Is Gaia endothermic?

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(*Received* 5 November 1991; *accepted* 2 December 1991)

Abstract – Geological evidence suggests that Gaia is endothermic: her body temperature has varied, but within limits; there has been no runaway greenhouse like Venus, nor deep freeze like Mars. This paper presents a hypothesis that the Earth's climate has been ameliorated by living organisms: they have served either as heaters or air-conditioners, and their ecological tolerance is the sensor of Gaia's thermostat. At the beginning, 3.8 or 3.5 Ga ago, only anaerobic autotrophs capable of tolerating high temperatures thinned out the atmospheric CO_2 through carbon fixation. Fossil organic carbon was utilized by anaerobic heterotrophs to reinforce the effectiveness of the late Archean greenhouse, when solar luminosity was weaker than it is now. With the increasing solar luminosity during early Proterozoic time, new life forms such as cyanobacteria evolved, removing CO_2 from the atmosphere and storing it in stromatolitic carbonates. Over-eager cyanobacteria may have consumed too much greenhouse CO_2 to cause glaciation. Their decline coincided in timing with the rise of the Ediacaran faunas which had no carbonate skeletons. The change in the mode of carbon-cycling may have started the warming trend after the Proterozoic glaciation. The Cambrian explosion was an event when skeletal eukaryotes usurped the function of prokaryotes in removing greenhouse CO_2 through $CaCO_3$ precipitation. With the evolution of land plants, coal-makers took over the 'air-conditioning' duty. They over-did it, and Permo-Carboniferous glaciation ensued. After a wholesale turnover of the faunas and floras at the end of the Palaeozoic, more CO_2 was released than fixed in early Mesozoic time. The warming trend reached its zenith in the early Cretaceous, when flowering trees and calcareous plankton began to flourish. The decline since then, with a temporary restoration during early Palaeogene time, could be a manifestation of the varying efficiency of extracting and burying carbon dioxide, in the form of inorganic and organic carbon. The relation of atmospheric CO_2 and climatic variation is documented by study of air bubbles in ice cores. Yet there is also correlation to astronomical cycles. The latter seem to have triggered changes which are amplified by feedback mechanisms of carbon cycling.

1. The concept of Gaia

'Ours is an age of machination', so lamented D. H. Lawrence. We arrived at this age because of two ideological revolutions induced by scientific discoveries. People used to feel close to God; His only Son was sent to us for our salvation; there was something special about us, and about the place we live in. The Copernican Revolution deflated our ego: there is no Heaven, nor Hell, and the Earth is only a planet, a star among jillions of stars. The Darwinian Revolution did the rest: we are just *Homo sapiens*, one species of living organisms among millions of species. We entered the age of machination, when we felt that God had no time for us; He had too many other stars and too many other intellectual beings to worry about us. God was so distant.

As the twentieth century is drawing to a close, we are witnessing the movement towards a third ideological revolution. The Earth is not just another star: ours is a very special planet, and we have no evidence that there is another star like ours in the whole universe. We are not just another animal species: we are *Homo sapiens*; we do not know if there are any other intellectual beings anywhere else in this cosmic world. Now we are dissatisfied with the age of machination, we have the Green Peace, and the conditions seem to be ripe for a renaissance of religion.

Is Gaia endothermic? What is Gaia? What is endothermic? What do we know about the Earth's climatic history? Does such information help answer the questions posed?

Gaia is a metaphor to some, and a theory to others. I shall use the word as an abbreviation for a Leitbild – a concept – that the terrestrial processes in the atmosphere, hydrosphere, lithosphere, and biosphere are interrelated in such a way as to sustain life on Earth, and that the actions of living organisms are an indispensable element of this interaction. The Earth has become Gaia after there was life on Earth; Gaia was sick when there was a biological crisis of mass extinction; and Gaia dies when all living organisms become extinct.

Endothermism refers to the ability of a living organism to maintain its body temperature within a range necessary for its survival; mammals are endothermic. If Gaia is endothermic, what is the internal temperature-adjusting mechanism of Gaia?

2. The carbon budget

The surface temperature on Earth depends on three factors: (1) the radiant energy emitted by the Sun – the solar luminosity; (2) the fraction of solar energy reflected back into space – the albedo effect, and (3) the fraction of the infrared radiation emitted by the planetary surface absorbed by the atmosphere – the greenhouse effect. Gaia has no control over solar luminosity, and the albedo effect is of second-order importance. Current theories suggest that the varying concentration of greenhouse gases in Earth's atmosphere has been mainly responsible for moderating climatic changes.

Carbon dioxide is the main species of the greenhouse gases, and its ultimate source is the planetary interior. Experts believe that all planets may have had initially a dense atmosphere of carbon dioxide and water vapour, because of the extensive outgassing of volatiles through volcanism. Since then, the atmospheric carbon dioxide has either increased or decreased, depending on the balance of the supply by volcanism and the loss through removal from atmosphere. We all know that the supply must have exceeded the loss on Venus, the planet has a dense atmosphere of carbon dioxide, and the surface of Venus at about 500 °C is much too hot to sustain life.

In the case of our other neighbour, Mars, the loss from atmosphere has exceeded the supply, although the initial Martian atmosphere may have been as dense as that on primaeval Earth. With the decline of outgassing and the escape of the volatiles to outer space, temperature declined. At first, the temperature was still sufficiently warm that the Martian atmosphere held large amounts of water vapour. Continued deficit of greenhouse gases caused further decline. It rained then. As there was no negative feedback mechanism to reverse the trend, permafrost came. Eventually the Martian temperature dropped below – 110 °C, carbon dioxide started to be frozen together with water to form a solid mixture of CO_2 and water, a compound called clathrate. That further speeded up the reduction of atmospheric CO_2, until much of that greenhouse gas is frozen. Although the present Martian atmosphere is like that on Venus, which also consists mostly of carbon dioxide, the atmosphere is so thin that the pressure is only about 6 millibars at the Martian surface, or 0.6% of the terrestrial atmospheric pressure. The carbon dioxide which could have kept the planet warm is now largely frozen in its ice caps. Mars has lost his chance, if he ever had one.

Why did the Earth evolve differently? Lovelock, the original proponent of Gaia, voiced the opinion of many scientists that the Earth has become what it is because there has been life on Earth. The 'greenhouse' provided by the atmospheric carbon dioxide is Gaia's clothing. She puts on more clothes when it gets colder and she takes some off when it is hot.

3. Atmospheric CO_2 and carbon cycling

On a lifeless planet, carbon dioxide spat out of volcanoes would get into the atmosphere, where, if it rains, it would fall onto the ground to cause weathering and erosion. But part of the carbon dioxide would never go back to the atmosphere. In its dissolved form, biocarbonate ions combine with calcium to form a precipitate, calcium carbonate, or limestone. The atmosphere can only maintain a constant carbon dioxide pressure if the demand is balanced by supply. That seems to be a difficult task: neither Venus nor Mars could do that. The Earth, alone of the planets of the solar system, has done just that; Gaia could balance her carbon budget.

The CO_2 in the Earth's atmosphere today totals about 50000 units, each unit being 10^{12} moles C (Fig. 1). It has an income of 11.7 units from volcanism, and a debit of 16.7 units for weathering on land (MacKenzie, 1990). If there had been no life on Earth, the negative balance would be 5 units per year, and it would take only 10000 years to use up all the carbon dioxide in the present atmosphere. We would all freeze.

At first sight, life consumes more that it gives back; organic production takes a whopping 38.3 units from the atmosphere every year. The record shows, however, a balanced carbon budget for the last 10000 years. We have thus to conclude that there were other sources of income for the atmosphere than the volcanic degassing. Part of the dead organisms decayed, producing thereby CH_4 and other gases, and oxidation of those would return 5 units to the atmosphere. That was not enough; the big share of the deficit of 38.3 units had to be supplied by the ocean.

Where did ocean get its carbon dioxide? From land, of course! When terrestrial organisms died, only a small part of their carbon, or about 0.1 unit, was stored in continental sediments, the rest went into the

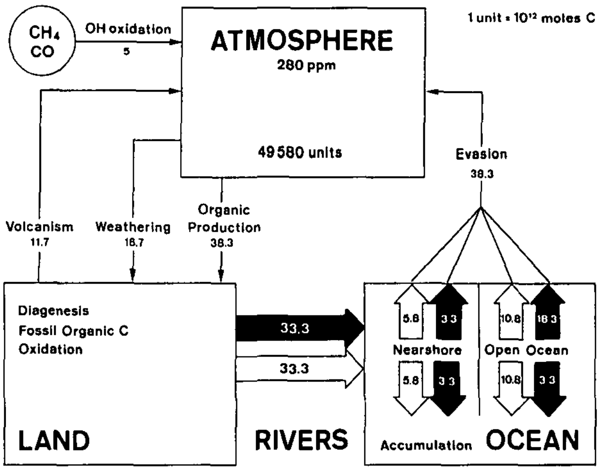

Figure 1. Wollast & MacKenzie model of the long-term geological cycle of CO_2 (after MacKenzie, 1990). Fluxes in units of 10^{12} moles per year. Organic carbon fluxes are shown in black, and inorganic carbon in open arrows.

oceans, delivering some 33.3 units of organic carbon per year (Hayes, Kaplan & Wedeking, 1983; MacKenzie, 1990). The ocean, however, also needed its share of carbon. Marine organisms utilize carbon for their cell issues and for their $CaCO_3$ skeletons, and part of that, after their death, was fossilized in marine sediments, accounting for 23.2 units, leaving only an excess of about 10 units for escape to the atmosphere. Where did the rest come from? It must be from land, then. There are two banks on land: carbon in reduced state as elementary carbon or hydrocarbon, and carbon in oxidized state as carbonate. The reserve of organic carbon in soil is 172000 units, more than five times, and the reserve of organic carbon in sediment is 10^9 units, 20000 times the atmospheric carbon. A more ready source is the carbonate carbon on land, which has a reserve of 5.4×10^9 units. The dissolution of inorganic carbon from weathering is thus a major source. This follows the simple relation

$$CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2HCO_3^-,$$

and we see that each unit of atmospheric carbon dioxide dissolved in water to form carbonic acid can dissolve limestone and deliver twice as much dissolved inorganic carbon to the ocean. The carbonate reserve is so great that it could take care of the annual Holocene deficit for hundreds of millions of years, even if there is no feedback mechanism to adjust the Earth's carbon cycling.

The secret of Gaia's balanced budget is thus the existence of a carbon bank. The carbon bank adjusts the carbon economy like the Federal Reserve Bank: when there is too much money (carbon dioxide) in the market (atmosphere), or too much inflation (carbon dioxide, or too hot), the bank will reduce the currency in circulation (carbon dioxide in carbon cycling). Or the bank could combat recession by reversing the procedure. We might imagine that we have just come out of a cycle of carbon recession. During the ice age the atmospheric carbon dioxide was only about 200 ppm (Barnola *et al.* 1987). Studies of ice cores indicate that this was increased to about 280 ppm during early Holocene time when it was stable for some time. There are many debates concerning the cause of this increase, but there is no controversy concerning the increase to 350 ppm since 1750; it is a catastrophe caused by *Homo sapiens*. With the release of carbon in fossil fuels, we are releasing so much to the atmosphere that the ocean is forced to be a sink, rather than a source, for carbon dioxide. About half of the industrial production is stored one way or another by ocean sediments, the other half of the output heats up the atmospheric 'inflation'.

This lesson on carbon budget gives a general idea of the complexity of the problem. There are producers, there are consumers, there are banks, there are tax collectors. A set of conditions at a given time will produce carbon surplus or deficit for the atmosphere, so that the climatic variations of Earth history could be considered a reflection of the intricacies of carbon cycling. The fact that Gaia has survived the last 4 billion years is an indication that the carbon economy has survived the many cycles of inflation and recession.

We are all familiar with problems of balancing budgets. One of the secrets is to book your incomes and expenditures into several accounts. I did that for 20 years, until two years ago when, in preparation of my forthcoming retirement, I decided to give up some of the accounts to my younger associates. Promptly, I overspent more than 60% of my sole budget in 1989, when I had only a single account. Venus and Mars could not balance their budgets because their income and expenditures were rigidly programmed. The Earth has had a balance budget, because there is life on Earth. Life consumes, life delivers, life saves, and life has a sense of moderation so that Gaia has never had to fear for her life, even at times of greatest crisis (e.g. at the end of the Cretaceous), except perhaps now when here life is endangered by the excess of human beings.

Using economy again as a parable, we avoid bankruptcy by making savings or taking up insurances. A balanced carbon budget for the Earth is only possible through an expenditure of the 'savings' on land through erosional processes. Going back to 3.5 or 4 billion years ago, when the first life first started, there was little carbon reservoir on land. If Gaia had squandered her carbon resources to the atmosphere like Mars, the Earth would now have a frozen ocean and would have been no place for organisms to live. Gaia has saved her carbon by carbon fixation. How did she do it?

4. The Archean greenhouse

We have to go back to the earliest history on Earth to find some of the answers. Thanks to the studies by the Precambrian Paleobiology Research Group (Schopf, 1983), we begin to have a gleam of understanding.

Different carbon and energy sources are used to make cell tissues of living organisms. An organism that uses CO_2, present in the environment or generated from some other compound, as the source of cellular carbon is an autotroph. An organism that uses organic carbon compounds (such as methane) as sources of cellular carbon is a heterotroph. An organism that can use light as the energy source is a phototroph and one that uses inorganic or organic substances as energy source is a chemotroph.

We can identify different processes of carbon fixation by carbon isotope analyses. There are two stable isotopes: ^{12}C and ^{13}C, and the average terrestrial ratio of the two is 89.4. When CO_2 is fixed by an enzyme (called RuBP) to produce carboxylic acid through this carboxylation reaction

$$CO_2\,(\text{external}) \rightarrow CO_2\,(\text{internal}) \rightarrow R\ COOH,$$

there is an isotope fractionation: this reaction discriminates very effectively against ^{13}C, and the carbon in the cellular tissue of living organisms produced by this reaction will have 25 to 30 pro mil less ^{13}C than the CO_2 carbon. Knowing this, we can analyse the carbon isotope ratio of fossil organic carbon, and determine if and when this process has been active on Earth. To make a long story short, isotope geochemists have found that the average for sedimentary carbon of all ages is more or less $-25‰$ (Fig. 2); they could thus tell us that 'carbon fixation by autotrophic life forms had gained control of the terrestrial carbon cycle as early as 3.5, if not 3.8' Ga ago (Schidlowski, Hayes & Kaplan, 1983, p. 163). We are not certain, however, if the oldest autotrophs were photoautotrophs or chemoautotrophs, were aerobic or anaerobic. None the less, as Schidlowski (1988) concluded, 'the basic uniformity of (the) isotope signature through time is testimony to an extreme degree of evolutionary conservatism in the biochemistry of photoautotrophy as the quantitatively most important process of CO_2 assimilation'. In everyday language, we could say that Gaia uses the same air-conditioning mechanism to keep her house cool.

What was the earliest form of life? Palaeobiologists seem to have reached a concensus that the earliest organisms were anaerobic fermenters, such as those found in the 3.5 Ga Warrawoona of Western Australia (Schopf & Walter, 1983, p. 237). They use glucose (the hexose sugar $C_6H_{12}O_6$), the universal cellular fuel, and the capacity for anaerobic fermentative utilization of glucose is the most ubiquitous of the biological energy conversion mechanisms known to extant organisms (Gest & Schopf, 1983, p. 136). A large fraction of the glucose fermented is converted to organic acids, ethanol, H_2 and CO_2, which was returned to the atmosphere. Not all the organic carbon was oxidized; the earliest terrestrial atmosphere had hardly any free oxygen. A part of fossil organic carbon was preserved in sediments; the carbon fixation resulted thus in a net loss of atmospheric carbon dioxide. The oldest Archaean microfossils were found in black chert deposited in reducing environment. Gest & Schopf described the Warrawoona biota as an entirely prokaryotic community that formed laminated microbial mats at the sediment–water interface in a shallow water to intermittently exposed setting; the biota included both autotrophs (probably photoautotrophs) and heterotrophs.

The existence of photoautotrophs prevented us from going the way of Venus. So there has been no problem in air-conditioning, but what is Gaia's heater? We may ask again, why did she not share the fate of Mars? We may indeed have gone the way of Mars, because astronomers told us that the solar luminosity was 25% less than that of the present in the early history of the solar system. To keep the surface temperature 3 Ga ago above freezing, carbon dioxide in the terrestrial atmosphere should have been 80–600 times the present value (Kasting, 1985). Did we have more of a greenhouse then?

One could refer to the much more active volcanism in Archaean times and postulate a surplus of volcanic degassing (Des Marais, 1985). Or one could suggest a feedback system involving weathering. Weathering consumes atmospheric CO_2 and deposits calcium carbonate:

$$CaSiO_3 + CO_2 + 2\ H_2O = CaCO_3 + H_4SiO_4.$$

The rate of silicate weathering is dependent upon carbon dioxide partial pressure and temperature. When the Earth's CO_2 pressure was reduced and its temperature was cooled to a certain degree because of the low solar luminosity at the time, consumption of CO_2 for weathering would be correspondingly reduced to a value not exceeding that of the volcanic degassing (Walker *et al.* 1983). If this mechanism of adjustment could work, why did Mars failed to activate this thermostat? Proponents of the Gaia concept search thus for the answer in the recycling of stored carbon by organisms.

Did the Archaean microbes have enough sense to tell Gaia that she was about to catch cold? If so, they could impose a lower limit on how thin the atmospheric carbon dioxide would become; microbes could no longer have done their job of carbon fixation. This lower limit is, however, very low, generally about 10–30% of the present atmospheric value. If the Archaean microbes were the same kind as those of today, their thermostat would have been set too low to prevent the Earth from freezing at the time of reduced solar luminosity. There must have been another regulating mechanism.

The isotope record suggests extensive involvement of methane-utilizing biochemical pathways (heterotrophs) to produce kerogenes with $\delta^{13}C$ values of about $-50‰$ some 2.8 to 2.5 Ga ago, when methanogenesis was important in the anaerobic decomposition of organic matter. Methane is a greenhouse gas several times more effective than CO_2. Were methanogenic bacteria harder at work than sulphate-reducing bacteria when Gaia needed warmth?

5. Proterozoic air-conditioning

Sooner or later, however, solar luminosity increased to that of the present strength. Gaia had to take off her winter coat, the atmospheric carbon dioxide had to be reduced by a factor of 100 or more. How did she do it? And when?

A benchmark in the history of life was the development of oxygen-producing photosynthesis. Earliest photosynthesis by anaerobic photoautotrophs could not make oxygen; those microbes can use H_2, H_2S, or various organic substrates, but no H_2O, as a

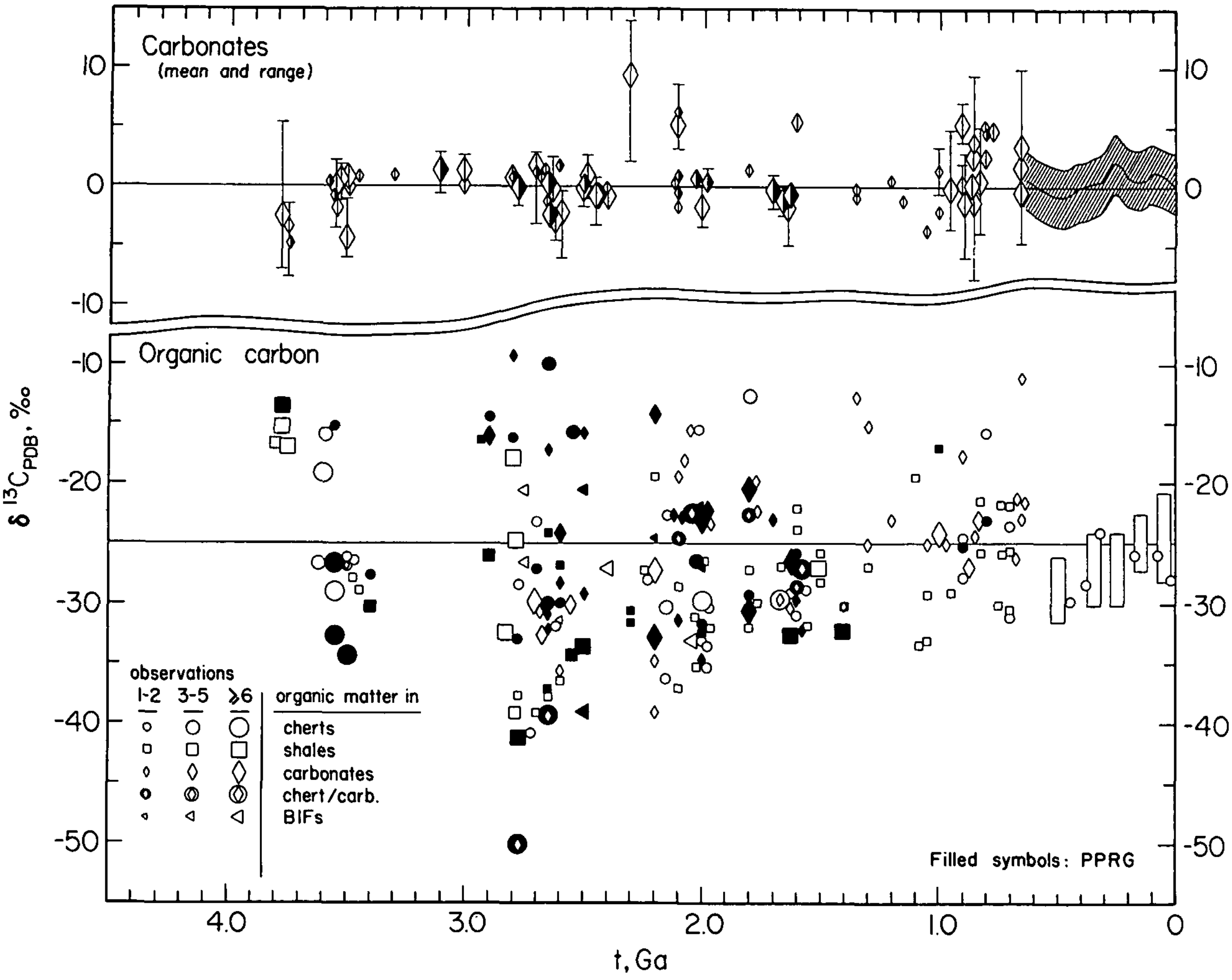

Figure 2. Carbon isotope geochemistry of sediments (after Schidlowski, Hayes & Kaplan, 1983).

source of electrons for the light-driven reduction of CO_2 to produce cellular organic compounds. Schopf, Hayes & Walter (1983, p. 378) told us that 'the Late Archean (2.9–2.5 Ga) appears to have been a time of profound transformation of the surficial planetary environment...It was...a time characterized by the occurrence of such evolutionary advances as oxygenic photosynthesis, aerobic metabolism, and the development of an amphiaerobic mode of life, critical events...that set the stage for the subsequent transformation of the Earth's surficial environment from an anaerobic to an aerobic state and for the derivation of a physiologically fully modern anaerobic–aerobic ecosystem.'

Earlier anaerobic life forms could not survive in an environment with free oxygen. The newly evolved proto-cyanobacteria had the ability to tolerate oxygen; they could also photodissociate H_2O to produce oxygen. They were resistant to UV-irradiation, and they became highly successful occupants of photosynthetic space in benthonic habitats. The evolution of oxygenic photosynthesis permitted the co-evolution of oxygen respirers, which include cyanobacteria and all higher forms of life. At the same, the build up of the ozone layer in the upper atmosphere permitted the appearance of new life forms which are not resistant to UV-irradiation, such as the planktonic prokaryotes, and facilitated the global spread of stromatolitic biocoenoses into numerous previously unoccupied locales. Most important, perhaps, in our consideration, is the fact:

> Coupled with an increase in the efficiency of carbon and nutrient recycling via aerobiosis during this period, both of these consequences would have combined to produce a feedback effect, the increasing dispersal of cyanobacteria resulting in an increase in photosynthetic biomass; this increased biomass resulting in an increase in the sedimentation and burial of carbon derived from oxygen-producing photosynthesizers. (Schopf, Hayes & Walter, 1983, p. 381)

The extraction of atmospheric carbon dioxide took two forms: fossil organic carbon and carbonates. With increasingly more oxygenic environments and thus more extensive oxidation of organic carbon, the relative importance of fossil organic carbon as a storage should have declined. The deposition of carbonates took two forms, as witnessed by the wide

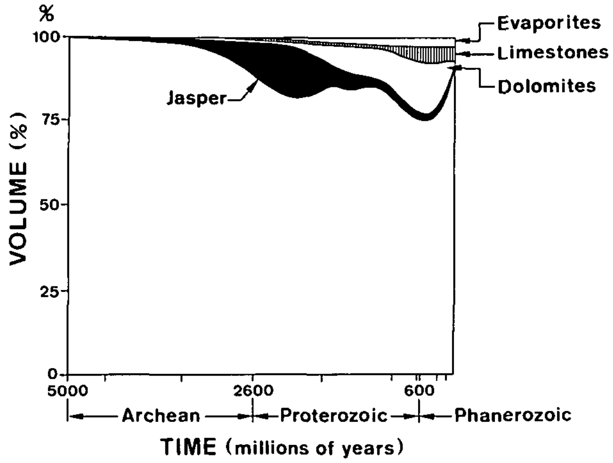

Figure 3. Replacement of cherts (jasper) by carbonates as the dominant sediments during the Proterozoic (after MacKenzie, 1990).

occurrences of banded iron ores and of stromatolites in late Archean and early Proterozoic time.

Sedimentary iron deposits in a reducing environment are commonly siderite, an iron carbonate. Interlaminated siderite and diatom ooze have been sampled by deepsea drilling in the Black Sea (Hsü, 1978); those sediments could be the Neogene analogue of the Proterozoic banded iron ores before their oxidation (siderite to haematite) and metamorphism (ooze to chert). Although occurrences are reported from Upper Archaean and Lower Proterozoic, the bulk of Precambrian iron formations, according to Goldich (1973), was deposited between 2.2 and 1.8 Ga ago.

Another major sink for carbon was the stromatolitic carbonates. Stromatolites are known from Archaean times. The oldest stromatolites (3.5 Ga) occur in 'a lenticular unit of chert and barite', but late Archaean (2.8–2.5 Ga) stromatolites occur within carbonate formations (Walter, 1983). Microbes forming stromatolites could be anaerobic, or aerobic, autotroph or heterotroph, phototroph or chemotroph (Hofmann & Schopf, 1983). The necessarily aerobic microbes originated, however, only about 2.0 Ga ago, and first became abundant and globally widespread between 1.7 and 1.5 Ga (Schopf, Hayes & Walter, 1983). The increasing importance of carbon fixation is evidenced by the Proterozoic record, when carbonates replaced cherts as the dominant biogenic sediments (Fig. 3).

Precipitation of carbon as carbonates is an effective mechanism for removing carbon dioxide from the atmosphere. The Earth did not go the way of Venus, when the Sun began to increase its luminosity, because atmospheric CO_2 may have been reduced by the activity of oxygenic photosynthesis and the consequent carbon fixation, especially in the form of stromatolitic carbonates.

Assuming that the late Archaean Earth atmosphere had 500 times more CO_2 than it does now, or 25000000 units, all that atmospheric CO_2 would have been consumed in 250 Ma even if the carbon storage was only 0.1 unit per annum as the present rate of storage in continental sediments. The occurrences of early Proterozoic glaciations (2.5 to 2.0 Ga) indicate that the removal of atmospheric CO_2 was probably a very efficient process. The Earth's atmosphere may have approached that of the present when the first aerobic microbes flourished.

What was the forcing mechanism? Was it a random mutation for microbes to develop the new strain? Or did Gaia act out of necessity and improvise when there was the threat of a runaway greenhouse?

There could be, of course, an extraterrestrial influence on the history of life. We have little evidence of what may have happened during the late Archaean, but the middle Proterozoic Vredefor–Bushvelt structure, considered by many the largest known impact crater on Earth, is 2.1 Ga in age (Elston & Twist, 1989), which is about the same time when the 'modern' anaerobic–amphiaerobic–aerobic ecosystem was established. A biologically effective UV-absorbing atmospheric ozone layer came into existence then. Land areas and the photic zone of open ocean became wholly habitable. Strict aerobes diversified to become widespread, abundant, and ultimately the dominant components of the Earth's biota. Atmospheric oxygen pressure came under biological control, and the geochemical redox cycles of numerous elements became increasingly biologically meditated (Schopf, Hayes & Walter, 1983). Gaia seemed to have come of age after the meteorite hit, and there was a billion years of stability. Is that a pure coincidence?

6. The crisis at the beginning of the Cambrian

Two big steps forward in biological evolution were taken prior to the beginning of the Cambrian, when the first trilobites appeared. Earliest life forms are prokaryotes, bacteria, cyanobacteria ('blue-green algae'), etc., characterized by cells that lack membrane-bound nuclei and similar organelles. Some time after 1.5 Ga, during late Proterozoic time, the eukaryotes appeared. Those are unicellular or multicellular organisms, such as protists, fungi, plants and animals, characterized by nucleus cells that are capable of cell division by mitosis, namely division of cell nucleus leading to formation of two daughter cells each of which is an exact copy of the parent. The eukaryotes as a group became well established, when the metazoans of the Ediacaran faunas flourished. Palaeobiologists see the development as a consequence of having an oxygenated atmosphere on Earth: not only was there oxygen for respiration, but also nitrate could be produced. Nitrate was probably absent in the anaerobic Archaean Earth, because this nutrient could be synthesized only under oxidizing conditions (Ochiai, 1978).

The second major development was the 'Cambrian explosion', about 600 MA ago. The Ediacaran faunas have no hard parts, no $CaCO_3$ skeletons. The trilobites, and other calcareous organisms, came suddenly onto the scene. On the other hand, this event need not be over-emphasized; we now know that life on Earth did not originate at the beginning of the Cambrian; only the ancestors of many modern life forms, with 'Baupläne' familiar to us, came into existence then (Valentine, 1986).

Those two 'revolutionary' steps in evolution were taken at the time of an environmental crisis when there was glaciation on every continent, except perhaps Antarctica, between about 1.0 and 0.6 Ga (Walker *et al.* 1983). The rise of eukaryotes coincided with the decline of the stromatolitic communities. Is that an evidence of Gaia's endothermic forces at work?

Stromatolites are found mainly in carbonate sediments. Two hypotheses are competing for the origin of the carbonate (Ginsburg, 1991). In Recent environments the evidence is clear, that cyanobacterial mats grow in intertidal zones. Like sticky paper trapping flies, those sticky algal mats trap carbonate sediments, which are either biochemical precipitates of green algae, or skeletal debris of animals. No skeletal debris was available in Precambrian time, and stromatolites are found in places as lenticular bodies in non-carbonate sediments. Some palaeontologists, therefore, suggest that stromatolitic carbonates, at least most of the Precambrian varieties, were directly or indirectly precipitated by cyanobacteria. No matter which hypothesis is correct, cyanobacteria were very effective in consuming CO_2 to make limestones; they are good 'air-conditioners' for Gaia.

Metazoans without calcareous skeletons give back to Gaia what they take from her. They utilize CO_2 to build their cells, and their dead bodies decay and release CO_2.

Now we could return to the conclusion by isotope geochemists that the total biomass on Earth has remained more or less the same since life first began. Their conclusion was based upon the relatively constant $\delta^{13}C$ values of carbonate carbon during the last 3.8 Ga, and the data indicate that organic carbon had always been about one-fifth the total carbon on the surface of Earth (Schidlowski, 1988). This is not surprising, if we recall that the RuBP enzyme catalyses the carboxylation with CO_2 and cleavage of ribulose 1.5-diphosphate to yield two molecules of 3-phosphoglycerate, and that this enzyme has been at work from the dawn of life to the present. Phosphorus is thus always a limiting nutrient for life. Later, after eukaryotes evolved to utilize nitrate, phosphorus and nitrogen have become the limiting nutrients. The total biomass may have to remain more or less constant, but the partition of nutrients, and thus the carbon among the various groups, could vary from time. When eukaryotes evolved to compete for available nutrients and carbon, prokaryotes had to share.

The cyanobacteria took more than they gave back. Was the Proterozoic glaciation a warning to Gaia, that she had been a spendthrift of the carbon in the bank? Were the metazoans the 'God-sent' gift to Gaia to balance her carbon budget?

How does Gaia's thermostat work? Gaia's air-conditioner works when it is hot. Gaia's heater is switched on when it is too cold. Gaia's thermostat is then the temperature tolerance of the various forms of life.

Using an oxygen isotope palaeothermometer, Knauth & Epstein (1976) suggested that the surface temperature on Earth may have been 70 °C at about 3.0 Ga and 52 °C at 1.3 Ga. When once I worked on the tidal flats of Abu Dhabi where the daytime temperature reached 50 °C at times, the only living organisms I could see, except for a few gastropods here and there, were the ubiquitous stromatolites. Cyanobacteria could thrive and get a big share of Gaia's carbon budget when it was very hot; they could thus have worked effectively as a conditioner. When the temperature became moderate, or cold, the metazoans, with their more advanced organization, had a chance to take over a bigger share of the carbon pie. Gaia was switching off her air-conditioner, when stromatolitic biocoenosis declined. We could imagine that anaerobic heterotrophs are Gaia's heater. When too much fossil organic carbon is preserved in an anoxic environment, they become busy and make CO_2 to keep Gaia warm.

A manifestation of activities that the heater was switched on while Gaia froze is given by the changing $^{32}S/^{34}S$ ratio of sedimentary sulphate. The reduction is coupled with the oxidation of organic substances, commonly lactate, for example (Schidlowski, Hayes & Kaplan, 1983):

$$2\ \text{lactate} + SO_4^{2-} = 2\ \text{acetate} + 2\ H_2O + 2\ CO_2 + S^{2-}.$$

The sulphide ions combined with iron to form iron sulphide, or pyrite, and this biogenic sulphide is enriched in ^{32}S, causing thus a positive ^{32}S anomaly. Claypool *et al.* (1980) found a sharp rise of $\delta^{34}S$ in sedimentary sulphate, from about 15‰ at 700 Ma to about 35‰ at 600 Ma (Fig. 4). This rise indicates that sulphate-reducing bacteria were busy at work, releasing carbon dioxide to the atmospheric greenhouse.

While the evolution of the Ediacaran faunas may have been related in some way to climate, the sudden appearance of calcareous organisms at the beginning of the Cambrian could not be correlated to strong climatic signals. The Cambrian explosion took place in the midst of an apparently warming trend, while the stromatolitic community declined. Stanley (1973) thought that some unknown single-celled herbivores ate up the cyanobacteria, which had formed widespread algal mats, and had all but choked off other forms of life; their destruction created new ecological niches for higher forms of calcareous organisms. I

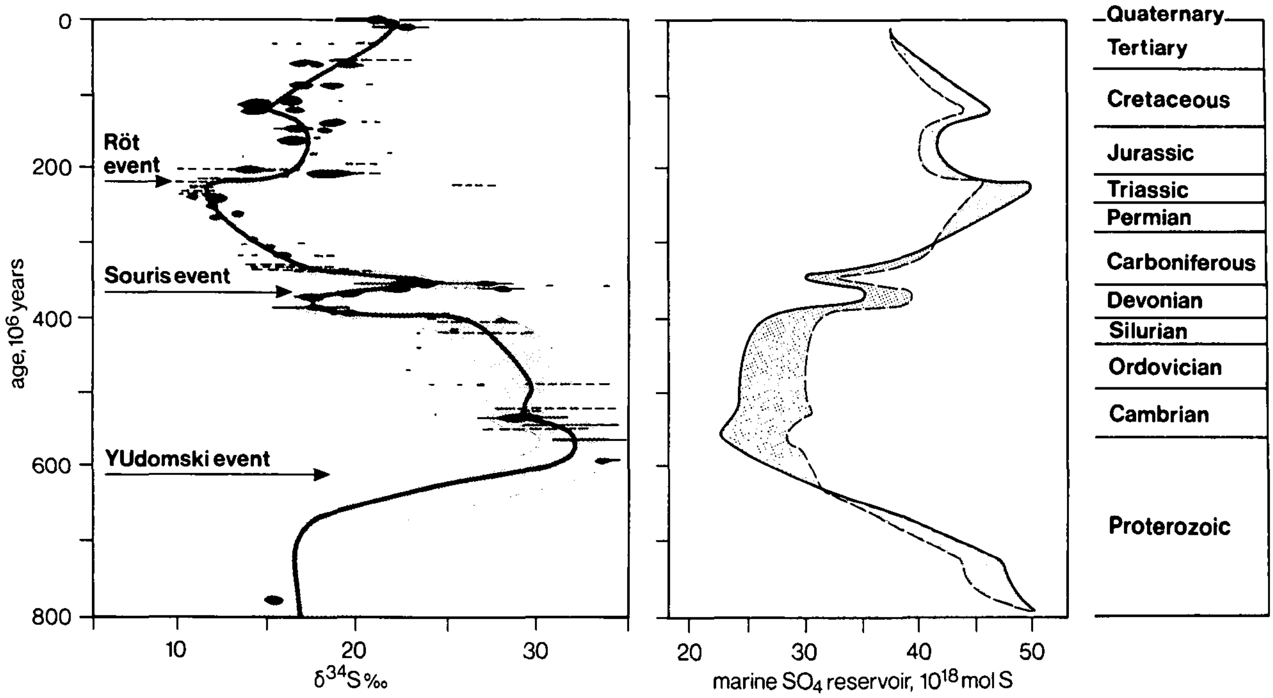

Figure 4. Sulphur isotope geochemistry of sediments (after Degens, 1989).

tend to agree that the Cambrian explosion may have been triggered by a significant reduction of the stromatolite biocoenosis, but the damage may have been wrought by a meteorite impact (Hsü *et al.*, 1985).

Degens (1989) came up with an unorthodox idea of a soda ocean to explain the absence of calcareous organisms in the Precambrian ocean; there was too little calcium in seawater for skeletons to grow. He pointed out that acritarchs, planktonic unicellular eukaryotes, were abundant because they did not have to secrete calcareous skeleton. This idea was criticized by geochemists, because a more (than present) acidic ocean would be more consistent with estimates of Precambrian atmospheric CO_2 pressure. I have, therefore, been speculating that the calcite undersaturation was related to calcium-ion concentration, not to pH.

Cyanobacterial communities, flourishing in coastal areas, were effectively removing calcium influx to the oceans, while they directly or indirectly precipitated stromatolitic limestones. That the Precambrian ocean was calcium deficient is indicated by the occurrence of the Middle Proterozoic banded iron ores, iron–carbon deposits before their oxidation. Siderite is precipitated in waters with a Ca/Fe ratio less than 20, a value much less than that of modern seawater (Berner, 1971). This shortage of calcium in open marine waters was not likely to have been relieved, when late Proterozoic stromatolites were piling up on tidal flats. Did the extensive destruction of the cyanobacterial communities, whatever their cause, lead to an excess of calcium in seawater? Was that the cause of the sudden appearance of conditions conducive to skeletal growth at the beginning of the Cambrian?

Cambrian–Ordovician calcareous organisms did not seem to have prevailed as much as the Proterozoic cyanobacteria. Faunal communities preserved in Cambrian anoxic sediments indicate that the medusa-like metazoans were still the dominant life forms then. After they died, their soft bodies would decay, and the storage of organic carbon in marine sediments was favourable for activities by sulphate-reducing bacteria. Cambrian–Ordovician pyritic shales are very widespread, and the $\delta^{34}S$ value in marine sulphate reached a maximum, when the climate became warm (François & Gérard, 1986).

7. Carboniferous forests and Permian glaciation

The next milestone in evolution was the rise of land plants. From a few species of vascular plants of primitive morphologies in Silurian and Devonian time, more than 300 species are found in the Carboniferous fossil record, including the first big trees called gymnosperms (Niklas, 1986). Their production was so rapid that the swampy environment of their growth would soon become oxygen deficient. Some of the organic carbon is preserved in the form of thick coal seams. Gaia had never been such a spendthrift since the Proterozoic. We can imagine that the atmospheric CO_2 was again depleted: continental glaciers covered Gondwanaland at the beginning of Permian time. Gaia was again freezing, and she had to build a better greenhouse.

The culprits would have to be the first to go. The abundance of luxuriant plants caused the freeze and they were the first victims for their lack of moderation. Other thermophilic (warm-loving) forms also had

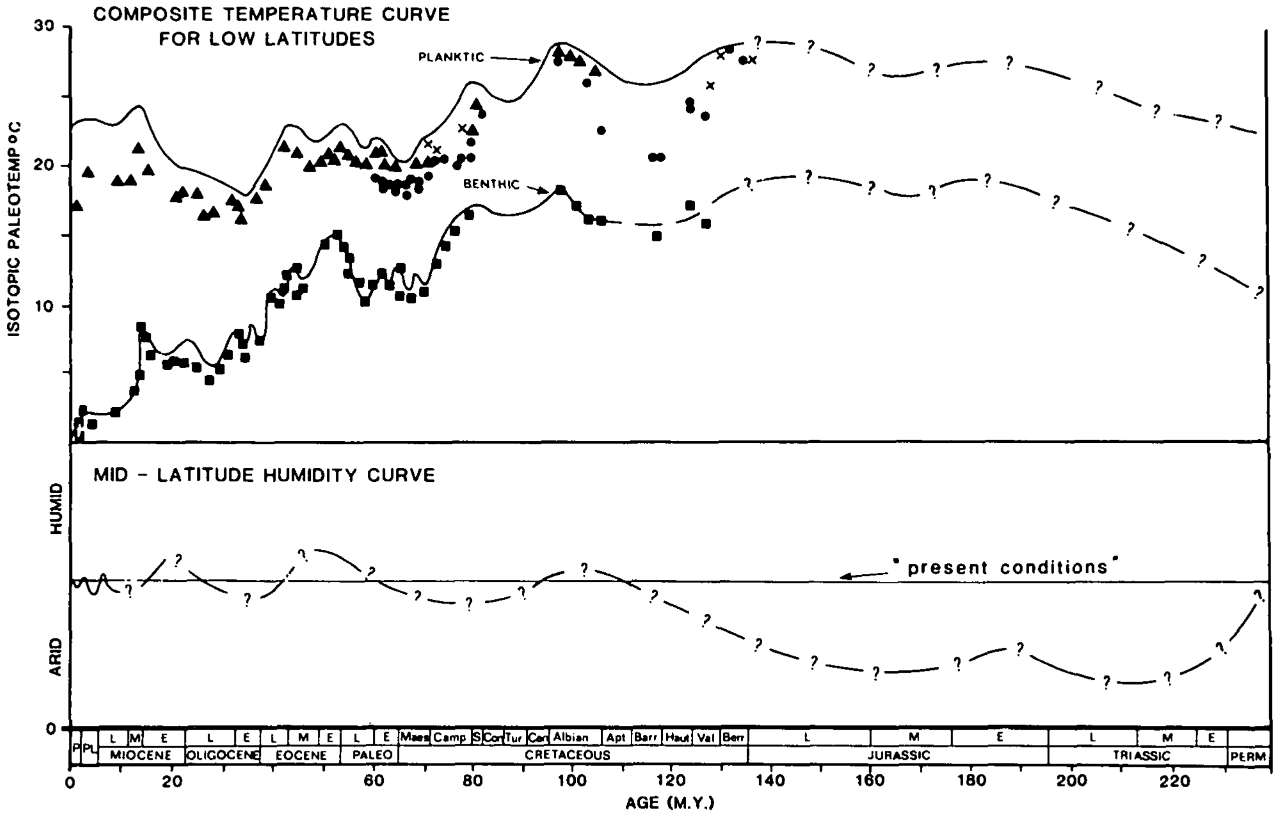

Figure 5. Mesozoic and Cenozoic climatic history (after Frakes, 1986).

suffer. Already weakened towards the end of the Permian, when a killer bolide hit (Hsü & McKenzie, 1990), the devastation was almost complete; almost 95% of Permian species did not survive to see the dawn of the Triassic.

8. Triassic desert and Cretaceous ocean

The continent grew into a Pangaea towards the beginning of the Triassic, and the interior of that supercontinent was a giant desert, where few trees grew. Carbon fixation by plants was reduced to a minimum, and increased terrestrial erosion may have set free much fossil carbon in circulation. The climate was warming up in Triassic and Jurassic time (Fig. 5). A greenhouse climate prevailed during the early Cretaceous, but there were, however, cooling episodes, or even glacial interludes (Weissert & Lini, 1991) and the trend was definitely reversed sometime during the middle Cretaceous. What happened?

The most significant advances of Mesozoic life history are the rise of the flowering plants on land, and the evolution of calcareous plankton in the ocean. Although we still argue when exactly they first appeared, we all agree that they did not constitute significant fractions of the global biomass until Cretaceous time.

Theorists and experimentalists have come up with a consensus that temperature variations on Earth, since the early Cretaceous at least, were related to atmospheric CO_2 pressure, although opinions differ concerning the timing, the magnitude and the causes of the changes (Frakes, 1986). Budyko & Ronov (1979) had a simplistic model for relating the CO_2 budget to variable output of volcanic degassing, but their conclusion of a warming trend in late Cretaceous and middle Miocene time is contradicted by oxygen isotope data (Fig. 5). Computer modelling of the carbonate–silicate geochemical cycle suggested that atmospheric CO_2 and correspondingly temperature decreased during late Cretaceous time, and again, after a Palaeocene partial restoration, after the late Eocene, leading to Neogene glaciations. Assuming the volcanic degassing rate was directly proportional to the rate of seafloor spreading, Berner, Lasaga & Garrels (1983) concluded that the degassing has been the primary factor in controlling atmospheric CO_2 and the Earth's surface temperature. Their computed results are contrary to those of Budyko & Ronov (1979); a part of the discrepancy could be related to unjustified assumptions by Lasaga, Berner & Garrels (1985). They assumed, for example, a variable seafloor spreading rate to obtain results of a maximum CO_2 content at, and thus a Tertiary warming trend until, about 40 Ma. Having worked on that problem for years, I could say neither the assumption nor the conclusion is correct: there is no evidence of an acceleration of seafloor spreading during that period of time, nor was there a climatic optimum at 40 Ma. The onset of global cooling took place at 55 Ma, and the cooling trend led to the Antarctic glaciation during the late Eocene, 40 Ma (Hsü &Weissert, 1985; Oberhänsli & Hsü, 1986).

A more promising approach is to relate the atmospheric greenhouse to palaeoceanography and further to organic production. We should recall that precipitation of $CaCO_3$ from the oceans plays an important role in removing CO_2 from circulation. MacKenzie (1990) suggests that 16.6 units of inorganic carbon per annum are removed from the ocean today, in the form of marine sediments. Calcareous plankton, deposited as calcareous oozes in open oceans, account for two-thirds of the loss, thus using up almost all of the degassing from volcanism. The burial of carbonate and organic carbon in sediments reaches 22.2 units per annum, almost twice as much as volcanic degassing. Gaia has been balancing her carbon budget by drawing heavily from her carbon bank on land. Prior to Cretaceous the, there was little carbon removal by ooze deposition. As will be discussed later, the variation of atmospheric CO_2 during the Quaternary ice age was related to the production of calcareous plankton, which was in turn conditioned by the palaeoceanographic nutrient supply.

The production and preservation of organic carbon is also related to palaeoceanography. Weissert & Lini (1991) correlated palaeoclimatic data to isotope data, and concluded that the unusually higher plankton production and higher preservation rate of marine organic carbon may have led to glacial interludes during the time of the Cretaceous greenhouse climate.

The rise of the angiosperms may have also contributed to global cooling during the last 100 million years. Volk (1989) suggested that the spread of angiosperm–deciduous ecosystems has caused a higher rate of global weathering, and the increased fluxes of Ca and Mg ions from continental silicates contributed to the increasing importance of calcareous plankton. The plankton precipitation in turn depleted the atmospheric carbon dioxide.

9. Terminal Cretaceous catastrophe and Palaeocene restoration

The steady temperature decline since middle Cretaceous time came to an abrupt halt at the end of the Cretaceous, and the Palaeocene started with a steady rise. The temporary reversal was halted early in middle Eocene time, when step-like decreases of ocean temperature continued except for minor oscillations (Oberhänsli & Hsü, 1986). What happened?

That there was a terminal Cretaceous environmental catastrophe and a biotic crisis is a consensus (Hsü, 1986), although whether the trigger was bolide impact or explosive volcanism is still being debated. I have presented my review of the evidence in favour of the bolide hypothesis (Hsü & McKenzie, 1990). What happened to Earth's climate during this catastrophe?

The first consequence was an 'impact winter'. Dust excavated from the impact crater rose to the stratosphere, and total darkness prevailed until the dust settled months or years later (Alvarez *et al.* 1980). Suddenly came an ice age, when the Earth's surface temperature dropped to −40 °C. Oxygen isotope studies have found evidence of a chilled ocean in sediments deposited thousands of years after the event, suggesting that the feedback mechanism, such as increased albedo effect of a snow- and ice-covered planet, delayed the recovery long after sunlight reappeared (Hsü, 1986).

Then there was warming. The reduction of ocean plankton production had enabled the ocean to release more than a usual share of carbon dioxide to the atmosphere, so that the CO_2 may have risen to 3 times the normal value (Hsü, 1986). Yet, nutrients were abundant in the oceans, and periodic plankton blooms could cause significant reduction of atmospheric CO_2 and thus lead to chill. The climatic instability, as shown by the lack of a systematic trend in the oxygen isotope values, may have lasted during the first million years of the Tertiary (Hsü, 1986).

When a steady state was re-established, the interrupted temperature decline should have resumed – yet there was the Palaeocene restoration (Fig. 5)!

This trend reversal could be related to a redistribution of the 'carbon wealth' among different groups of living organisms. Regression of marine waters from continents, which started during late Cretaceous time, continued. North America was inundated by a Cretaceous inland sea, which all but disappeared during the Palaeocene, and Europe experienced a similar regression. China was a Cretaceous desert stretching from the Pamir to the Pacific until the climate was moderated by Palaeocene monsoons originating from the new marginal seas of southeast Asia. The early Tertiary increase of land surface and the amelioration of climate both favoured forest expansion. The shift of biomass production to land plants caused a depletion of ^{13}C in ocean water, and the $\delta^{13}C$ value increased from about $+2‰$ to a late Palaeocene maximum of $+4.5‰$. Meanwhile calcareous plankton were only slowly recovering from the terminal Cretaceous catastrophe; the calcite compensation depth was high during Eocene time, and this indicates reduced calcite production in the open ocean (Hsü & Wright, 1985). Siliceous plankton flourished during the Eocene, as witnessed by the widespread occurrence of Eocene radiolarian oozes. All those circumstances are responsible for less efficient removal of $CaCO_3$ from the ocean during the Palaeocene restoration.

Increased organic production may have a positive feedback mechanism. Organic extraction of atmospheric CO_2 causes cooling, and the consequently more vigorous ocean circulation supplying nutrients to continental margins leads to further increases of production and preservation of organic carbon in anoxic sediments. Vincent & Berger (1985) used such a model to explain the drastic polar cooling in the Miocene (Fig. 5).

10. Ice ages and Milankovitch cycles

The calcite compensation level dropped significantly at the beginning of the Oligocene. The change implies more production of calcareous plankton, more removal of $CaCO_3$, less greenhouse CO_2, and colder temperature. All those changes have been documented by one or another line of evidence. Now fully recovered from the Cretaceous–Tertiary catastrophe, the ocean calcareous plankton resumed their efficiency in reducing the level of atmospheric CO_2. Antarctic glaciation started in the late Eocene or early Oligocene, and the polar ice cap expanded during the middle Miocene. The last ice age started about 2.5 Ma ago in the northern Hemisphere. There were glacial and interglacial stages, and there were times of more or less greenhouse CO_2 in atmosphere.

The correlation of atmospheric carbon dioxide to climate during the last ice age has been well documented by ice cores (Fig. 6). On the other hand, there is a correlation of 40000-year and 100000-year climatic cycles to astronomic periodicities in the tile angle of the rotation axis (41000 years), the precession of the Earth's axis (21000 years), and the excentricity of its orbit (93000 years), called Milankovitch cycles, because a Yugoslav geophysicsist, Milutin Milankovitch, was the first to suggest that astronomical cycles could account for a change from an interglacial to a glacial epoch and vice versa.

Is the CO_2 variation the consequence, rather than the cause, of the Quaternary glaciations? The coincidence of climatic variability to the Milankovitch radiation curve can certainly not be dismissed. Yet it has been suggested that variations in Milankovitch radiation could account only for a 3–4 °C change, hardly enough to cause an ice age. But they were enough to cause variation of atmospheric CO_2, which amplified the Milankovitch forcing mechanism: cold oceans are better sinks for CO_2 because stronger oceanic circulation brings more nutrients to tropical waters for production of calcareous plankton, and thus removal of $CaCO_3$ (Broecker, 1982).

11. What are we doing to Gaia?

The steady state of a balanced carbon budget has been completely disturbed by *Homo sapiens*, as suggested by MacKenzie's (1990) model. The burning of fossil fuel is contributing 500 units annually to the atmosphere (Fig. 7). Even if half of that is somehow absorbed by the ocean, the atmospheric CO_2 content would be doubled, even if we freeze the CO_2 production to the present level. The consequent long-term temperature changes can be easily envisioned. Is that good or bad?

Perhaps our species was created by Gaia to prevent a catastrophic chill. Perhaps the Earth was heading toward the Martian condition, and we arrived on the scene to release fossil carbon to warm up the Earth again. Of course, we could be over-doing that. The Proterozoic bacteria dug their own graves when they became too proficient in carbon fixation. We could be such good heaters that the terrestrial environment would no longer be habitable for *Homo sapiens*. When the atmospheric temperature again reaches 70 °C, the world would return to the Proterozoic world of cyanobacteria, and the circle would be complete.

Of course, we may never get to such extreme temperature. One of the major sinks is the preservation

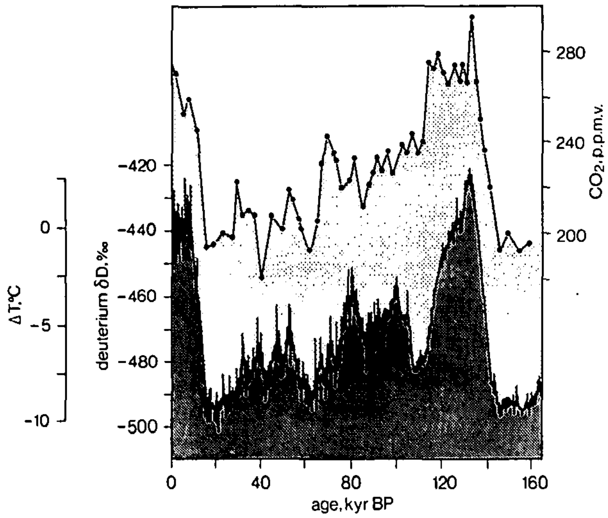

Figure 6. Variation of CO_2 concentration in gas bubbles of ice cores (after Barnola *et al.* 1987).

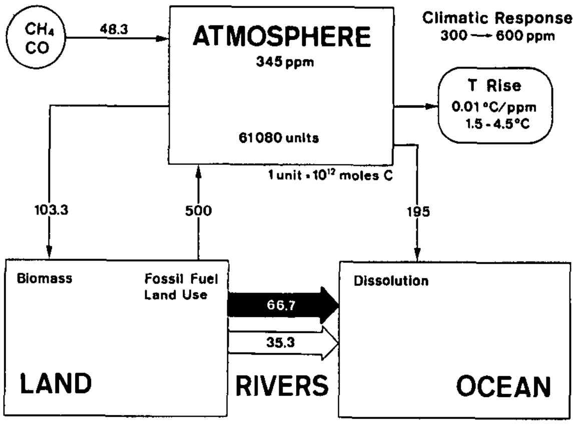

Figure 7. Wollast & MacKenzie model of the anthropogenically disturbed geological cycle of CO_2 (after MacKenzie, 1990). Fluxes in units of 10^{12} moles per year. Organic carbon fluxes are shown in black and inorganic carbon in open arrows.

of organic carbon in marine environments. The anoxia of the Baltic Sea has expanded to such an extent that some 10% of anthroponic CO_2 is being stored in the dead plankton in black sediments there. A naive correspondent asked us, if that could be the solution of the excess CO_2 in the atmosphere. Yes, it may have been Gaia's solution, when the wide areas of the Cretaceous sea became anoxic, and the Cretaceous black shales are the main source beds of the hydrocarbon reserves on both sides of the Atlantic Ocean. However, *Homo sapiens* can hardly expect to survive on this planet if the world oceans become a Black Sea.

Early proponents of the Gaia hypothesis have overestimated the ability of Nature to take care of herself. Like short-sighted exponents of Reaganomics, deficit spending could be a mechanism to adjust the economy, but permanent deficit spending only leads to bankruptcy. We have taken enough from Gaia, and it is about time for us to realize that she, like a government with a perennial hundred-billion-dollar annual deficit, will soon find herself in a situation where she could no longer cope with the runaway inflation anymore.

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