Climate and atmosphere of the young earth

Weather and Climate

We define weather as the temperatures, precipitation, cloud cover, and winds that prevail on the Earth's surface at a particular place and time, or - more generally - the instantaneous state of the atmosphere.

We all know how different the weather can be - hot and humid one day, cold and rainy the next. Because the atmosphere behaves in an extremely complex way, it is difficult to make a weather forecast beyond 4 or 5 days. However, we can make a rough estimate of how our weather will develop in the somewhat distant future because the prevailing weather is determined primarily by seasonal and daily changes in the supply of solar energy: summers are hot, winters are cold, daytime is warmer, nights are cooler. If we observe these weather elements, the temperature, but also the other variables such as precipitation over a longer period of time, we can deduce regularities that we call climate (Fig. 1).

Fig. 1: Climate and weather

The term climate refers to the characteristic atmospheric conditions prevailing in a particular region. It is the result of a daily and seasonal statistical description of relevant climate parameters such as air temperature, humidity, cloud cover, precipitation, wind speed, sunshine duration, and other weather conditions over a specified observation period, generally of at least 30 years.

The climate system includes all parts of the Earth system and all interactions necessary to explain how climate behaves in time and space.

The major components of the climate system are the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere (Fig.2). Each of these components plays a different role in the climate system.

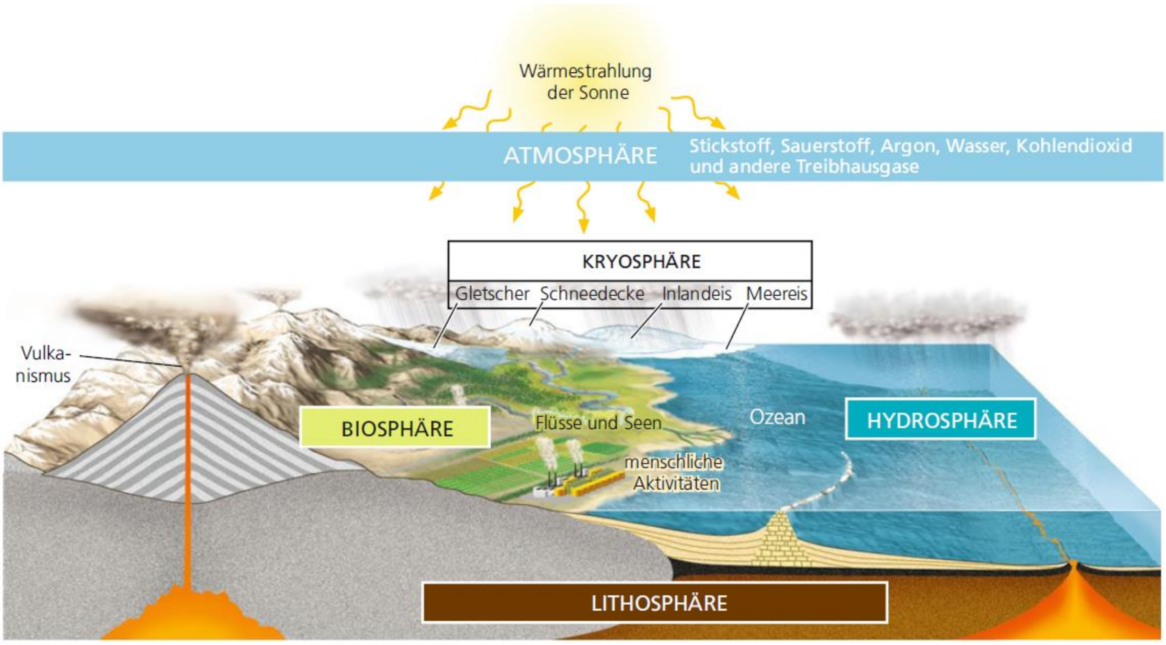


Abb. 15.1 Das Klimasystem der Erde besteht aus komplizierten Wechselwirkungen zahlreicher Komponenten

Fig. 2: Climate system

While the atmosphere is the gaseous envelope of our Earth's surface, which can be divided into several stages (troposphere, stratosphere, mesosphere, thermosphere and exosphere, Fig. 3), the hydrosphere is the part of the Earth's surface covered with water, i.e. the oceans, rivers and lakes. The cryosphere is the ice caps of the polar regions, as well as the glaciers and areas of the Earth covered by snow and ice. The lithosphere is the solid shell of the Earth consisting of rocks; it includes the Earth's crust and uppermost mantle down to an average depth of about 100 km. The biosphere is all the organic matter at or near the Earth's surface and thus includes life and its metabolic processes.

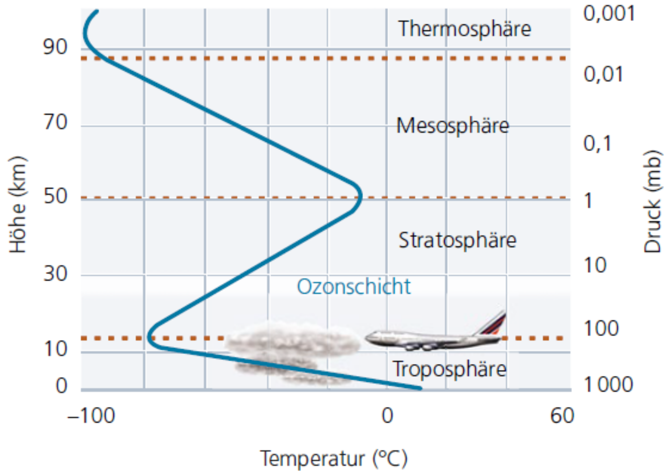


Abb. 15.2 Der Aufbau der Atmosphäre mit Temperatur- (*blaue Linie*) und Druckverteilung in Abhängigkeit von der Höhe

Fig. 3: Atmosphere

When the sun heats the earth's surface, some heat is trapped in the atmosphere by water vapor, carbon dioxide, and other gases, just as, for example, heat radiation is trapped by the glass in greenhouses (Fig. 4).

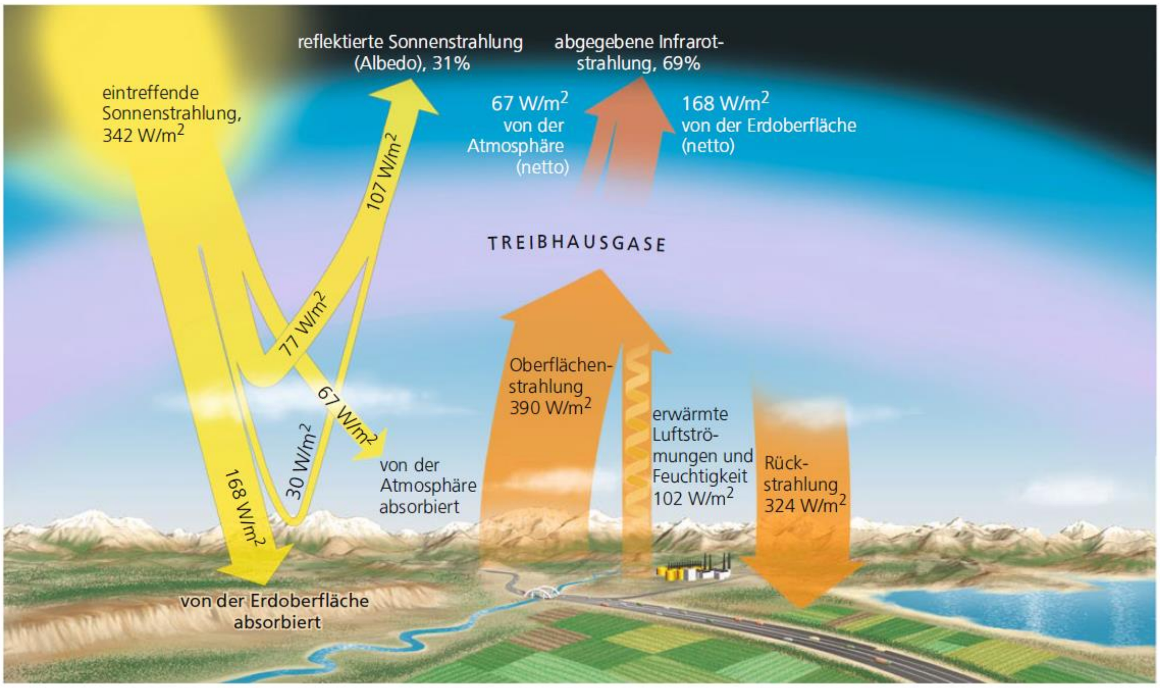


Abb. 15.7 Um das Strahlungsgleichgewicht aufrecht zu erhalten, strahlt die Erde im Durchschnitt so viel Energie in den Weltraum ab, wie sie von der Sonne erhält (340 W/m²). Von der auftreffenden Strahlung werden 100 W/m² (= 29 %) reflektiert, 161 W/m² werden von der Erdoberfläche und 79 W/m² von der Atmosphäre absorbiert. Durch Strahlung, warme Luftströmungen und Feuchtigkeit wird mehr Energie von der Erdoberfläche abgeführt (502 W/m²) als zugeführt wird. Die in der Atmosphäre vorhandenen Treibhausgase reflektieren den größten Teil dieser Wärmeenergie als Infrarotstrahlung auf die Erdoberfläche zurück (342 W/m²) (IPCC (2013): Climate Change: The Physical Science Basis)

Fig. 4: Greenhouse effect

This greenhouse effect explains why the Earth has a pleasant climate that makes organic life possible in the first place. If the atmosphere did not contain greenhouse gases, much of the heat would be released into space and the Earth's surface would be a frozen solid - at least on its shaded side. Therefore, greenhouse gases, especially carbon dioxide, play an important role in regulating the climate. The concentration of carbon dioxide in the atmosphere results from the balance between the amount released from the Earth's interior during volcanic eruptions and the amount sequestered during the weathering of silicate rocks and the formation of carbonate rocks. In this way, the climate system is regulated by interactions with the lithosphere.

The biosphere is also part of the climate system. For example, the plant cover of the continents can affect the temperature of the atmosphere because plants absorb solar energy for photosynthesis and release it as heat and water vapor during respiration as they absorb water from the soil and release it as water vapor. In addition, organisms affect the composition of the atmosphere by either absorbing or releasing greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4). Therefore, the biosphere plays a central role in the carbon cycle.

Of course, humans are also part of the biosphere, although not a very common one. Our impact on the biosphere is rapidly increasing and we have now become the most active contributors to environmental change. As an organized society, we behave very differently from the rest of the species. For example, we can scientifically study climate changes and modify our activities according to our level of knowledge. In doing so, we are able to scientifically study not only the current changes in climate, but also those of the past. In this paper, we will look at the climate of the early Earth in the Archean and Paleozoic eras.

The early atmosphere

What did the atmosphere of the early Earth look like (Fig. 5)?

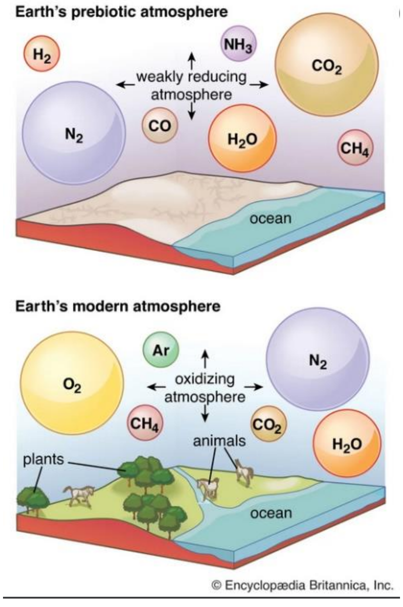


Fig. 5: Comparison between early and present atmosphere of the Earth.

If we look at other giant gas planets like Jupiter, Saturn, Uranus, and Neptune, we can get a pretty good idea of what Earth's earliest atmosphere looked like. The main gases in these giant gas planets are hydrogen and helium (as in the Sun), which make up about 99% of the total mass of the solar system. However, the Earth was not large enough to generate a gravitational pull strong enough to hold these light elements in its atmosphere, and they floated off into space soon after the Earth was formed.

Once hydrogen and helium escaped, the next most abundant gases would be those we see around the other smaller planets. Both Venus and Mars have a lot of CO_2 in their atmospheres, and it would also have been an important component of Earth's early atmosphere. Most important, however, was nitrogen (N_2), which today makes up 78% of the air we breathe and was probably so dominant in the early atmosphere. In turn, if we look at planets like Jupiter and Saturn, we find that other gases are very important, especially methane (CH_4) and ammonia (NH_3). So our planet was initially rich in hydrogen and helium, but quickly lost these light gases because Earth's gravity was not strong enough. What remained was an atmosphere rich in nitrogen, some carbon dioxide, water vapor, and small amounts of methane and ammonia. What it did not have, however, was free oxygen.

The sun's radiant output in the Hadean and early Archean was about 30% lower than it is today. With today's atmospheric composition, the Earth would have been completely iced over. Nevertheless, there is no evidence for glaciation. For example, we have shown that the 4.4 billion year old zircon crystals provide circumstantial evidence for liquid water on the young Earth, so the Earth remained ice-free despite the lower solar radiation. This supposed contradiction is called "faint young sun paradox": The high amount of CO_2 compensated for the lower radiation of the young sun, so that a warm climate can be assumed on Earth (Fig.6).

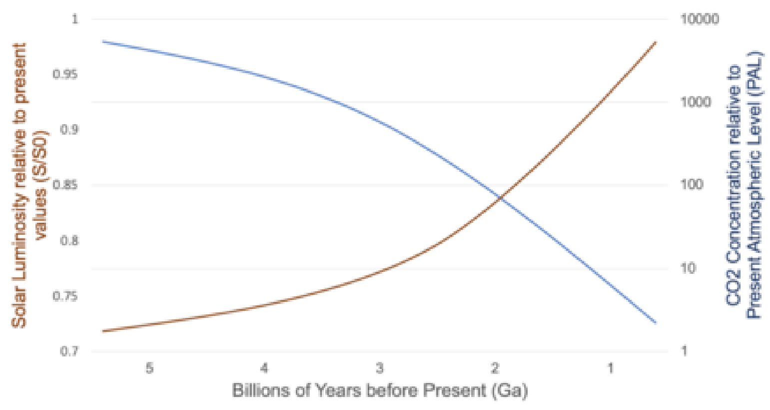


Fig. 6: This graph shows the relationship between solar radiation and the greenhouse effect, which in this case is dominated by changes in carbon dioxide.

However, it is unclear how rapidly the CO_2 content in the atmosphere was reduced. Some CO_2 was probably leached into the ocean, but the vast majority was degraded by a high rate of weathering and, after the emergence of life, by bioproduction. This process probably took a very long time, but is difficult to quantify. Calculations have shown, however, that CO_2 concentrations would have to be 1,000-10,000 times higher than they are today for the early Earth not to become a frozen ice planet. However, such a high concentration is too unrealistic. Another alternative is the greenhouse gas methane. Methane would have been abundant in the weathering of lavas on the ocean floor, and some of it might also have reached Earth through comet impacts, which carry a lot of frozen methane. Later, after life evolved, some of the earliest life forms were methane-producing bacteria that break down complex organic matter and release methane gas. Methane is a very powerful greenhouse gas that traps the Earth's heat much more effectively than CO_2, so a little goes a long way. If methane were only 1/1000 as common as CO_2, the Earth would only need 15 times the current CO_2 concentration to keep surface water from freezing (Fig.7).

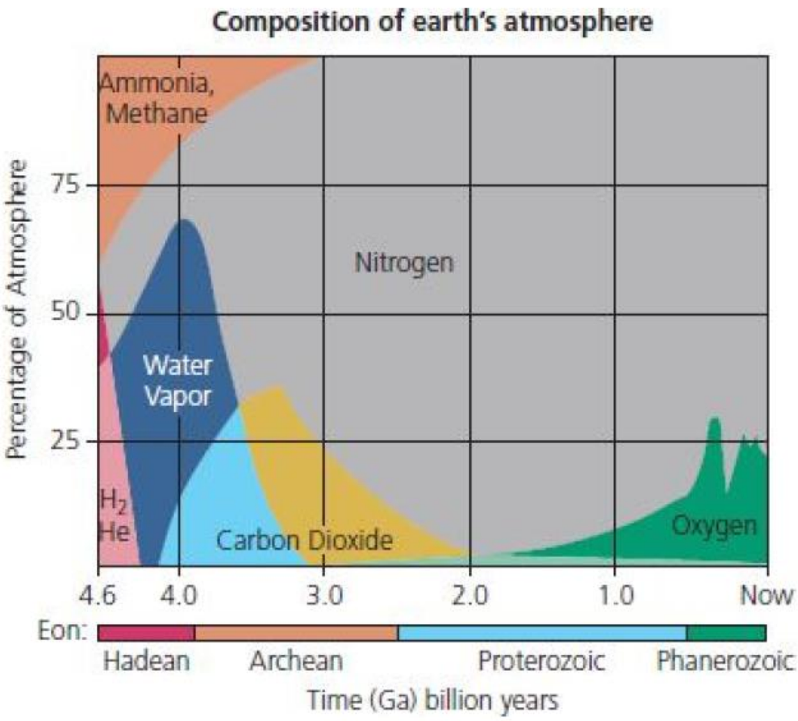


Fig. 7: Percentage of atmospheric gases in Earth's history. Note the high percentage of methane during the Hadean and Archean.

Indeed, there are good correspondences for methane-rich planetary bodies. Not only Jupiter and Saturn are rich in methane, but also Saturn's moon Titan has a methane-rich atmosphere that it even appears orange (Fig. 8).

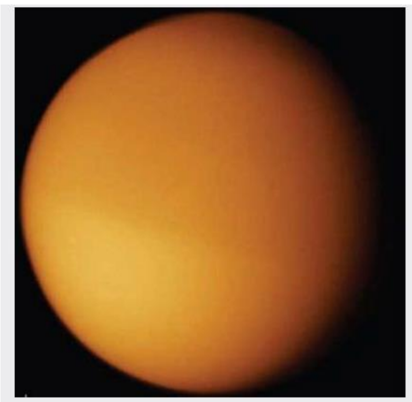


Fig. 8: Saturn's moon Titan

The carbon cycle

With the onset of weathering and plate tectonics, the carbon cycle also began. The carbon cycle consists of the silicate-carbonate cycle and the organic carbon cycle (Fig. 9). The silicate-carbonate cycle can be simplified with three partial reactions: silicate weathering on land, carbonate formation in the ocean, and subduction and degassing of CO_2 by volcanism. The precondition for the silicate-carbonate cycle is plate tectonics.

Der Kohlenstoffkreislauf, bestehend aus dem Silikat-Karbonat-Kreislauf und dem organischen Kohlenstoffkreislauf.

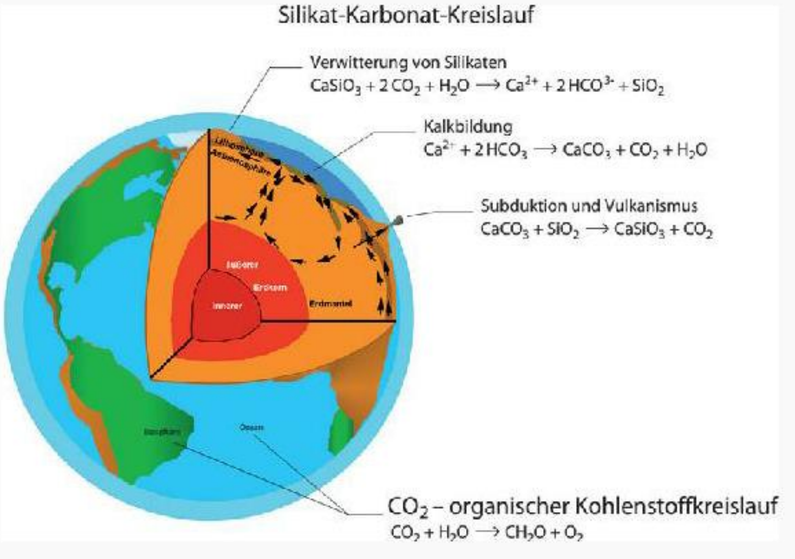


Fig. 9: Carbon cycle

The high CO_2 content of the atmosphere caused an "acid rain" and thus a high weathering rate at the earth's surface, where calcium silicate ($CaSiO_3$) reacts with CO_2. This produces calcium (Ca^{2+}), hydrogen carbonate ions (HCO^{3-}) and silica (SiO_2). Ca^{2+} and HCO^{3-} are transported by rivers to the oceans where they react to form calcium carbonate ($CaCO_3$), CO_2 and H_2O. During subduction, the subducted lime reacts with silica to form calcium silicate and CO_2 again, some of which is returned to the atmosphere via volcanism. In the balance, these reactions are balanced. However, the partial reactions proceed at different rates in different periods of Earth history, leading to strong variations in the CO_2 content of the atmosphere and thus promoting either a greenhouse or an ice age climate. In the long term, transport into the mantle is greater than outgassing via volcanism, which has led to a long-term decrease in atmospheric CO_2.

In the Hadean, Archean, and Proterozoic, weathering dominates as a CO_2 consumption reaction because of intense crust formation and continental growth. During this time, much CO_2 is sequestered from the atmosphere. Consequently, it is plausible to assume that the CO_2 content of the atmosphere, and thus the greenhouse effect, decreased significantly in the Archean. The loss of CO_2 was compensated by methane, which did not lead to a cooling and ice age.

The organic carbon cycle only begins with the emergence of life and initially played only a minor role. In most forms of primary production, CO_2 is converted to organic carbon. Through heterotrophic metabolic pathways, consumers convert the organic carbon back to CO_2. Reaction and re-reaction are nearly balanced, but a small portion of the organic carbon escapes the re-reaction and is incorporated into the rock sphere. Some of this organic carbon forms coal, oil and gas deposits in the long term. This is another way CO_2 has been removed from the atmosphere in the long term.

Decisive for the carbon cycle is in which reservoir the carbon is located and in which quantity and with which turnover rate (transfer rate) it is transferred to another reservoir by the reactions. The organic carbon cycle has very small reservoirs but high transfer rates, while the silicate-carbonate cycle has very large reservoirs but comparatively low turnover rates.

The Oxygen Holocaust

The early Earth had an unusual atmosphere consisting mainly of nitrogen and CO_2, with abundant methane and ammonia, but no free oxygen (Figs. 5 & 7). How is it then that today have an oxygen content of 21%? What is the circumstantial evidence for the earliest oxygen on Earth?

The best circumstantial evidence comes from certain places, such as the Iron Ranges in Minnesota, the Hamersley Range in Australia, and some other really unusual places. They are the most important sources of iron in the world that drove the Industrial Revolution. These iron deposits come from banded iron formations (BIFs). As the name implies, these rocks have red or black bands of iron (Fig. 10), ranging from a few millimeters to a centimeter thick, alternating with bands of pure silica (in the form of chert or jasper).

Fig. 10: Banded Iron Formations (BIFs)

When they were discovered in the mid-1800s, their significance was a mystery. Even more surprising, the rocks are pure iron and chert, with little or no silt or sand that would normally be expected when the iron was deposited into ancient seas. So how could sediments consisting of dissolved iron and silica be deposited on the ocean floor without being mixed with sand and mud? First, it is important to know that iron cannot remain dissolved in seawater in modern oceans because it is rapidly oxidized to various forms of iron oxide ("rust") and attaches to other minerals. Large amounts of iron can only be transported and concentrated in seawater when oxygen levels are low enough to prevent iron from rusting. This indicates that the early seafloor must have been low in oxygen when the iron formations were deposited, and most geologists assume that the atmosphere was also very low in oxygen.

Next, the seafloor must have been far enough from land that almost no sand or mud from the land in the deep-sea basin could mix with the chemical deposits of iron and silica. Perhaps the iron basins were in the middle of the ancient seas, while the sands and muds were trapped in basins at the edge of the ancient continents.

However, the Hamersley deposits in Australia appear to have formed on a shallow ocean shelf, so this model does not apply to all BIFs. Finally, it would be much easier to deposit huge concentrations of iron if there were an abundant source of dissolved iron entering the ocean. Most geologists assume that most of the iron comes from the weathering of basaltic lavas (which contain iron). Recently, geologists studying BIFs have noted that some of the largest deposits were formed when Earth experienced giant eruptions of flood basalt known as "large igneous provinces" (LIPs, Fig. 11). These huge lava eruptions would have produced a lot of iron as they weathered, as long as the atmosphere and ocean were low enough in oxygen that the iron could remain in solution and not rust.

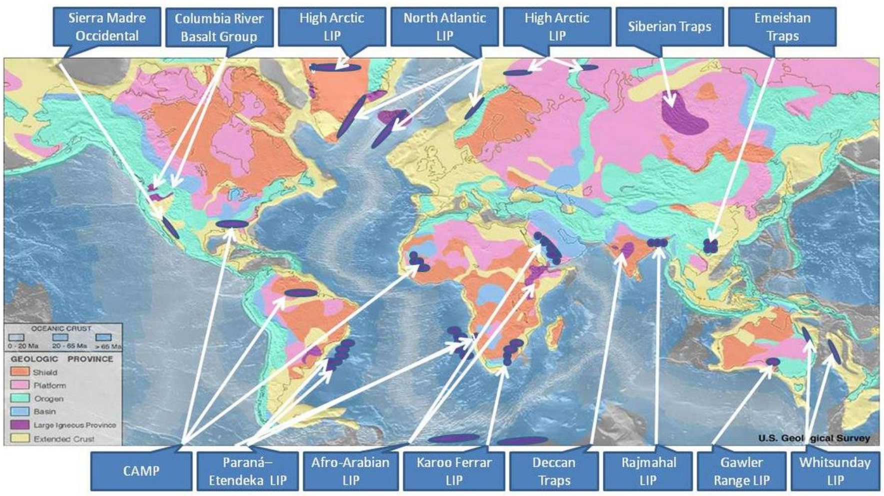
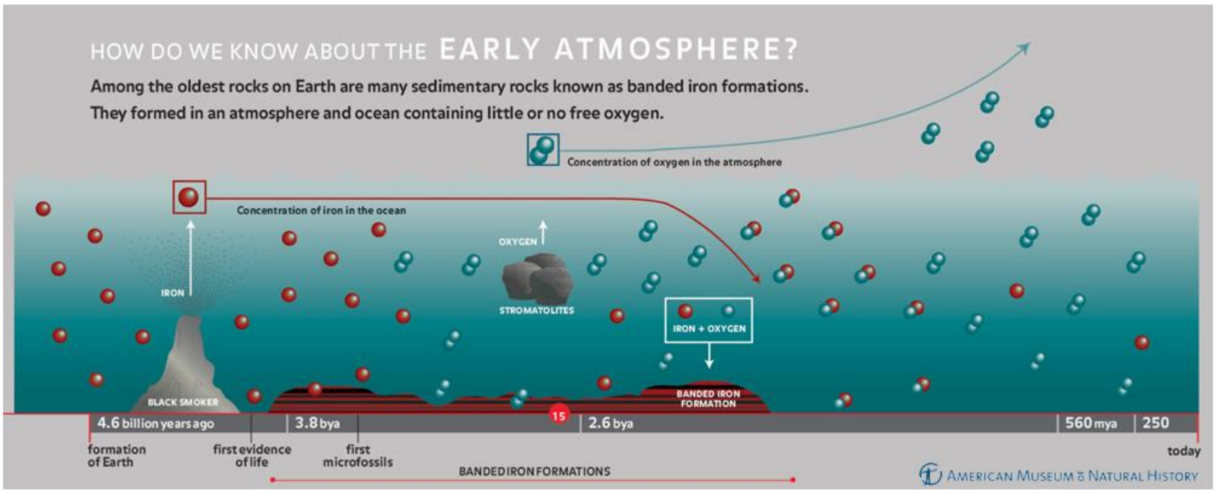


Fig. 11: Large igneous provinces (LIP).

Most BIFs (Fig. 12) were formed in the Archean, when the Earth not only had an anoxic atmosphere but was also covered by small proto-continents floating around in the proto-oceans.



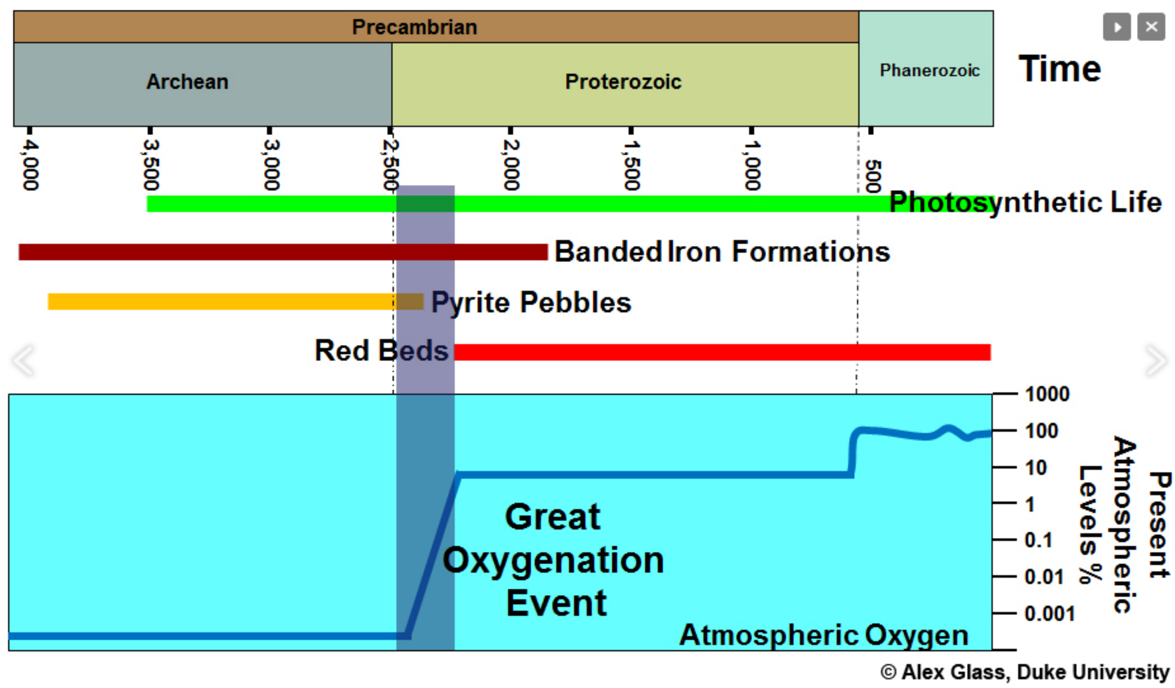


Image credit: Alex Glass *Item 16 of 16*

Fig. 12: Great Oxidation event

Between 2.6 and 2.4 billion years ago, the largest volume of BIFs was deposited, notably the giant iron mountains in the Hamersley Range in Australia, the Iron Ranges around Lake Superior, and similar deposits in Brazil, Russia, Ukraine, and South Africa. During this time window, the huge eruptions in the major magmatic provinces were also at their peak.

Then, 2.4-2.3 billion years ago, something happened. The BIFs began to disappear, although there were still large deposits of iron in granular rather than banded form, known as "granular iron formations" (GIFs, Fig. 13). From 1.9 billion years ago, the BIFs and GIFs disappeared completely, with a few exceptions.

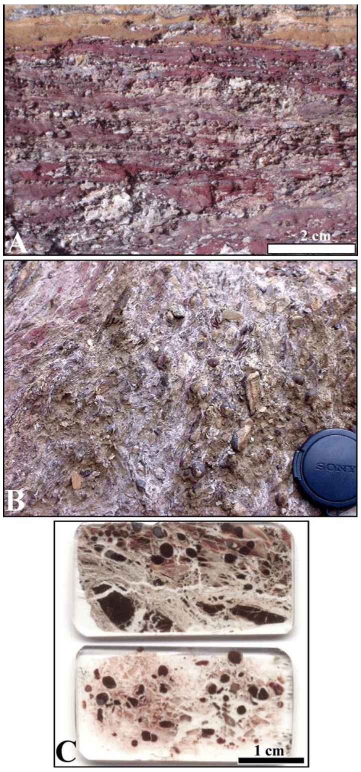


Fig. 13: granular iron formations, GIFs.

Most geologists consider this time to be when oxygen finally reached significant levels in the Earth's atmosphere and possibly also in the ocean. This point in time is called the "Great Oxidation Event" (GOE for short; Fig. 12). At that time, oxygen levels in Earth's atmosphere were still about 1% in the oceans, sufficient to cause dissolved iron in the oceans to rust. Then, about 1.9 billion years ago, geologists believe that the oxygen content in the oceans was so high that oxygen could escape into the atmosphere and possibly weather rock on land, although it was still not abundant in the atmosphere. It wasn't until the last 500 million years that oxygen levels reached levels like today's and completely saturated the oceans and atmosphere.

There is other geochemical evidence as well. From 1.9-1.8 billion years ago, we find sand grains and pebbles in river deposits composed of the mineral pyrite (Fig. 14), also known as fool's gold, an iron sulfide (FeS_2). Today, pyrite forms only in places with very low oxygen levels, such as the bottom of standing water. Once the pyrite grains weather at the surface, they quickly turn into red ironstone (Fe_2O_3, hematite; Fig. 15) rather than iron sulfide. As the pyrite decomposes, the iron is released and the sulfur is oxidized to sulfate, producing minerals such as gypsum (calcium sulfate or $CaSO_4$, Fig. 16). Not surprisingly, we find few significant gypsum deposits older than about 1.8 billion years. Sand grains of uranium oxide (uraninite, UO_2) are common before 1.7 Ga, but are not found after that time. Like dissolved iron, they are unstable in an oxygen-rich atmosphere.

Fig. 14: Pyrite Fig. 15: Hematite Fig. 16: Gypsum

There are also other indicators. For example, sulfur isotope values in Archean rocks are highly variable and fluctuate constantly. But after 2.4 billion years, they are very stable because they are no longer floating freely in minerals like pyrite, but are stabilized in gypsum and other minerals common in an oxygen-rich world.

So the world went through a dramatic change once oxygen became available. The Great Oxidation Event has also been called the "oxygen holocaust" because the appearance of a molecule as reactive as O_2 would have been toxic to life on the planet, which was accustomed to anoxic conditions. Today, these bacteria and other microbes adapted to low-oxygen conditions must live in low-oxygen places like the bottoms of stagnant lakes and ocean basins. However, 2.3 billion years ago, they dominated the planet. When the atmosphere became too oxygen-rich, a true holocaust occurred for them, and they lost the world to microbes that can survive in oxygen-rich conditions. It was the first great mass extinction.

So the burning question arises, where does the Earth's atmosphere get its free oxygen? The answer is clear: photosynthesis, first by cyanobacteria (Fig. 17) and later, when true eukaryotic algae evolved, by plants as well. The great puzzle is that fossils of cyanobacteria are known from 3.5-3.8 billion years ago, but the Great Oxidation Event did not begin until about 2.3-1.9 billion years ago. Was the oxygen production of cyanobacteria so low that they did not make an impact on the planet? Or perhaps true eukaryotic algae evolved 2.3 billion years ago, with much larger cells and producing more oxygen? Whatever the reason, the fact is that after 1.7 billion years there were true eukaryotic algae everywhere and there was an atmosphere with about 1% or more oxygen, which changed the Earth's oxygen balance forever.

And another thing to consider is that without free oxygen, multicellular animals could not have evolved - and we would not be discussing this issue because humans could not have evolved either. In fact, the evolution of all life as we know it depends on an oxygen-rich planet, which is not possible without the evolution of photosynthetic microbes and plants.

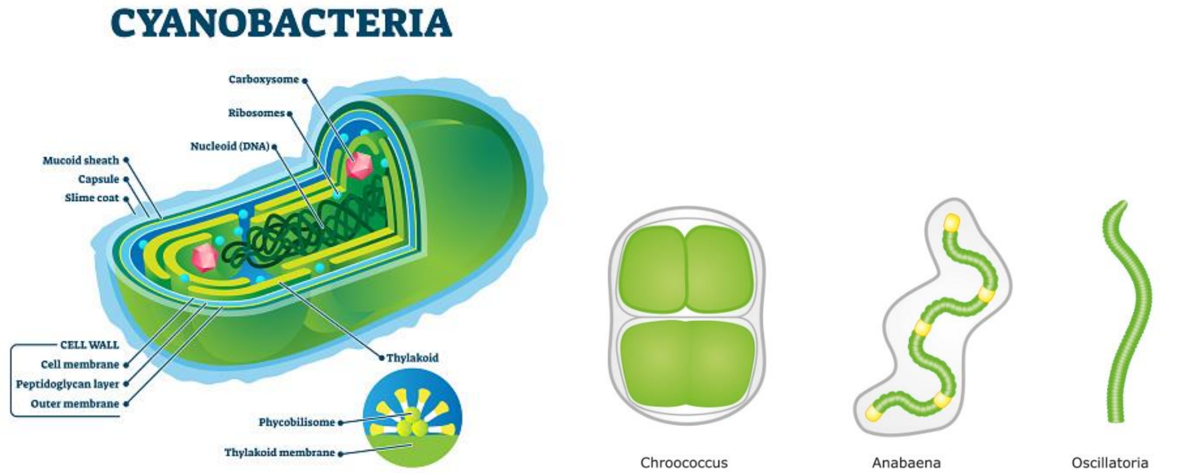


Fig. 17: Cyanobacteria

Snowball earth

The high photosynthesis rate consumed together with the weathering very much CO_2. At the same time, however, O_2 was released. In the Neoarchaic relatively high methane concentrations (0.1%) prevented a decrease of the greenhouse effect. Due to the oxygen, the methane content was now oxidized more rapidly than in the Archean. Its content decreased to about 0.01% (Fig. 7). The greenhouse effect was thus drastically reduced, whereupon the Huronian glaciation began, lasting in several phases of about 2.4-2.1 billion years. Evidence in the form of tillites (fossil bedloads or moraines) and dropstones for this glaciation is found in southern Canada, the USA, Finland, India, Australia and South Africa, which also belonged to different continents at that time (Figs. 18, 19).

Fig. 18: Snowball earth glacial deposits are found in many places around the world. A. The Gowganda till, from the Early Proterozoic snowball event (the Huronian glaciation), northern shore of Lake Huron, Blind River, Ontario, Canada. B. The Elatina diamictite, an interbedded sequence of limestones and glacial tills from Australia, which was a few degrees from the equator in the later Proterozoic Varangian glaciation. This deposit proves that there had to be sea-level glaciers in the tropics C. Upper Proterozoic glacial deposits of the Kingston Peak Formation, near Death Valley, California. It is capped by a carbonate deposit, the Noonday Dolomite, and underlain by a carbonate, the Beck Spring Dolomite, showing that the Death Valley region was warm and subtropical in the Late Proterozoic before the snowball earth event and then went back to tropical conditions. D. A thick glacial deposit in Namibia with huge angular boulders, overlain by the “cap carbonate” limestone body precipitated abruptly when the Varangian glaciation ended

Fig. 19: left: Tillite, right: Dropstone. Tillite is a rock consisting of deposits in the glacier margin (lateral, terminal or ground moraine). A dropstone is an isolated rock fragment of pebble to boulder size that has been deposited within fine-grained sediments. They can be formed, among other things, by the melting or sliding of rocks from icebergs or glaciers.

Because of large-scale glaciations, the weathering rate and bioproduction declined very sharply. Thus, during the Huronian Glaciation, which lasted about 300 million years, volcanic outgassing allowed CO_2 to reaccumulate in the atmosphere. In addition, solar radiation also slowly increased. The methane content of the atmosphere was now much lower than in the Archean, but was probably still 10-100 times the present value. All three mechanisms contributed to the return of warm conditions in the late Paleoproterozoic that persisted throughout the Mesoproterozoic and oldest Neoproterozoic. During this period, bioproductivity again increased sharply. When the world thawed again after the Huronian Glaciation, however, not much out of the ordinary happened in Earth's history. It is postulated that perhaps the first multicellular organisms formed, but even these did not evolve extraordinarily. Therefore, researchers call the time from 1.8 to 0.8 billion years ago the "Boring Billion" (Fig. 20).

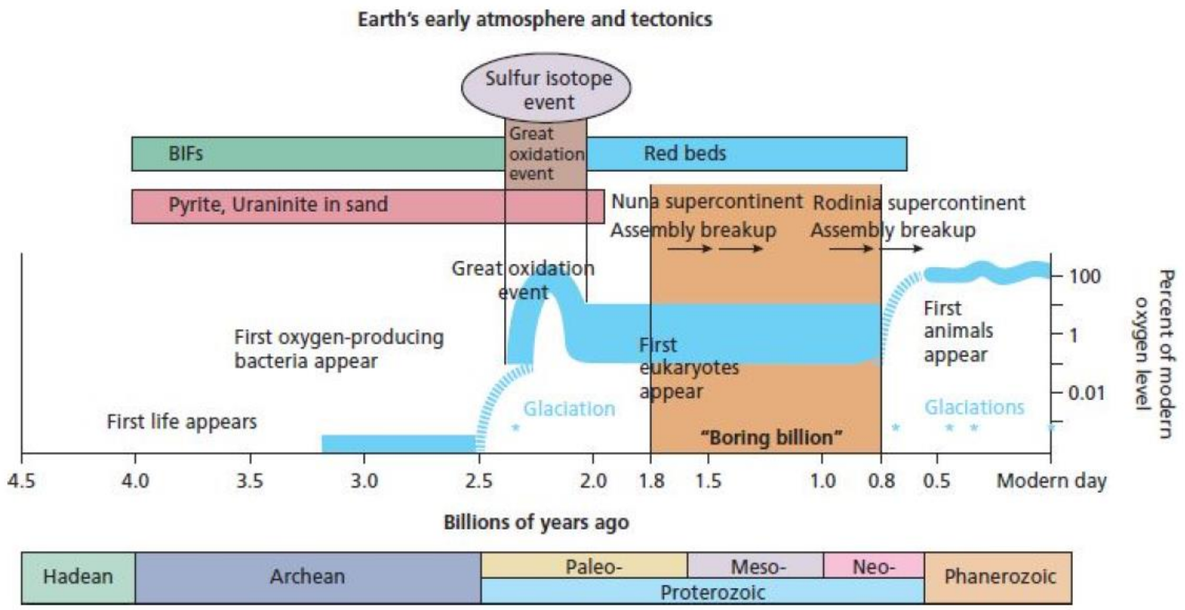


Fig. 20: Time period of the "Boring Billion

During this time, nothing of particular relevance occurred, either geologically or biologically. The reason could be that in this time the plate tectonics was extremely stable. The continents formed a single large landmass most of the time, called Columbia in the early days, and Rodinia after a brief breakup and subsequent reunion. The land masses drifted back and forth along the equator, but without geological forces piling up mountain massifs on top of it. Every small hill was thus immediately eroded away by the erosion. Since the living conditions hardly changed in this time, there was likewise no necessity for the living beings.

In the Young Proterozoic the events analogous to the Huronian glaciation repeated themselves once again. A high bioproductivity, combined with a high weathering rate, consumed a lot of CO_2. The resulting increase in oxygen content reduced the methane content of the atmosphere once again. CO_2 and methane thus fell in the Neoproterozoic to the lowest levels during the entire Precambrian. The consequence of this was the very large-scale Young Proterozoic glacial period, possibly extending into the equatorial region. It lasted from about 850-550 million years ago with the main phase between 740-630 million years ago. Glaciation largely collapsed bioproduction and reduced the rate of weathering. Volcanic outgassing caused CO_2 levels to rise again until the thaw set in. In this way, several ice and warm phases alternated.

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