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The Ocean in the Earth System: Evolution and Regulation

1.1. The Earth system and its components

It is very common today for our planet to be called an "Earth system". The scientific meaning is both a necessary tool of communication and an area of potential confusion. Therefore, let us first endeavor to probe this concept and define how the Earth is a "system" of which the ocean is one of the "components".

A system is classically defined as a group of elements (or components), each of them interacting with the others through certain principles or rules. This definition seems trivial and merits some comments and clarifications.

1.1.1. *A system is a set of objects whose limit is arbitrary, but pertinent*

First, the word "set" implies a grouping within a boundary, defined in a subjective and arbitrary manner by the observer. In what circumstances is the arbitrary choice of a grouping relevant? For the scientific observer, the grouping is most often relevant because it

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corresponds to the category of “an area of study”, generally a characteristic of an academic field. This might be a cell for a cytologist, a multicellular organism for a physiologist, a population or settlement for a population biologist, the ecosystem for an ecologist, the society for a sociologist or for an economist, the area beneath the Earth’s surface for a tectonician or volcanologist, the Earth’s surface and atmosphere for a climatologist or an oceanographer, etc. For the non-scientific observer, the intuitive grouping is that which corresponds best to a visual entity, whether that be observed by eyesight alone or through images furnished by means of modern technology (from the microscope that allows cells to be seen to satellites that allow the Earth to be seen from space). It is not surprising that the disciplines in the natural sciences, for the most part, are derived from the visual perceptions of the “man on the street” and from technological progress.

The arbitrary identity of a system, through a grouping, is therefore a form of categorization of the type that biologists use for very broad families of life forms (e.g. bacteria and archaea, protist eukaryotes, multicellular or metazoan eukaryotes). We note, however, that this is different from phylogenetic categorization (modern day taxonomy), as this is founded upon similarities in the attributes and in the genetic proximity amongst a range of objects: that of individual living beings.

In the case of a living being, the definition is, in general, relevant because of its physical limits (e.g. cuticles and skin) and its autonomy. Note that the idea of autonomy can after all be very weak. Is an ant autonomous without its anthill? Is a cell autonomous in a multicellular organism? Is a man or woman autonomous on a reproductive level?

The definition of a system is, in retrospect, very arbitrary when the proportion of non-living components of the system is important (e.g. ecosystems and societies). Such a system should therefore be the subject of a precise and rigorous description within the framework of the limits that have been arbitrarily fixed upon it. Too often, the notion of an ecosystem is, unfortunately, employed as a generalization, each user implicitly conferring a different typology on it.

In the extreme case of a planetary system, the limit again becomes pertinent (the summit of the atmosphere, if there is one, or the soil surface, or the sea surface), since there is a great contrast between a medium where, under the effect of gravitational attraction, the density of the matter is high (the interior of the system, atmosphere included) and a medium where the density of matter is close to zero (the planet's exterior, interplanetary space). However, unlike living beings, such a system is not "reproducible" in a biological sense; in other words, it has no equivalents. Despite that, it can, like living beings, have global characteristics essentially invisible to the non-scientific observer, notably in terms of self-organization, regulation and adaptive evolution.

1.1.2. *One system is necessarily built into another*

A multicellular organism is, as the name suggests, an organized living being; in other words, it is composed of organs that interact with each other in that they maintain the existence of the organism as a whole. But the organisms themselves are composed of specialized (somatic) cells that have interactions between them. It is therefore evident that the arbitrary limit of the internal components of a system, which amount to subsystems but not necessarily to organs, depends directly on its external definition, that is to say on the identity that we attribute to it.

The natural systems are therefore like Russian dolls on the small just as on the large scale, the absolute theoretical limits only being imposed on a small scale by: the indivisibility and the indetermination of the most fundamental quantum particles (e.g. quarks), the indivisibility of the information (quantum information, Boltzmann constant h) or the indivisibility of time ("Planck" time = 10^{-43} s). On a large scale, they are imposed by the spatio-temporal frontiers of the observable universe, in the case of the Big Bang, 13.7 billion years ago, and the finite speed of light, places or events that have occurred at a great distance from us. However, there is a theoretical intermediate limit between the ensemble of "macroscopic" components, dominated by interactions that can be described in a mechanistic way (contacts, flux of matter and energy), and that of "microscopic" components, dominated by interactions that can only be described statistically (movements, interactions at a distance and collisions of quantum particles, atoms and molecules). We can, for example, place this limit at the level of biological cells, the cells being in some way the smallest macroscopic systems, but their contents are relevant for much of the microscopic world (strictly speaking, intracellular organelles are also macroscopic and the base sequences at the heart of a gene on a strand of deoxyribonucleic acid (DNA) can be described in a mechanistic way).

Another theoretical intermediate limit distinguishes isolated or closed systems from open systems. It is this point that we will now tackle.

1.1.3. *The Earth is a "closed" system*

In thermodynamics, a system is called "isolated" when it does not exchange energy nor matter with the outside world. The term "matter" is theoretically useless here, when we consider that from a physicist's point of view, according to Einstein's theory of general relativity, matter is only a particular form of energy. This only accounts for the principle of conservation of energy, matter being only an approximation for the scales of time and space relevant to the life of mankind or the history of humanity.

By virtue of the second law of thermodynamics, an isolated system naturally evolves toward a situation of equilibrium, which is known as "thermodynamic death". In our own perceptions, such a system does not exist because any attempt to observe it would, in fact, break its isolation. It is therefore only theoretical and can only give rise to non-refutable hypotheses whose scientific character can be discussed [POP 62] (such as the cosmological hypothesis of multiverses where universes evolve in isolation from one another).

Conversely, a system is called "open" when it exchanges energy and matter with the outside world. In this case, the system can depart from a situation of thermodynamic equilibrium to reach, eventually, a stationary situation without equilibrium (regulation) whose maintenance is assured by the transformation of a flux of energy during its passage to the heart of the system. This transformation is the price to be paid in order for the level of organization of the system to be maintained or increased. This is what occurs during photosynthesis in plants by directly transforming light energy from the Sun, but also more indirectly, during respiration in animals, plants or bacteria. By doing so, these reuse, more or less directly, the chemical energy that the products of the initial photosynthesis contain; that is to say organic matter (reduced carbon) and oxygen (O_2).

A stable system does not accumulate energy in the long-term. Apart from a few insignificant and temporary fluctuations, such as phases of lipid stocking and the development of living creatures, the entirety of the adsorbed energy is sent back outside the system, only with a modification in quality (an increase in entropy). This is, for example, the case with changes in quality of the energy contained in organic matter (chemical energy) which, after being used by a living consumer (via respiration, by using oxygen or another oxidizing compound), is partly transformed into heat that is then transferred into the surrounding fluid. In this sense, this flux of energy can be considered a mediator that reduces the entropy to the system. As entropy is a physical concept of the measurement of chaos, this reduction results in the system maintaining or increasing its “order”, otherwise known as its level of organization.

The Earth, during its accretion phase (around 4.5 billion years ago), which lasted around 100 million years, was a largely open system which received a very significant influx of matter relative to the mass already accumulated. It was in the next phase, during this continued influx of matter, that terrestrial water, which we know today in the form of oceans, ice, rivers, lakes, groundwater, clouds and vapor, accumulated on the new planet. Simple organic molecules, formed in space, also arrived on Earth during this period. It remained a very open system around 4 billion years ago during a phase of late and intense meteoric bombardment.

But since this very distant epoch, the Earth has not experienced any further significant accumulation of matter. Of course, the current average inward and outward fluxes of matter, at the boundary of the Earth system, are not null – in the order of several hundreds of thousands of tons per year – but they are entirely negligible compared to the fluxes of matter that are exchanged between the internal components of the Earth system. The former, therefore, has almost no influence on the latter. Of course, the exceptional impact of a large meteorite occurs from time to time with important consequences for evolutionary dynamics, the most well known of them being the extinction of the dinosaurs, with the exception of the ancestors of birds, 65 million years ago. However, such an event, even if it heavily impacts the nature of present and future species, has no long-term effect on the Earth system's general biogeochemical dynamics. Once the event and its climatic consequences have passed, the system regains the normal course of its regulations and evolutions, which we will describe in this chapter and which are also addressed in Chapter 4, and in Chapter 2 of [MON 14b].

If the Earth has had an exchange with the universe in the pst 4 billion years, it is likely to have been through a flux in radiative energy. For thermodynamics, this means a non-isolated, but "closed", system. The Earth receives a certain quantity of radiative energy from the Sun and from space and sends an equal quantity back into space, but increases the average wavelength of its radiation; that is to say it shifts its spectrum to infrared. The individuality of the Earth system is thus partly due to the fact that it is a closed system and its perimeter is not arbitrary since it corresponds to the pragmatic image that we have of it as an object, well separated from the exterior universe. Moreover, we will show later that the maintenance of an atmosphere, oceans, a climate and life, for 4 billion years, is largely due to the fact that the Earth is a closed system through which energy travels and is transformed. This is an exceptional situation in the solar system, since we can observe other neighboring planets, formed at the same time, such as Mars and Venus, where these characteristics are not present simultaneously.

The atmosphere of Mars is extremely thin and liquid oceans do not currently exist on Mars nor Venus. The condition of a "closed planetary system" is therefore necessary, but not sufficient, to explain the preservation of the principal characteristics of Earth – atmosphere, liquid water, life – over the course of 4 billion years. The other conditions stem from adaptive interactions that have been established progressively, on the one hand between the larger components of the Earth system (e.g. geophysical, geochemical and biogeochemical exchanges) and on the other hand between those components and life forms that constitute them (flux due to the metabolisms of life forms). The objective of this chapter is to describe these interactions.

1.1.4. *The major components of the Earth system*

The general physics and biogeochemistry of the Earth system show that the most important internal fluxes of matter and energy only occur within a few particular interfaces. The interface that separates the "solid" Earth from external envelopes of fluids (the ocean and the atmosphere) is found at the location of volcanic emissions, erosion, sedimentation and the subduction of tectonic plates. The interface between the ocean and the atmosphere gives rise to evaporation, precipitation and exchanges of gas. The interface between the continents and oceans is the location of transfer of continental matter eroded into the oceans, in particulate and dissolved forms, that partly fuels the sedimentation of the oceans.

A simplified but pertinent description of the Earth system therefore consists of defining the internal "base" components through a few very large compartments (or reservoirs), which include the geosphere, ocean and atmosphere. They are like the vital organs of an animal between which fluxes of matter and energy travel. In this sense, they are physical compartments, whose role in the Earth system is "organic".

Improvements in our knowledge of these compartments, through active research over the last few decades, have, of course, led to the refinement of the understanding of the system. It is in this way that we are able to make distinctions between the different reservoirs of water on earth (the hydrosphere) – the oceans, continental fresh water, ice and water vapor. However, further distinctions between subcompartments have proven to be necessary. For example, the ocean's surface and its interior do not have the same physical properties and are separated by a discontinuity in temperature (the thermocline) but also a discontinuity in density. These two subcompartments exchange matter and energy between themselves (via thermohaline oceanic convection and turbulence in the thermocline), but also experience exchanges with the atmosphere at its upper surface, in the case of the ocean surface, and with the seafloor, in the case of ocean's interior (underwater volcanic activity, sedimentation, early diagenesis, circulation of hydrothermal fluids, etc.). Similar distinctions exist between the upper and lower atmosphere, or between the geosphere in contact with the atmosphere (soils, outcrops, lavas and basalts on continents and islands) and that which is in contact with the ocean (sediments on continental margins and abysses, lavas and basalts).

1.1.5. *What is the biosphere?*

The notion of a "biosphere", in parallel with the large components that we have just described above, brings us back to considering the sum of all life forms as simply an additional component. Evidently, this would not correspond to the reality and would moreover be fundamentally dismissive in regards to the importance and complexity of the role of life in the functioning and evolution of our planetary system.

Firstly, life forms are neither homogenous nor continuous. They have effectively colonized a great number of niches, whether that is the surface of the geosphere (sediment), the oceans, continental water or the surfaces of continents. Moreover, although they represent only a slight mass (biomass) compared to that of the large compartments of the Earth system, life forms are the mediators of an important part of the flux of matter between compartments through the phenomena of photosynthesis and respiration, the mobility of organisms, the phenomenon of bio-mineralization leading to the construction of internal skeletons and shells, and the production of organic and mineral waste (senescence, death, production of feces and urine, etc.). A life form is therefore not, strictly speaking, a reservoir of the Earth system, but rather a motor, or mediator, of its internal interactions. But the definition of the biosphere does not stop there. When we speak of the evolution and regulation of the Earth system across large scales of time, life is also characterized by its endlessly renewed diversity, from which its adaptive plasticity develops under the pressure of natural selection. It is this plasticity of life forms that, via its role in the exchange of matter, allows the entirety of the Earth system to be evolutionarily flexible.

Thus, we acknowledge that the description of an ecosystem, whatever its perimeter, does not just come down to its life forms. It cannot limit itself to describing instantaneous states, but should also describe the dynamics and retroactions, where living and non-living entities enter simultaneously into play. We will, therefore, conclude here that the term “biosphere” is equivalent to that of the Earth system (or global planetary ecosystem) from the advent of early life on Earth (around 4 billion years ago) to today, as such, for the greater part of its history. But in order to avoid any confusion, we will restrict ourselves to using a single expression: “Earth system”.

1.2. The ocean, from its origins

1.2.1. *Was there an ocean 4.4 billion years ago?*

Isotopic studies carried out on zircons from Australia dating from 4.4 billion years ago [WIL 01] have given rise to the emergence of the hypothesis that liquid water could have been present on the primitive Earth from the end of its principal accretion phase, characterized by the presence of a magma ocean resulting from the transformation of gravitational energy into heat. The liquid water would have accumulated on a solid crust that had only just cooled.

Even if this hypothesis still remains widely disputed, it is generally acknowledged that the oceans were probably formed more than 4 billion years ago. Evidently, this early liquid water was in equilibrium with an atmosphere much denser than that of today, of which the pressure at ground level was several tens of times greater than that of today. The original oceans therefore probably experienced a very hot phase, in the order of several hundreds of degrees Celsius.

1.2.2. *The origin of water on Earth (4.5 – 4 billion years ago)*

It is self-evident to say that water on Earth has an extraterrestrial origin because this is true of all the elements that constitute our planet.

Nothing is created from nothing in our observable universe! Nevertheless, the arrival of water, carried on meteorites and comets, was not in exact synchrony with the arrival of rocky elements and this is due to the history of the formation of the solar system. Fervent research activity carried out by planetologists and astrophysicists particularly endeavors to explain the differences in composition and orbit of objects in the current solar system (the Sun, telluric “rocky”, planets, giant “gas” planets, satellites, asteroid belts, comets, the Oort cloud). The explanatory model develops particularly in the form of a historical sequence of several important events such as the formation, differentiation and the progressive cleaning of the protostellar disk, the movement of volatile components (including water) associated with the thermonuclear ignition of the Sun, the formation of telluric planets, the formation of giant gas planets, the migration of Jupiter (the “hot Jupiter” hypothesis) and substantial impacts.

It is not possible to give here an overview of the state of current knowledge in this field; the interested reader can refer to more specialized works on the formation of the solar system. We can, however, emphasize a major point for this present chapter: most water, brought through influx asteroids and comets, accumulated late, after the principal phase of accretion by rocky material, but probably in the first 500 million years of the Earth’s history. It is this water that would constitute the majority of the current oceans (93% of water on earth) and the different reservoirs of fresh water (glaciers and ice caps above all, then lakes, rivers, groundwater, atmospheric water vapor and clouds).

1.2.3. *The ocean and the end of the “Venus” phase of the Earth’s history (between 4.5 and 4 billion years ago)*

During accretion, the heaviest elements were concentrated by the effect of gravity at the center of the Earth’s sphere (especially iron and nickel, but also other, rarer heavy elements), whereas the lightest elements became concentrated on its surface. Taking into account the initial conditions in temperature and radiation, the Earth’s very first atmosphere was probably dominated by gaseous and stable components, formed by the chemical combination of light elements such as hydrogen, carbon, oxygen and nitrogen – the most likely candidates being carbon dioxide (CO_2), dinitrogen (N_2) and water (H_2O). This is the reason why, in the absence of natural archives from the era, the current theoretical models propose an initial atmosphere that was very dense, dominated, apart from water, by around 98% CO_2 and 2% N_2; these proportions can vary slightly depending on the models used [GAR 06]. Certain minor or trace components (such as gaseous SiO_2) are not excluded from these hypotheses, particularly because of the very turbulent conditions caused by enormous, repeated meteoric impacts or by the mega-impact that gave rise to the formation of the dual Earth–Moon system.

The primordial atmosphere was probably very dense (from 60 to 160 times the current atmospheric pressure) because it contained, in the form of gaseous CO_2, the carbon that is present today in the form of solids (carbonated rocks and sediments and organic matter, notably fossils). In such conditions, the greenhouse effect was enormous and it kept the Earth's surface temperature at several hundred degrees Celsius. This phase is sometimes called the Earth's "Venus" phase by analogy with the conditions that prevail today on Venus.

Water, which arrived on Earth progressively carried by meteorites and comets, progressively accumulated, at first in gaseous form, increasing the greenhouse effect, then in liquid form when the saturation pressure was reached. It is therefore very probable that the first reservoirs of liquid water contributed considerably to the reduction of the greenhouse effect [LIU 04] as they constituted chemical reactors by which gaseous carbon in the form of CO_2 could be transformed into solid carbon in the form of carbonates ($Metal^{2+}CO_3^{2-}$), via the equilibriums between the different forms of carbon mineral dissolved that coexist in the aqueous phase, CO_2, HCO_3^- and CO_3^{2-} [ZEE 01].

It is helpful to note that this general process is constantly occurring today, but through biologically mediated processes (biomineralization of calcium shells and skeletons) and via the alteration of aluminosilicate rocks. This alteration consumes CO_2 and some of this carbon is ultimately found in the ocean in the form of carbonate ions (CO_3^{2-}) due to oversaturation. These will then be transformed into solid form by the biological processes that create shells and skeletons, then stored in the sedimentary reservoir. Details on these processes can be found in Chapter 4, and in Chapter 2 of [MON 14b].

It is unknown how much time the end of this "Venus" phase could have taken; many specialists on the primitive Earth now believe that conditions favorable to the emergence of life were already present 4 billion years ago, that is to say, before the late meteoric bombardment, and it is not impossible that an emergence of life may have taken place in the ocean from this era [GAR 06]. If it existed, did this life survive a late meteoric bombardment? Did other emergences, successful or abortive, take place later? These questions remain largely open.

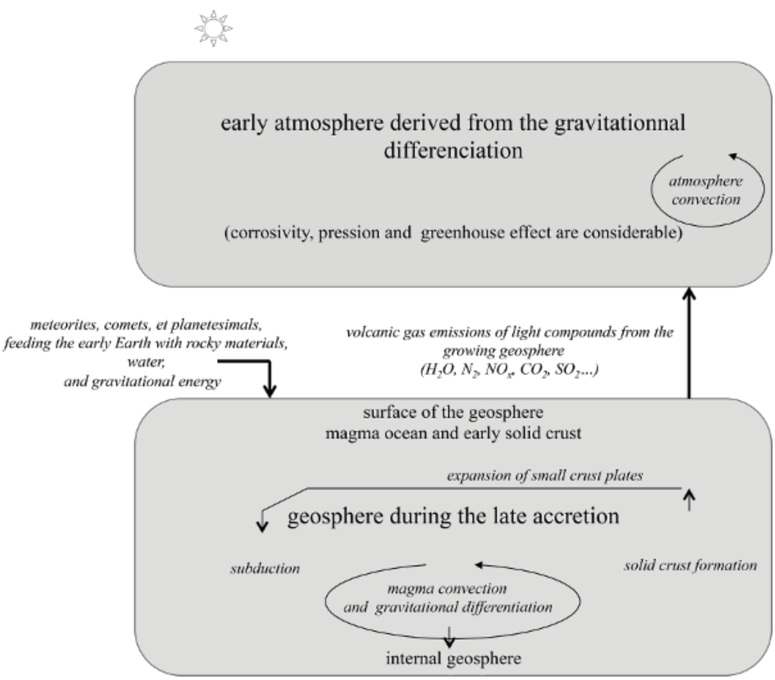

Figure 1.1. *Diagram of the Earth system at the end of accretion around 4.5 billion years ago (see color section)*

COMMENTARY ON FIGURE 1.1.– The influx of evaporation into the atmosphere is not compensated for and the planet is surrounded by a very dense atmosphere mainly composed of carbon dioxide (CO_2), dinitrogen (N_2) and gaseous water, resulting from gravitational differentiation (the heaviest elements being concentrated as a core at the heart of the geosphere). The greenhouse effect is enormous and an ocean of water cannot form. This is the Earth's "Venus" phase.

1.2.4. *Why are there oceans on Earth and a "Venus inferno" on Venus?*

Earth and Venus are two neighboring telluric planets, formed at the same time and of a very comparable size. How do we explain the fact that the conditions on their surfaces and in their atmospheres are so dissimilar today? [1]

Aside from the conditions on their surfaces and the composition of their atmospheres, two important characteristics distinguish the two planets. First, there are no active plate tectonics on Venus, whereas Earth maintains one. We can observe this in everyday life through earthquakes, volcanic activity or, more poetically, through contemplating our mountainous countryside. The second characteristic is the presence of an important satellite, the Moon, which revolves around the Earth. The Moon and the Earth have a very important mass ratio (1/81), now known to us as the most important between two planetary bodies in orbit around their common center of gravity (which is naturally much closer to the center of the Earth than to the center of the Moon). This duo resulted from a giant impact between two planets in the process of formation just over 4.5 billion years ago. Because of its kinetic conditions (notably speed and angle of incidence), this impact threw out a very significant quantity of matter into space while still preserving the core of the larger of the two

1 Remember the story that Venus, the morning star, was known to the Romans by the name of Lucifer (carrier of light), whereas the Christian tradition ended by transposing Lucifer, the angel dethroned after wanting to supplant his creator, into Satan.

proto-planets. The result was the formation of an orbital disk, followed by the progressive cleaning of this disk to form the Moon [KOK 00].

However, another scenario could have involved the instantaneous introduction of a significant quantity of water into the magma mantle of this protoplanet, a precursor to Earth in the right conditions, an event that did not occur, or which occurred differently, in the formation of Venus [BIB 09]. As we now know, thanks to the study of plate tectonics on Earth, the filtration of light components (including water) into the mantle leads to a decrease in its viscosity [BIL 01, DIX 04] and to a chemical differentiation between the continental crust and the ocean along the subduction zones. Together, these two phenomena favor the maintenance of an active tectonic system, at least as we know it on Earth.

Some results of the exploratory mission *Venus Express* published in 2009 by the European Space Agency [ESA 09] suggest that a tectonic system nonetheless existed at the beginning of Venus' history, but it would have ceased to develop due to the lack of ocean. The primordial water was in fact systematically vaporized with a positive retroactive effect on the greenhouse effect, leading to its enhancement and to the gravitational escape of hydrogen.

In the case of the Earth, one hypothesis is that a much more active tectonic system, initiated by the giant impact that led to the formation of the Earth–Moon duo [RUI 11], could have absorbed some of the primordial water via subduction, sufficiently slowing the enhancement of the greenhouse effect so that sizeable oceans could form. After that, the reduction of the initial greenhouse effect by the precipitation of carbonates could have become considerable and the first stage of abiotic regulations of the Earth system was established. This is illustrated in Figure 1.2.

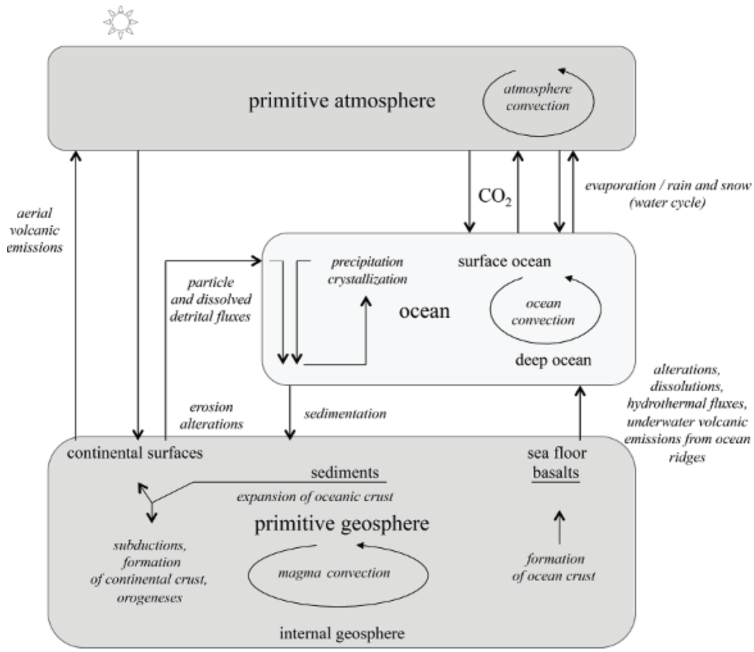

Figure 1.2. *Diagram illustrating the bases of the first abiotic regulations of the Earth system (see color section)*

COMMENTARY ON FIGURE 1.2.– Due to an ocean being in place, the inward fluxes are from now on potentially compensated by outward fluxes for each of the reservoirs of matter. Short-term regulation is assured by the chemical equilibriums of the ocean (the detail of which will be addressed later), whereas the long-term regulation depends on the tectonic cycle. The tectonic activity of the Earth system has been maintained up until today, whereas that of Venus ceased to be very early on. It is probable that this difference arises from the permanent introduction of water into the mantle via the phenomena of subduction. Such a communication between the upper geosphere and a liquid ocean would be established on the Earth system while the early tectonic was still sufficiently active, perhaps because of a more significant initial hydration of the mantle resulting from the mega-impact that formed the Earth–Moon duo.

1.2.5. *The ocean, cradle of the first living creatures (between 4.4 and 3.5 billion years ago)*

What criteria can we use to distinguish a living state from a non-living state? This question is an inexhaustible source of impassioned conversations where different viewpoints clash, from those of scientists (the presence of a cellular metabolism, the presence of a genetic “code”, the presence of a capacity for “reproduction”, the presence of an open, self-regulated system, the presence of a steady state maintaining or increasing the level of organization, that is to say locally going against the second principle of thermodynamics, etc.), up to those beliefs of a spiritual, philosophical or religious order (essentialism, vitalism, creationism, etc.).

On a strictly scientific level, does this question have only one meaning? Is there a scientifically based reason for which it would be necessary to distinguish a living state from a non-living state, or is this only, once more, a question of definition and limits of an arbitrary nature?

To develop an argument in reply to this question here would take much too long and would not be relevant to this work. This is why we will restrict ourselves here to defining, arbitrarily, the “minimal” state of a life form as that of a biological cell possessing a metabolism, genetic information and a capacity for reproduction. This arbitrary definition should be distinguished from that of life in a general sense, which is richer and more complex, and to which we will return later.

A biological cell needs water, and the chemical prebiotic systems that preceded the first cells also needed it. The presence of liquid water, indeed of an aquatic environment, is therefore a necessary condition for the emergence of life. Researchers working on prebiotic conditions and the first life forms do not rule out the possibility that these could have appeared in multiple locations and on multiple occasions, in isolated lakes or seas that probably coexisted and succeeded each other in different places and at different stages of the initial evolution of our planet, even 4 billion years ago [GAR 06]. However, the geological evolution (primitive tectonics), the environmental variability (local climate, deposits of sediment and drought) and major hazards (volcanic activity, falling asteroids, notably before and during the last phase of meteoric bombardment around 4 billion years ago) render the survival of small, local autonomous ecosystems on timescales in the order of a million years or more almost impossible.

The question of the "origin" of life in the Earth system is therefore not only that of the processes by which the first living beings appeared in general, but it is also that of the conditions that permitted one of these life forms to become the common ancestor of all life today. How has life been able to develop into the lattest form, i.e. human beings, over billions of years, as phylogenetic trees indicate, which stretch back to a last common ancestor having lived 2 or 3 billion years ago (*Last Universal Common Ancestor* (LUCA)) and from the findings of paleontology, which stretch back to around 3.5 billion years ago (the age of the most ancient known bacterial fossils, in the form of stromatolites)?

The presence of a sufficiently developed ocean at different latitudes and in different climates is an element of enquiry that concerns the crucial phase of development of the first ecosystems. For life to have been able to "survive" hazards of all types in the long-term, it is necessary that its random destruction was only partial and rapidly compensated by a new colonization of the destroyed environments. It is necessary to underline here that the colonization is not a response to the necessity of increasing the chances of survival of the entirety of the population, but simply that of increasing the chances of survival of each individual by finding the resources that it needed elsewhere. The necessity is individual, but its effects extend to the scale of populations and ecosystems.

There is therefore every reason to think that the life from which human beings originated appeared and developed in an already significant ocean. That this origin may have been associated with deep hydrothermal environments through the use of chemical energy available at high temperature [REY 01, SHO 96], or rather in the surface environments through the use of solar energy, is a question that remains very open to research. Many of the life forms from deep hydrothermal environments, notably animals, have adapted to these extreme nutritional niches by natural selection, beginning from the ancestors that they shared with bacteria, cephalopods, fish, or crustaceans from other marine environments. However, it is unknown whether it is the same for thermophile and chemosynthetic bacteria or if these forms of life appeared locally.

1.3. The ocean, oxygen and the evolution of life forms

1.3.1. *The essential characteristics had been selected in the ocean before the Cambrian period, over 540 million years ago*

The work of the famous American paleontologist Charles Doolittle Walcott led him to discover, at the beginning of the 20th Century, the extraordinary diversity of fossils in the "Burgess Shale" (a fossil field in British Columbia, Canada) [WHI 80]. The corresponding organisms, dating from the Cambrian period (between 540 and 500 million years ago – even if the majority of fossils are in the *later* Cambrian period), were the most ancient forms of animal known at the time. They were marine animals, characterized by the presence of endoskeletons or exoskeletons and by a body organized into segments, such as we can still find today in arthropods, insects and their distant cousins: the vertebrates. This discovery formed the origin of the idea that an accelerated diversification of living species, known as "the Cambrian explosion", occurred at this time. The exceptional preservation of these fossils includes not only their carapaces (toughened external body parts, e.g. an exoskeleton or shell), but also morphological traces of soft tissue situated in the area of the body. It was therefore legitimate to delve deep in the study of the diversification, functioning and behavior of these organisms.

In light of today's knowledge, it is sensible to acknowledge this idea of an evolutionary explosion belonging to this era and to which we can associate the genesis of the entirety of living things. After close inspection, the fossilized organisms of the Cambrian era are for the most part animals; living beings already displaying certain fundamental characteristics in common, selected for over the course of numerous former diversifications. Some of them (on which there will be a new question later) are aerobic organisms: symbiotic cells with a differentiated nucleus (eukaryote) and a characteristic multicellular organisation. Furthermore, the development of carapaces is an evolutionary innovation of the Cambrian period which naturally favored the preservation of fossil traces of animals in possession of these attributes, and which focused the attention of paleontologists on the Cambrian and post-Cambrian periods. Indeed, we know today that many more ancient marine animals without carapaces existed 600 million years ago (the Ediacarian fauna, after the name of the Australian site where these fossils were discovered). This is evidence of the diversification of multicellular organisms in this era, plants as much as animals as no fauna is possible without flora. Some proterozoic fossils dated from 2.1 billion years ago have been found recently in Gabon [ELA 10]. Their morphological complexity intrigues paleontologists and leads to the belief that they could be either multicellular organisms (plant and/or animal) or colonies of prokaryotic cells (bacteria or archaea) possibly in possession of a rudimentary form of functional organization, highlighted by the work of microbiologists using modern examples [KEI 04]. Whatever they are, numerous important diversifications have occurred since the origin of terrestrial life forms, before the Cambrian period, to promote those that led to the selection of the molecular intracellular system that we know today (DNA/RNA/proteins) and of all its genomic and functional variants. The largest number of these diversifications occur in the domains of bacteria and archaea: unicellular prokaryotic microorganisms (cells without a differentiated nucleus), in contrast to eukaryotic cells whose diversity remains largely unexplored.

Figure 1.3 illustrates the principal evolutionary innovations that occurred, mainly in the ocean, between the beginning of life on Earth (over 3.5 billion years ago) and 400 million years ago (early Devonian Period). It also shows the major environmental evolutions, from an exclusively anoxic environment to a very heavily oxygenated environment, where only a few anoxic niches remained (organic sediments, digestive tubes and poorly ventilated deep zones of the ocean or certain lakes). These environmental evolutions matched evolutionary developments, such as the emergence of oxygenic photosynthesis, at the same time creating a new framework of parameters for later developments, such as the emergence of aerobic respiration.

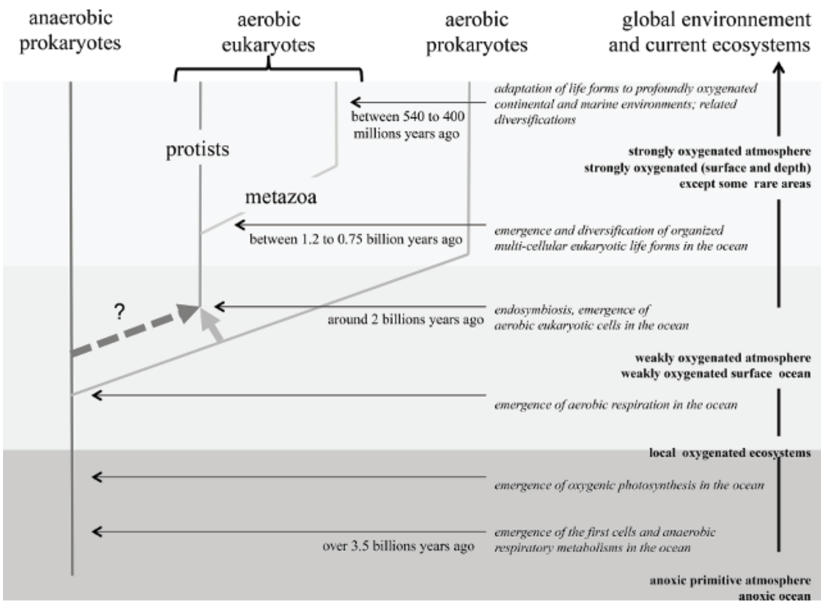

Figure 1.3. *The main evolutionary developments and the major environmental evolutions between the beginnings of life on Earth (over 3.5 billion years ago) and 400 million years ago (early Devonian Period) (see color section)*

The links of cause and effect between the oxygenation of the environment and the major developments previous to the emergence of aerobic respiration are however less evident and still constitute working hypotheses for research. In the emergence of eukaryotic cells, it is not unreasonable to assume that prokaryotic cells, subjected to an increasingly oxygenated environment, were able to find mutual benefits by sharing respective innovations in the framework of endosymbiosis [MAR 91]; some taking the best part of their energy from aerobic respiration (mitochondria) and others furnishing the protective mechanisms of cytoplasm or DNA against the toxic effects of oxygen. As far as the emergence of multicellular organization is concerned, it is not unreasonable to assume that such an organization could have caused external contact with oxygen to be reduced. The aim of natural selection would then be to specialize the external cells in resisting the toxic effects of oxygen and to ensure an influx of matter into the internal cells. A major question for research is to discover how the change occurred from a malleable and temporary adaptation, responding to external conditions, to a biologically cemented situation, where it is the endosymbiotic cell or colonial cell group that reproduces itself as such.

Finally, the colonization of continental environments can also be linked to the history of oxygen. An atmosphere globally enriched with O_2 is favorable to the formation of ozone (O_3) because of the photochemical reactions that occur in its upper layers, which are subjected to very powerful rays from the Sun. The formation of a permanent ozone layer, even if subject to fluctuations with the seasons, certainly favored, indeed rendered possible, the selective adaptation of marine organisms in continental environments. The term "out of water" is too often used incorrectly here, since the organisms adapted first to environments from which water periodically retreated, such as in the intertidal zones of marshes, up to the point where they were capable of leaving the water for increasingly longer periods.

On a global scale, life forms and their environments have thus coevolved, through the device of retroactions, for over 3.5 billion years. Upon careful observation, we can confirm that the most fundamental characteristics of present day life forms (aerobic or anaerobic respiratory metabolism, endosymbiosis of eukaryotic cells and multicellularity) were all selected for in the ocean, before the start of the Cambrian period, over 540 million years ago.

1.3.2. *How did oxygen accumulate?*

Oxygen is an element very receptive to electrons; is it therefore very chemically reactive. The word "oxidize" comes moreover from this property since oxygen, in its O_2 form, is capable of oxidizing almost all the other elements or chemical compounds. Only a few halogens, such as fluorine or chlorine, hyperoxygenated anions (permanganate MnO_4^-, dichromate $Cr_2O_7^{2-}$) or ozone (O_3), have a greater oxidizing power.

Because of this property, the gaseous form of oxygen, the form that nevertheless composes 21% of our current atmosphere, is extremely unstable. In this form, oxygen has a tendency to react with the majority of bodies (gas, liquids or solids) with which it comes into contact, to form oxides while releasing energy. Combustion is an accelerated manifestation of oxidation, maintained by the large heat flux it gives off (see also Chapter 4 of this book, and Chapter 2 of [MON 14b].

Consequently, the massive presence of O_2 in our environment can only be explained by a shortage of potential chemical partners and/or by a permanent production of O_2 stimulated by an energy supply. As we will describe, these two conditions have almost always coexisted in the history of the Earth, even if the availability and nature of the chemical partners have varied in the course of time. If the atmosphere and, later, the continental surfaces, have been important players in this history, it is in the ocean that it essentially occurred.

The Earth's primitive environment was strictly anoxic, i.e. O_2-free [HOL 84, SCH 10]. Even supposing that some rare abiotic processes were locally susceptible to form O_2, this would immediately consume the poorly oxidized (reduced) compounds that surrounded it and would immediately disappear, in this process of chemical "predation".

Starting from the first living cells, the most efficient metabolic mechanisms, at first anoxic, were selected to supply to these cells the energy and matter that they needed. Some of them were anaerobic mechanisms for photosynthesis. They allowed the cell to use, at least partially, solar energy to carry out the synthesis of organic molecules necessary for maintaining cellular machinery just as for its development and duplication. The cells in possession of this new mechanism gained the opportunity to free themselves from the need to capture and digest, through respiration or anaerobic fermentation, other cells or organic molecules available in their environment (heterotrophy). This evolutionary development was likely selected for because the energy supply of light from the Sun was less random than that of organic fuel in the first ocean. Some anaerobic photosynthetic cells still exist today in a few rare anoxic environments where light manages to penetrate. They live, for example, in the subsurface of certain fine deposited sediments subject to marsh tides [SEI 93].

To simplify the discussion, below, we will only speak about oxygenic photosynthesis (which produces oxygen) and leave aside the more anecdotal case of photosynthesis which does not produce oxygen, even though it could have played an important role at the very beginning of life on Earth.

The simplified equation for oxygenic photosynthesis is:

$$H_2O + CO_2 + \text{light} \rightarrow CH_2O + O_2 \qquad [1.1]$$

This formula is the same for photosynthetic anaerobic life forms (which can only live in the absence, or near absence, of oxygen, essentially bacteria) and aerobic life forms (bacteria, algae, terrestrial plant life). In effect, oxygen is certainly a product of this formula, but this does not imply that O_2 is locally concentrated to the point where photosynthetic cells are necessarily aerobic. The adaptation of these cells, aerobic or anaerobic, can differ according to the confinement and the concentration of oxygen that results, but the balance in carbon and oxygen from oxygenic photosynthesis is always the same.

The CH_2O is evidently only an approximation of the average proportion of carbon, hydrogen and oxygen of the organic molecules of the cell. Moreover, this formula neglects the role of the other necessary elements (nitrogen, phosphorus, iron, etc.).

The key trait of this balance is that the production of organic matter by photosynthesis is accompanied by a production of oxygen (O_2). The anaerobic photosynthesis in the ocean was the first source of O_2 in the terrestrial environment since the first ocean was an anoxic environment. Still, the existence of this source was certainly a necessary, though not sufficient, condition for the oxygenation of the environment. This condition, still true today, can only be produced by the ocean, even if the continents are now largely colonized by plants. This condition is explained in the paragraph below.

The oxygen produced by photosynthesis is, as we have already seen, highly unstable. It therefore reacts immediately with numerous compounds or chemical elements present in the primitive anoxic environment. It reacts, for example, with sulfurs (S^{2-}) to produce sulfates (SO_4^{2-}). We note in passing that it thus recycles the oxidizing compounds necessary for certain anaerobic (sulfate-reducing) cells to fulfil their energy needs, since these "respire" sulfates by transforming them into sulfurs. In consequence, without the oxygen issuing from anaerobic photosynthesis, any aerobic respiration would not have been able to maintain itself or to develop in the long-term in the terrestrial environment. A massive and non-localized source of external energy was necessary, which only solar rays could furnish via photosynthesis.

However, O_2 also reacts with CH_2O to form the more stably composed CO_2, releasing a small amount of heat as it does so. This is expressed by a formula strictly inverse to photosynthesis, where only the form of the energy is modified but not its quantity. The following formula summarizes the oxidation of organic matter:

$$CH_2O + O_2 \rightarrow H_2O + CO_2 + \text{heat} \tag{1.2}$$

For an excess of O_2 to accumulate in the environment, it is thus necessary that the availability of its chemical partners, (whether sulfur or organic matter, but also oxidizable ions in solution such as Fe^{2+} (which is transformed into solid iron oxide Fe_2O_3)), is inferior to the flux of oxygen produced by photosynthesis.

The precipitation of solid oxides did, certainly, consume some of the chemical prey present in the ancient oceans. We can observe traces of it within certain sedimentary accumulations of the Archean Period, for example in the banded iron formations at Barberton in South Africa dated around 3.2 to 3.5 billion years ago [HOF 05]. Nevertheless, the key to the accumulation and maintenance in the long-term of an excess of O_2 in the environment, up until to today, is found in the fact that a proportion of the organic matter produced by photosynthesis is constantly transferred into oceanic sediments and, thus, prevented from oxidation by O_2.

$$H_2O + CO_2 + \text{light} \rightarrow \text{sedimentary } CH_2O + O_2 \text{ in the environment} \quad [1.3]$$

Even if this sedimentary flux of organic matter is very small relative to the flux exchanged during photosynthesis and the oxidation of organic matter, its accumulation over long periods of time has enabled the construction of important stocks. The O_2 oxygen in our environment can thus be considered as the counterpart of the global stock of organic sedimentary matter, the living biomass being quantitatively negligible in relation to it.

1.3.3. *The first important accumulation of oxygen (around 2.5 billion years ago)*

Although sedimentary archives stretching back several billion years are rare and fragmented, it has been possible to show that a first important global accumulation of oxygen was produced around 2.5 billion years ago [CAT 05, VOE 10]. This accumulation increased the partial pressure of O_2 (pO_2) at ground level from around 10^{-5} bar to $10^{-1.5}$ (= 0.03) bar [CAT 05], in equilibrium with the oxygen dissolved in the ocean's surface. This first oxygenation only represented around 15% of its total transformation into the pO_2, of which the current atmosphere is 0.21 bar. It nevertheless considerably modified the course of biological evolution just as that of the evolution of the Earth system.

It is not possible to confirm if this first accumulation was principally linked to aerobic or anaerobic photosynthesis, or both. A local and temporary oxygenation of the medium is undoubtedly a prerequisite produced where, in a generally anoxic world, photosynthetic marine ecosystems were the most productive (in certain seasons). Such fluctuations created toxic environments for the photosynthetic cells, since they were initially anaerobic; they poisoned themselves.

We cannot dismiss that aerobic photosynthesis, the type which principally occurs today, could have appeared very quickly after anaerobic photosynthesis and that it could have rapidly become the principal contributor to the global accumulation of oxygen.

1.3.4. *A moderate increase in oxygenation (between 2.5 and 0.5 billion years ago)*

After the first rapid accumulation of oxygen, around 2.5 billion years ago (beginning of the Proterozoic Period), it is very likely that the terrestrial environment continued to accumulate oxygen, albeit more slowly. Reconstructions [BER 04] suggest levels of O_2 in the atmosphere were in the order of only 10 – 15% 500 million years ago (either 0.1 and 0.15 bar of pO_2 for a hypothesis with an atmospheric pressure of 1 bar). This signifies a very slow augmentation average, in the order of 4% volume increase per billion years.

The cause of the deceleration that followed the initial rapid accumulation of O_2 is based on evolutionary adaptations that permitted an increase of oxygen recycling from organic matter, thus consuming more of the oxygen produced by photosynthesis. The first of these adaptations was aerobic respiration, which is only, in fact, the biological version of the oxidation of organic matter by oxygen as described above. This adaptation could only appear after anaerobic photosynthesis, under the selective pressure of an environment at least temporarily oxygenated, and could only spread with the first global accumulation of oxygen.

Aerobic respiration has a better energy yield than anaerobic respiration. As such, it provides the cell the advantage of counteracting the toxic effects of oxygen. In this case, it is possible that the preferential oxidation of certain molecules (external fuel or synthesized reserves of the ATP type) enabled the preservation of essential molecules of the cellular machinery (DNA, RNA, proteins).

From the moment aerobic respiration was selected for, other evolutionary refinements could develop, particularly in the ocean.

This was first the case of endosymbiosis (an aerobic eukaryotic cell issuing from the symbiosis of several initially prokaryotic cells), just over 2 billion years ago, followed by that of the emergence (in several separate stages), of the first organized multicellular life forms: fauna and flora consisting of eukaryotic aerobic cells [RUI 07, SAC 08]. Multicellular life forms were already present in the Ediacarian Period (fauna from around 600 million years ago) and phylogeneticists generally place their appearance between 1.2 and 0.75 billion years ago. It is, however, possible that they are older. This is suggested by a few rare paleontological discoveries, but whose interpretations are still much disputed [ELA 10, RAS 08].

All these evolutionary refinements contributed to the improvement of recycling organic matter and limited the global accumulation of oxygen in the environment. At the same time, evolution prepared itself for a new acceleration of global oxygenation, which we will now describe.

1.3.5. *The second important accumulation of oxygen (between 500 and 350 million years ago)*

As of 500 million years ago (end of the Cambrian Period), two major characteristics were already in place. They constituted the contingence that would make possible the colonization of continental surfaces by life forms.

The first characteristic was a large atmospheric O_2 content in the order of 10 – 15% so that a stratospheric ozone (O_3) layer could form, which filtered the most harmful of the Sun's rays. It is probable that these conditions were established before or from the start of Cambrian Period, over 500 million years ago.

The second characteristic was the evolutionary diversification of the forms and functions of multicellular marine life forms, such as those attested by the Cambrian fauna of the Burgess Shale [WHI 80], which date back to 500 million years (see section 1.3.1). The development of limbs for pinching or moving, and equally the presence of carapaces, make the progressive adaptation of animals to intermediate environments, where water periodically retreated, possible. Some of these organisms probably developed the capacity to briefly leave the water, then to move into an aerial medium, after which point they would rejoin the water by their own means. In this way, they perhaps promoted the adaptation of marine bacteria to continental sunlight, notably those N_2 nitrogen-fixing bacteria that terrestrial plant life needed. Unlike their marine equivalents, the terrestrial plants are only slightly directly provided with nitrate and they depend largely on the fixation of nitrogen (and transformation into nitrate) for their photosynthesis. We note, however, that even in the ocean we can find situations where nitrate is lacking, which leads to the use of N_2 through this fixation.

The colonization of continental surfaces by life forms consequently gave rise to new adaptations, but was also the source of an increased influx of organic matter into the sedimentary reservoir of the Earth. Rivers drained organic debris, essentially plant matter, from the watersheds into the sediments of flood plains and deltas. On the other hand, from the Devonian Period (around 400 million years ago), the evolution of flora and the geographical characteristics of the continents enabled the accumulation of large quantities of peat and coal, the maximum flux having been attained in the Carboniferous Period (around 350–300 million years ago).

As explained above, the sedimentary burial of organic matter triggered a global accumulation of oxygen in the environment and it is precisely between 400 and 350 million years ago that a new acceleration in oxygenation occurred [BER 04, CAN 07]. It may have increased the atmospheric O_2 level to around 30–35%, the most the Earth system has ever known. However, it is necessary to note that this value is considered too high by some paleoenvironmentalists, since the risk of natural combustion exists at 13%, becoming a substantial risk at 25%. Natural fires, of which we find a permanent trace in sediments from the Devonian Period (carbonaceous particles of the "fusinite" type), definitely limited the maximum oxygenation of the terrestrial environment. Moreover, it is uncertain that the capacity for regulating the internal oxygen pressure of multicellular eukaryotes [MAS 03] could have adapted to a hyperoxygenation of the environment. If it could not, the oxygenation would have been self-limited by the drop in biological productivity of the eukaryotes (notably that of plants).

After having reached its saturation point, the atmospheric oxygen level diminished, probably due to a partial release of sedimentary organic carbon accumulated in the course of the Devonian Period (410–360 million years ago) and the Carboniferous Period (360–295 million years ago). 200 million years ago, the atmospheric oxygen level would fluctuate around a value close to the current one (21% in volume), which leads us to think that the flux of oxygen consumed by the oxidative destruction of recent or sedimentary organic matter, which is principally due to aerobic respiration, became equivalent to that of oxygen produced by photosynthesis. This also means that the flux of organic carbon released from old sediments through erosion, then oxidized, is balanced in the long-term by the flux of photosynthetic organic carbon buried in new sediments. The Earth system reached here its long-term regulation (millions of years), one that simultaneously integrated exchanges of matter between the ocean, atmosphere and sediments, the result of 3 billion years of biological evolution, and the tectonic plates that enabled the recycling of sediments *via* erosion and volcanic activity.

1.4. The regulation of the greenhouse effect by the ocean

1.4.1. *There is no life without a minimum greenhouse effect*

Without CO_2 in the atmosphere, the atmospheric greenhouse effect would be extremely reduced and the average temperature at the surface of the Earth would be –18°C, much lower than it is today (+15°C). Such conditions would have been unfavorable for the presence of life forms on the surface of the Earth and would have limited them to a few rare oases where they would have had every likelihood of being destroyed by natural hazards (asteroid falls, significant volcanic events, etc.). For life to persist for several billion years, it was necessary that the life forms were able to extend their area of distribution very greatly and to diversify, as they had done in the oceans, on the continents. This could not occur without a minimum greenhouse effect, of which the regulation was ensured, and still is, by the ocean and its exchanges with the atmosphere on the one hand and sediments on the other.

1.4.2. *The regulation of the greenhouse effect by the ocean*

Firstly, it is useful to recall that today carbon is very unequally distributed between the atmosphere, ocean and sediments. For one atom of carbon present in the atmosphere (in the form of CO_2), 65 are present in the ocean (mainly in the dissolved forms HCO_3^-, CO_3^{2-} and CO_2) and 150,000 are present in the sediments (mainly in the form of calcium carbonate and organic matter).

On the one hand, the level of CO_2 in the atmosphere results from carbon dioxide exchanges, which tend to permanently establish equilibrium between the partial pressure of CO_2 in the lower atmosphere and the partial pressure of CO_2 dissolved in the surface ocean. On the other hand, the ocean can exchange carbon with the sediments through the precipitation of calcites (carbonates of calcium, $CaCO_3$) from dissolved CO_3^{2-} or, conversely, through them being dissolved.

The exchanges of inorganic carbon between the ocean and atmosphere (exchanges of CO_2 between its dissolved form in the surface ocean and its gas form in the atmosphere) and between the ocean and the sediment (precipitation or dissolving of $CaCO_3$) depend largely on chemical equilibriums which tend to establish themselves between the different forms of inorganic carbon dissolved in the ocean. A unique and simplified expression of these equilibriums is as follows:

$$2HCO_3^- \leftrightarrow CO_3^{2-} + CO_2 + H_2O \quad [1.4]$$

In the current conditions of weak acidity in the ocean (pH = 8.2), these equilibriums lead to the significant presence of carbon in the form of dissolved bicarbonate (HCO_3^-) and minor proportions in the form of dissolved carbonate (CO_3^{2-}) and CO_2. The readers who are interested by the links between the pH of seawater and this speciation of dissolved inorganic carbon will find further details in Chapter 4, and in Chapter 2 of [MON 14b], and equally in the specialized work of Zeebe and Wolf Gladrow [ZEE 01].

Here, we can immediately grasp that the current greenhouse effect, whose modification is mainly linked to variations in the atmospheric oxygen level of CO_2, cannot significantly diminish in the very stable chemical conditions in the ocean.

All increase in CO_2 in the atmosphere is compensated by a change in equilibrium that tends to increase the major reservoir of HCO_3^-, but to diminish in parallel that of CO_3^{2-} dissolved in the ocean and to a slight degree, acidify the ocean (a drop in pH). The related subsaturation of the ocean in CO_3^{2-} ions tends to be compensated by the dissolution of CO_3^{2-} ions present in the calcite sediments. In parallel, it creates conditions where the bioprecipitation of $CaCO_3$ by life forms is made more difficult, which can damage species with shells and skeletons. These retroactive effects restore the initial situation by having imperceptibly modified the enormous sedimentary reservoir of calcite sediments.

Conversely, all loss of oceanic CO_2 by filtration into the atmosphere tends to be compensated, *via* the equilibriums of inorganic dissolved carbon, by a supersaturation of dissolved CO_3^{2-} and a transfer of dissolved inorganic carbon to solid carbonate, notably *via* the biological path (bioprecipitation and subsequent sedimentation), implying only a slight relative drawing on the reservoir of inorganic carbon dissolved in the ocean (mainly in the form of HCO_3^-).

Here, therefore, are two inverse oceanic mechanisms by which the major short-term regulation (a few centuries, the time oceanic convection takes) of the Earth system's greenhouse effect occurs. The ocean thus plays the role of a real climatic "mediator" which responds to perturbations that can induce other natural (fluctuation in emissions of CO_2 linked to volcanic activity) and anthropogenic phenomena (solid carbon destocking by combustion of organic fossil carbon and industrial calcination of calcites for the production of cement).

In the longer term (thousands to millions of years), certain conditions can lead to a significant change in the greenhouse effect. This was the case for episodes of the “Snowball Earth”, similar to the Varanger glaciation [HOF 98] which occurred between 900 and 540 million years ago, that is to say, before the Cambrian Period. Numerous authors consider that such episodes were not total glaciations, but that they preserved the hydrological cycle and the life that is associated with it across a peri-equatorial unfrozen belt that became larger or smaller according to the seasons. These phenomena could have been caused by phases of fragmentation of super continents such as Rodinia, the most ancient of the super continents that would have been formed more than a billion years ago and that would have fragmented 750 million years ago [DON 04]. The volcanic phenomena that would then be produced would have been similar, but much more extended, to those of the current large East African rift and would have greatly extended the basalt surface exposed to chemical weathering, favoring the following sequence of transformations:

– chemical weathering of aluminosilicates (the example of anorthite is used here), which consumes two molecules of atmospheric CO_2 to dissolve each molecule of aluminosilicate, and transport of the dissolved products by rivers:

$$[CaAl_2Si_2O_8]_{solid} + 3H_2O + 2CO_2 \rightarrow [Al_2Si_2O_5(OH)_4]_{solid} + [Ca^{2+}]_{dissolved} + 2[HCO_3^-]_{dissolved} \quad [1.5]$$

– adjustment of the equilibriums of inorganic carbon dissolved in the ocean, restitution of one molecule of CO_2 to the atmosphere and creation of a supersaturation of the ocean in CO_3^{2-}:

$$2[HCO_3^-]_{dissolved} \rightarrow CO_2 + [CO_3^{2-}]_{dissolved} + H_2O \quad [1.6]$$

– precipitation of solid carbonate in the ocean and its stocking in the sedimentary reservoir:

$$[CO_3^{2-}]_{dissolved} + [Ca^{2+}]_{dissolved} \rightarrow [CaCO_3]_{solid} \quad [1.7]$$

The equilibrium of inorganic carbon dissolved in the ocean having been adjusted, the final result of the alteration of aluminosilicates therefore really constitutes a sink for CO_2. If this loss is not rapidly compensated by volcanic emissions, the greenhouse effect can greatly diminish and provoke very widespread and long-lasting glaciations (over millions of years).

Another possibility for significant and long-lasting variations of the greenhouse effect depends on long-term variations in the alkalinity of the ocean.

The paragraph below calls on the notion of the *conservative* chemical form in seawater. It is therefore important first to define this notion. A dissolved chemical form is called *conservative* in seawater if it does not transform into any other in the usual oceanic conditions. For example, this is the case for ions such as Na^+, Cl^- and SO_4^{2-}. In contrast, the molecule CO_2 or the ions HCO_3^- and CO_3^{2-} can transform through the equilibriums summarized in equation [1.4], and are called *non-conservative*.

The pH of the current ocean (pH 8.1– 8.2) is greater than that of pure water (pH 7.0) because the slight electric imbalance (an excess in positive charges) between the conservative cations (essentially Na^+, Ca^{2+}, Mg^{2+} and K^+) and the conservative anions (essentially Cl^- and SO_4^{2-}) is compensated by the slight electric imbalance (excess of negative charges) of non-conservative ions (mainly HCO_3^-, CO_3^{2-}, $B(OH)_4^-$, OH^- and H^+). As the excess of positive charges is mainly due to the alkaline cations, the concentration of charges of non-conservative ions that compensates it is called the total alkalinity of seawater [DIC 81, ZEE 01]. A simplified form of alkalinity for practical use is as follows:

$$AP = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] - [H^+] \qquad [1.8]$$

The alkalinity of seawater can be significantly modified in the long-term (thousands to millions of years), essentially because of the variation in concentrations of conservative ions. Moreover, all things being equal, the concentrations in non-conservative ions, so also the pH (which reflects the concentration of ions H^+), are only involved in adjusting to the change in alkalinity. Nevertheless, this adjustment can cause a variation in the greenhouse effect. Indeed, the concentrations in H^+ ions (so the pH) and in HCO_3^- and CO_3^{2-} ions, which contribute to alkalinity, are interdependent *via* the equilibriums of dissolved inorganic carbon, as shown in Figure 1.4. If the ocean becomes more acidic (a drop in pH), the levels of CO_2 and HCO_3^- increase while that of CO_3^{2-} diminishes. The consequences are an exportation of CO_2 into the atmosphere, so an amplified greenhouse effect and conditions favorable to the dissolving of solid carbonate. These conditions are detrimental to the existence of some organisms that construct shells or skeletons. The consequences are inversed if the pH increases.

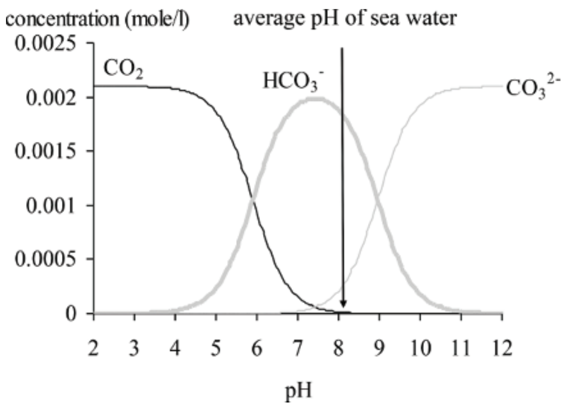

Figure 1.4. *Relative distribution of three chemical forms of dissolved inorganic carbon as a function of the pH in the average current conditions of seawater on the Earth's surface (total concentration of inorganic dissolved carbon or DIC = 2.1 mmole.kg*$^{-1}$*, salinity = 35 g of salts kg*$^{-1}$ *of seawater, temperature = 25°C) (from [BER 08])*

COMMENTARY ON FIGURE 1.4.– Because of the general composition of dissolved compounds in seawater and with respect to electric neutrality, the current average pH of seawater is adjusted to around 8.1 to 8.2.

Evidently, periodic variations in the concentration of borate ion $B(OH)_4^-$ also play an important role in this adjustment and therefore have an effect on the fluxes of CO_2.

To summarize, the tectonic activity (either on land or on the ocean floor), with the ocean as chemical mediator, is the primary cause of long-term variations in the greenhouse effect. A lasting surplus in volcanic emissions of CO_2 with respect to the flux of CO_2 consumed by the alteration of extruded (mainly) basalt and other aluminosilicate rocks, favors the introduction of CO_2 into the ocean. This infiltration leads to an adjustment of the equilibriums of inorganic dissolved carbon with a slight increase in the acidity and a drop in alkalinity, which favors the CO_2 form of inorganic dissolved carbon and, through a physical exchange, increases the atmospheric level of CO_2, and therefore, the greenhouse effect. These modifications are only transient since the dissolving of sedimentary carbonates tends to cancel them out. For them to last, it is necessary that a relative excess of CO_2 emissions also lasts.

Conversely, a relative excess of weathering-related CO_2 consumption relative to volcanic emissions of CO_2 favors an increase in alkalinity due to the introduction of conservative cations dissolved in the ocean (see, for example, the formula [1.5] given above for the chemical weathering of anorthite), a drop in acidity and a reduction in the greenhouse effect. The modifications here are also fundamentally transient since they are compensated by the precipitation of solid carbonates. They are only long lasting if the disequilibrium between basalt extrusion and volcanic CO_2 emissions is maintained.

CO_2 emission resulting from the combustion of organic carbon (oil, gas, coal), in response to the energy demand of current human activity, is the main reason for the recent short-term increase in greenhouse effect. The increased rate of this process of destocking of organic fossil carbon evidently creates a great excess of CO_2 emissions relative to its consumption by the chemical weathering of aluminosilicate rocks. The long-term effects will be the same as those of the natural processes, although this imbalance starts with a short-term transitory accumulation of CO_2 in the atmosphere and has an immediate and very strong impact on the greenhouse effect.

Over the last few decades, after anthropogenic CO_2 started to be injected into the ocean, its direct effects, notably an increased ocean acidification, are clearly measurable [TUR 12]. More indirectly, this acidification has consequences for ecosystems where organisms that construct carbonate tests (small external shells) and other shells play an important role, such as coral reef systems.

On the scale of a few centuries after the stabilization or cessation of anthropogenic emissions of CO_2, the transitory disturbance of the greenhouse effect will cease. If emissions where to be stabilized, a new steady state of the Earth system will establish itself with a warmer global climate, slightly more acidic oceans, and communities biologically adapted to this new environment. If emissions where to cease, the perturbation will be compensated by the dissolving of sedimentary carbonates and the chemical weathering of aluminosilicate rocks with, perhaps, a return to the initial pre-industrial state. We note that this second hypothesis will occur sooner or later, when the reserves of fossil fuel are exhausted. Of course, this is theoretical and will only be true if the impacts of climatic variations that we are experiencing, or will experience, are strictly reversible. Indeed, many of them are probably not reversible, at least not in the short-term. This is the case with the release of methane during thawing permafrost, or with that of the deep methane hydrates. This is also the case with the positive retroaction linked to the decrease in the albedo of sea ice and seasonal snow coverings. Moreover, the combination of effects in a system as complex as the Earth system is almost unforeseeable (it is said that the system has a nonlinear behavior). It follows that a strict compensation for the anthropogenic disturbance of the greenhouse effect will perhaps not take place, and that the Earth system will attain another climactically steady state, different from the one that mankind knew before the industrial era.

1.5. Oceanic photosynthesis regulates itself on a short timescale

Section 1.4 has just described the regulation of the greenhouse effect, essentially through the regulation of the atmospheric level of CO_2 by the equilibriums of inorganic carbon dissolved in the ocean. The dissolved inorganic carbon, in the form of CO_2, is, moreover, the major nutrient for photosynthesis of which the simplified equation is shown in section 1.3. CO_2 itself is thus regulated through this process. This regulation has no direct impact on the biological productivity of the ocean since, as we will see, it is above all limited by nutritive elements other than carbon. An indirect impact could be that of variations in the acidity of the ocean, which make the development of certain species of primary producers (phytoplankton) of calcium tests more difficult. Nevertheless, the quantitative effect has not been proved yet and it is very possible that some species without tests could rapidly occupy the nutritive niche left vacant by the disadvantaged species.

We will now return to the instance of regulation of other major nutritive elements for photosynthesis.

On average, the current organic matter resulting from photosynthesis (primary production, essentially carried out by phytoplankton) has a composition of major elements in the following atomic ratios: $C_{106}H_{263}O_{110}N_{16}P$. Of course, the composition of different species of phytoplankton can vary slightly from this mean, but it remains within a narrow range of variations.

The average composition above likely evolved in the Earth's distant past, in parallel with the oxygenation which modified the chemical forms of available nutrients, and with the biological evolution which adapted the phytoplanktonic metabolism to new conditions. The current average relative element composition of photosynthetic organic marine matter is, however, known precisely for carbon, nitrogen and phosphorus ($C_{106}N_{16}P$).

This composition means that each time photosynthesis consumes 106 atoms of carbon (via the unlimited use of CO_2), it must also find 263 atoms of hydrogen (via the unlimited use of H_2O in aquatic mediums), 110 atoms of oxygen (via the unlimited use of H_2O), 16 atoms of nitrogen (mainly via the eventually limited use of NO_3^- or N_2) and 1 atom of phosphorus (via the eventually limited use of PO_4^{3-}).

In the set of major nutritive elements (C, H, O, N, P), it is therefore essentially nitrogen and phosphorus that limit oceanic photosynthesis. The atomic ratios C/N = 106/16 and N/P = 16 are called the Redfield ratios, from the name of the author who brought them to light for the first time in the 1950s [RED 58]. When the minor nutritive elements are sufficient, which is most often the case, photosynthesis is limited by nitrogen if the N/P ratio in the ocean is less than 16 or by phosphorus if the N/P ratio in the ocean is greater than 16.

Phosphorus in the form of dissolved PO_4^{3-} is a result of continental erosion and is carried to the ocean by rivers. It escapes the ocean through the accumulation of sediments as organic matter or precipitated solid phosphates. The latter are mainly created by living organisms or by epigenesis in superficial sediments (dissolution of carbonate particles in certain conditions, leaving room for a precipitation of calcium phosphate). The phosphorus used by photosynthesis is largely recycled in the ocean by the breaking down of organic matter (respiration). As the variations in inward and outward flux are weak relative to the oceanic stock of dissolved phosphorus, the variation in this stock is very slow. It is estimated that the average residence time of phosphorus in the ocean is in the order of 80,000 years [FRO 82]. As a result, the control on oceanic photosynthesis by the availability of phosphorus occurs on the same timescale [TYR 99].

Unlike phosphorus, the inward and outward fluxes of oceanic nitrogen do not occur only through continental erosion and sedimentation, since nitrogen can evaporate quickly into the atmosphere in the form of N_2. The average residence time of nitrogen in the ocean, mainly as nitrate (NO_3^-), is only 8,000 years [SCH 91]. The stock of oceanic nitrogen can therefore be modified fairly rapidly in response to fluctuations of the Redfield ratio N/P in the ocean, which tends to regulate the general photosynthetic productivity in the ocean. In the following sections, the processes by which the regulation is carried out are presented.

1.5.1. *When the ocean is deficient in nitrate*

The majority of species of phytoplankton find nitrogen in its nitrate (NO_3^-) form. Some, a minority, are capable of carrying out photosynthesis using nitrogen (N_2) dissolved in seawater, of which the partial pressure on the surface tends to balance with that of atmospheric

N_2 (a major component of the atmosphere). The process of biological fixation of nitrogen is also called “diazotrophy”.

The use of nitrates by oceanic photosynthesis has a better energetic yield than that of N_2. Moreover, nitrate is the dominant form of nitrogen dissolved in the ocean. Therefore, where the photosynthetic production is not limited by other nutritive elements locally, it preferentially uses nitrate.

The limit on this use lies in the fact that the photosynthetic products are not entirely recycled in the ocean surface (a fine mixed layer, some tens of meters thick, of which the upper, or euphotic part, is where oceanic photosynthesis occurs), but it leads to an exporting of organic matter, including nitrogen and phosphorus, into the ocean. Numerous transitory phenomena, where non-photosynthetic species (heterotrophs) are also involved, may or may not favor the yield of this exportation. The turbulent mixing is the main process by which nitrate or phosphate is reinjected from the reservoir of the internal ocean, which constitutes the greatest part of the oceanic volume. This mixing takes place under the mediation of certain physical phenomena such as variations in the thickness of the layer of mixture, turbulence affecting the base of this layer [FOR 12], known as thermocline, as well as oceanic resurgences, or *upwellings*.

The use of nitrate by oceanic photosynthesis is therefore limited by the atomic ratio N/P in the interior ocean, where the exported organic matter is usually recycled, a small proportion being integrated (fossilized) in sediments. When this ratio is less than the Redfield ratio (16), the replenishing of the nutrient content of the mixed layer spreads the deficit in nitrate up to the surface. The nitrate of the euphotic zone is thereby rapidly exhausted, which favors the photosynthetic species capable of carrying out the fixation of N_2 (this concerns only a few species, which are sometimes represented by a very large number of individuals). Thus, this time the replenishing comes from the atmosphere. The exportation of organic matter and its degradation in the interior ocean nevertheless continue, which leads to the recycling of nitrogen, initially coming from the atmosphere as gaseous N_2, in the form of dissolved nitrate. The ocean thus replenishes itself with nitrate from the atmospheric reservoir and readjusts the proportion of nitrate/phosphate to biological demand.

1.5.2. *When the ocean has an excess of nitrate*

A regulation would not be possible if an inverse process did not exist, consisting of emptying the ocean of some of its nitrate in favor of the atmospheric N_2.

In the interior ocean, the organic matter coming from the surface is broken down, mainly by the aerobic and anaerobic respirations. The aerobic respiration, whether it is that of organized multicellular life forms (plant and animal) or that of monocellular life forms (protists, bacteria, archaea), uses O_2 to oxidize the organic matter and finally releases organic nitrogen in the form of rapidly oxidized nitrate, ammonium NH_3 being only an intermediate.

In the current ocean, there exist a few anoxic environments, permanent or transient, which facilitate anaerobic bacterial respiration. These are always environments where the replenishing of oxygen, by the circulation of water (ventilation) or by molecular diffusion, is insufficient to compensate for the flux in oxygen consumed by the breaking down of organic matter. These environments therefore extend the anoxic perimeter until the two fluxes are in equilibrium.

Such conditions, which were dominant in the Earth's distant past (before the accumulation of oxygen), are found today in certain sediments and certain masses of water in the global ocean subject to significant fluxes of organic matter and insufficient ventilation (layers of water at intermediate depth with a minimum oxygen level and certain waters at the bottom in contact with sediment). On the periphery of the anoxic zones, where nitrate enters by diffusion, occurs, among others, an anaerobic respiration called denitrification, which is carried out by specialized bacteria. It transforms nitrate into oxides of nitrogen (NO or NO_2) or N_2 nitrogen, all these products being in gas form in the conditions at the surface of the Earth, so transferable to the atmosphere. In the case of N_2 , the formula for its transformation is the following:

$$NO_3^- + 1{,}25CH_2O + H^+ \rightarrow 0{,}5N_2 + 1{,}25CO_2 + 1{,}75H_2O \qquad [1.9]$$

The compounds produced by denitrification, which contain nitrogen, are transported in dissolved form by oceanic circulation and molecular diffusion up to the surface of the ocean, where they are then in excess and cause a balancing flux into the atmosphere. The quantity of oceanic nitrate is thus diminished.

When the atomic ratio N/P in the interior ocean is greater than 16 (Redfield ratio), photosynthesis is not limited by the nitrate and, all things being equal, gives rise to a greater productivity and an increased exportation of organic matter into the interior ocean. The consequences are a development of anoxic environments, an increase in denitrification and, finally, a loss of nitrate from the ocean. This decreases the N/P ratio, thus readjusting the proportion of nitrate/phosphate to biological demand.

1.5.3. *The regulation of the N/P ratio*

Measurements made over a number of years in the diverse water masses of the current global ocean (e.g. [FOR 12]) show a statistical nitrate/phosphate ratio whose slope is close to 16, which is also the N/P ratio of the biological demand for phytoplanktonic productivity in the ocean.

For a long time, oceanographers wondered whether this similarity was due to the fact that the phytoplankton had adapted to the ocean's chemistry or whether, conversely, the chemistry resulted from the long-term action of the phytoplankton. Monitoring, over the course of the last 20 years, of the phenomena described above [ALT 95, AND 07, MAR 06] now enables us to confirm that both participants, the life forms and the biochemistry, permanently adjust to each other. This adjustment reacts especially to disturbances linked to climate change on timescales of the order of a few thousand years.

But this adjustment also reacts to more long-term evolutions. For example, the influx of phosphate and the ocean thermohaline circulation change, not only under the effect of climate changes, but also under tectonic and paleogeographic variations on timescales ranging from hundreds of millions of years to a few million years. Despite the regulation that we have just described, such modifications can lead the ocean to diverge slightly, but permanently, from the Redfield ratio N/P, thus creating conditions for a Darwinian evolution where new species are selected for, which promote a new Redfield ratio. The global data compiled in the NOAA Levitus Atlas in 1994 suggest an overall nitrate/phosphate ratio slightly under 16, which is perhaps evidence of such a transitory state. In the Earth's distant past, the variations in oxygen enrichment of the environment have themselves also contributed to variations in the Redfield ratio, either by reducing the extent of anoxic zones where the denitrification could occur or by modifying the average N/P ratio of the cell. For example, it is possible that the membrane arsenal, a major consumer of phosphorus, was developed and perfected in the course of evolution, leading to an increase in the demand for P by the organisms and, thus, to a decrease in the N/P ratio of the biological demand.

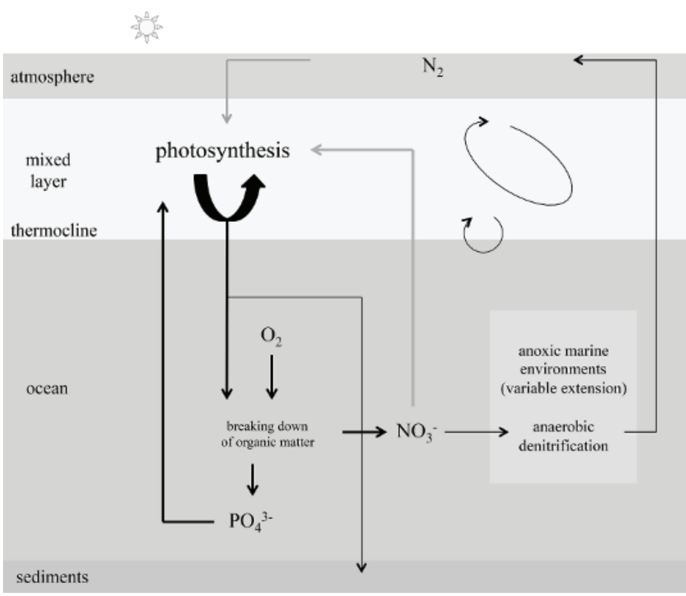

Figure 1.5. *The principle of the regulation of oceanic photosynthesis across the rapid cycle of major nutrients, nitrogen and phosphorus. (see color section)*

COMMENTARY ON FIGURE 1.5.– The majority of organic matter produced is recycled in the mixed layer through respiration in the trophic network. A small part is exported out into the interior ocean, where it is almost entirely degraded, always by respiration of the trophic network, whether it is deep pelagic or benthic. A very small fraction escapes degradation and fossilizes in the sediments, from where it is then integrated into the long-term geological cycle. When the nitrate is not limited relative to the phosphate, photosynthesis uses it preferentially and the flux of organic matter exported is at saturation, which consumes the oxygen in the inner ocean and creates anoxic environments. But these favor the denitrification and exportation of nitrogen into the atmosphere, thus reducing the oceanic stock of nitrate. If the nitrate is limited relative to the phosphate, photosynthesis calls upon species capable of fixing atmospheric nitrogen, whom then restock the oceanic nitrate through the process of exporting organic matter into the deep ocean and breaking it down.

1.6. Conclusion

1.6.1. *The ocean in the Earth system*

The few examples that have just been given, which are summarized in Figure 1.6, do not exhaust the complexity of the mechanisms of the Earth system. The previous section has shown the central role that the ocean plays in this system, notably through the following:

– plate tectonics and the related geological recycling of biogenic elements;

– the abiotic regulation of the greenhouse effect due to the chemical system of inorganic carbon dissolved in the ocean;

– the long-term increasing enrichment in oxygen O_2 of the environment and its self-regulation, both being due to the Darwinian evolution of respiratory metabolism in the ocean;

– the short-term self-regulation of the N/P ratio in the ocean due to oceanic circulation and the dynamic of phytoplankton species.

It would have been equally possible to examine other characteristics of the system that have played and still play a fundamental role in its evolution and regulations. Would life have existed without the magnetosphere protecting the Earth's surface from the Sun's ionizing radiation? What would the climate be like without the stability of the Earth's oblique axis of rotation, due to the existence of the Earth–Moon duo? How is the regulation of oceanic photosynthesis modulated by other nutritive elements, such as iron [PIC 09]?

But, of course, it requires more than a chapter, more than an entire book, to describe these phenomena in all their diversity and complexity. Interested readers will be able to find something to satisfy their curiosity in different individual or collected volumes [BER 07, BER 08, GAR 06, GAR 11, GAR 12, REI 06].

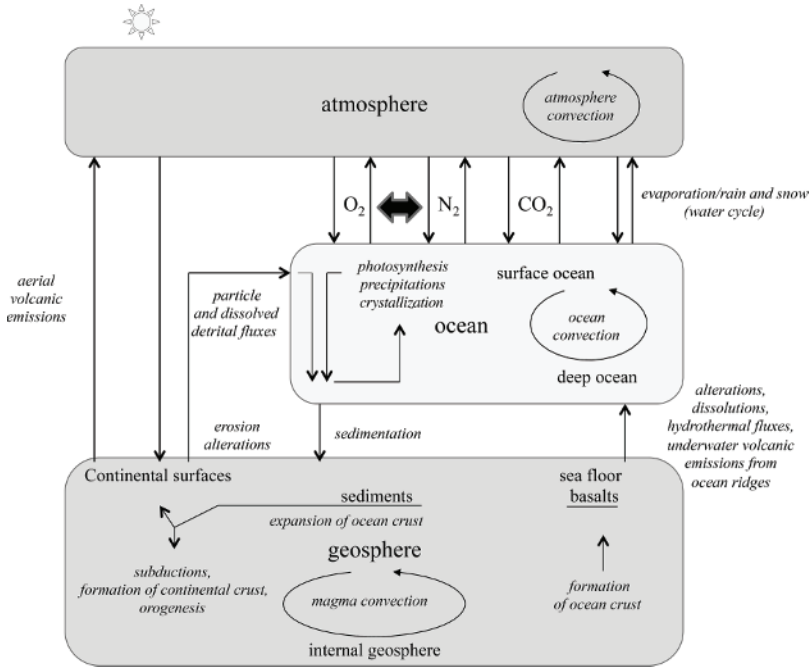

Figure 1.6. *The Earth system as it has functioned since the massive colonization of the ocean by photosynthetic life forms producing oxygen, that is to say for more than 2.5 billion years (see color section)*

COMMENTARY ON FIGURE 1.6.– Oxygen has only played an important biogeochemical role since its first global accumulation at the beginning of the Proterozoic Period (2.5 billion years ago). However, it is possible that it had a role previously (in the Archaean Period), by promoting the Darwinian selection of the first manifestations of aerobic respiratory metabolism in a few local environments where oxygen had already accumulated.

1.6.2. *The anthropogenic disturbance of the Earth system*

For two centuries, the demographic, technological and industrial development of human society has been such that it now has a global impact on the functioning of the Earth system. This is what is known as the ‘anthropogenic disturbance’.

Certainly, this does not date from the industrial revolution since, from the Neolithic Period, man has modified his environment by deforestation and the mobilization of surfaces dedicated to agriculture and rearing livestock. Nevertheless, it is only from the end of the 19th Century that the global impact has started to be felt with the large-scale use of coal and then of petroleum and natural gas. This evolution very quickly accelerated in the course of the 20th Century with technological developments and the demographic explosion of the human population and its needs.

Technological progress is made available to a large proportion of people (electricity, automobiles, the personal computer, the mobile telephone, etc.), thus multiplying the industrial need for energy to make industrial products and meet individual energy needs for their use. In parallel, technological progress has enabled the mobilization of natural resources of solar fossil energy, through the combustion of coal and petroleum and natural gas, using oxygen from the atmosphere. The most recent technologies for exploration and exploitation now permit us to look for resources which, until recently, would have been impossible to access (e.g. deep oceanic environments, polar regions and shale gas), whereas the economic conditions of today render possible exploitation of reserves that were not, or were less, profitable a short time ago (e.g. bituminous shale and certain types of carbon). The direct consequences of this evolution are a massive destocking of organic fossil carbon and a degradation of the ecological status of the continental and marine environments.

Through combustion, we combine organic fossil matter with the oxygen from the atmosphere to form CO_2. This is in some way a gigantic biological respiration, even if it is not metabolic, with a result strictly inverse to that of photosynthesis. But this respiration uses the resource at a speed greatly exceeding that of its renewal. We consume in a few decades matter that accumulated in deposits (e.g. coal, petroleum and natural gas) over the course of tens of millions of years. We observe that while coal is a sedimentary rock initially rich in organic matter (mother rock), petroleum and natural gas accumulate in porous deposits (sandy or carbonated rocks, the so-called reservoir rocks) topped by impermeable layers of clay or salt deposits. These deposits can only be formed as the result of a long process in the course of which the mother rock reaches, by burying layer after layer over several kilometers, the conditions in temperature and pressure necessary for the formation of petroleum and natural gas (by natural thermal cracking), to their very slow expulsion from the mother rock (primary migration), and to their transfer and trapping in reservoir rocks (secondary migration). The use of shale gas implies a retrieval of gaseous hydrocarbons that have still not been expelled from the mother rock. It requires artificially creating porousness in the mother rock and a draining toward the surface to accelerate the expulsion.

The imbalance between the speed of exploitation and natural reconstitution of these resources does not affect the Earth system, but will oblige the human population itself to modify its way of life. It concerns the transition of energy, which is a major subject but which is outside the scope of this chapter. According to some thinkers and economists, such as Bourg and Jancovici [BOU 11, JAN 07], a lasting human civilization will oblige mankind to consume five times less energy than today.

The second impact is, of course, the increase in the concentration of greenhouse gases in the atmosphere, mainly CO_2 and CH_4

(methane), and the climatic consequences that follow: global warming, local modification of the climate, the melting of glaciers and ice caps, a rise in the average sea level, acidification of the oceans, possible destabilization of hydrates of methane in oceanic sediments at depth, positive retroaction by an increase in albedo, etc.

Despite its enormous power as a buffer, the ocean cannot regulate in the short-term the disturbance due to the current rate of anthropogenic greenhouse gas emissions. We are therefore in a transitional phase in the course of which the climate is modifying as a result of human activity. The consequences are already perceptible in numerous parts of the world. Beyond the immediate adaptation of human societies, man should also make sure not to modify the climate in an irreversible manner (threshold effect, irreversible melting of polar caps) so that a future way of energetically sustainable life can be established in habitable climatic zones as widespread as they are today.

On geological timescales, the Earth as a whole system, including the presence of life forms, will adapt itself and will pursue its existence, with or without mankind.

1.6.3. *And life among all that?*

In this chapter, the use of the term “life” has been carefully avoided, preferring that of “life forms” or “living things” or “living beings”. As already underlined at the beginning (section 1.2.5), life is a concept much richer and more complex than the simple arbitrary definition that can be given to the term “alive” or “biological”.

Before asking ourselves about the profound nature of life, it is sensible to ask what, among its characteristics, can differentiate it from “living”.

As far as we presently know, terrestrial life has been uninterrupted for more than 3.5 billion years. This continuity is partly due to the phylogenetic link between all living beings. Life never ceases with the death of living beings; it is transmitted into new living beings. Even if a line of descent is interrupted, other branches continue to diversify in eventually using other ecological niches. Life is therefore an adaptive and colonizing phenomenon.

However, for life to be life, it requires that no living being is isolated. The isolation of a living being, whether that is for its reproduction, nutrition or respiration, means that it no longer participates in life during the time that separates it from its own death, which can be counted in thousands of years (certain trees) or in seconds.

Life therefore consists of all the evolutionary interactions and retroactions, whether between living beings themselves (trophic relations, cooperation, reproduction), or between living beings and the conditions in their environments (which are also evolving). Living beings are local and temporary self-regulating entities, which establish their own growth, cohesion, organization and the renewal of the matter from which they are constituted for the duration of their “life”. However, we know that numerous sequences of DNA are transmitted totally or partially to their eventual descendants and this transmission is at the root of the ontogenesis of new living beings. Even if the deterministic impact of DNA on ontogenesis is strongly contested today by certain biologists [KUP 11], it constitutes no less than the initial information that the embryo of each living things receives. This information has been transmitted through the descendants of life forms for more than 3.5 billion years and it is this which evolves [DAW 11, GOU 02], even if its determinist role in the development of a given living creature (the “genetic code”) is undoubtedly less important than it was thought during the years that followed the discovery of DNA. In the history of the Earth, the reproduction of a nucleic acid carrying genetic information (RNA having perhaps preceded DNA as the initial carrier of information) is therefore a characteristic of terrestrial life.

On a planet largely colonized by life forms, the plasticity of expression of phenotypes and the evolutionary plasticity of genotypes contribute together to adapt life forms to their non-biological environment. Reciprocally, this evolves in response to the pressure that these life forms exert on it. This ancient dynamic, more than 3.5 billion years old, is nothing other than life.

Our common life to which we contribute in this short instant!

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