Existence of Life and Homeostasis in Atmospheric Environment

SHIGERU MORIYAMA

Physical Science Laboratories, College of Industrial Technology, Nihon University, 2-11-1 Shin'ei, Narashino-shi, Chiba-ken 27.5, Japan

Abstract — A geophysiological model is used to show how a regulation of the atmospheric CO_2 level could counteract the effect of a gradual increase in solar luminosity. In our model, the biosphere and the atmosphere-ocean system exchange carbon through a biological process which includes the internal and mutual antagonism. It is suggested that as soon as the biologically regulated system had appeared on the early earth, the regulatory aspect of the ecosystem would have been fully operational, and thus, that the earth's environment has been maintained in homeostasis for a long time. One model for the temporal variation of the carbon distribution on the earth, which is in agreement with observed carbon isotopic data, is also suggested. An important result is that our ecosystem left a completely biologically controllable state some six hundred million years ago, and that the current trend is toward destruction of the ecosystem on the earth.

Introduction

Recent carbon isotopic data suggest that, contrary to the generally accepted opinion, our planet's environment may have been strongly controlled by life from a very early stage (Schidlowski, 1988; Holser et al., 1988). Geophysiology is one of the most effective approaches to the question of biological control of the environment. However, the system composed of the biota and the environment is vastly complex; consequently it is very difficult to verify geophysiological evidence. Despite this difficulty, some simplified approaches have recently been applied to this problem (see, for instance, Lovelock and Margulis, 1974; Lovelock, 1986). The Daisyworld model by Watson and Lovelock (1983) is a new approach based on geophysiology. They studied the homeostasis that resulted from the coupling process between albedo due to the color change of Daisy World and the temperature of this world.

It is widely accepted that although solar luminosity has been increasing from early in the earth's history, the earth's average temperature has remained constant and favorable for life. Owen et al.(1979) proposed that the amount of CO_2 was great enough to warm the primitive earth's surface so as to maintain its condition in homeostasis. However, we do not know through what process, or by what mechanism, it has been regulated.

The main objective of this work is to study whether it is simply a coincidence that as solar luminosity has increased, the amount of atmospheric CO_2

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was reduced at such a rate as to maintain a quasi-constant temperature. More-over, we are interested in why the mean surface temperature of the earth is on the cool side of the optimum for the biota, and why the concentration of CO_2 in the earth's atmosphere is anomalously low. In this paper, we argue that a simplified geophysiological model can explain a regulation of the atmospheric CO_2 level.

Walker et al. (1981) proposed that the long-term stabilization of the earth's surface temperature was brought about through a nonbiological mechanism (hereafter called the Walker cycle). This cycle includes a strong negative feed-back mechanism in which the rate of weathering of silicate minerals, followed by deposition of carbonate minerals and hence removal of CO, from the at-mosphere-ocean reservoir, depends on surface temperature, which in turn, through the greenhouse effect, depends on the partial pressure of CO_2.

However, silicate weathering may be enhanced by biological activity and current weathering of silicate rocks may be biologically controlled (Lovelock and Whitfield, 1982; Schwartzman and Volk, 1989). Lovelock and Whitfield argue that geological input and removal of CO_2 constitute only a few tenths of a percent of the biologically driven fluxes, and that the chemical weathering of rocks is controlled by the biota which maintain the high partial pressure of CO, in the soil through oxidation of organic detritus. The nonbiotic Walker cycle predicts an atmospheric CO_2 concentration 100 to 1000 times higher than the observed levels. Without biota that significantly enhance weathering rates, the earth would be over 30°C warmer than it is today (Schwartzman and Volk, 1989).

Moreover, the nonbiological model has a weak point: it does not explain that despite the gradual increase in solar luminosity, there has been homeostasis in the earth's environment. External disturbances greatly influence its solution. According to the abiotic model, unexpected but common events in the earth's history (such as rapid and vast release of CO_2 by volcanoes, by metamorphism and by a reduction of the land area exposed to weathering) would bring about a new, warmer steady state discontinuous from the previous climate.

To circumvent this weakness and keep constant condition on the earth, the modified Walker cycle model (e.g., Matsui and Tajika, 1989) proposes the ex-istence of a continent as a stable reservoir for huge amounts of CO_2. However, this modified Walker cycle model cannot be valid because of the scarcity and small sizes of continents in the Archaean. Continents seem to have appeared on the earth barely 2.5-3 Gyr ago (e.g., Veizer,1988). Using the hydrothermal interaction model, Walker(1985) showed that in the early stages of the earth's history, before the emergence of a continent, the atmospheric CO, concentra-tion would reach 1 MPa. The modified Walker cycle model including silicate weathering inevitably comes to the conclusion that our planet would have pos-sessed an atmosphere with a CO_2 partial pressure of above a few hundred kPa during the first half of its history due to the scarcity of continents (Matsui and Tajika, 1989). There is no evidence that supports the existence of an atmos-

phere of this composition. The Walker cycle is more likely to apply to the Mesozoic and Cenozoic than the Archean (Berner et al., 1983; Volk, 1987).

As will be discussed later, the isotopic data (6 ^{13}C/δ ^{12}C) imply that the ancient earth was not abiotic but, rather, has been in a state of global biotic saturation since almost 4 Gyr ago. Carbon isotope records in sedimentary rocks indicate that marine microbial photoautotrophs may have been fully operative for almost 4 Gyr, and, strangely enough, that organic carbon would have always made up about one-fifth of the total carbon in the surficial compartment (Schidlowski, 1988). This reveals that our environment has been under the influence of life since its early stage.

We investigate this regulation of the atmospheric CO_2 level, which appears to be linked to the gradual increase of the solar luminosity, and propose a model quite different from the Walker cycle. Our results indicate that when the biosphere and the atmosphere-ocean system exchange carbon through a biological process which includes the internal and mutual antagonism, CO_2 level can be regulated by the biological control so as to be habitable for life. Recent isotopic data, studies on the sources of inorganic carbon and the impact on the carbon cycle of photosynthesis and calcification of algae are discussed. We also present new ideas on fluxes of carbon throughout the earth's history.

The Model

Our model, which consists of three boxes, is presented in Fig.1. Carbon moves between the biosphere and the atmosphere-ocean system through photosynthesis and the formation of organisms (this rate is represented by C in the following equations), and through respiration and decay (the rate is expressed by E). Carbon moves from the biosphere to the lithosphere through burial (D). The atmosphere-ocean system exchanges carbon with the lithosphere by way of volcanism and weathering (G). It is assumed that, within the time step used in our calculation, the dissolution equilibrium of CO_2 is instantaneous between rocks and the ocean, and also between the ocean and the atmosphere. We also assume that the biological activity k is a parabolic function of the globally averaged surface temperature T as shown in eq.(1). T is estimated, as in eq.(2), to include greenhouse effects due to CO_2 and H_2O. Incident solar flux S, which is expressed as the ratio to the current value, has a direct relationship to the effective temperature T_e as in eq.(3).

$$k = C \{ 1 - a(T_1 - T)^2 \} \tag{1}$$

$$T = 285 + 2(T_e - T_{e,0}) + 4.6(p/p_0)^{0.364} - 4.6 \tag{2}$$

$$T_e = S^{1/4} T_{e,0} \tag{3}$$

In the above equations, p is the partial pressure of CO_2 in the atmosphere, a and T_1 are constants, and suffix 0 stands for the conditions at present. Eq.(1), in which biological activity k shows a maximum versus temperature, is a universal property of living things.
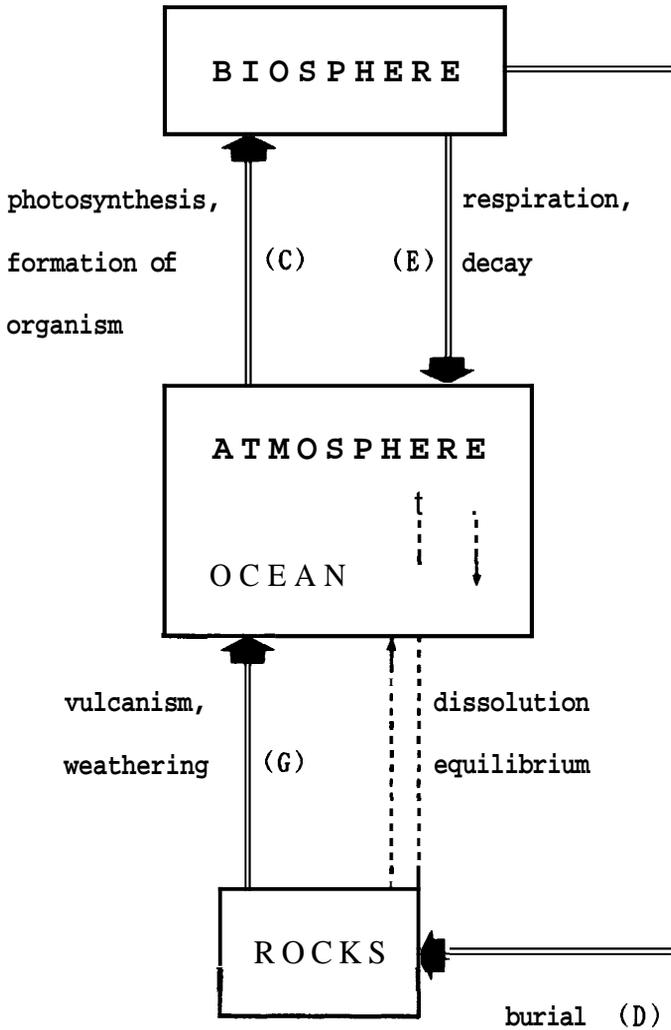
Fig.1.   Model diagram of the bio-related system.

The biological processes governing the prosperity and decline of the biosphere can be expressed using an equation which includes what is called the internal and mutual antagonism (Nicolis and Prigogine, 1977). This antagonism expresses the interdependence of resources and consumers, and reflects the intrinsic property of life to proliferate exponentially to limits ultimately set by the availability of critical resources. That is, it reflects the fact that biota blooms to limits determined by resources. Because the total amount of carbon

on the earth is limited and, as a consequence, the amount of carbon available to biota is also limited, development of a biosphere is thought to be under a strong control of the internal and mutual antagonism.

Carbon can be regarded as a resource offered to the biosphere for its development, because an increase in biota is contingent on a consumption of carbon stored in the atmosphere-ocean system. In other words, the activity of biota is closely related to the scale of photosynthesis. On the other hand, death of biota implies an increase in the amount of carbon available to the other two spheres. These processes, which exemplify the internal and mutual antagonism, are shown in the first term on the right-hand side of eq.(4) or (5). Here, the resource and the consumers correspond to carbon and biota, respectively.

Biological activity is determined by many factors. For example, phosphorus input from the continents may be a determinant of the maximum size of the earth's biomass in the present ocean. However, the scarcity and small size of continental areas during the early earth's stage suggest that this common idea about the phosphate cycling should not be applied throughout the whole earth's history (Schidlowski, 1988). Thus, although biological activity is dependent on many other factors, e.g., temperature, phosphorus and so on, the development of a biosphere is thought to be primarily controlled by the internal and mutual antagonism.

Our proposed system constructs a mathematical model composed of a set of non-linear equations as follows:

$$dx_b/dt = kx_a x_b - Dx_b - Ex, \qquad (4)$$

$$dx_a/dt = -kx_a x_b + Gx_r + Ex, \qquad (5)$$

$$dxJdt = Dx_b - Gx_r \qquad (6)$$

where t is time, and x_b, x, and x_r indicate the proportion of the earth's carbon which is in the biosphere, atmosphere-ocean and rocks, respectively.

The procedure used to obtain the solutions was as follows: for a fixed value of S, initial values of x,, x, and x_r were set at the previous steady state values; the equations were integrated forward in time until a steady state was reached; the value of S was changed incrementally and the procedure was repeated. Calculations were performed for various values of the parameters. Some of the results are shown in Figs.2-5. In these figures, the distribution of carbon (%) for each sphere of influence or temperature is plotted for S. In the following figures, P_0 gives one measure of the ratio of the amount of CO_2 circulating in the cycle shown in Fig.1 to the total CO_2 existing on the present earth's crust. This P_0 is expressed with percentage of the current amount of atmospheric CO_2 (0.03 kPa) to the total CO_2 cycling through the system shown in Fig.1. For instance, $P_0 = 0.001(\%)$ means that 3 MPa of CO_2, i.e., about one half of the total CO_2 existing on the earth's crust, is assumed to be circulating within the cycle shown in Fig.1. Similarly, $P_0 = 0.01(\%)$ corresponds to 0.3 MPa, and $P_0 = 0.1(\%)$ to 0.03 MPa.
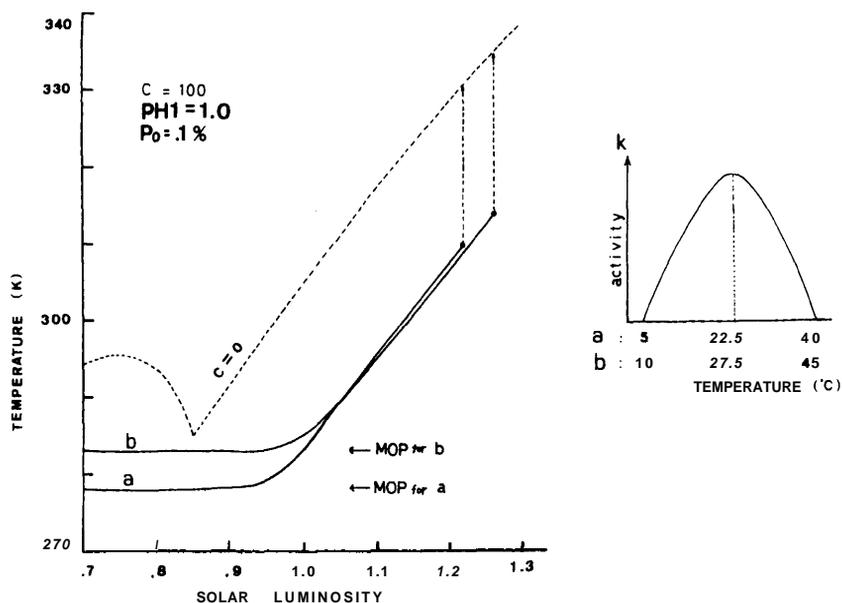
Fig.2. Temperature change of the earth for the gradual increase in solar luminosity S, for varia-
tion in temperature dependence of biological activity k. In the case $\underline{a}$ minimum activities
appear both at 5°C and at 40°C, and in the case b at 10°C and 45°C. $C=0$ represents abiot-
ic conditions. At the dot mark drawn at the end of each solid line, our ecosystem is sud-
denly destroyed and the temperature jumps toward that which prevails at $C=0$. Case b can
survive longer than Case a, owing to a shift of the biological activity toward higher tem-
perature range. Where, $G=1$, $D=E=10$. A minimum operating point (MOP), i.e., a mini-
mum temperature for both the biota and its environment to coexist is indicated for each
Case a and b.

Results

Although the partitioning of CO_2 between the atmosphere and the ocean is
thought to be mainly determined by acidity of the ocean, historical records of
the changes in this acidity are still lacking. So, we have tentatively parameter-
ized the partitioning of CO_2, by introducing the partition rate PH1 which ex-
presses the proportion of carbon present as CO_2 in the atmosphere at the initial
time, as follows: from the initial time corresponding to $S=0.7$ (the factor 0.7
of the current solar flux) to the time of $S=0.85$ (the factor 0.85 of the current
one), i.e., from 4.5 Gyr ago to 2.25 Gyr ago, and assuming linear increase in
solar luminosity, the proportion of total carbon present as CO_2 in the atmos-
phere decreases linearly with time from PH1 toward the current value, i.e., one
tenth of the total amount of carbon existing as CO_2 within the ocean-atmos-
phere system because of the change in acidity of the ocean. As the standard
case, PH1 = 1.0 is used in the following calculations.

After the time of $S=0.85$, the partitioning of CO_2 between the atmosphere
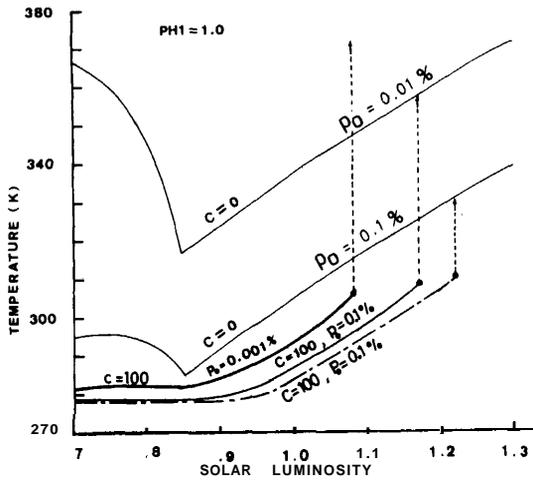and the ocean is assumed to become constant. Discontinuities appearing at

Fig.3.   Same as Fig.2 but for the variation in P_0.

$S = 0.85$ in the following figures are due to this assumption. However, the assumption about the change in acidity of the ocean does not affect our conclusion at all.

Fig.2 shows that, within the solar flux range, $S<0.96$, in which biota can control freely the amount of the atmospheric CO_2, there is a minimum operating point (MOP), i.e., a minimum temperature for the biota to coexist with the earth's environment. And Fig.2 reveals that the earth's environment is always set up to the MOP state if there is a sufficient amount of the atmospheric CO_2 for biota to control freely. The existence of MOP is independent, despite variation in temperature dependence of the biological activity (the Case a and the b). The reason that this MOP state is set up is described in (A) in Conclusions and its conceptual explanation is given in Fig.7. In the following, we use the Case a as a standard one.

Fig.3 indicates that, independent of the magnitude of P_0, the earth's surface temperature is set up close to the MOP condition. As discussed later, the independence of the results on P_0 plays a very important role in the establishment of the bio-regulated system on the earth. Fig.3 also shows that the more P_0 increases, i.e., the more CO_2 the bio-system must control at a given level of activity, the more precarious becomes survival of the ecosystem.

Fig.4 shows the existence of a unique solution (AO in this figure) for CO_2 level in the atmosphere-ocean system, independent of various values of transportation rates. Thus, the regulation of CO_2 level in the atmosphere-ocean system is a universal phenomenon. Even if S exceeds 0.96, the atmospheric CO_2 level remains low and the amount of carbon in the lithosphere and the biosphere remains high, although, because of very small values of these variations, there seems nothing in this figure that shows any continued lowering of the atmospheric CO_2 level, or increasing levels in rocks and biosphere.
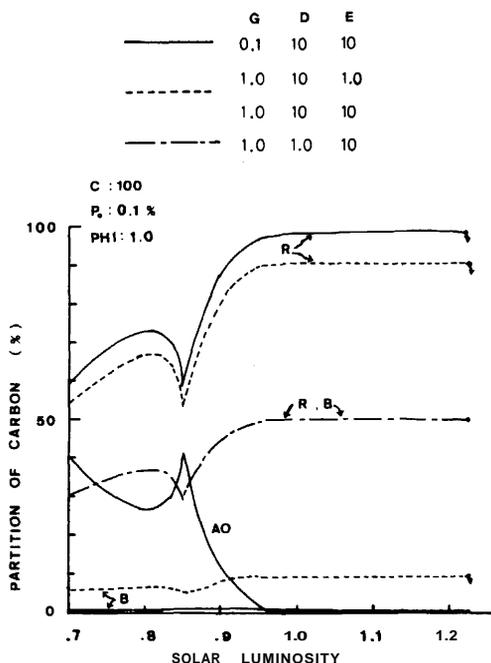
Fig.4.   Distribution of carbon in each sphere for an increase in solar luminosity S. Calculations
are carried out for various changes in transportation rates G, D and E in eqs.(4)-(6). De-
spite the various values given to these rates, the distribution of carbon in each sphere is
regulated for all the cases, so as to maintain the same homeostasis as in the standard case $\underline{a}$
of Fig.2. Consequently, a unique solution, AO in Fig.4, exists, independent of various
values of transportation rates. Where, B, AO and R indicate the biosphere, atmosphere-
ocean and rocks shown in Fig.1, respectively.

Fig.4 explains why there was less biomass on the earth in the past than there
is at present. This is surely due to the regulation of the atmospheric CO, level
to counteract an increase in solar luminosity, and not only to the problem of bi-
otic evolution. Strangely enough, the beginning of the breakdown of the MOP
state coincides with the start of the Cambrian, when life suddenly flourished
on the earth's surface. This implies that, by adding carbon to the biomass, the
earth's ecosystem may have been opposing an increase in solar luminosity.

We also investigate the effects of the temporal development of biological
activity on regulation. In this case, the biological activity C' which varies with
time, is defined as follows and replaces C in eq.(1):

$$C' = C \times 10 \frac{S_L - S}{S_L - S_O} \log r \tag{7}$$

with this C', the following k is used instead of eq.(1):
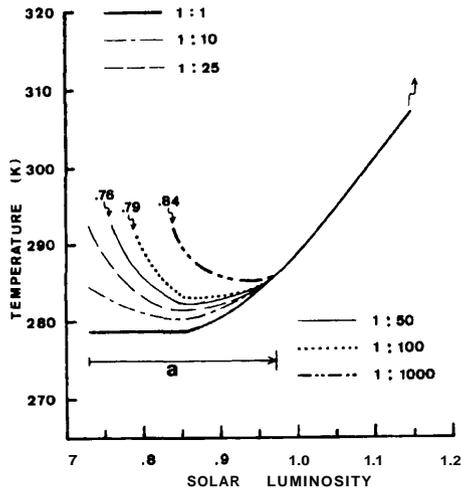
$$k = C'\{1 - a(T_1 - T)^2\} \tag{8}$$

Fig.5.   The averaged temperatures of the earth's surface adjusted to the dim Sun, when biological
activity increases by degrees with ratios described in the figure within a certain period of
time, from 4 Gyr to 0.4 Gyr, which is shown by an arrow head marked with a.

Here, S_0 and S_L are constants about S. We assume that at $S = S_0 = 0.74$ biota
start to be active and after $S = S_L = 0.97$, C' is fixed to be equal to C. The para-
meter r gives the ratio of potential biological activity at $S = S_0$ to that at $S = S_L$.
By r, we can parameterize tentatively the evolution over time of the ability of
the biota to regulate CO_2.

As indicated by the $r = 1:1$ case, (the solid line in Fig.5) wherein the poten-
tial biological ability for regulation has been constant, our earth's environment
has been controlled by biota so as to be in homeostasis from the early ages of
the earth. However, as the $r = 1:1000$ case shows, if the biological ability to
regulate CO_2 was very weak in the early ages, the earth's environment is out-
side biological control until S reaches 0.84. We can see from Fig.5 that the
greater the biological ability at $S = S_0$, the longer the earth's environment can
maintain the MOP state. Fig.5 is in good agreement with some data which
show that the early earth might have been rather warmer than at present (e.g.,
Knauth and Epstein, 1976). Our results suggest that evolution of the ability of
the biota to regulate CO_2 may greatly have affected the earth's early environ-
ment.

Discussions

It should be stressed that, unlike the Walker cycle, our model does not as-
sume any explicit feedback mechanism. The only assumption is that tempera-
ture influences the biological activity (cf. eq.(1), Fig.7), which is a universal
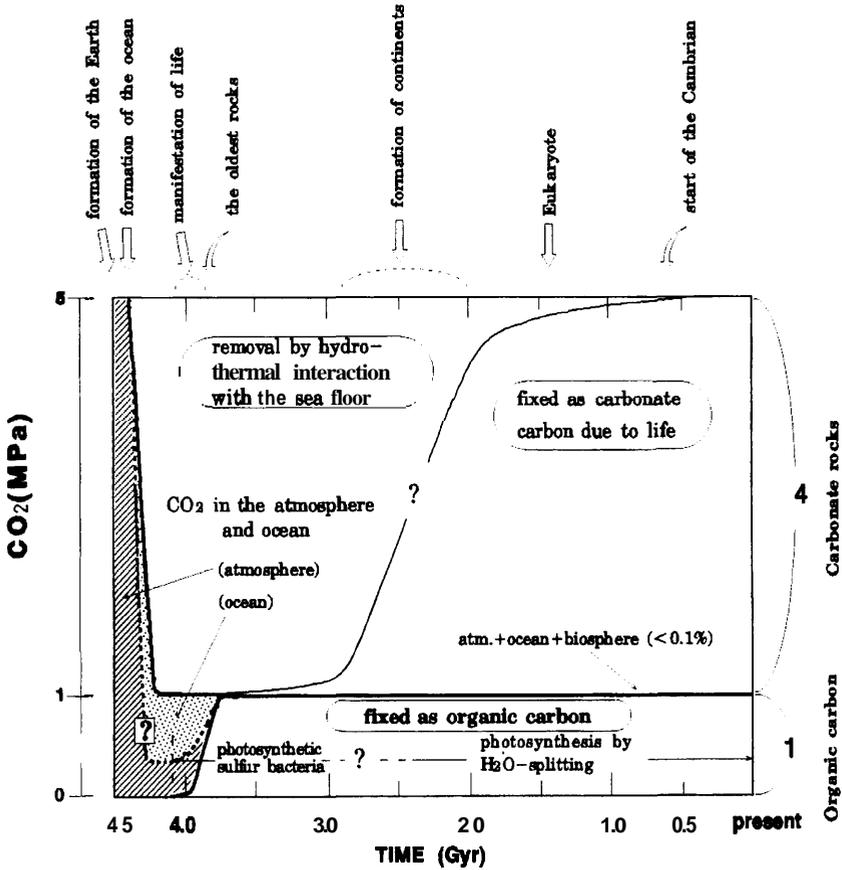property of life.

Fig.6.   Time-dependent distribution model for carbon on the earth.

The existence of our proposed bio-controlled system on earth from the early stage, not long after the earth's formation, is not mere speculation. There is sufficient evidence that photosynthesis has existed as a biochemical process for almost 4 Gyr. The $^{13}C/^{12}C$ ratio in sedimentary rocks is an indicator of the principal carbon-fixing reaction of photosynthesis. Based on a 3.8 Gyr isotopic record, Schidlowski (1988) and Holser et al.(1988) recently pointed out that biological control of the terrestrial carbon cycle may have been established very early and that it was in full operation when the oldest sediments were formed. These authors also point out that photosynthesis has been an important agent in the geochemical transformations of the earth's surface for almost 4 Gyr. Moreover, their results that the $^{13}C/^{12}C$ ratio has been nearly constant suggest that about one-fifth of the total carbon in the surficial compartment has been in organic form throughout the ages. As Schidlowski says, this means that the ancient earth could have been in a state of global biot-
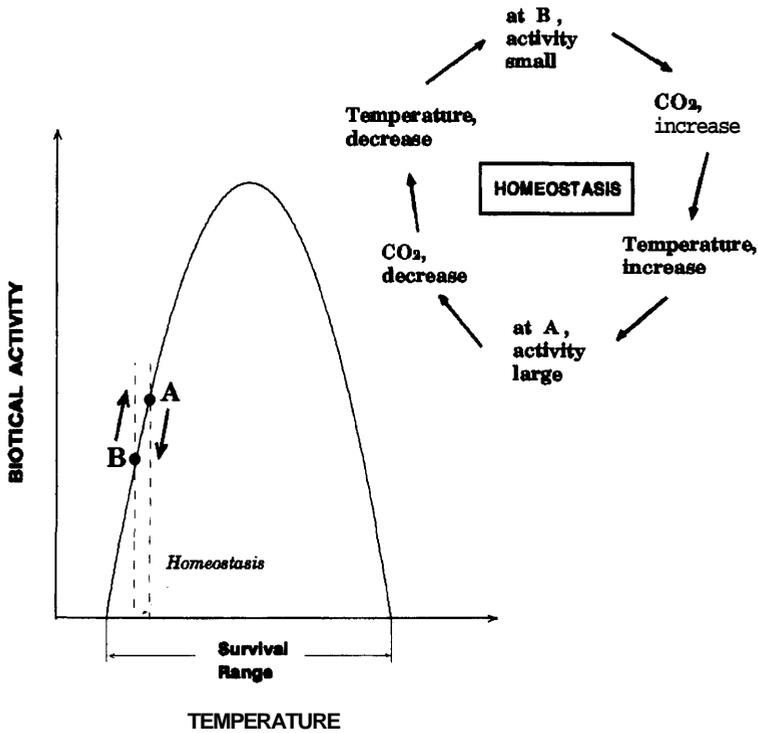
Fig.7.   A conceptual diagram on a mechanism for life to make homeostasis of the earth's environment.

ic saturation. Prolific prokaryotic communities probably bloomed to limits ultimately set by the availability of critical resources.

Bio-regulation of carbon cycling may have been much more effective than our results suggest. CaCO, in the sea must have been produced mostly by marine biota, in the past just as in the present (Broecker,1974). Marine biota would have controlled the atmospheric CO, levels from very early in the earth's history by controlling the production of CaCO,. As for the changes in the atmospheric CO, concentration which occurred during the ice age, Knox and McElroy (1984) propose a model in which the production of CaCO, is closely linked with the activity of the marine biota. Thus, considering an important role of marine biota upon the production of CaCO,, regulation due to biota would have been stronger than that in the model of organic production only. Introduction of such an effect will be put into our model in the future since our results are obtained on the basis of the bio-regulation relating to organic carbon production only.

The carbon excluded from our proposed cycle would, through hydrothermal interaction at the sea floor (Walker, 1985) produce large amounts of inorganic

carbonate rocks. However, it should be emphasized that as soon as carbon appears to the atmosphere-ocean system in a form available to biota, it falls under the control of our bio-regulated system. Thus, again, carbon has been redistributed into each reservoir so as to maintain homeostasis in the earth's environment, i.e., so as to keep the amount of the atmospheric CO_2 nearly invariant in order to hold temperature constant. Whatever disturbances may occur in our system, our proposed mechanism still keeps our environment in homeostasis, because, as indicated in Fig.3, homeostasis is not disturbed by variations in the magnitude of P_0.

For instance, let us suppose that there is 1 MPa of CO_2 in the atmosphere-ocean system in the early Archaean, before our bio-controlled system appears. Most of the rest, i.e., about 4 MPa of CO, , was in the form of inorganic carbonate rocks. Most of the CO_2 in the atmosphere-ocean system (1 MPa) would be present in the air, due to the acidity of the early earth's ocean until our bio-regulated system for the carbon cycling had appeared about 4 Gyr ago. The abiotic model, i.e., the hydrothermal interaction cycle described above, estimates a very thick atmosphere composed of about 1MPa of CO_2 due to the scarcity of continents (Walker, 1985). However, once our proposed system was established on our planet, the MOP state would appear on the earth before long.

It is by no means difficult for biota to bring the system under control in a short time, because biota sustain a formidable rate of fixation of atmospheric carbon. One should note that microbial communities (specifically cyanobacteria), which are among the most productive ecosystems we know of, have rates of CO_2 fixation that render them capable of producing all the organic carbon currently on the earth within 10^4-10^5 yr.

Thus, about one-fifth of the carbon within the earth crust would be in circulation in the organic carbon cycle proposed, so as to regulate the amount of the atmospheric CO_2 to maintain our environment in homeostasis. This inference is in accord with the records of carbon isotopes indicating that organic carbon has comprised about one-fifth of the total carbon in the surficial compartment for almost 4 Gyr.

One should recall that, as previously mentioned, the ancient earth was never abiotic but, rather, was in a state of global biotic saturation from an early stage. It should also be noted that the rate of carbon fixation in microbial mat communities, stromatolites, would have been higher at the greater levels of atmospheric CO, that were present in the past (Rothschild and Mancinelli, 1990).

In Fig.6, we propose one model for distribution of carbon (or CO_2) on the earth, which is in agreement with the carbon isotopic data. Before the ocean was created, all the carbon was in the atmosphere in the form of CO_2 gas. Once the ocean had been formed, the atmospheric CO_2 would gradually have dissolved into the ocean, with an increase of pH of the sea due to release of cations supplied by dissolution of basalt into the ocean. Deposition of carbonate rocks followed, due to hydrothermal interaction at the sea floor (Walker, 1985). The partitioning of CO_2 between the atmosphere and the ocean is strongly dependent upon the pH of the ancient ocean. However, as soon as life

had appeared on our planet about 4 Gyr ago, the bio-regulated system for the carbon cycle that we suggest in this paper would have been in full operation. Thus, from the early stage up to now, the ratio of organic carbon to carbonate carbon has been fixed at 1:4, as indicated by the isotopic data. Life would have taken charge of removal of about 1 MPa of CO_2 from the atmosphere, and have deposited it as organic carbon. If life had been absent, this CO_2 would have remained in the atmosphere. Fig.6 shows that this CO_2 fixation was at first accomplished through bacterial photosynthesis by e.g. sulfur bacteria. Bacterial photosynthesis preceded the evolution of the H_2O-splitting reaction (e.g., Holser et al., 1988).

In the early stage, carbonate rocks would have been produced by the abiotic mechanism of hydrothermal interaction at the sea floor, as pointed out by Walker. However, more carbon would gradually have been fixed by marine micro-organisms as CaCO, (Omori, 1988; Okazaki and Setoguchi, 1988). As the process of photosynthesis intensified, this increase would have accelerated because the rate of calcification in micro-organisms such as algae increases linearly with photosynthesis (Borowitzka and Larkum, 1976). The increase in continental area would also have accelerated the CO, fixation into CaCO,. As the supply of cations increased through weathering of the land masses which emerged some 25 Gyr ago, marine biota would gradually have become the predominant source of CaCO,. After the Cambrian, marine life had developed such calcification mechanisms as formation of coral skeleton and mineralization of mollusk shell. The so called silicate weathering mechanism for deposition of carbonate minerals would have been highly accelerated by the emergence of these marine biota. Today, above 95% of carbonate rocks are of organic origin. This is also shown in Fig.6.

Conclusions

In summary, we conclude as follows:

(A) Until the incident solar flux reaches the value point $S = 0.96$, biota attempt coexistence with the earth's environment by regulating the atmospheric CO, level so that the average temperature coincides with their MOP. On the other hand, if the average temperature were to be set at higher level, atmospheric CO, would decrease in time, due to the higher activity of biota. In consequence, the temperature would decrease to a point which biota would not tolerate. This conflict between CO, level and biological activity is the reason why biota prefer to keep the MOP on the cool side of the optimum for the biota and to keep the earth's surface temperature in homeostasis. As soon as the biosphere had appeared on the early earth, biota and the earth's environment started to coevolve as a holistic system. Or, we can say as follows: life cannot coexist with an environment which is unfavorable for life. This "Principle of Existence" has kept the earth's environment in homeostasis for a long time. A conceptual diagram of this is given in Fig.7.

(B) Our bio-regulated system must resist the increase in solar flux by lowering the atmospheric CO, level. According to our result, when the solar flux S reaches 0.96, even an atmospheric CO_2 level nearly equal to zero is too large to maintain the MOP condition. Today, only a few hundred ppm of CO_2 remain in the atmosphere for biota to regulate. Although biota do their best to lower the CO, level in the atmosphere and to survive as long as possible by transporting carbon into the biosphere and the rocks, the increasing solar flux will eventually overcome the effort of the biota. This will bring about the end of our bio-regulated system. This prediction is in good accordance with that of Lovelock and Watson (1982). According to the present model, our ecosystem in now on the way to ruin, having already left the MOP state some six hundred million years ago, which strangely enough, coincides with the start of the Cambrian, when life suddenly flourished on the earth's surface.

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