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Earth's Historic Atmospheres

Earth's Primordial Atmosphere

Our solar system originated from the debris of explosions of earlier Suns and was formed from some of that debris. The Sun and its associated planets that were formed from this solar nebula, coalesced ≈ 4.6 BY ago. The initiation of hydrogen fusion into helium gave birth to our Sun. The planets orbiting the Sun were also formed by accretion; the heavier elements from the nebula were concentrated within their cores and the lighter elements, e.g., H_2 and He became the initial atmosphere. Figure 5.1 reflects that we lost much of our initial atmosphere, e.g., H_2 , He, CH_4 etc. during the Hadean time. The geologic history of the composition of the Earth's various atmospheres with respect to time is presented in Table 5.1 and Figure 5.1.

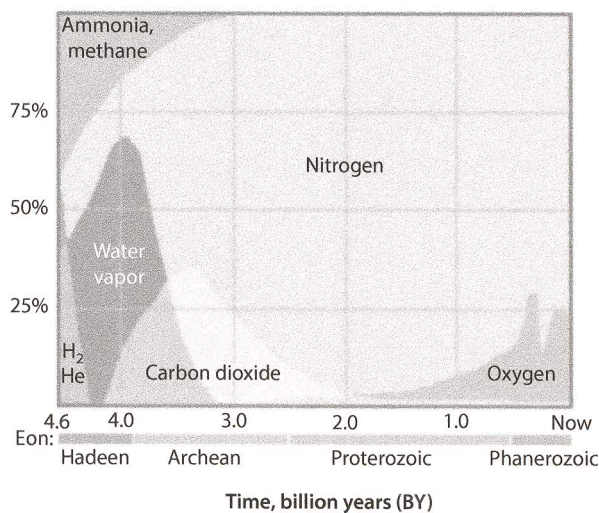


Figure 5.1 Variation of the composition of the Earth's atmosphere with time. (After Scientific Psychic, 2017.)

Table 5.1 Evolution of the Earth's Atmospheres.

	Atmospheric composition	Source of its components	Other characteristics
1 st Atmosphere Hadean time	CH ₄ , He and H ₂	Asteroids, comets, etc.	Atmosphere mainly H ₂ and He. Volatile compounds tripped out
2 nd Atmosphere Archean and 1st half of Proterozoic time	CO ₂ , H ₂ O and methane (decreasing) and N ₂	Mantle degassing	Primarily CO ₂ and N ₂ by end of Archean, presence of bacteria producing N ₂ .
3 rd Atmosphere 1 st half of Proterozoic and Phanerozoic time	Primarily N ₂ and O ₂ with small amounts of Ar, CO ₂ , etc.	O ₂ generated by photosynthesis	Development of ozone layers

Earth's
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The initial atmosphere accreted from the gas clouds that surrounded the young Earth. It was composed of hydrogen, helium, and other gases. This atmosphere was quickly lost to space by a process called hydrodynamic escape. The second atmosphere was formed by outgassing from the Earth's interior. It was composed of carbon dioxide, water vapor, and other gases. This atmosphere was also lost to space by hydrodynamic escape. The third atmosphere was formed by outgassing from the Earth's interior. It was composed of nitrogen, oxygen, and other gases. This atmosphere was also lost to space by hydrodynamic escape. The fourth atmosphere was formed by outgassing from the Earth's interior. It was composed of nitrogen, oxygen, and other gases. This atmosphere was also lost to space by hydrodynamic escape.

At the time of the formation of the Earth, the atmosphere was composed of hydrogen, helium, and other gases. This atmosphere was quickly lost to space by a process called hydrodynamic escape. The second atmosphere was formed by outgassing from the Earth's interior. It was composed of carbon dioxide, water vapor, and other gases. This atmosphere was also lost to space by hydrodynamic escape. The third atmosphere was formed by outgassing from the Earth's interior. It was composed of nitrogen, oxygen, and other gases. This atmosphere was also lost to space by hydrodynamic escape. The fourth atmosphere was formed by outgassing from the Earth's interior. It was composed of nitrogen, oxygen, and other gases. This atmosphere was also lost to space by hydrodynamic escape.

The result of this process was the formation of the Earth's atmosphere.

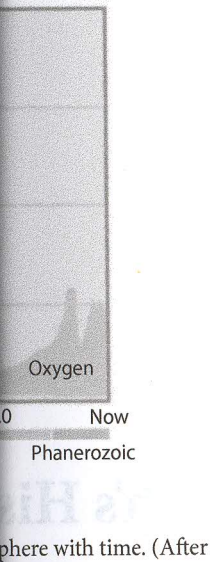
Earth's First Atmosphere (Hadean time—4.56 to 4.0 BY ago)

The initial atmosphere formed when the material forming the Earth accreted and melted, forming layers of material with the heavier compounds toward the core of the Earth. The surface of the Earth was covered by a layer of ultrabasic porous regolith. This layer consisted of a loose, heterogeneous superficial material covering the solid rock of the Earth's surface, which included dust, soil, broken rock, and other related materials. This regolith material absorbed all chemically active gases, e.g., CO₂, CO, O₂, or H₂O. As a result, the Earth's initial primordial atmosphere primarily consisted of (1) H₂, (2) He, (3) nitrogen (N₂), and (4) a trace of noble gases (Figure 5.1). The atmospheric pressure was ≈1 atm.

At the beginning of the Hadean time (4.6 BY ago) the Earth's surface consisted of molten rock and water existed as vapor in the atmosphere (see Figure 5.1). Because of the elevated temperature, the average speed of the hydrogen molecules (H₂) and the helium atoms (He) was greater than their escape velocity from the Earth. In the Early Hadean time, due to Earth's weaker gravity, these initial lighter gases escaped from the Earth's atmosphere and were swept away from the Earth through photoevaporation by the solar winds. At the end of the Hadean time, the Earth's atmosphere was left with less methane and ammonia, water vapor, and small percentages of nitrogen and carbon dioxide as shown in Figure 5.1. Scientific Psychic (2017) has noted that at the end of the Hadean time, there was likely a cataclysmic meteorite bombardment (≈3.9 BY ago) that kept much of the Earth's surface in a molten state. The incoming impactors likely brought additional water, methane, ammonia, hydrogen sulfide and other gases that supplemented the Earth's atmosphere. High surface temperatures of 700 °C to 1100 °C during the Hadean time were common on the hot Earth's crust along with lakes of magma on its surface. These elevated temperatures were the result of: (1) collisions and compression during accretion, (2) decay of short-lived radioactive elements and (3) constant volcanism. Water only existed in gaseous form in the atmosphere and the Earth's atmosphere was depleted of methane through the following endothermic reaction:



The resulting carbon monoxide (CO) gas readily combined with metals to form carbonyl compounds and, thus, the methane etc. were removed



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from the atmosphere. The existing high temperatures would have been too hot for liquid water to condense on the surface of the Earth; however, at high elevations, water vapor might have condensed and produced rain in the upper atmosphere that quickly evaporated as it fell lower toward the Earth's surface (Scientific Psychic, 2017).

Earth's primordial atmosphere had a paucity of matter, as compared to that of the Sun, in volatile and mobile elements and compounds. Had it been otherwise, today's atmosphere and hydrosphere would likely be much thicker and denser. Maison (1971) estimated that: (1) the relative hydrogen content on Earth vs. silicon is lower than in the outer space; (2) nitrogen is lower; (3) carbon is lower; and (4) noble gases are lower. Despite the commonality in outer space of such volatile compounds as H_2 , He, N_2 , H_2O , CO_2 , CH_4 , NH_3 , they are very scarce in the Earth's atmosphere. It has been proposed that such substantial differentiation in the primordial Earth's matter occurred in the pre-planetary stage of the solar system's evolution, when the Sun was at the *t*-Taurus stage of stellar evolution. It may have happened due to removal of the volatile components from the internal portions of the protoplanetary gas-dust cloud into its periphery (into the giant planet formation zone).

The volatile compounds and elements found on the Earth, e.g., H_2O , CO_2 , N_2 , HCl, HF, HI, etc., probably came in a bonded state from comets, asteroids, etc. Water was likely bonded with hydro-silicates; nitrogen, with nitrides and nitrates; carbon dioxide, with carbonates; halogens, with haloids, etc. Therefore, as the Earth's atmosphere developed, these components were buried in sediments. Some of these residual chemically active volatile compounds were released during the shock explosions of planetesimals hitting the Earth. These residual volatiles were likely then reabsorbed by the ultramafic-regolite on the Earth's surface and buried under new layers of the precipitating meteoritic matter.

Toward the end of the Hadean time, volcanic activity increased the percentage of carbon dioxide in the atmosphere. The Earth's surface changed from molten lava, cooling to a solid rock and liquid water started to accumulate on the Earth's surface.

For the above reasons, Earth's atmosphere, by the end of the Hadean time, was composed mainly of inert nitrogen and noble gases. Due to a short helium *flight time* from the Earth's atmosphere on the order of 10^6 years, its partial pressure in the primordial atmosphere over the time of its formation (about 10^8 years) had enough time to equilibrate, so that its concentration in the atmosphere was similar to that of today. The product of ^{40}K radioactive decay (^{40}Ar) was not likely to have been present in the atmosphere in noticeable amounts. Therefore, it is reasonable to anticipate

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that the partial pressure of the noble gases in the primordial atmosphere did not exceed 2×10^{-5} atm.

It is much more difficult to estimate the partial pressure of the other active components in the primordial atmosphere, e.g., H_2O , N_2 , CO_2 , and CO. To calculate them, it would be necessary to know the absorption and reactive capacity of the gases with the ultramafic regolite. The regolite contained free metals, e.g., Fe, Ni, Pt, Co, C, etc., although their partial pressures likely did not exceed 10^{-4} atm.

Earth's Second Atmosphere (Archean time, 4.0 to 2.5 BY ago)

At the beginning of the Archean time, the Earth's crust was cooling. As shown in Figure 5.2, an increase in the Earth's tectonic activity marked the beginning of the Archean and reached maximum levels toward its end. During the Archean time, water vapor in the atmosphere began to condense from the Earth's atmosphere, forming the oceans and decreasing the water

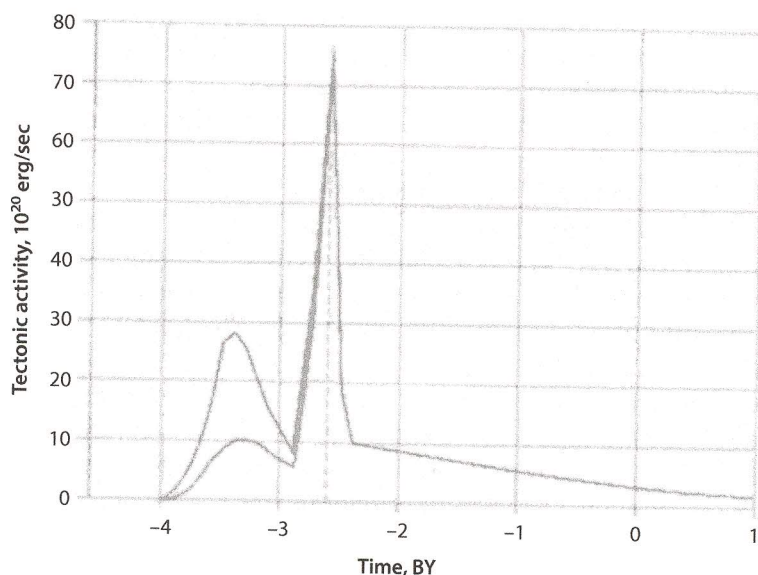


Figure 5.2 The Earth's tectonic activity as measured by depth of heat flow from the mantle. *Curve 1* – average for Earth as a whole. *Curve 2* – tectonic activity within a wide ring belt of the Archean Earth crust formation above the differentiation zone of Earth's matter. Dashed line corresponds to the time of Earth's core separation.

content in the atmosphere (Figure 5.1). Continuous rainfall on the Earth's surface for millions of years led to the buildup of oceans. Scientific Psychic (2017) suggested that as steam condensed into liquid water on the Earth's surface, the atmospheric pressure of the Earth became lower, permitting water to remain as liquid as the Earth cooled. The liquid water absorbed greater volumes of the volatile gases, e.g., ammonia and methane (as dissolved gas), removing these gases from the atmosphere and by creating ammonium compounds, amines and other nitrogen-containing substances:



The chemical reaction of water with volatile gases (e.g., sulfur dioxide and carbon dioxide) produced acid rain (e.g., carbonic acid), which, in turn, reacted with other compounds on the Earth's surface forming new minerals:



Scientific Psychic (2017) reported that microfossils of sulfur-metabolizing cells have been found in sediments (≈ 3.4 MY ago) along with the first aquatic photosynthetic organisms that originated about this time. The oxygen produced by *cyanobacteria* (blue-green algae) during the Archean time reacted with the metal ions in the anoxic sea. However, it was not until the Proterozoic time before the photosynthetic microorganisms could eventually produce sufficient oxygen to change the composition of the atmosphere. By the middle of the Archean time, the Earth had cooled enough so that much of the water vapor in the atmosphere had condensed out as liquid water, and there were no clouds. By this time: (1) ammonia and methane were the only minor constituents of the atmosphere (see Figure 5.1); (2) carbon dioxide comprised $\approx 15\%$ of the atmosphere; and (3) the percentage of nitrogen was $\approx 75\%$. Most of the original components of the Earth's atmosphere had either: (1) escaped, (2) precipitated as liquids, or (3) reacted chemically to form solid compounds, which were buried with sediments. By the end of the Archean time the major factors influencing the Earth's atmospheric composition were volcanic activity and the photosynthetic bacteria.

Earth's Third Atmosphere (Proterozoic to mid-Phanerozoic time – 2.5 to 0.54 BY ago)

Monocellular life proliferated during the Proterozoic time developing into multicellular life. During this period, tectonic activity decreased (see

Figure 5.1. The evolution of the Earth's atmosphere. As the atmosphere cooled, the gases condensed and were removed from the atmosphere. The atmosphere became anoxic and anaerobic. The atmosphere was composed of hydrogen, helium, and neon. The atmosphere was obtained from the Earth's interior.

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By the middle of the Archean time, the Earth's atmosphere had cooled enough so that much of the water vapor in the atmosphere had condensed out as liquid water, and there were no clouds. By this time: (1) ammonia and methane were the only minor constituents of the atmosphere (see Figure 5.1); (2) carbon dioxide comprised $\approx 15\%$ of the atmosphere; and (3) the percentage of nitrogen was $\approx 75\%$. Most of the original components of the Earth's atmosphere had either: (1) escaped, (2) precipitated as liquids, or (3) reacted chemically to form solid compounds, which were buried with sediments. By the end of the Archean time the major factors influencing the Earth's atmospheric composition were volcanic activity and the photosynthetic bacteria.

Figure 5.1. The evolution of the Earth's atmosphere. As the atmosphere cooled, the gases condensed and were removed from the atmosphere. The atmosphere became anoxic and anaerobic. The atmosphere was composed of hydrogen, helium, and neon. The atmosphere was obtained from the Earth's interior.

Figure 5.2). Early in the Proterozoic time, anaerobic microbial life thrived on the Earth as there was little oxygen in the atmosphere (see Figure 1.1). As the oxygen content in the atmosphere increased during this period, anaerobic bacteria activity decreased. The various bacteria chemically obtained their energy in several ways. (Scientific Psychic, 2017):

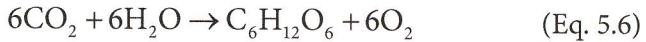
1. Anaerobic methanogens combined hydrogen and carbon dioxide to produce methane and water:



2. Anaerobic sulfate-reducing bacteria combined methane and sulfate radicals:



3. Other organisms, capable of photosynthesis, used the energy of sunlight to convert the abundant carbon dioxide in the atmospheric and water into carbohydrates ($\text{C}_6\text{H}_{12}\text{O}_6$) generating oxygen, which in turn was deadly to the anaerobic bacteria and eventually killed out much of the anaerobic bacteria on the surface of the Earth:



By the Proterozoic time, the content of the carbon dioxide (CO_2) in the Earth's atmosphere had been nearly depleted and there was only a small percentage of oxygen in the Earth's atmosphere. Nitrogen, N_2 , which is chemically inert, became the primary gas in the Earth's atmosphere (see Figure 5.1), as the other gases had become almost completely stripped from the Earth's atmosphere.

Figures 5.1 and 5.3 show that from the beginning of the Proterozoic time to 1.85 BY ago, atmospheric oxygen levels slowly rose as the rate of flora photosynthesis increased. Scientific Psychic (2017) has reported that the shallow seas became partially oxygenated; however, the deeper water layers in the oceans continued to be anoxic. Although photosynthetic organisms had been releasing oxygen since Archean times, the oxygen levels had not built up in the atmosphere because the free oxygen in the atmosphere was being depleted through the oxidation of metals:



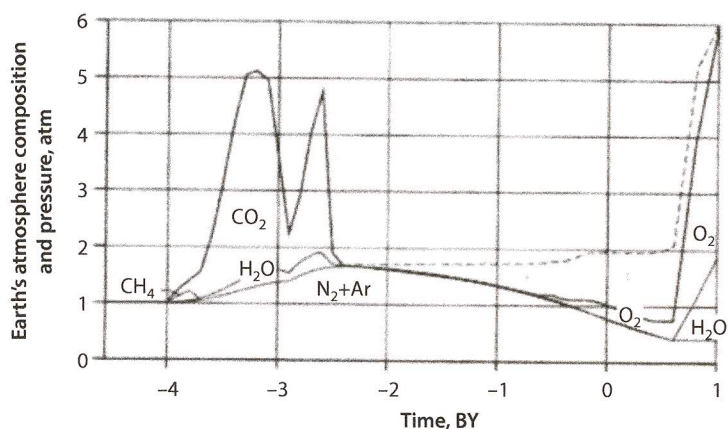


Figure 5.3 Evolution of the composition of the Earth's atmosphere and its pressure with time (dashed line is the atmosphere pressure assuming the absence of bacterial nitrogen consumption).

and by the oxidation of methane:



to yield carbon dioxide and water in the presence of ultraviolet (UV) radiation.

The cooling of the Earth during the Proterozoic time stabilized the land masses and reduced the volcanic outgassing of carbon dioxide (Scientific Psychic, 2017). Some additional oxygen was consumed by oxidation of minerals in the Earth's crust; however, greater quantities of oxygen were generated by plants so that additional free oxygen accumulated in the atmosphere, killing the anaerobic bacteria near the Earth's surface. This created an opportunity for the development of aerobic life forms.

The atmospheric composition stabilized (between 1.85 to 0.85 BY ago) with the Earth's atmosphere containing $\approx 10\%$ oxygen (Scientific Psychic, 2017). Photosynthetic organisms were still producing oxygen at a high rate, but the reaction of oxygen with the dissolved minerals in the deep oceans and with sediments and rocks on the Earth's surface did not allow atmospheric oxygen levels to increase. By 0.85 BY ago, the minerals in the sea and on land could not bind as much oxygen, and the excess oxygen began to accumulate in the atmosphere.

Today's Atmosphere (Phanerozoic time, 0.542 BY ago to today)

The Cambrian period, at beginning of the Phanerozoic time, is marked by an abundance of multicellular life. This was a time when: (1) most of the major groups of animals first appeared; (2) vegetation covered Earth's surface; and (3) the atmospheric oxygen concentration was $\approx 30\%$. By 228 MY ago, the Earth's atmospheric oxygen concentration level was $\approx 15\%$, and by the end-Cretaceous (100 MY ago) oxygen had risen to $\approx 23\%$ (see Figure 5.3). For the last 100 MY years, the percentage of oxygen in the atmosphere has fluctuated between 18% and 23% to the present level of about $\approx 21\%$.

The Earth's Future Atmosphere

Figure 5.3 illustrates the Earth's atmospheric composition and the resulting pressure over the entire time of the Earth's existence along with a negative future projection for life on the Earth. This figure shows both the historic and future projections of the atmospheric composition. Sorokhtin and Ushakov (2002) projected a sharp increase in the oxygen partial pressure in 600 MY in the future which is the result of abiogenic oxygen degassing in the process of the Earth's core formation. At present, the formation of the outer layer of the Earth's core occurs because of the reduction of the iron oxide according to the following reaction:



The released oxygen, under high pressure and release of the compression energy (due to a smaller volume of magnetite molecule) will be bonded with the iron oxides forming the magnetite component of the mantle:



After a total oxidation of the mantle silicate iron to magnetite stoichiometry, formation of the Earth's core matter will have to be accompanied by the release of free oxygen not consumed by any reactions:



As a result, after 600 MY in the future, additional free oxygen will begin entering the Earth's atmosphere. The Earth's atmospheric pressure will rise above 10 atm. This change of atmospheric pressure will increase the greenhouse effect on the Earth (see Eq. 2.26). The Earth's average surface temperatures will rise above 180 °C. At this temperature, the oceans will vaporize, increasing the atmospheric pressure even higher. The Earth's surface temperatures will rise to over 600 °C (which is higher than that on Venus: ≈ 460 °C). In such an environment, there is little possibility of preservation of life as we know it.