 kilometres 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.

### 3,5000 – 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 cm 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

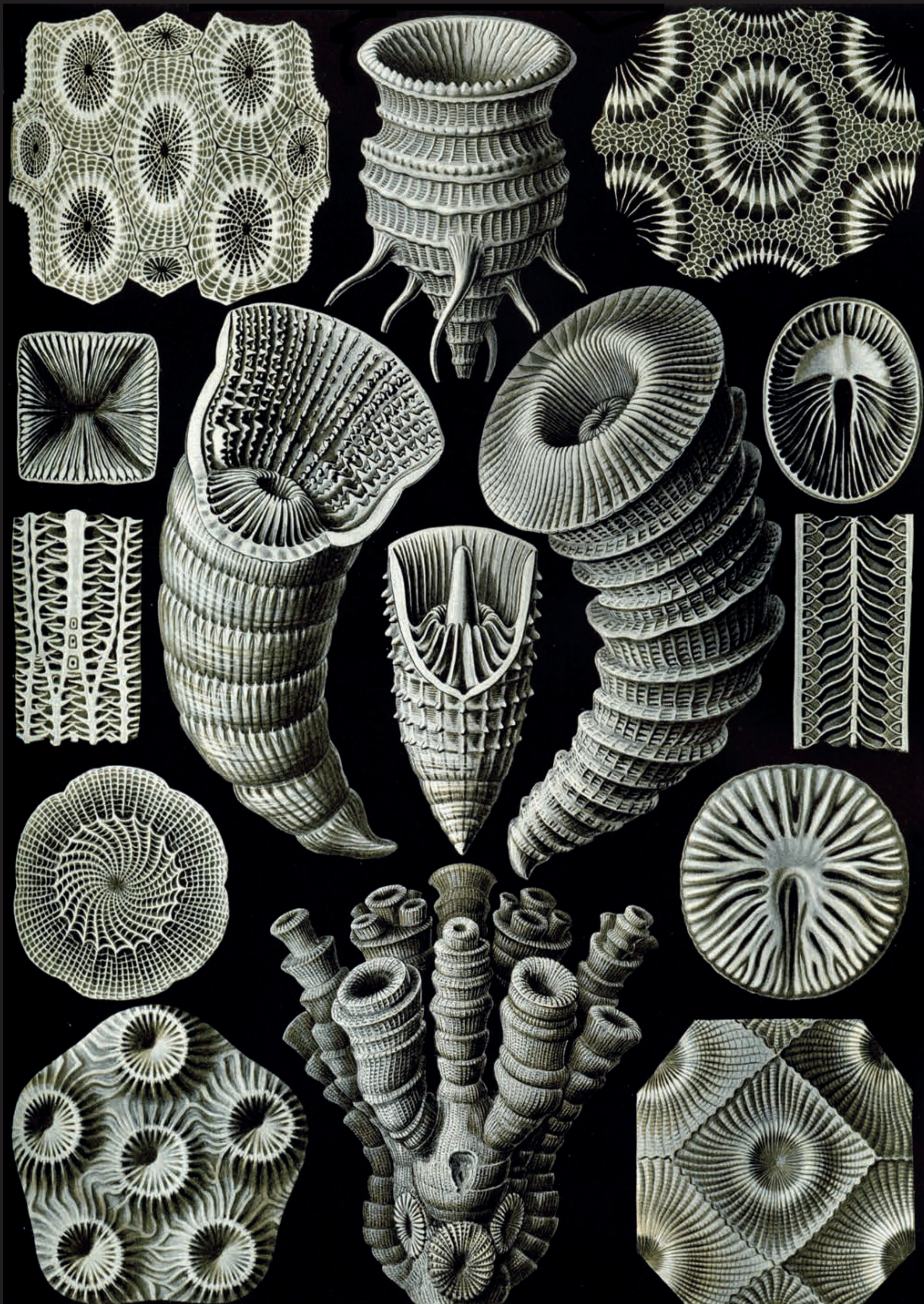

**Figure 11:** *rugose coral fossils in a lithograph by Enrst Haeckel who gave us the word 'phylum'*

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 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.

**Figure 12:** *the Great Pyramids at Giza in Egypt were made from the remains of reefs constructed by foraminifera*

**Figure 13:** *a fringing reef with individual coral colonies discernible*

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 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.

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

**Figure 14:** *Porites fingers fighting off the competition - green algae and a branching soft coral*

**Figure 15:** *in these turbid waters surrounded by mangrove trees, the reef is present but not very diverse*

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.

### 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. 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.