The biosphere, a major geological player

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The biosphere, that is, the terrestrial environment and the living organisms that have developed there, deeply shapes the planet Earth. With

the *genesis of carbonaceous rocks, the biosphere is co-responsible for the presence of atmospheric oxygen and its variations. It is a major player in the manufacture of limestone and other sedimentary rocks. Thanks to limestones and, to some extent, carbonaceous rocks, the biosphere participates in the long-term variations of atmospheric CO_2. And even the continental biosphere is a major player in the chemistry of the oceans and the rocks that are formed there.*

1. The facts of the problem

In recent years, there has been rightly concern about the negative impact of civilization on the environment. If humanity is fortunately unable to destroy the planet, it can significantly disturb its upper envelopes: **atmosphere**, hydrosphere{ind-text} Areas of the Earth occupied by water or ice (oceans, seas, rivers, lakes, glaciers, polar ice caps and groundwater). Note that the atmosphere also contains large amounts of water vapour: {end-tooltip}, lithosphere{end-text}Surface part of the earth composed of two superposed terrestrial layers: the crust (oceanic or continental) and the rigid upper mantle. It is between 60 and 70 km thick under the oceans and 100 km under the continents.{end-tooltip} and biosphere{ind-text}Earth environments adapted and/or maintained by living organisms. They are an integral part of the ecosystems present in the lithosphere, hydrosphere and part of the atmosphere.{end-tooltip}. The different actors of the biosphere have always interacted with each other (thus, lions eat antelopes which, if they were in excess, would devastate entire ecosystems...). But, independently and before the disruptive actions of a single species (**Homo sapiens**) that seriously began only with the Neolithic revolution{ind-text}Expression used to express the profound change in the habits, techniques and lifestyle of prehistoric humans from the development of polished stone. In the Near East, this period begins around 8000 BC, with the appearance of agriculture, and ends with the appearance of writing.{end-tooltip}, did other species influence the Earth's envelopes? Has life influenced, or even drastically changed, the atmosphere, the hydrosphere, the earth's crust...?

2. Life and atmospheric oxygen

2.1. Ecosystems, through photosynthesis, produce oxygen

Green plants, algae and many bacteria make photosynthesis {ind-text}A bioenergetic process that allows plants, algae and some bacteria to synthesize organic matter from the CO_2 in the atmosphere using sunlight. Solar energy is used to oxidize water and reduce carbon dioxide in order to synthesize organic substances (carbohydrates). The oxidation of water leads to the formation of O_2 oxygen found in the atmosphere. Photosynthesis is the basis of autotrophy, it is the result of the integrated functioning of the chloroplast within the cell.{end-tooltip}: they capture **water** (H_2O) and **carbon dioxide** (CO_2) and transform them into **carbohydrates** and **oxygen** (O_2) **using sunlight** energy. The photosynthesis equation can be summarized as follows:

$$6\ CO_2 + 12\ H_2O \rightarrow C_6H_{12}O_6\ (glucose) + 6\ H_2O + 6\ O_2$$
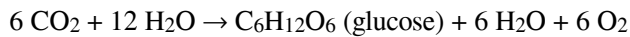
equation that can be simplified and remain accurate in terms of mass balance (while being false from the point of view of reaction mechanisms): $CO_2 \rightarrow C\ (Carbon) + O_2$.

Considering the respective atomic masses (C = 12 g, O = 16 g), it can be said that 44 g of CO_2 gives 32 g of O_2 and 12 g of C fixed in the biomass (proportion of 32/12) by photosynthesis. Is this release of O_2 by current and recent photosynthesis alone sufficient to explain all atmospheric O_2?

2.2. Ecosystem respiration consumes the oxygen produced by photosynthesis

Figure 1. Example of a remarkable oak tree (Angel Oak, Quercus virginiana; South Carolina, USA) Probably over 500 years old; this tree is more than 20 metres high and has a circumference of more than 8.5 metres. It generates a shadow area of 1,600 ^{m2}. Photosynthesis has allowed its growth and development, thanks to the fixation of carbon dioxide. But given the lifespan of such a tree, it is a spectacular example of temporary carbon storage. Oak wood weighs 600 to 1200 Kg/m3; it consists of 40 to 60% cellulose, 15 to 20% hemicellulose, 15 to 40% lignin, as well as 2 to 8% various compounds including sugars. Its overall chemical composition is 50% carbon, 43% oxygen, 6% hydrogen, 0.5% nitrogen and between 0.5 and 1.5% ash. Sooner or later, all these elements will return to the atmosphere or soil after the tree has decomposed or burnt (in a fire, for example): the fixed CO_2 will then return to the atmosphere. [Source: © Galen Parks Smith; License Creative Commons Attribution-Share Alike 3.0 Unported, via Wikimedia Commons]

Let's take a 100-year-old oak tree of 20 tons of wood (dry weight) (Figure 1). This corresponds to about 10 tonnes of carbon contained in the molecules of lignin{ind-text}Complex macromolecules formed by the polymerization of phenyl-propane monomers and associated with polysaccharides in the plant wall. Present mainly in vascular plants, lignin is the second most abundant renewable biopolymer on Earth, after cellulose. Together, they represent more than 70% of the total biomass. Lignin appeared 380 million years ago, in the Devonian, with the first vascular plants, the Ferns, and almost simultaneously the first trees.{end-tooltip}, the main compound of **wood**. To make these 20 tons of wood, this oak will have absorbed about 36 tons of CO_2 and a lot of water; it will have incorporated 10 tons of carbon into its lignin molecules and will have released 26 tons of oxygen. That's why when I was a child, my mother explained to me that plants "made" oxygen. The same is commonly said for **plankton**, all **forests**, and even stromatolites{ind-text} Often calcareous structures that develop in shallow, marine or freshwater aquatic environments. They are both biogenic (*i.e.*, built by cyanobacterial communities) and sedimentary in origin. The stromatolite as a structure is not alive, only the cyanobacteria that build it are. Stromatolites already existed 3.5 billion years ago as shown by fossils found in Western Australia; they exist on all continents.{end-tooltip}: making 20 tonnes of biomass (dry) containing 10 tonnes of carbon effectively provides 26 tonnes of oxygen.

But my mom forgot that trees, planktonic organisms... are deadly. When an oak dies, it is preyed upon by **insects** xylophages{ind-text}Living organisms whose diet is mainly composed of wood. The so-called wood-eating insects, like termites, cannot digest cellulose and lignin alone. The presence (either in the substrate, or in their digestive tract or in wood) of fungi or symbiotic bacteria is essential for the assimilation of wood by woodworms. {end-tooltip}, moulds... that "feed" on lignin. After a few years, all the wood will have been decomposed by breathing organisms. This breathing will absorb 26 tons of O_2 that will oxidize the 10 tons of carbon in the wood, producing 36 tons of CO_2. We have returned to the starting point, and the balance is totally zero: no CO_2 absorbed, no O_2 produced! All **balanced** ecosystems, from Amazonian forests to ocean phytoplankton, have

a zero balance against O_2 and atmospheric CO_2. Of course, a young growing forest growing on soil previously devoid of vegetation or a planktonic bloom temporarily produces O_2. But as soon as the forest matures and each growing tree "replaces" a recently dead tree, as soon as theplanktonic bloom{ind-text}Also called planktonic bloom. Relatively rapid proliferation of the concentration of a few algal species, usually phytoplankton, in an aquatic system of fresh, brackish or salt water. It usually results in a coloration of the water (red, brown, yellow-brown or green). These colours are due to the dominant photosynthetic pigments of the algae involved. The phenomenon may be natural or favoured by pollution (nitrates, phosphates). {end-tooltip} stops, the balance is zero.

There is about 3,000 x 10^{12} kg of reduced carbon in the biosphere, taking into account all living **biomass** or, very temporarily, stored in the soil (see [A carbon cycle disrupted by human activities](#)). The production of this current biomass has produced O_2 in the mass proportions of 32/12, or 8,000 x 10^{12} kg of O_2. However, the current atmosphere contains about 1,000,000 x 10^{12} kg, or 125 times more. More than 99% of the current atmospheric O_2 is not the counterpart of the current biomass. A forest would be like a pastry cook who bakes cakes but eats them before selling them; he is not the one who supplies the city!

So where does this current oxygen come from, which comes neither from forests nor from living plankton...?

2.3. Where does today's atmospheric oxygen come from, since current forests and plankton are not enough?

For a photosynthetic ecosystem (forest, phytoplankton, etc.) to produce O_2 in the *very long term*, a process must prevent dead organic matter from being consumed and re-oxidized in this very long term. This process is geological, it is the **fossilization** of organic matter. When, after their growth, geological circumstances cause dead trees, soils or plankton to settle and become **coal**, **oil** or fossil organic matter dispersed in **clays** or **marls**, then there is a net input of O_2 into the atmosphere. Each time 12 g of reduced carbon is produced and fossilized, the 32 g of O_2 produced by photosynthesis remains in the atmosphere because it is not used by breathing organisms. The current 1,000,000 x 10^{12} kg of atmospheric O_2 is, in mass, the fossil reduced carbon counterpart of sedimentary rocks (coal, oil...), and not of the **Amazonian forest** or living **plankton**.

Photographie : Pierre Thomas

Figure 2. Layers of coal in the Carboniferous Cévennes. It is the formation of such carbonaceous rocks (rich in reduced carbon) that has allowed the accumulation of oxygen in the atmosphere. [Source : © Pierre Thomas]

The atmospheric oxygen content since the appearance of life 4 billion years ago is therefore determined by a "competition" between various biological processes, such as photosynthesis and respiration, and geological processes, such as the trapping of organic matter in sediments and other phenomena such as the oxidation of iron, mineral sulphur, old sedimentary rocks... This O_2 content, which is currently 21%, has "peaked" at about 35% over 300 million years ago (**Carboniferous**). It is precisely at this time that the combination of biological processes (the poor degradation of lignin by the fungi of the time) and geological events (the hercynian chain{ind-text} Mountain chain that forms between the Devonian (-400 million years) and the end of the Permian (-240 million years). This chain is now eroded and most of the geological evidence of its formation is metamorphic rocks and granites, which were once the deep root of the massif. In France, the Hercynian chain corresponds essentially to the Armorican Massif, the Central Massif and part of Corsica. These massifs are generally referred to as variscan massifs.{end-tooltip} and its numerous subsidised zones{end-text} Areas with a progressive, regular or jerky subsidence of the earth's crust due to a load that is added either above the crust (water, sediment, volcano, ice cap, mountain range, lithospheric plate.), either inside it (phase change by metamorphism) or below it (heavy mantel material). The subsidence was first known at the surface by the geology of sedimentary basins.{end-tooltip}) preserved from oxidation the debris from the forests of the time that became coal deposits (Figure 2), among the most important on the planet.

2.4. Iron oxides

Current seawater contains almost no iron, as it is oxidized by dissolved oxygen in the form of ferric ion (Fe^{4+}), insoluble at

ordinary pH. Recent iron-bearing sedimentary rocks are therefore rare, due to the lack of soluble iron to precipitate. However, the situation was completely different before -2 billion years ago.

From -3.8 billion years ago, the age of the oldest sedimentary rocks, to -2.5 billion years ago, iron ores in the Fe^{4+} form are present, but dispersed and in relatively limited quantities. This presence of Fe^{4+} shows that there were oxidizing environments at least locally, so that very probably there was an oxygenic photosynthesis very early in the history of the Earth. Stromatolites (see Figure 6 and introductory photo of the article) aged 3.5 billion years also suggest this precocity. These iron-rich Fe^{4+} ores explode in quantity around -2.5 billion years, then almost disappear around -2 billion years. They consist of alternating silica and iron oxides Fe^{4+}, hematite (Fe_2O_3) most of the time. They are called "Banded Iron Formation" (BIF). Where do they come from? Before -2.5 billion years ago, the atmosphere and ocean contained almost no O_2: 10^{-6} compared to the current amount. The sea contained iron in the ferrous state Fe^{2+}, soluble, brought by the hyperactive volcanism at that time. The combination of "photosynthesis and fossilization of organic matter" produced O_2, but this O_2 oxidized Fe^{2+} iron, which precipitated as banded Fe^{3+} iron (Figure 3). Oxygen did not accumulate in the atmosphere or the ocean. Around -2.5 billion years ago, due to a combination of complex and still poorly understood reasons in 2016 (biological and metabolic revolutions perhaps, major changes in volcanism and tectonics certainly, climatic variations undoubtedly...), O_2 is multiplied by 100 000 (Figure 4). All the Fe^{2+} of the sea precipitates, and forms the gigantic deposits of Fe^{3+} dated -2.5 billion years ago (see Figure 2). This event is known as **Great Oxygenation** (GO) (see Focus Oxygen, a revolution). This Great Oxygenation was certainly accompanied by a major biological crisis since O_2 must have been very toxic to organisms of the time, mainly anaerobic; but the fossil record is far too incomplete to appreciate its importance.

Figure 3. Example of South African banded iron dating back to -3.25 Ga, well before the Great Oxygenation, which strongly suggests that oxygen photosynthesis already existed. The dark bands are made of pure hematite (Fe_2O_3). The pink or red stripes correspond to silica coloured red by traces of Fe^{4+} iron. [Source: © Pierre Thomas]
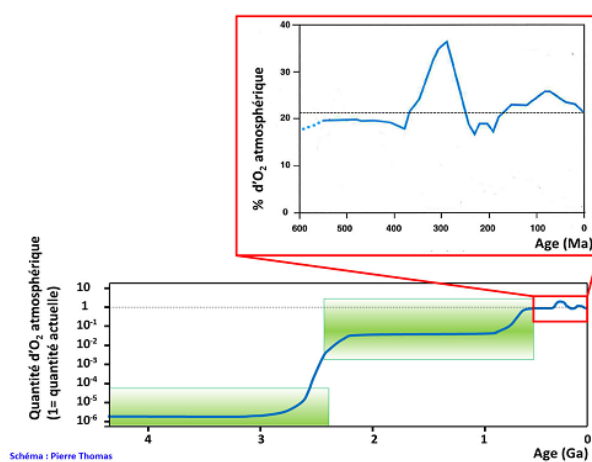

Figure 4. Evolution (very schematic) of atmospheric O_2 over the course of Earth's history. The lower diagram represents the main lines of the evolution of terrestrial O_2. We can see very well the Great Oxygenation around -2.5 billion years ago. The green rectangles represent the uncertainty of data and models. It is not clear whether the relatively sharp rise to around -0.7 billion years is a reality or a bias in observations and models. The upper diagram represents the Phanerozoic evolution, known with less uncertainty. Note the maxima at -300 and -100 million years My, respective counterparts of the genesis of much coal and oil. [Source: © Pierre Thomas]

Since this Great Oxygenation, there is almost no more Fe^{2+} to precipitate into the sea. Oxygen varies very slowly, but generally increases more often than it decreases, due to relative variations between photosynthesis and trapping of organic matter in sediments that produce O_2 and other phenomena that consume it such as oxidation of iron of magmatic origin, mineral sulphur, old sedimentary rocks, etc. A content of more than 15% seems to have been reached for 600 million years. Since then, this content has fluctuated between 15 and 35% depending on the relative importance of production and consumption in the long term, a relative importance regulated by interactions between biology and geology.

Figure 5. Helicopter view (left) and underwater view (right) of the Great Barrier Reef off Cairn, Australia. It is a good example of a site where life is currently producing limestone. The limestone will be made largely by the "skeleton" of the coral, directly secreted by the animal (polyp). [Source: © Photos Pierre Thomas]

3. Life, rocks and CO₂

3.1. The limestones

All you have to do is walking in the Alps, Quercy... to see a lot of limestone ($CaCO_3$). In current nature, and this has most likely been the case for hundreds of millions of years, almost all limestone is of biological origin (Figures 5 to 8):

Directly, when limestones consist of the accumulation of tests{ind-text}Limestone or silica-based mineral envelopes, which are used to protect certain animals, such as sea urchins.{end-tooltip} and shells of organisms that collect calcium and hydrogen carbonate ions from water (coccolithophorids, foraminifera, corals, bivalves, crinoids, etc.);

Indirectly, when the presence of living organisms locally modifies environmental conditions and causes $CaCO_3$ to precipitate (stromatolite, Figure 7).

Figure 6. Example of ancient limestone of coral origin: the limestones of the Upper Jurassic (150 Ma) of the southern Paris basin. [Source : © Photos Pierre Thomas]

The biosphere thus plays a massive role in the production of rocks on the surface of the Earth's crust. This precipitation would be lifeless because surface seawater is saturated with calcium carbonate, but life catalyses{ind-text}Action of an element that accelerates or slows a chemical reaction.{end-tooltip}, accelerates and localizes this precipitation. This precipitation is possible because there is a balance between dissolved CO_2, HCO_3^-, CO_3^{2-}, H^+, Ca^{2+}, solid $CaCO_3$, etc. In the same way, on land, there is a balance between flush $CaCO_3$, rainwater, CO_2 from the atmosphere and the ground. These very complex balances can be summarized with a single formula:

$$2\ HCO_3^- + Ca^{3+} \leftrightarrow CaCO_3 + H_2O + CO_2\ (1)$$
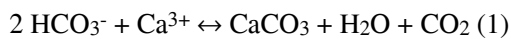
In the aquatic environment, the reaction goes mainly to the right (limestone precipitation), either by direct metabolism of living organisms that produce their test, or by capture of CO_2 by photosynthesis of phytoplankton that shifts the balance to the right, or by mucoproteins{end-text}Protein containing carbohydrate macromolecules. Present in extracellular matrices...{end-tooltip} bacterial matrices that catalyse carbonate precipitation...In the air, the reaction to the left takes place: dissolution of limestones in karsts{ind-text}Geomorphological structure resulting from water erosion of carbonated rocks, mainly limestones.{end-tooltip} (Figure 8). There is an overall balance in the medium term. The quantities of limestone and HCO_3^- in the sea, and CO_2 in the sea and atmosphere, would be stable if no other phenomena were to occur.


Figure 8. Example of karst, a limestone zone where runoff water loaded with CO_2 (atmospheric CO_2 and especially soil CO_2 produced by the respiration of roots, fungi...) leads to the dissolution of limestone. [Source : © Photo Pierre Thomas]

Figure 7. The stromatolites of Lake Thetis (Australia) in periods of drought and low water, a current example of indirect biogenic precipitation of CaCO₃. These calcareous domes are due to precipitation under the limestone water around and on a bacterial veil. These photosynthetic bacteria absorb CO_2, which leads to the precipitation of carbonate microparticles that are trapped by the "sticky and sticky" bacterial veil. [Source : © Photo Pierre Thomas]

However, another series of reactions can permanently modify the relative quantities of limestone, atmospheric CO_2 and dissolved CO_2: the alteration of rocks containing calcium silicates (very frequent case). This sequence of reactions can be summarized and schematized as follows:

(1) $CaSiO_3$ (calcium silicate) + H_2O + 2 CO_2 → SiO_2 (dissolved silica) + Ca^{3+} + 2 HCO_3^-
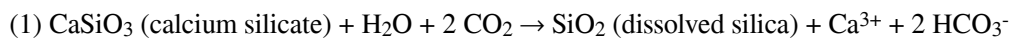
This reaction occurs in continental soils. Life participates in this stage because the soil is enriched with CO_2 by the respiration of roots, fungi, soil bacteria (Figure 9). This CO_2 comes from the atmosphere through plant photosynthesis. The ions involved are transported to the sea by runoff and rivers.


Figure 9. Example of alteration under a ground. The waters that alter the mother rock, here granite, are enriched in CO_2 by the respiration of soil organisms, made acidic by organic acids... [Source: © Photo Pierre Thomas]

(2) At sea, Ca^{3+} + 2 HCO_3^- (brought in by rivers) react:

2 HCO_3^- + Ca^{3+} → $CaCO_3$ + H_2O + 1 CO_2

As we have seen above, life has a lot to do with this reaction.

The assessment of these steps can be written as follows:

$$CaSiO_3 + H_2O + 2\ CO_2 \rightarrow SiO_2 + Ca^{3+} + 2\ HCO_3^- \rightarrow SiO_2 + CaCO_3 + H_2O + 1\ CO_2 \ (3)$$
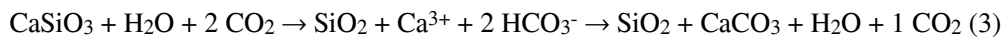
If the dissolution-precipitation of carbonates (equation 1) does not change the overall amounts of limestone or atmospheric CO_2, the alteration of calcium silicates and the subsequent alteration (equation 3) increases the amount of limestone and decreases the amount of atmospheric CO_2. Life actively participating in the alteration of silicates therefore actively participates in this mechanism of atmospheric CO_2 reduction, much more than through the photosynthesis-fossilization of organic matter: there is more limestone than coal!

Figure 10. Example of an outcrop of radiolarite (quite often red in colour as here) in the Italian Alps. Photo Pierre Thomas

3.2. Siliceous rocks

The alteration of continental silicate rocks, favoured by life, releases silica which is brought to the sea by rivers. In the sea, organisms live with test{ind-text}Limestone or silica-based mineral shells, which serve as protection for certain animals, such as sea urchins.{end-tooltip} or spicules{ind-text}Extracellular mineral secretions from various invertebrate groups (e.g. sponges, echinoderms). Spicules can consist of silica, calcite, chitin or protein. {end-tooltip} silica (diatomaceous, radiolar, spongial). The accumulation of these tests and spicules can constitute huge sedimentary accumulations and form diatomites{ind-text}Light-coloured sedimentary rocks formed by the accumulation in large quantities of siliceous frustules surrounding the diatom cell.{end-tooltip}, radiolarites{end-text}Fine grain sedimentary rocks composed mainly of radiolar siliceous shells, actinopod planktonic protozoan living in warm seas. Radiolarites are the source of part of the jasper, {end-tooltip}, gaizes{end-text}Siliceous, fine-grained, porous sedimentary rock. Colloidal silica, of the opal type, impregnates the porous parts. Often fossiliferous, it can contain a carbonate and clay fraction {end-tooltip} (Figure 10).

4. Life on the continents, marine life, climate variations, water chemistry, sedimentary rocks: everything is linked!

4.1. Continental life, alteration/erosion and marine sedimentary rocks

Life on the continents favours the alteration of rocks. Roots increase rock fracturing and increase the surface area of rock-soil water exchange. Roots, fungi, bacteria produce respiratory CO_2, organic acids that alter rock minerals much more than just rainwater (Figure 11). This alteration in soils produces ions that are exported by surface or groundwater, but also clays and unaltered minerals that are much less mobile than ions. On the other hand, the vegetation cover (grasses, tree roots) retains soil particles (clays, residual minerals) and limits erosion (Figure 12). The biosphere therefore promotes the chemical alteration of emerged rocks and the transfer of ions from the continent to the sea, but limits erosion and the transfer of solid particles to the sea.

Figure 12. Example of a root system with a protective action against erosion. Without these roots, the nearby watercourse would completely erode the soil with each flood. [Source: ©Photo Pierre Thomas]

Figure 11. Example of a root system that tends to cause and/or widen cracks in the rock. This physical action of the roots is real, but its role is very often exaggerated. [Source : © Photo Pierre Thomas]

Sedimentary rocks, to simplify, are of two types: rocks of (bio)chemical origin, especially limestones, formed by the precipitation of ions dissolved in water, and detrital rocks, formed by the sedimentation of solid particles (mud, sand, gravel, pebbles...) brought to the sea by rivers. The continental biosphere, which promotes the release of ions but limits erosion and the release of detrital particles, has a significant influence on marine sedimentation. The evolution of the continental biosphere over the geological ages has completely changed the nature of the sea and marine sediments.

4.2. Biosphere-planet Earth interactions over the last 542 million years

It was in the **Devonian** (-420 to -360 million years ago) that Evolution "invented and selected" lignin and trees. Before the Lower Devonian (-420 million years ago), continental vegetation was very reduced. At the end of the Upper Devonian (-360 million years), most of the continents were to be covered by forests, which then prospered considerably in the **Carboniferous** (-360 to -300 million years), the period following the Devonian (Figure 13, [1]).
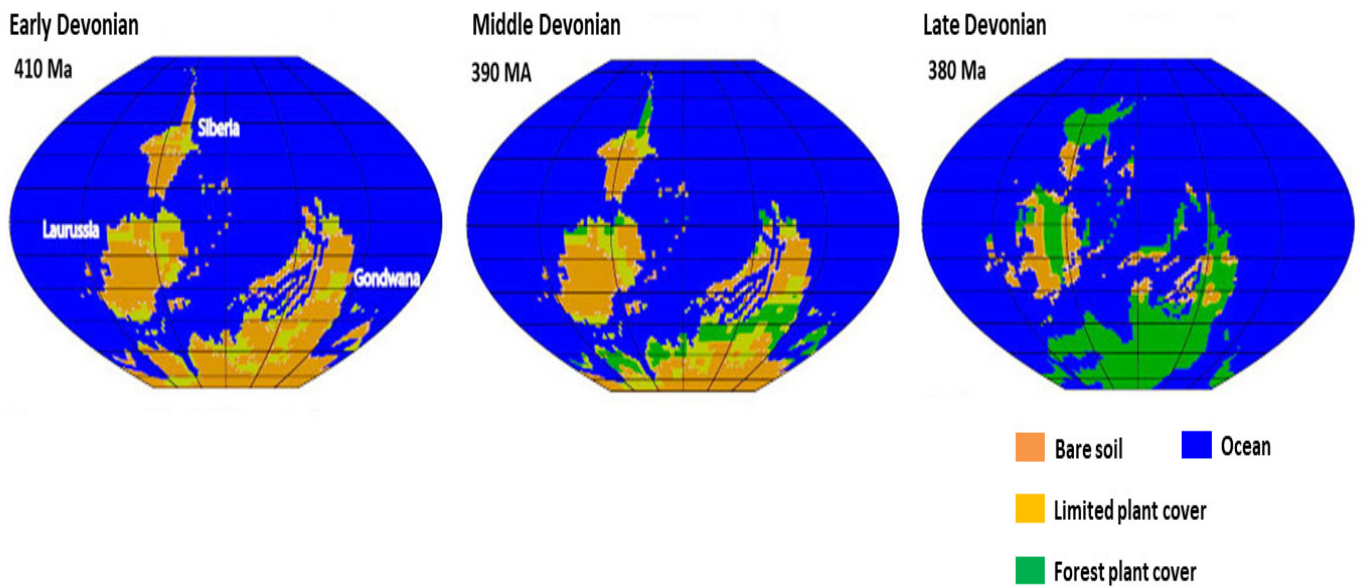
Figure 13. Evolution of land cover on the continents during the Devonian (between -420 and -360 million years ago). In the Lower Devonian, the continents were desert (brown in colour) or covered with bacterial veils or simple plants such as bryophytes... (light green in colour). In the Upper Devonian, most of the surface of the continents were covered with forests. [Source: These maps were obtained by combining climate models and paleontological data. After Guillaume Le Hir (IPGP) (see ref. [2]), modified. Copyright 2011, Elsevier B.V.]

However, marine sedimentation varied during the same period: before the Devonian, limestones were proportionally rare and sedimentary rocks were mainly detrital rocks (sandstone, clays, etc.). In the Devonian, we witness the "explosion" of limestones, which then become very abundant sedimentary rocks. A stroll through Brittany and the Alps is enough to appreciate the rarity of limestone in Brittany in the Lower **Paleozoic** (first half of the Primary Era, -540 to -420 million years) and its abundance in the Alps in the **Mesozoic** (Secondary Era, -245 to -65 million years). This explosion of limestones (due to the scarcity of detrital inputs and especially to the abundance of Ca^{2+} from the alteration of the continents) led to a decrease in atmospheric carbon dioxide, a decrease reinforced in Carboniferous by the formation of many coals (which also, in parallel, caused atmospheric oxygen to rise). This decrease in CO_2 has led to a cooling of the climate, and the appearance of the greatest glaciation from the **Phanerozoic** (which covers the last 542 million years), to the Upper Carboniferous - Lower Permian (-320 to -280 million years), with some less significant glacial episodes from the Upper Devonian.

The history of the Phanerozoic (Figure 14) is punctuated by five major extinctions, where at least 50% of fossil biodiversity disappears in a very short geological time. One of these extinctions, the second chronologically speaking, takes place in the Terminal Devonian (around -374 million years ago). Like the other four, this extinction is probably multifactorial, but one of the proven causes is an anoxia{ind-text} Insufficient oxygen supply.{end-tooltip} widespread oceanic. This ocean anoxia is believed to be due to two causes directly related to the colonization of continents by forests, which has completely disrupted all ecosystems and led to a temporary "eutrophication{ind-text}A singular but natural form of pollution of some aquatic ecosystems that occurs when the environment receives too many nutrients assimilable by algae and they proliferate. The main nutrients responsible for this phenomenon are phosphorus (contained in phosphates) and nitrogen (contained in ammonium, nitrates, and nitrites).{end-tooltip}" from the seas:
(1) sudden inflows of organic matter from continental soils being installed;
(2) planktonic blooms due to the sudden richness of the sea in ions and other mineral nutrients;
(3) consumption of all O_2 dissolved in water during the decomposition of dead bodies of accumulated plankton.

It is often said that the appearance of Man is responsible for the sixth extinction that is looming; but who knows that the appearance of trees is probably partly responsible for the second extinction? And all these major changes just because Evolution "invented and selected" lignin and supporting tissues!

5. Life, ocean stratification and the nature of ocean sedimentary rocks
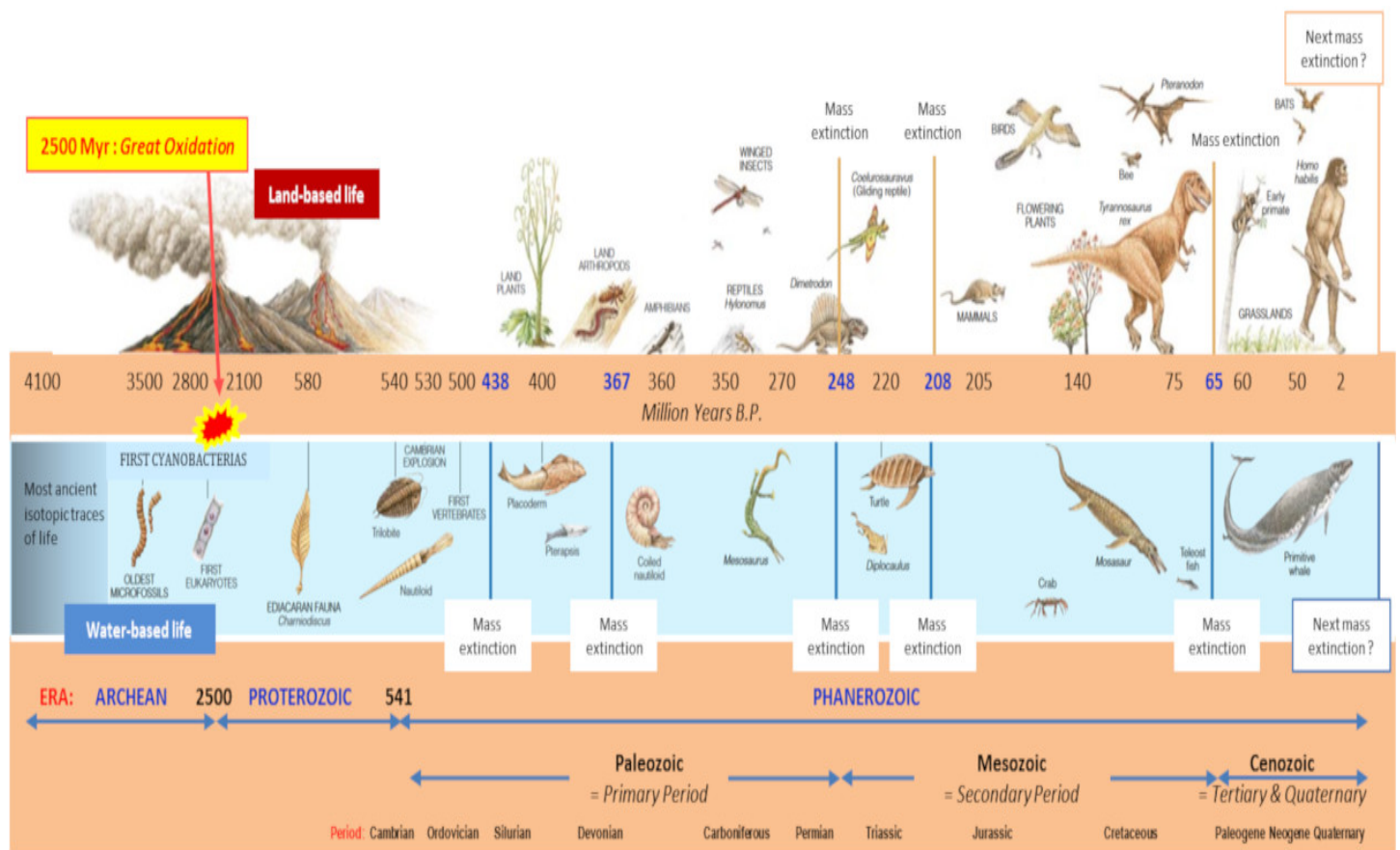
Figure 14. Evolution of living organisms over geological time. [Source : Diagram adapted from a drawing by Tomo Narashima originally published in "Scientific American" (October 1994) and included in "Pour la Science" (December 1994)]

The surface of the ocean is a biological desert. Productivity and biomass (per unit area) are very low, except near the coast and in some specific contexts. Productivity is low because these waters are low in mineral nutrients such as phosphates. These surface waters are also low in CO_2, and saturated in $CaCO_3$ (because they are low in CO_2). On the other hand, deep waters are rich in nutrients and dissolved CO_2; they are under-saturated in $CaCO_3$, because they are rich in dissolved CO_2. The boundary between water saturated with $CaCO_3$ (where limestone can precipitate) and water under saturated with $CaCO_3$ (where limestone cannot precipitate and dissolves if it falls from above) is calledCarbonate Compensation Area{ind-text}Surface of equilibrium of the seas and oceans corresponding to the depth at which all calcium carbonate brought from the surface is dissolved.{end-tooltip} *(Carbonate Compensation Depth* = CCD in English). The depth of this CCD currently varies from 3 to 5 km depending on the ocean. The biosphere is a major actor in this chemical stratification of the oceans. Primary producers (mainly phytoplankton) absorb CO_2 and nutrients to make their organic matter and test. These organisms are eaten by primary and then secondary predators. All this little world produces feces, then dies. Excrements, corpses and tests fall to the bottom of the ocean, taking with them organic matter, phosphorus, etc... The organic matter is oxidized by breathing bacteria, which releases CO_2 and mineral nutrients into deep waters. CO_2 and nutrients will reach the surface after a few centuries thanks to the global ocean circulation and the loop will be closed. In ocean regions where deep waters rise (upwelling), their high CO_2 and nutrient content generates highly productive ecosystems.

As for the depth of the CCD, it is a function, among other things, of the release of deep CO_2 which tends to raise it and the rain of carbonate tests (the corpses of planktonic organisms) which tends to lower it. Since Evolution "invented and selected" an abundant pelagic plankton with calcareous test (since the Jurassic, -201.3 to -145 million years ago), the CCD is several kilometres deep. Before the Jurassic, there was no calcareous plankton and no carbonate rain; the CCD was much more superficial. And there are no oceanic limestones before the Jurassic. Life and its variations are therefore major actors in ocean chemistry.

6. As conclusion and perspective

In everything that has just been said, important points have not been addressed, for example everything related to methane, phosphates, the sulphur cycle... And moreover, we have only talked about the superficial biosphere, which is only the tip of the iceberg. About twenty years ago, we discovered a whole biosphere made up of bacteria and archaea living in the first few kilometres of the lithosphere, both continental and oceanic: theendogenous life{ind-text}Community of organisms living underground, as opposed to epigeous species that germinate or live on the surface of the ground{end-tooltip}. These microorganisms can be heterotrophic{ind-text}Describes the characteristic nutritional mode of organisms using exogenous organic matter sources for their growth and development. Animals, fungi, many protozoa, most prokaryotes and a few rare plants

are heterotrophic.{end-tooltip} and use the organic carbon present in these first few kilometres. They are often autotrophic{ind-text}Describes the ability of an organism to produce organic matter from the reduction of inorganic matter and an external energy source: light (photoautotrophy) or chemical reactions (chemoautotrophy).{end-tooltip} (more precisely chemiolithotrophic{ind-text}Characterizes the metabolism of autotrophic organisms that differ from each other in the nature of oxidation reactions energetically coupled to CO_2 reduction. There are soil nitrification bacteria that oxidize ammonium salts to nitrites or nitrites to nitrates. Others oxidize either sulphides, colloidal sulphur suspended in water, thiosulphates, and many other mineral sulphur compounds, depending on the biological species. Other soil bacteria oxidize ferrous salts into ferric salts and use the energy released for their synthesis. {end-tooltip}) and live through reactions such as:

Fe^{2+} of silicates + H_2O + CO_2 → Fe^{4+} + organic molecules
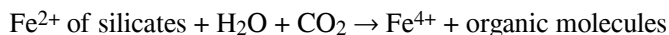
Such a metabolism certainly modifies, but in what proportion, the chemistry of the crust (or even the upper mantle). All that remains is to study what is perhaps the main (mass) compartment of the biosphere.

Everything that has just been said concerns the action of the biosphere on the other envelopes of the planet (atmosphere, hydrosphere, crust...). That is why we cannot be a "complete" geologist if we are not also a bit of a biologist and ecologist. But the reverse is true. The Earth's "mineral" envelopes influence the biosphere: the atmosphere through its climates and their variations, the hydrosphere through its movements and composition, the solid Earth through its chemistry, its slow movements ("continental drift" and its action on evolution), its violent crises (giant volcanic blooms called trapps{ind-text}Lava flows over more than 2000 metres thick located in India. They were formed 60 to 65 million years ago and could be involved in the Cretaceous-Tertiary crisis, which saw the disappearance of non-avian dinosaurs in particular... {end-tooltip}...), have an influence on the biosphere. You can't be a "complete" biologist and ecologist if you're not also a bit of a geologist.

References and notes

[1] Le Hir G. et al. (2011) *The climate change caused by the land plant invasion in the Devonian.* Earth and Planetary Science Letters 08-042; http://dx.doi.org/10.1016/j.epsl.2011.08.042