Speculation about Earth's Early Atmosphere

Octave Levenspiel,[*] Thomas J. Fitzgerald,[**] and Donald Pettit[***]

Abstract

This paper asks us to consider the possibility that young Earth's atmosphere was at a higher pressure than it is today, maybe as high as 50 to 100 bar, consisting mainly of CO_2, and that the pressure was still higher than today's during the age of dinosaurs.

This conjecture is tested against and is found to be consistent with various kinds of evidence from the past: the early faint sun, the formation of coal, the vast limestone deposits, and the recent formation of limestone caves. It also effectively resolves the puzzling anomaly as to how the giant flying creatures of the past could fly when physiology and aerodynamics say that such flight was not possible.

---

[*] Chemical Engineering Department, Oregon State University, Corvallis, OR 97331.

[**] Chemical Engineering Department, Oregon State University, 1970-1981; now at TRW Inc., Redondo Beach, CA 90278.

[***] NASA/JSC, MC CB, Houston, TX 77058-3696.

Scientists have exhaustively studied Earth's surface extracting its history from rocks and ocean bottoms. However, little attention has been given to the history of Earth's atmosphere because its historical record is ephemeral. In fact, most scientists have just accepted that the atmosphere was not much different in the past from what it is today. True, some [1,2] have speculated that the CO_2 concentration was as much as 800 times today's value, or about 0.25 bar, but little else is assumed to differ.

Here we collect clues and evidence from various sources, and from these propose a history which indicates that in the past the atmosphere was very different from what it is today. Let us present this evidence.

The Quetzalcoatlus Anomaly

In the Cretaceous fossil record we find flying creatures which have an estimated mass between 86 and 100 kg [3], the Washington D.C. Museum of Natural History displays a full sized model of quetzalcoatlus having a 13 to 15 m wingspan, while a Texas find is estimated to have a wingspan of 15.5 m [4]. This is about half the wingspan of a Boeing 737 commercial airliner, see Fig. 1. How could such large and heavy creatures fly?

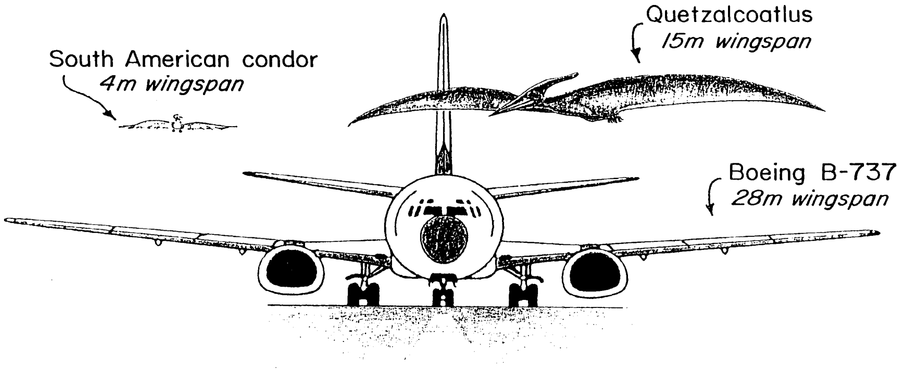

Figure 1.

Today, the world's largest flying birds, the South American condor, the Kori bustard, and the largest swans have wingspans of no more than 4 m. Considering the limitation of skeletal structure and musculature, physiologists and aerodynamacists [5,6] estimate that these birds which weigh about 15 kg represent the upper size limit of creatures which can support and propel themselves through air. How then could 86 to 100 kg creatures fly in the age of dinosaurs, 64 to 100 Mya? Let us look at this anomaly.

The minimum power needed for warm blooded creatures to live (in effect their metabolic rate) is represented by the mouse-to-elephant curve, see Fig. 2, and its representative equation

$$\begin{pmatrix}\text{Minimum power}\\ \text{needed to live}\end{pmatrix} = k_1 M^{0.734} \tag{1}$$

where M is the creature's body mass.

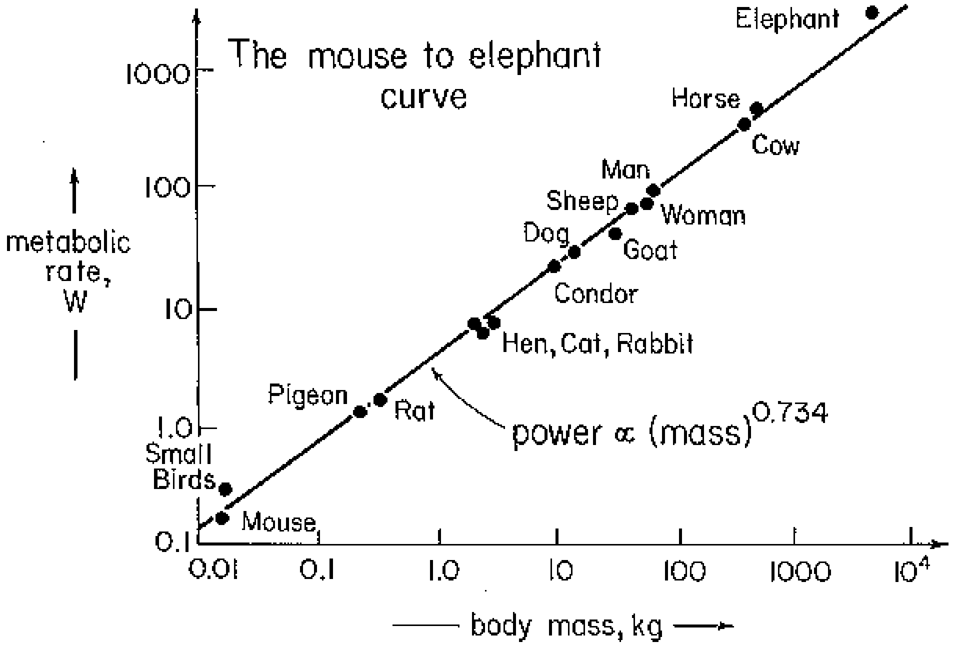

Figure 2

The maximum power output is roughly 15 times the minimum for birds, 20 times the minimum for man, dog, and horse, and 10 times the minimum for all other warm blooded animals [6]. In general then

$$\text{Maximum power output} = k_2 M^{0.734} \tag{2}$$

These curves are shown in Fig. 3.

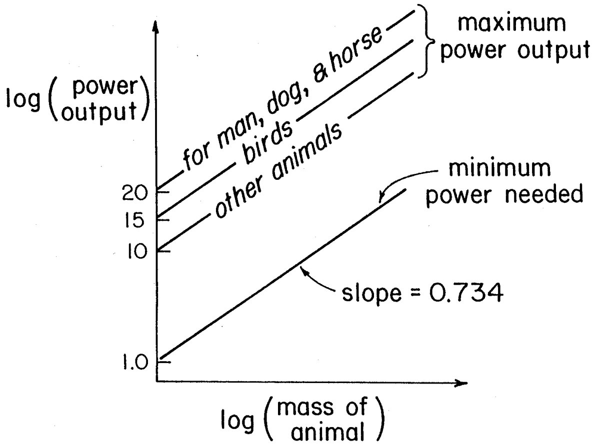

Figure 3

Now the minimum power needed for the level flight of any creature was given by Renard [7] over a century ago as

$$(\text{minimum power})_{\text{needed}} \propto \frac{M^{3/2}}{\rho^{1/2} A^{1/2}} \tag{3}$$

where A is the wing area of the creature and ρ is the air density. It was pointed out by von Kármán [8] that this expression is quite similar to that used today by aerodynamicists to represent the power needed to keep an aircraft aloft, from Piper Cub to the largest of passenger planes.

If L represents the size of a flying creature, then for creatures of different size but of similar geometry

$$\left.\begin{aligned} \text{mass,}\quad M &\propto L^3 \\ \text{wing area} &\propto L^2 \end{aligned}\right\} \tag{4}$$

Replacing eq 4 in 3 we find that the power needed for a creature to fly is given by

$$(\text{Minimum power})_{\text{needed}} \propto \frac{M^{7/6}}{\rho^{1/2}} \tag{5}$$

Let us compare the power needed to fly with the power available, all at 1 bar. This is shown in Fig. 4.

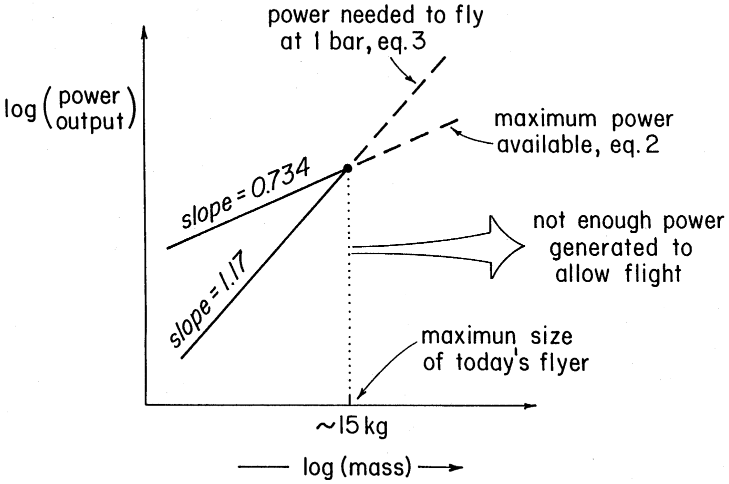

Figure 4

This graph shows that there is a maximum size above which no creature can fly. Today this limit is the 4 m wingspan, 15 kg bird [6]. But how do we explain the existence of the flying quetzalcoatlus? The explanations which have been forwarded today are as follows:

This graph shows that there is a maximum size above which no creature can fly. Today this limit is the 4 m wingspan, 15 kg bird [6]. But how do we explain the existence of the flying quetzalcoatlus? The explanations which have been forwarded today are as follows:

1. The biology of these ancient flyers differs from today's living creatures in that they were more efficient in their use of oxygen, living at a much higher metabolic rate. This would put them far above the present day mouse-to-elephant curve.
2. These creatures were not true flyers. They sat on the ground and waited for a strong wind. With a wind speed above 5 m/s, they would spread their wings and glide about.
3. They sat on top of hills peering down. When they spied dinner hopping about down below they would swoop down, snatch their meal, then trudge back up the hill, to rejoin their cousins there, see Fig. 5.

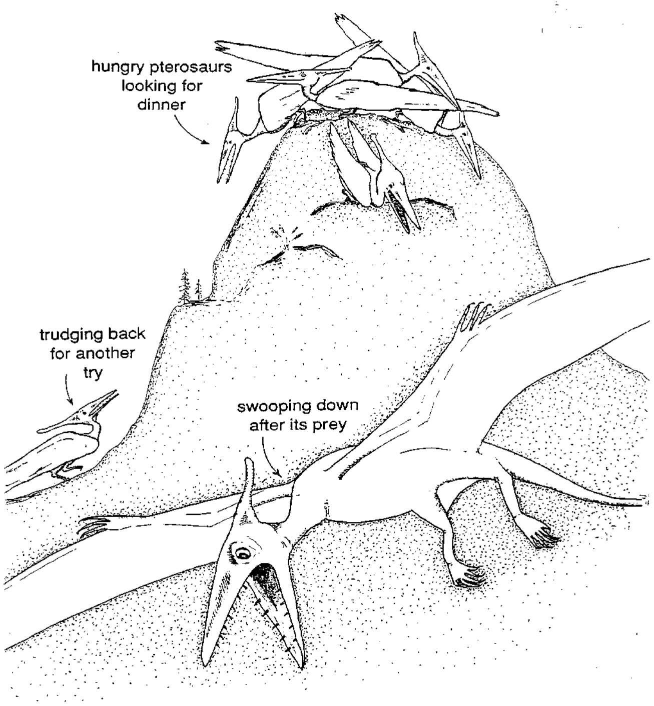

Figure 5

However, an analysis by Bramwell and Whitfield [9] raised all sorts of difficulties with these explanations. They suggest

1. The pteranodon could not stand bipedally because its legs were positioned wrongly on its body.
2. It probably slid along on its stomach by reaching forward with its legs, gripping the ground with its feet and pulling itself along, as does a crawling bat. Hankin and Watson [10] and Abel [11] come to similar conclusions.
3. With this physiology, Bramwell and Whitfield could not see how the pteranodon could care and feed its offspring.
4. Most importantly, large pteranodons appear to have lacked the physical power to perform hovering, and thus could not have taken off from level ground (see Romer [12]).

All these difficulties lead to improbable scenarios. To have survived and thrived for millions of years these flyers had to be fast, efficient, and well adapted to their environment. Since the power needed to fly is lower at higher atmospheric pressure, see eq 3, let us propose an alternative explanation, that

> ***the atmosphere in the Cretaceous period was different from today's, in that it was denser***

Comparing masses (100kg vs. 15kg) or wing sizes (15m vs. 4m) and assuming geometrical similarity, equations 3, 4 and 5 combined tell that the atmospheric pressure, at the time of the quetzalcoatlus, was somewhere between 4 bar and 5 bar. So whatever parameters are compared we always find that the pressure had to be greater than today's one bar. Graphically we illustrate this conclusion in Fig. 6.

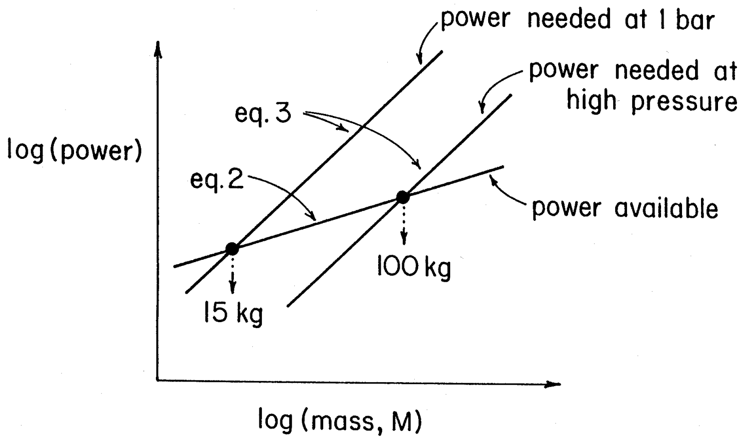

Figure 6

From a different point of view, from flight energetics, Fig. 7 shows the bird portion of the Great Flight Diagram of Hennekes [13] (quetzalcoatus point added by us). Here we clearly see that the points for the pteranodon and the quetzalcoatlus are far from the correlation for all of today's birds. To bring these points to the correlation line would require having a higher gas density.

To summarize: the density of the atmosphere in the late Cretaceous period had to be denser than today's atmosphere, somewhere between 4 and 5 bar. Since the late Cretaceous period represents the most recent 5% of Earth's life, what was it before that, at the beginning of life? Most likely it was even higher still. But how high? The following sections present our hypothesis, a scenario for change, and the evidence to support this hypothesis.

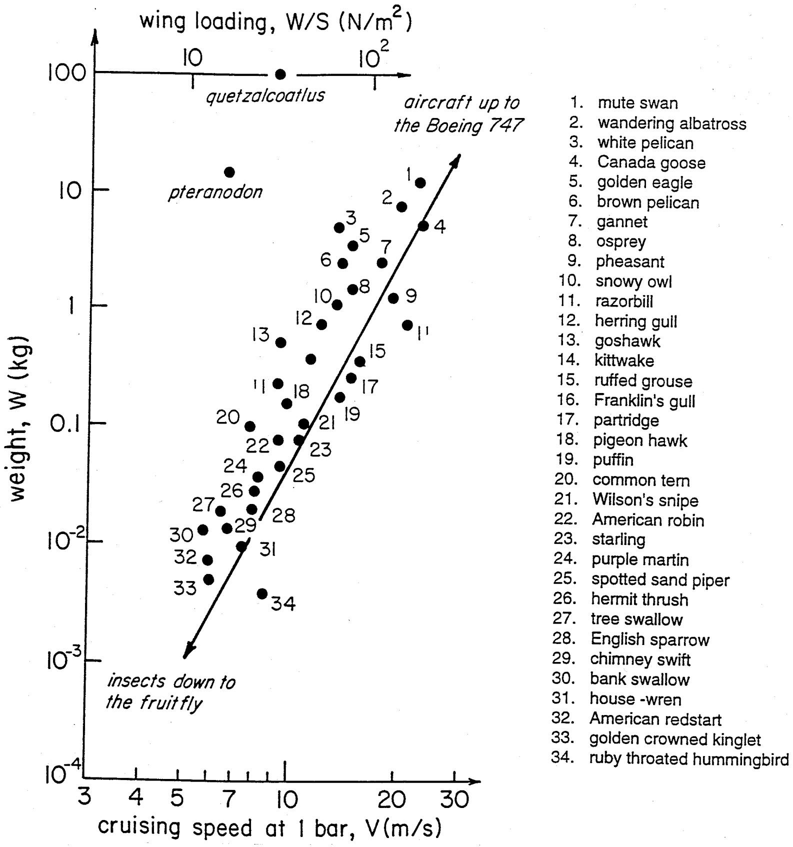

Figure 7

Surface of Earth

Since the atmosphere is largely influenced by the characteristics of Earth's surface, let us first consider the history of Earth's surface.

Evidence today shows that fresh mantle material upwells at fractures in midocean, spreads to the continents, and then sinks back into the interior. Measurements today [14] show a surface movement of 2 cm/yr to 30 cm/yr or more. Although this may seem to be very slow to us on our life's time scale, it is not slow on Earth's time scale. For example, measurements indicate that Greenland is drifting away from Europe at 36 m/year, that South America and Africa separated a mere 125 Mya [15], or that you could have walked directly East from New York to the Sahara a mere 155 Mya [16]. Also, the ocean floors of the Atlantic and Pacific are all swept clean and are replaced by fresh upwelled material roughly every 300 My [16]. Recognizing that Earth is 4500 My old, there is enough time for more than 15 exposures of completely fresh solids on the ocean floors.

At the same time the crust floating on the mantle wandered about. Today's thinking is that today's continents were all part of a super land mass less than 200 Mya. What about the other 4400 My? How many times did the crust split apart and rejoin? Our clues come from the distribution of various life forms. For example, since dinosaur skeletal remains are found on all of the continents, this suggests that the land masses were joined 65-135 Mya.

All of this indicates that Earth's surface is very plastic, deformable, and mobile, with much mixing with the interior. We plan to show that this movement greatly influenced the atmosphere.

Earth's Original Atmosphere

Thinking today is that the young hot Earth (more than 4500 Mya) had most of its carbon in the form of gaseous carbon dioxide, carbon monoxide, and methane. With time the carbon monoxide, and methane reacted with oxide minerals and were transformed into carbon dioxide. These reactions did not change the total amount of carbon in the atmosphere.

Our sister planet, Venus, contains an atmosphere of 90 bar, consisting 96% of CO_2 [17]. Why should Earth be so different? Ronov (see Hay [18]) measured at least 55 bar of CO_2 tied up as carbonates around the world, while Holland [19] estimates at least 70 bar of CO_2 presently tied up as carbonate materials. These carbonates had to come from the atmosphere, via the oceans, so let us propose that after the original oxidation

Earth's early atmosphere was a very high pressure, let's say about 90 bar, and that it consisted primarily of CO_2

If so, why did Venus' atmosphere remain at 90 bar while Earth's decreased to a few bar in the age of dinosaurs about 100 Mya and then come down to one bar today? What happened to Earth's CO_2 and by what mechanism did it just about disappear?

Let us compare Venus with Earth, see Fig. 8. Venus, Earth's sister planet and nearest neighbor, is practically the same size as Earth; however, it has no moon while Earth has one of our solar system's largest moons. Now Fig. 8 shows that our moon has the same density as Earth's crust. This suggests that in its formation the moon stripped Earth of some of its crust. If not for this crustal loss, Earth's crust, presently only 5 to 30 km thick, would be 42 km thicker. Being thinner, Earth's crust was fragile and broke up under the action of the mantle's

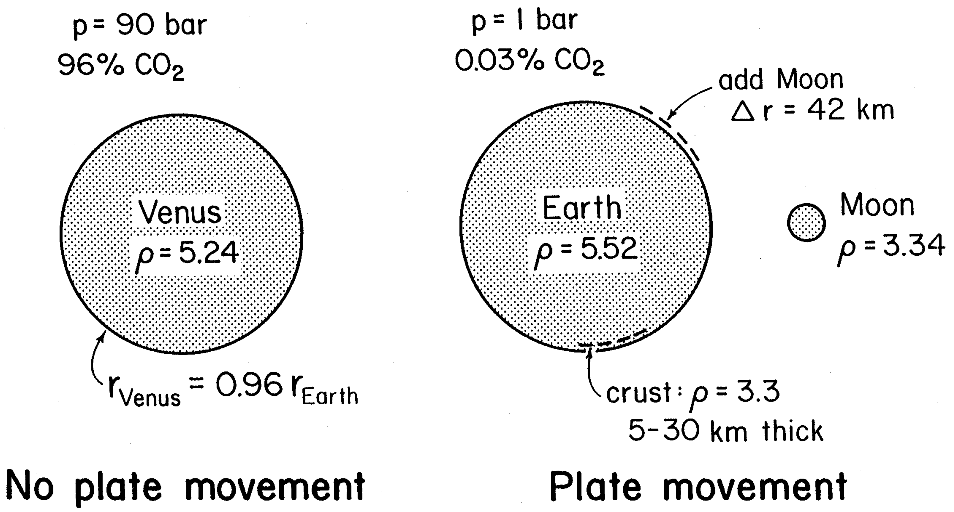

Figure 8

convective forces. In contrast to this, Venus' thicker crust remained rigid and did not allow mechanisms to act which removed the CO_2.

Secondly, Venus is closer to the sun, and is hotter than Earth, so free liquid water cannot exist there whereas Earth has its giant oceans. These oceans played an important secondary role in removing CO_2 from the atmosphere, as we next show.

Dissolution of CO_2 in Earth's Oceans

With the ocean below and atmospheric CO_2 at about 90 bar, CO_2 dissolves in water according to the equilibrium relationship

$$\begin{pmatrix}\text{partial pressure of } CO_2 \\ \text{in the atmosphere}\end{pmatrix} = H \begin{pmatrix}\text{mol fraction of} \\ CO_2 \text{ in water}\end{pmatrix}$$

where H, Henry's law constant, depends on the temperature but is about

$$H = 1000 \text{ bar/mole fraction of } CO_2\text{, from [20]}$$

$$H = 876 \text{ bar/mole fraction of } CO_2\text{, from [21]}$$

Assuming Earth's surface to consist two-thirds of ocean, 2 km deep, the above numbers are equivalent to saying that at equilibrium, for each mole of CO_2 in the atmosphere, there is one mole of CO_2 dissolved in the ocean.

So an atmosphere originally consisting of 90 bar CO_2 will drop down to 45 bar CO_2 just by dissolution alone. However, another factor acts to even further lower the concentration of CO_2 in the atmosphere.

Reaction of Dissolved CO_2 with Upwelling Minerals

As mentioned earlier, our picture today is of continents floating above a circulating layer of mantle which rises at midocean ridges and sinks down elsewhere, as shown Fig. 9. This movement tells that the ocean bottom is renewed at least 15 times during Earth's lifetime.

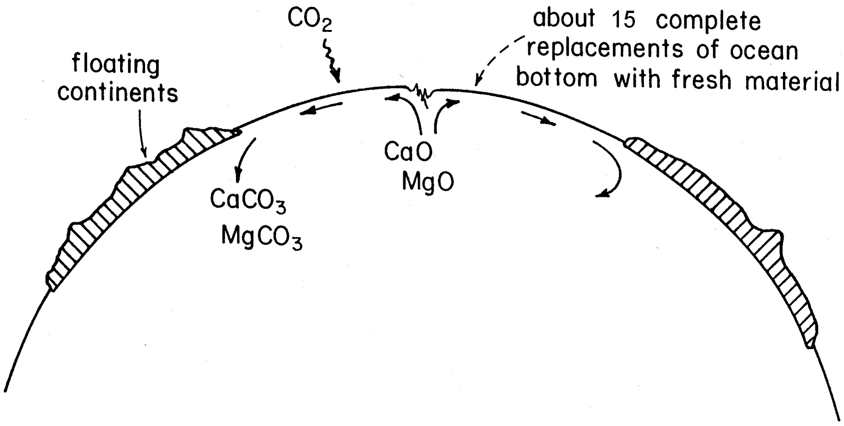

Figure 9

This upwelling brings up fresh minerals from Earth's interior including oxides of calcium, magnesium, etc., which dissolve in the ocean waters and then combine with dissolved CO_2 to form carbonate deposits by reactions such as

$$\underset{\substack{\uparrow \\ \text{from} \\ \text{earth's} \\ \text{interior}}}{CaO} + \underset{\substack{\uparrow \\ \text{from} \\ \text{the} \\ \text{atmosphere}}}{CO_2} \longrightarrow \underset{\substack{\uparrow \\ \text{deposits} \\ \text{on ocean} \\ \text{bottoms}}}{CaCO_3}$$

We assume here that the rate controlling step of this reaction is the upwelling of the basic oxides at the tectonic plate boundaries, and not the solution and transport of CO_2 from the atmosphere to sea water. With a conservative assumption of a roughly constant sea floor spreading rate, this means that the concentration of CO_2 in the atmosphere decreased roughly linearly with time (zero order kinetics).

In sinking back into the mantle the carbonates heat up and decompose, releasing captured CO_2 which returns in part to the atmosphere from volcanoes and into the ocean from vents in the ocean floor.

$$CaCO_3 \longrightarrow CO_2 \uparrow + CaO \ .$$

This action is depicted in Fig. 10.

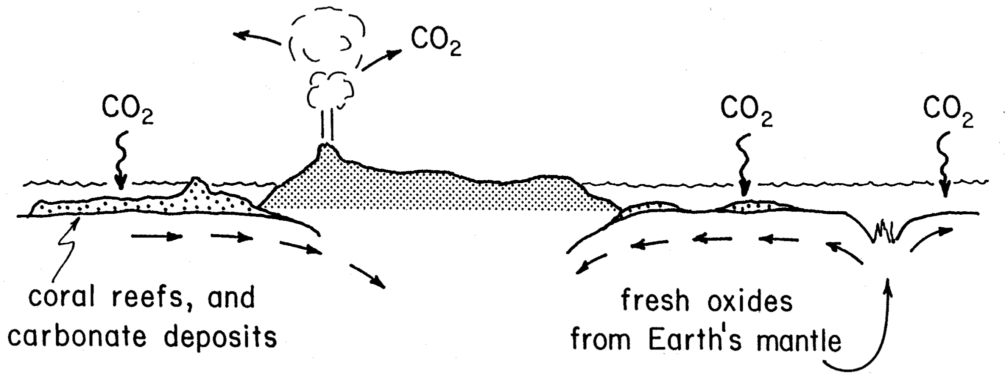

Figure 10

Today we find vast deposits of sedimentary carbonate rocks on land and on ocean bottoms, over a million cubic kilometers in extent throughout the world. Over the continents the CO_2 was taken up by rainwater and by groundwater. This CO_2-rich water reacted with rocks to form bicarbonates followed by transport to the ocean and precipitation there into calcium and magnesium carbonates. In the ocean dissolved CO_2 combined with the hydroxides to form deposits of chalk or was taken up by living creatures to form giant coral reefs. A study of the distribution through time of these deposits give us clues to the past history of CO_2 in the atmosphere.

A detailed analysis by Hay [18] of the extensive measurements taken from around the world by Ronov and Yareshevsky [22] are summarized in Fig. 11. This shows that the continents today contain at least 2.82×10^6 km^3 of limestone which are the remains of limestone deposited in the last 570 million years and which have not been washed to sea or subducted back into Earth's interior. This translates to an atmospheric source of CO_2 of 38 bar. If we add the carbonates also found on the ocean floor we find that we need a source of 55 bar of CO_2 to give these deposits. Integrating the numbers of Fig. 11 gives the progressive depletion of CO_2 from the atmosphere. This is shown in Fig. 12. Thus, CO_2 is recycled, 55 to 70 bar or more already accounted for on the surface of Earth, about 20 bar in the process of recycling, down deep.

Figure 11 verifies what we said earlier, that the oceans of our world are relatively young since they contain limestone not older than 170 My of age. On the other hand, the continental land masses are much older. Remembering that ocean and atmosphere roughly equally share the free CO_2, Fig. 12 indicates that the pressure of CO_2 in the atmosphere was not over about 8 to 10 bar in the age of the flying creatures, 65 to 100 Mya. These figures are not inconsistent with the pressures needed for quetzalcoatlus to thrive.

So the geological evidence is consistent with and lends support to the physiological and aerodynamic arguments presented earlier that the atmospheric pressure was somewhat higher in the age of dinosaurs.

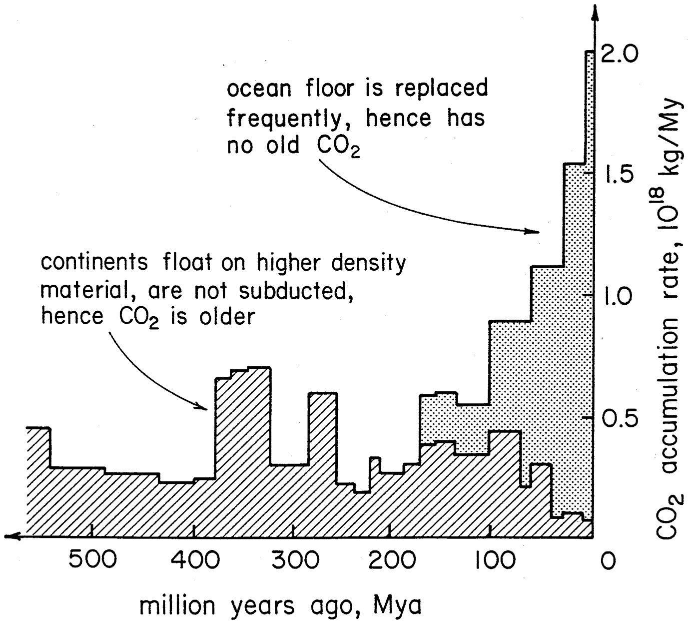

Figure 11

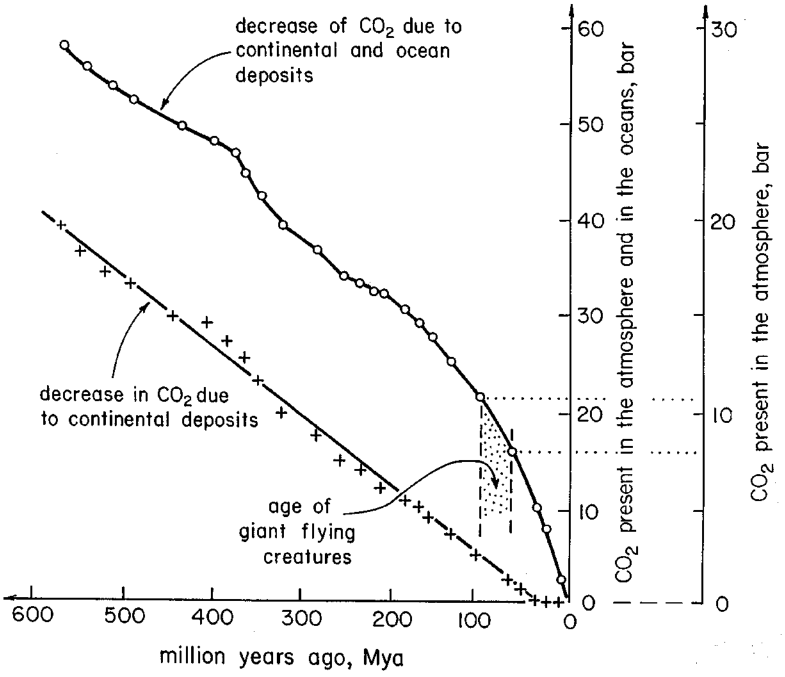

Figure 12

The Astronomical Argument

From a different viewpoint, that of the modern theory of stellar evolution, Sagan and Mullen [23] discussed the "faint early sun" paradox which asks why Earth's surface did not freeze in its early days, given a 25% to 40% lower solar luminosity at that time. These values represent the range of five estimates. With these lower luminosities the average temperature of Earth would have been somewhere between -5 and -21°C instead of the present +13 to 15°C. With frozen oceans covering our planet, how could life have established itself and thrived under these inhospitable conditions?

One reasonable answer to this question is that CO_2, the atmosphere's efficient greenhouse gas, was present at very high concentration in these early times. Kasting [24,25] suggests a factor of 100 to 800 times as high as today, all at 1 bar; however, he did not consider the possibility of a higher total pressure of the atmosphere, as we do here.

Earth's History

As our original planet cooled and condensed into solid, it was surrounded by a thick soupy atmospheric mixture. Hydrogen and hydrogen containing compounds combined with oxygen to form the waters of our oceans, while the carbon containing compounds, CO, CH_4, etc., combined with oxygen to form CO_2 at high pressure. All this took about one half of Earth's lifetime and it left the atmosphere impoverished of its oxygen.

Probably life got its first foothold in the oceans of our barren planet as blue-green algae and cyano-bacteria. These were organisms which had no need for oxygen to live.

Photosynthesis had not yet been invented by plant life. So the reaction which sustained these life forms was

$$\begin{pmatrix}\text{blue-green}\\ \text{algae}\end{pmatrix} + CO_2 + H_2O \xrightarrow{\text{sunlight}} \begin{pmatrix}\text{more}\\ \text{blue-green}\\ \text{algae}\end{pmatrix} + O_2 \tag{6}$$

These algae spread throughout the world's oceans.

After about a thousand million years of additional experimentation, life came up with its most important invention, photosynthesis, and so learned how to live off the abundant CO_2 of the atmosphere plus sunlight and thereby invade the lands. Land plants evolved and lived by the reaction

$$\text{land plants} + CO_2 + H_2O \xrightarrow{\text{sunlight}} \text{more plants} + O_2 \tag{7}$$

During the Carboniferous period, 350 to 280 Mya, the last 6 to 8% of Earth's life, these plants proliferated widely, covering Earth's land surfaces with lush forests of giant ferns, trees, and plants of all types. Since the atmosphere then was rich in CO_2 but still very poor in oxygen, dead plant material did not decompose rapidly, so layer upon layer of dead plant material was laid down in very thick blankets to transform in time to coal.

Estimates are that each 1 meter thickness of coal comes from the compression of a 10 to 20 meter layer of dead organic matter [26]. This means that today's 10 meter thick coal seam represents an original 100 meters of decayed matter. Such a thick layer of decaying matter is something which we do not see anywhere today. Actually, our tropical forests today only support a very thin layer of decaying matter because of rapid oxidation of this dead material. Thus, 100 m thick layers can only occur if the atmosphere does not encourage oxidation. This is additional strong evidence that the atmosphere in those distant times was rich in CO_2 but poor in oxygen.

With time the concentration of CO_2 steadily decreased due primarily to the formation and deposition of limestone and other carbonaceous materials. CO_2 was also lost by photosynthesis followed by the deposition of carbonaceous fuels such as coal, petroleum, peat, shale, tar sands, etc. However, this loss was quite minor. Calculations show that the deposit of all these fuel reserves only lowered the atmospheric CO_2 by very much less than one bar. At the same time the concentration of oxygen slowly rose. These two changes, the decrease in CO_2 and the rise in oxygen, thinned the forests, the dead material began to be more rapidly oxidized, so that dense layers of dead organics were no longer deposited. As evidence of this change in atmospheric conditions, we cannot today find any massive coal deposits younger than 65 My old.

Animal life found this changed atmosphere (rise in oxygen, drop in CO_2 concentration) to its liking so mammals and dinosaurs flourished, first as very small creatures, but then in increasing size under evolutionary competition. This led to the giant flying creatures close to the end of the dinosaur age. It could be that these creatures died out as the total pressure of the atmosphere dropped below their sustainable level, see Fig. 13. The whole history of the earth is sketched simply in Fig. 14.

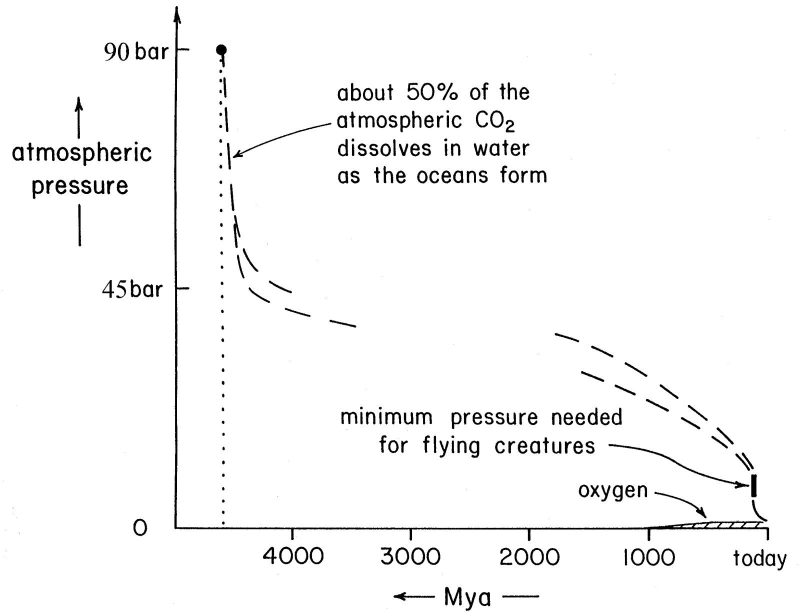

Figure 13

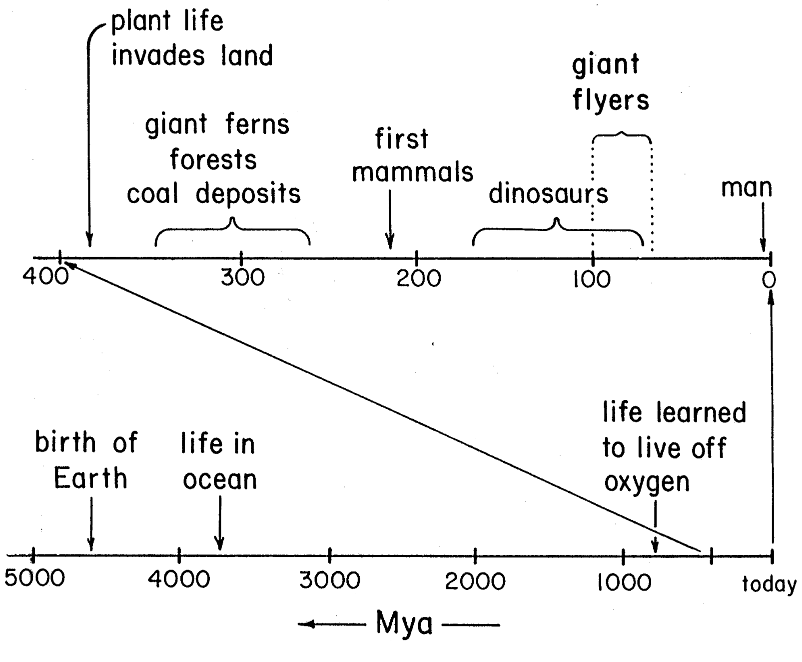

Figure 14

The Formation of Limestone Caves

Our world today contains many limestone caves, some of which are many kilometers in extent. These caves were all carved out by running water dissolving the limestone. We also know that these caves are all relatively young, mostly less than 100 My old. This tells us something about our atmosphere, as we explain.

With high CO_2 concentration in the atmosphere, consequently dissolved in rainwater and groundwater, the reaction

$$Ca(OH)_2 + CO_2 \rightleftharpoons CaCO_3 + H_2O \tag{8}$$

is driven to the right. However, when the atmosphere becomes lean in CO_2 then the above reaction shifts to the left.

The fact that the limestone caves were formed relatively recently indicates that the CO_2 concentration in the atmosphere was very high long ago, leading to the deposits of limestone, but became very low recently, allowing limestone to dissolve.

Experimental Verification

Besides the general findings supporting the theory of plate movement, perhaps the most tangible and unambiguous evidence for the recycling of Earth's material from crust to deep mantle and back again comes from a recent report by Harte et al. [27].

Regarding life in high CO_2 and other hostile environments, recent findings show that life takes advantage of free energy in an amazing range of environments: from above the boiling point and below the freezing point of water, in pressures as high as 300 bar, in oxygen rich, in oxygen poor environments, in and in the absence of sunlight [28,29]. There are even bacteria which thrive on rocks and water alone in the absence of sunlight and any carbon source [30]

$$\text{basalt} + H_2O \xrightarrow{\text{bacteria}} H_2 \tag{9}$$

On a more homely level, the champagne producing microbe operates at pressures up to 7 bar of CO_2.

Estimates of CO_2 Concentrations in Earth's Past

Researchers have speculated that the CO_2 concentration may have been somewhat higher in the past than it is today. Des Marais [31], studying carbon exchange between mantle and crust, suggests that 3000 Mya the atmosphere contained at least 100 times as much CO_2, or 0.03 bar, as it does today.

Holland [19] estimated Earth's earliest atmosphere contained up to 20 bar of CO_2, and that approximately 10 bar could conceivably have persisted for several 100 My [32].

Many such proposals have been forwarded.

Plant Growth at High CO_2 Concentrations

It is pertinent to ask whether any experiments have been performed to suggest whether life could live and thrive at higher CO_2 concentrations. Recently, pine and aspen trees grown at the University of Michigan's biological station at Pellston, Michigan, were found to respond dramatically to elevated CO_2 levels. They grew 30% faster than normal trees at about double the normal CO_2 level (700 ppm) [33].

However, to test our speculation we need to see if plants can survive, not at double today's CO_2 concentration, but at thousands of times today's CO_2 concentration.

We put this proposal to the test by growing plants in 32 sealed containers (1 and 2 liter plastic soda and "pop" bottles pressurized with a weighed mass of dry ice) at pressures from 2 to 10 bar. These conditions gave a CO_2 partial pressure 3000 to 27,000 times greater than normal, or 50% CO_2 to 90% CO_2.

Of the species tested, Taxodium, Metasequoia, Araucaria, Equisetum, and Sphagnum did best at these higher pressures, one specimen of Taxodium growing 7 cm over a period of 2 years at 2 bar (50% CO_2). However, in general, plant growth was notably slower than at 1 bar. On the other hand, mosses, ferns, and flowering plants died within a month at these high CO_2 levels.

It should be mentioned that the poor growth observed in these experiments is most likely due to the buildup of product gases in the sealed containers. Thus, these experimental results could be flawed. We would expect that vigorous growth would be observed in a rejuvenated atmosphere.

Although present day plant life is probably not adapted to living at those very different atmospheres and pressures of the past, our preliminary experiments do suggest that a dense CO_2 atmosphere could have existed on early Earth without violating any known constraints on the planet's evolution.

Summary

If we assume that Earth's early atmosphere was very different from today's, both in composition (mainly CO_2) and total pressure, that would explain and make sense of findings in a variety of disciplines, findings which puzzle us today. Some of these are as follows:

- How the flying creatures from the age of dinosaurs actually had enough energy to fly when physiology, biology, and aeronautics say that this was impossible?
- How could life ever have come to Earth when astronomy says that Earth was too cold (-13°C average) to sustain life?
- If Earth's atmosphere had stayed at about 1 bar throughout Earth's life, how could 50 to 70 bar of CO_2, as measured today, have deposited as limestone and other carbonates on Earth's surface?

This picture of high CO_2 concentration and high pressure in the past also explains

- Why most massive coal seams are older than 65 My.
- Why most limestone caves are younger than 100 million years.

Although we do not know the values for the atmospheric pressure in those early times, and although each of the arguments in this paper only leads to suggestions, still, when taken together, the evidence from these various sources all lead to the same conclusion, that the atmospheric pressure had to be higher in the past than it is today. This hypothesis presents a picture of our evolving planet which should be examined and which could have interesting consequences.

References

1. R.T. Bakker, *Sci. Amer.* **223** 58-78 (April 1975).
2. S. Weisbud, *Science News*, **130**, 103 (1986).
3. P. Wellnhofer, *The Illustrated Encyclopedia of Dinosaurs*, pg. 142, Crescent Books, Random House, New York, 1991.
4. D.A. Lawson, "Pterosaur from the Latest Cretaceous of West Texas: Discovery of the Largest Flying Creature," *Science*, **187**, 947-948 (1975).
5. J.M. Smith, *Mathematical Ideas in Biology,* Chap. 1, Cambridge Univ. Press, 1968.
6. K. Schmidt-Nielsen, *Scaling: Why is Animal Size So Important?* Cambridge Univ. Press, 1984.
7. C. Renard, "Nouvelles Experiences sur la Resistance de l'Air," *L'Aeronaute*, **22**, 73 (1889); from [8].
8. T. von Kármán, *Aerodynamics, Selected Topics in the Light of Their Historical Development*, McGraw Hill, 1963.
9. C.D. Bramwell and G.R. Whitfield, "Biomechanism of Pteranodon," *Phil. Soc.*, *Royal Soc. London*, **B-267**, 503-581 (1974).
10. E.H. Hankin and D.M. Watson, "On the Flight of Pterodactyls," *Aeronautical J.* **72**, 1-12 (1914); from [3].
11. O. Abel, *Geschichte und Methode der Rekonstruktion vorzeitlicher Wilbeltiere*, G. Fischer, Jena, 1925; from [3].
12. A.S. Romer, *Vertebrate Paleontology,* third edition, p. 146, U. Chicago Press, 1966.

13. H. Tennekes, *The Simple Science of Flight – from Insects to Jumbo Jets*, M.I.T. Press, 1996.

14. National Geographic Map, *The Earth's Fractured Surface*, April 1995.

15. A. Wegener, *The Origin of Continents and Oceans*, translated by J. Biram, Dover, 1966.

16. W. Sullivan, *Continents in Motion*, McGraw Hill, 1974.

17. *CRC Hadbook of Chemistry and Physics*, 66th edition, p. F-129, Chemical Rubber Company, Cleveland, OH, 1986.

18. W.W. Hay, "Potential Errors in Estimates of Carbonate Rock Accumulating through Geologic Time," *Amer. Geoph. Union Mon.* **32**, 573-583 (1985).

19. H.D. Holland, *The Chemical Evolution of the Atmosphere and Oceans*, Princeton Univ. Press, Princeton, NJ, 1984.

20. O.A. Hougen, K.M. Watson, and R.A. Ragatz, *Chemical Process Principles*, Part 1, second edition, p. 182, John Wiley, 1954.

21. *International Critical Tables*, **3**, 279, McGraw-Hill, 1928.

22. A.B. Ronov and A.A. Yareshevsky, "Chemical Composition of the Earth's Crust," *Amer. Geoph. Union Mon.* **13**, 37-57 (1969). These are the best existing estimates of sedimentary volumes from the whole earth.

23. C. Sagan and G. Mullen, *Science*, **117**, 52-56 (1972).

24. J.F. Kasting, "Photochemical Consequences of Enhanced CO_2 Levels in Earth's Early Atmosphere," *Amer. Geoph. Union Mon.* **32**, 612-622 (1985).

25. J.F. Kasting, J.B. Pollack, and D. Crisp, “Effect of High CO_2 Levels on Surface Temperature and Oxidation State of the Early Earth,” *J. Atmos. Chem.*, **1**, 403-428 (1984).

26. E. Stach et al., *Coal Petrology,* second edition, p. 18, Gebrüder Borntraeger, Berlin, 1975.

27. B. Harte, L.R.M. Daniels, and J.J. Gurney, *Nature*, **379**, 153 (1996).

28. R.A. Lutz et al., *Nature*, **371**, 663 (20 October 1994).

29. M.W.W. Adams and R.M. Kelley, *Chem. Eng. News*, 33 (December 1995).

30. T.O. Stevens and J.P. McKinly, *Science*, **270**, 450-454 (1995).

31. D.J. Des Marais, “Carbon Exchange between the Mantle and the Crust, and its Effect upon the Atmosphere: Today Compared to Archean Time,” *Amer. Geoph. Union Mon.* **32**, 602-611 (1985).

32. J.C.G. Walker, *Origins of Life*, **16**, 117 (1986).

33. *Chem. Eng. News*, p. 20, October 21, 1991.