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A Brief History of Our Seas

Our planet is the living image of change, of profound transformation through the geological ages. And the oceans have undoubtedly been major players in this complex scenario. Life began in the ocean, and also in the atmosphere as we know it today. Today's distribution of heat and our climate itself are the result of the dynamics of our seas. Initially, water emerged not only from Earth's interior but also from the comets that incessantly impacted the surface of our fragile planet, which was trying to survive in a violent environment. These same comets and other fireballs carried organic matter, the molecules that were to form the basis of life. Many fireballs that hit early Earth disintegrated or were exposed to high temperatures. Others, however, did so without destroying the delicate molecules that they carried inside them, creating some of the broth necessary for life to form. The other necessary ingredients came from our own planet, the result of chemical reactions stimulated by an atmosphere very poor in oxygen yet rich in methane and hydrogen. Experts have not yet agreed how the first step was taken. Some suggest the classic model of the 'quiet pond', in which organic molecules interact to create pseudo-membranes (called micelles) and self-replicating ribonucleic acid (RNA). Other experts, on the other hand, suggest a volcanic caldera, a place subjected to high temperatures and not isolated from the ferocious volcanic environment that dominated the very young Earth at that time. Yet others suggest an icy space—an icy blanket that might have covered part of the planet in the past. In that environment, in the low temperatures the molecules would have interacted slowly to create the first structures to which we owe the life that we observe today.

S. Rossi, *Oceans in Decline*,
https://doi.org/10.1007/978-3-030-02514-4_1

Not everyone is convinced that life originated on Earth. Some specialists speak of an exogenous origin: life from other planets or asteroids. However, the question remains the same, and at the moment there is no clear answer to how life originated. We know that RNA capable of replicating itself probably emerged about 4 billion years ago, and that the first single cells date back about 3,900 million years (Ma). Unfortunately, the remains are much altered due to the passage of time. But, from that moment on, life became an unstoppable phenomenon, destined to survive great change, meteorite impact and continental movements causing glaciation, desertification and spectacular volcanic eruption.

What we understand as life then emerged: a self-sustaining chemical system capable of replicating and evolving, in the Darwinian sense of the word. Methanogenic bacteria, the archetypes, were some of the first organisms in our oceans, thanks to their ability to take advantage of the atmosphere and the oxygen-deprived oceans that had reigned from the start. Organisms that have changed little or not at all since then surround us now—simple, imperturbable and capable of resisting practically everything. In that long period, the pre-Cambrian Period, the longest chapter in the history of life, steps were taken that would decide the future of the world's living matter. The first organisms to form stable populations were undoubtedly those adapted to high temperatures but, as the Earth gradually cooled, other organisms displaced these so-called thermophilic organisms.

An absence of oxygen was the norm until the first bacteria capable of photosynthesis emerged. Many specialists suggest a primeval soup of organisms that either nourished themselves with dissolved organic matter or were able to use hot springs for their metabolic functions, always surrounded by an environment lacking in oxygen.

Oxidization was a difficult process, as the organisms and chemicals were surrounded by electron-charged molecules. The appearance of the chlorophyll molecule added complexity to the system. The process of photosynthesis that results from this series of complex molecules is one of the most conservative biochemical processes on the planet: the organisms that use it have not changed their mode of operation in billions of years. We can imagine the strength of a process in which organic molecules and oxygen are produced from carbon dioxide and water. Oxygen, a mere waste product, began to invade first the oceans and, when they became saturated, Earth's atmosphere itself. Oxygen burns, rusting everything in its path. Therefore, although in a slow and stately way, all life had to adapt, to seek environments without oxygen or die from this new poison that was invading the planet. It has always surprised me how such a 'simple' change could transform the destiny of a planet. This revolution began about 3,500 Ma ago and culminated in a catastrophic setback for the anoxic world. The architects were the original cyanobacteria, which proliferated without ceasing, creating in some cases the stromatolites that we can still observe almost undisturbed along parts of Australia's coastline. It was undoubtedly a radical change, one of the deepest traumas that our living environment has suffered.

Another change was to put a stop to the dominion of prokaryotes, both bacteria and archaea: the arrival of eukaryotes. These 'higher' organisms (a term that seems absurd in the context of the type of life on our planet then) were probably the result of symbiosis between two or more prokaryotes. These were more complex and had something that the more primitive ones did not: sexual reproduction. It is something that seems trivial, yet it is not trivial at all. Among other things, sexual reproduction contributed something fundamental: an acceleration of diversity. Until then, cells had been dividing identical genetic material, altered only by casual mutations that could arise from gamma ray impact or another mutagenic actor. To this was added the exchange of information between cells, which promoted changes, adaptation … and thus evolution. Cyanobacteria and stromatolites began to be cornered by more advanced, more diverse plant cells capable of adapting to different temperatures, salinity, nutrient concentrations and carbon dioxide. Eukaryotic algae began to conquer the planet, along with other eukaryotes such as ciliate, flagellates and foraminifera.

Meanwhile, the oceans were constantly being reshaped by plate tectonics. Continents drifted, as unstoppable as the planet itself and its environmental conditions. The effect of the sun, at first weak (4,000 Ma ago, only 70% of the radiation that reaches us now reached the planet), grew in force by shining on Earth's surface in a more stable way. The ozone layer was consolidated, allowing minimal penetration of ultraviolet rays, which are harmful to life, especially on the surface. The Earth itself would slow its turning, going from 18-hour to our current 24-hour days, and alter its inclination to rotate around the king of all our stars: the sun.

Multicellular organisms began to emerge, with new metabolic and food requirements. The first animals took hundreds of millions of years to appear. The oldest fossil records date from about 550 Ma, in the Ediacaran Period. These were great changes to an environment in which life was gradually opening up an increasingly complex, increasingly interactive division between the various parties. In the Cambrian Period, 500 Ma ago, the rules of the game, as we know it today, were largely established. After an explosion of unparalleled diversity, life on the planet took on various forms: some survived, others perished, but the food chains (herbivores, predators, parasites;

commensalism or symbiosis) were consolidated at this time, when the first arthropods, the first protochordates and the first molluscs emerged. The oceans, then called Japeto and Panthalassa, bore no resemblance to the current configuration. The continental masses were much smaller than at present, concentrated in Laurentia, Baltica and the immense Gondwana, with some islands forming archipelagos. Continental drift (and the movements of the planet in its orbit) caused the appearance and disappearance of oceans, the regulation, acceleration or stagnation of currents, the existence of immense polar ice caps (such as that of the Carboniferous Period, 300 Ma ago) and the formation of hypersaline shallow seas, which were sometimes devoid of life. Transgressions (the sea flooding the land) or regressions (the formation of land from flooded territory) due to changes in sea level of more than 300 metres (m) in height were other factors that changed the life of the oceans—and, of course, of the mainland—throughout the geological eras.

And life always adapted to change, even if that change was abrupt, as in the Permian or Cretaceous extinctions. One such change was associated with the appearance of diatoms, microscopic algae whose oldest fossils are in fact quite recent, about 180 Ma ago. Diatoms are extremely productive. It is now estimated that 40% of the primary (photosynthetic) production of the oceans is due to these algae, accounting for up to 20% of the world's primary production. They are important producers of oxygen and organic matter, and their proliferation possibly stimulated the growth of small and large herbivores. The increase in the numbers of zooplankton, consumed by both diatoms and other microscopic algae, had also provided ideal conditions for marine food chains to diversify and for their actors to reach a remarkable size. The basis of production also took the form of a proliferation in multicellular algae and angiosperms, which, after their conquest of the mainland, returned to the sea in search of new territories and ecological niches.

Life came ashore about 430 Ma ago. First, it took the form of bacteria and algae in symbiosis with fungi (the most primitive lichens date from 280 Ma), moss-like plants, horsetails and ferns. Next, it took the form of arthropods (especially spider-like animals) and other heterotrophic organisms (i.e. needing to feed on other organisms, as unable to perform photosynthesis) that took advantage of the Eden that opened up to them on the land. In the Carboniferous Period about 300 Ma ago they reached their full height, thanks to a concentration of oxygen significantly higher than at present. The first vertebrates came ashore several million years later, causing the entire food dynamic of the planet another upheaval. The first fish to modify their fins possibly fled from predators without leaving their aquatic environment. Transformed into powerful limbs, these appendages allowed them to reach shallow waters that other animals could not reach. It is also possible that, in a world where terrestrial vegetation probably formed dense, invasive forests in shallow, swampy areas, these animals with modified fins were agile contortionists capable of dodging the branches and roots of both terrestrial and aquatic vegetation. Some began to develop something like prehensile limbs at the end of their fins, like fingers. They were therefore able to hold onto vegetation and rocks, keeping their position in strong currents and even guiding them, to some extent, in turbid waters.

When they came to possess primitive lungs, these tetrapods conquered the land. The most plausible first candidate so far is *Hypernerpeton*, an inhabitant of the seas, from about 365 Ma. This invasion of the land by life would change everything. Organisms, and especially plants, transformed the mineralogical composition of the soil (referring to the interaction of minerals and the living parts of plants) and its concentration of organic products in rivers or groundwater, ending up in the sea. Once again, life had to adapt to the changes brought about by increases in sediment, detritus, phosphorus and other nutrients, which would displace one yet give rise to another totally different form of life in an eternal transformation of a tireless system.

It is therefore important to maintain a dynamic view of the life of the oceans over the millions of years. Life, since it emerged from the early seas, has adapted to change of all kinds, ready to accept the challenge of surviving even major catastrophes that have put it in check, challenging time and again its balance and stability. I remember a conversation with a sadly deceased professor at the University of Barcelona, Javier Ruiz, who told me that 'as long as there is only one bacterium on the planet and there are environmental and energetic conditions adapted to the survival of life, the legacy of DNA will remain undisturbed'. Although it is not possible for humans to destroy life, the last ten thousand years have prompted a series of transformations that are once again challenging the balance that has endured until now.

But we are wrong if we think that these changes are due to our interference over the past century. Long before then we had begun to be one of the few organisms in Gaia's history capable of transforming the life and balance of an entire planet.

The Mother of All Extinctions

It is difficult to imagine an extinction in which 95% of marine organisms disappeared. But about 250 Ma ago that is what happened, according to the fossil record from the Permian Period. Some researchers conclude that it represented a real challenge to the more evolved life of both vertebrates and invertebrates, being more radical than the extinction in the Cretaceous Period 65 Ma ago. Entire reef structures disappeared with all their organisms, with some groups such as bryozoans, rugged corals or sea lilies forever displaced from their hegemony, relegated to smaller groups that, in some cases, still survive today. In less than a million years, nine-tenths of plant and animal life disappeared from the face of the Earth. In Italy, traces have been found of dead forests where fungi feasted on rotting primeval plants. After the extinction, dinosaurs emerged, among other organisms, to roam for more than 180 Ma as the first predecessors of the mammals that were to replace them.

But, while the extinction of these primitive saurians seems linked (although there is not full consensus) to the famous Chicxulub meteorite, the extinction in the Permian Period has several possible causes that are debated by specialists. On the one hand, it is known that there was incessant volcanic activity for no less than 100,000 years. This may have caused a cooling of the planet and subsequent desertification. In Siberia, one can still see primitive volcanic formations (traps) similar to those that would have been all over our planet at that time. Related to these changes in climate (in fact, potential glaciation), a stagnation of the oceans is referred to by some experts. This would have caused a deep anoxia (lack of oxygen) in the lower layers, rising to the surface to eliminate animals and plants at shallower depths. But the legacy of a meteorite is present here, too. In Australia, there is a crater of about 120 km in diameter caused by the impact of a 5-km bolide that would have devastated the Earth at that time. Apart from noxious gases put into circulation and the intense acid rain, the sun would have been hidden for months by a thick cloud of dust and incessant fires that could have devastated the planet. Without light, there were no photosynthetic organisms to feed the next level up in the food chain, resulting in extensive loss of life. In reality, the causes are not mutually exclusive. Many specialists talk about simultaneous factors. What is clear is that the history of our oceans (and of the whole of planet Earth) experienced a serious imbalance in the Permian Period, a time when the course of life was past turning back to other possibilities and other horizons.

Great Marine Beasts

One of the most impressive changes in the seafood chain has been the extinction of the great marine saurus. Like the land saurus, its decline some 65 Ma ago was due to the impact of the Chicxulub asteroid, leaving the way clear for predators such as sharks, fish and cephalopods for some time. Possibly, the collapse of primary production indirectly left the saurus without food, leading to its extinction. When evolutionary divergence began, scattering species and requiring adaptation to the different environmental conditions of the planet, some of these reptiles took advantage of shallow waters to return to the sea. Originally, some 250 Ma ago, the first dinosaurs to conquer the sea probably did so for two reasons: the food that the sea provided and an absence of predators. Moreover, new territories gave them a chance to flee from those who hunted them. The first were animals somewhat similar to a *Diplodocus* with fins. Beasts such as *Kronosaurus*, an elongated snout dinosaur with a skull 2 m long, more than 10 m long and weighing 10 tonnes, must have been a nightmare for fish, turtles, cephalopods and other aquatic dinosaurs. If these beasts grew to an unimaginable size, it was for one simple reason: there was food available to sustain their voracious appetite. Banana-sized teeth like those of *Nothosaurus* (one of the first saurian settlers more than 230 Ma ago) only develop if there is prey to devour.

The disappearance of saurians left an unfilled ecological niche. Bony fish and elasmobranchs (sharks) temporarily filled the gap, giving a further twist to the complex history of our oceans. Then, about 50 Ma ago, 15 Ma after their disappearance, the aquatic dinosaurs were finally replaced by organisms that had followed them from the land: mammals. The first prehistoric whales spent long periods on land and could not reproduce directly at sea. But the productivity of the seas was skyrocketing, and the opportunity was too good to pass up. That's why, 24 Ma ago, odontocetes (toothed whales) and mysticetes (baleen whales) reached similar proportions to our present-day whales, culminating in the largest vertebrates that have ever existed.

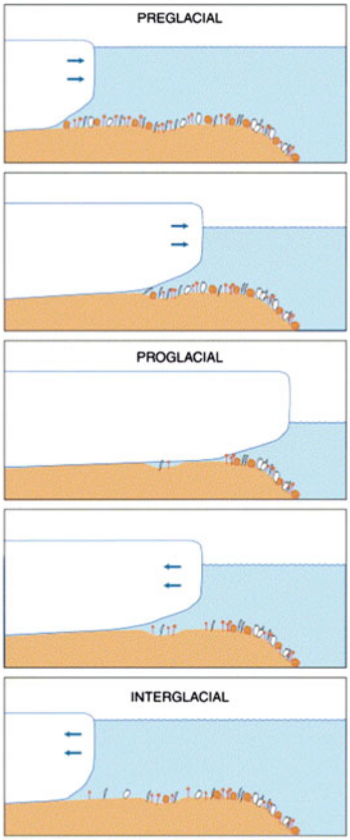
Survivors Born

At noon at the end of June, back in 2000, I went to lunch with my then head of research, Josep-María Gili. We sat down to eat a fixed-price menu in a restaurant near the old Institute of Marine Sciences in Barcelona's Plaza del Mar and he told me a fascinating story from the last Antarctic trip that we had shared just a few months earlier. What if the organisms that live at the bottom of the waters surrounding the 'white continent' were relics from tens of millions of years ago?

In Antarctica, living on the seafloor under hundreds of metres of water, are organisms that have been little modified by evolution over the last 100 Ma years. Prolonged continental drift has condemned this huge land to extreme isolation. When it began to drift south about 70 Ma ago, Antarctica's climate began to change, little by little. Some 40 Ma later it was totally isolated, due to the formation of a circumpolar current, such as that which today acts as an almost insurmountable physical barrier to most organisms in temperate or tropical latitudes. The formation of an immense mass of ice on land above sea level (in places up to several kilometres thick), due to the permanent extreme cold, created an environment of frost hostility paralleled only by certain areas of the North Pole. In that relentless external environment, along with the stability of the cold Antarctic water temperatures, the abundance of plankton established on the dark and impenetrable bottom an animal garden comparable in diversity and exuberance to coral reefs or the communities on the seabed of the Mediterranean. This community is made up of benthic suspensives, filter feeders that on live or dead suspended particles (debris, eggs, small crustaceans, etc.) without moving from the place, like animal trees. But they do it in a peculiar habitat: these animals (sponges, gorgonians, etc.) live where there is a soft bottom. What's so special about that? Gorgonians, corals and sponges can tolerate a moderate amount of sediment and other particles, although an excess simply chokes them. There are no rivers in Antarctica, and the amount of debris transported by glaciers from land is not comparable to that from rivers such as the Nile, Mississippi or Amazon.

In the past, animals such as these benthic suspension feeders at the bottom of the white continent's seas were found all over the planet, but little by little they have been displaced by animals such as bivalves or polychaete worms that (efficiently) filter those particles and adapt to soft bottoms full of sand and mud from the land. Many of the organisms that were dominant during the Cambrian Period or Palaeozoic Era were gradually cornered into deeper places where they could still dominate the space and go through their life cycles. The temperature in Antarctica, much lower than elsewhere on the planet, prevented the proliferation of large, fast and efficient predators such as sharks, large fish and decapod crabs (Fig. 1.1).

Another factor to take into account is that the ancestors of the organisms that we now observe on the Antarctic seabed survived one of the most traumatic cataclysms that Gaia has ever experienced: the impact of the meteorite some 65 Ma ago. But how? While the extinction of the Cretaceous Period had obvious consequences for the fauna of shallower parts of the planet, animals living at greater depth did not suffer as much. It has been inferred that the meteorite impact directly and indirectly caused a collapse in ocean primary production. But there, in the deepest parts of the ocean and in the Antarctic seas, sponges, gorgonians and many other organisms resisted



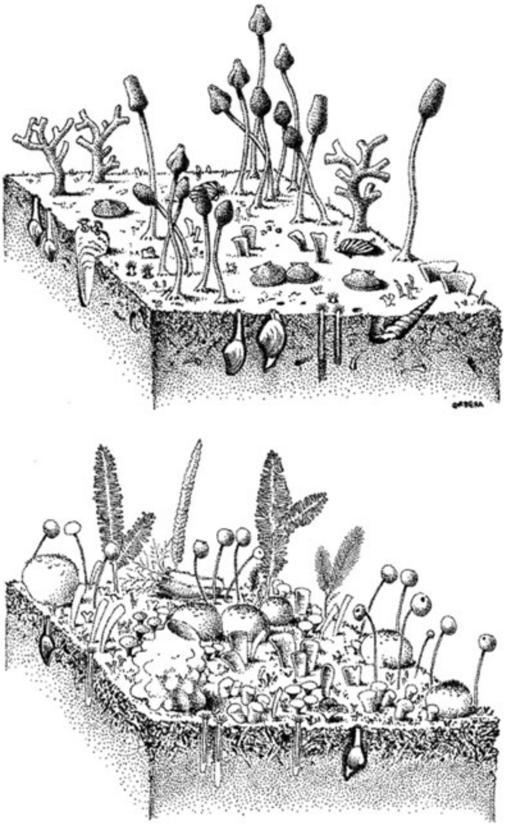


Fig. 1.1 Left image: glacier movement on the Antarctic shelf. Sessile organisms and associated fauna are dislodged and pushed to the shelf's edge; and the shelf once the glacier has retreated. Right image: structural and taxonomical similarities of ancient (Cretaceous) and actual benthic sessile fauna in the Antarctic benthos. *Source* Gili et al. (2006)

because they had adapted to food shortages: for months there is no light in Antarctica, therefore they have to manage without a continuous supply of microscopic algae, which need light to divide. In this, the most extreme area of the southern hemisphere, their diet is partly made up of fine particles on which other organisms can barely survive, and it has enabled them to resist the major fluctuations in food production that occur in the water column. In other words, not even the impact of the great meteorite could make them disappear. However, there remains the question of glaciation. Indeed, the advance and retreat of the glaciers and of the immense icecap, hundreds of metres deep, cleared them again and again from the continental shelf.

However, due to the ability of these organisms to take refuge in deep zones on the edge of continental shelves or in underwater canyons, where the ice was unable to scour the bottom, when the glacier receded they could reclaim the space that had been lost. That is why Antarctic organisms, adapted to a climate that is hostile in terms of temperature but rich in food (at least for a certain period in the annual cycle) and stable in many respects, have been able to withstand the adverse weather conditions of an ever-changing planet.