“ACTIVE PLANETARY COVER” CONCEPT AND LONG-TERM EVOLUTION OF PLANETARY CLIMATE

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Abstract: Earth’s surface skin can be characterised as the living boundary layer between the pedosphere and the atmosphere. Via various processes, this highly structured “bio-film” regulates the accumulation of energy and substances, their transformation and transportation and, in particular, the exchange of substances between atmosphere and sub-surface soils. Defining an “active planetary cover” (active planetary surface) as a dynamical system which directly dominates overall climatic processes and, in turn, is influenced by the climate, multiple equilibria states are generated which are determined by using the “virtual biospheres” concept (Svirezhev, 1994). New results concerning the early stages of Earth’s history (2 – 3 aeons ago) are achieved by regarding only one large and flat continent surrounded by mountains avoiding any contact to the slightly acid ocean existing at that time: The model-continent is thought to be covered by shallow water-bodies: epicontinental seas which were ideal niches for the Cyanobacter microbial mats (CBM) generating an early photosynthetic ecosphere according to Zavarzin’s biosphere approach. In accordance with thermodynamics calculations this system transforms the atmosphere of juvenile gases to an atmosphere containing of 1% of CO_2 and 8% of O_2 during one billion year forming a hot atmosphere with temperatures $\approx 40 - 50\ ^\circ$C and the pressure of about $\approx 5 - 8$ bar. After intensive orographic processes the depth of intercontinental seas increases and the early biosphere of the CBM perishes.

When we study the History of Science we discover two mutual contrary phenomena: either behind an apparent complexity a simplicity is hidden or, on the contrary, an evident simplicity conceals within itself an extraordinary complexity. (H. Poincaré, 1894)

INTRODUCTION

At the beginning of XIX. century J.-B. Lamarque had introduced the term "biosphere". In accordance with his definition the biosphere is a "scope of life" and it is an external cover for the Earth. In 1875 E. Süss, who also distinguished the biosphere as one of the Earth covers, introduced the same term in geology. But V. Vernadsky was the person who first created the modern concept of the biosphere as an active planetary cover, which does not only passively reflects its geological and geochemical environment but also transforms it. So that Lovelock (1979) has done only a next step when he has postulated that this transformation is an act of self-regulation creating optimal conditions for the biosphere existence.

If to formulate Vernadsky's concept as some axiomatic theory we have to understand: what kind of axioms lies at its basement? (Here they are presented in a more formal form than in Vernadsky's original work (1926))

1. In the course of all geological periods the living organisms have never been created directly from inorganic matter.

There is the analogue of this axiom in biology called Redi's Law ("life comes only from life").

2. The existing facts can not answer the question about the origin of the Earth life and its ancient history.

Certainly, we can use different speculations but having done that we go away beyond the framework of Vernadsky's Empirical Generalisation Method. There is only one way to resolve this contradiction, namely, to postulate that in spite of the fact that the possible pre-biosphere histories could be different, a result of the biosphere evolution in the course of all geological periods must be the contemporary biosphere. This is a typical ergodicity axiom. Mathematically this means that a topology of the system (biosphere) is sufficiently simple and it is "almost linear". May be this is true but it is now more and more clear that we are living in a "non-linear world". Therefore the "virtual biospheres" concept was suggested (Svirezhev, 1994): the contemporary Earth's biosphere is one of many possible (virtual) biospheres corresponding to multiple equilibria of some non-linear dynamical system, the "climate + biosphere + chemosphere + geosphere". In the course of planetary history and as a result of its own evolution and the evolution of its environment, the system passed through several bifurcation points, when external (in relation to the system) factors determined the direction, the biosphere would take.

3. There were no lifeless geological epochs.

This means that the contemporary living matter is genetically connected with living matter of all previous epochs *(continuity axiom).*

The next two axioms have, actually, a form of conservation laws. However, since they postulate some equilibrium properties of the biosphere, they can be called the axioms of *stationary state.*

4. The chemical composition of living matter was, on the average, the same as it is now.

5. The amount of living matter, on the average, was the same for all geological time.

These Vernadsky's axioms cause a lot of objections at the present time. And finally, the axioms, which determined the principles of functioning of the biosphere mechanisms, are:

6. The energy, which is stored and emitted by living organisms, is the solar one.

By means of them the energy is controlled the global chemical (in particular, the global biogeochemical cycles).

7. Vegetation plays the main role in the assimilation and allocation of the solar energy.

To agree with the axiom of the constancy of the total amount of living matter we have to assume that the biosphere evolution is followed by the way of only structural complication of the living matter.

Developed on the base of these axioms any model will be already the model of Vernadsky's biosphere, but any change of any axiom will give us some new model (of virtual biosphere). Let us try to consider an evolutionary tree of virtual biospheres instead of the almost linear graph of Vernadsky's biosphere. How to do this?

ACTIVE PLANETARY COVER AND POSSIBLE CANDIDATES TO PLAY THIS ROLE

If keeping in mind that life is a phenomenon, which can exist in some relatively narrow interval of temperatures, then immediately the following question arises: how is the planetary temperature kept within the interval? Is this a result of self-regulated interactions between the biosphere and climate (Lovelock, 1979; Schwartzman, 1999) or a purely random combination of different terrestrial and extra-terrestrial processes (Budyko et al., 1985)? Before to answer the question we introduce the following definition.

We define an active planetary cover ("planetary skin") as some system which directly affects the climate, forms it and, in turn, its dynamics depends on the climate. The system has to possess multiple equilibria.

Let $T(t)$ be the mean annual temperature of the Earth, $S(t)$ be the mean solar radiation, C be the total amount of atmospheric carbon, $\sigma(C)T^4$ the outgoing black-body radiation with $\sigma(C) = \sigma_0\phi(C)$ where σ_0 is the Stefan-Boltzmann constant and $\phi(C)$ is a monotonous decreasing function describing the greenhouse effect. The "skin" will be described by the variable p, which is a part of the Earth surface "covered" by skin with albedo α_p; a remaining part of the surface has albedo α_q. For instance, this can be the percentage of the

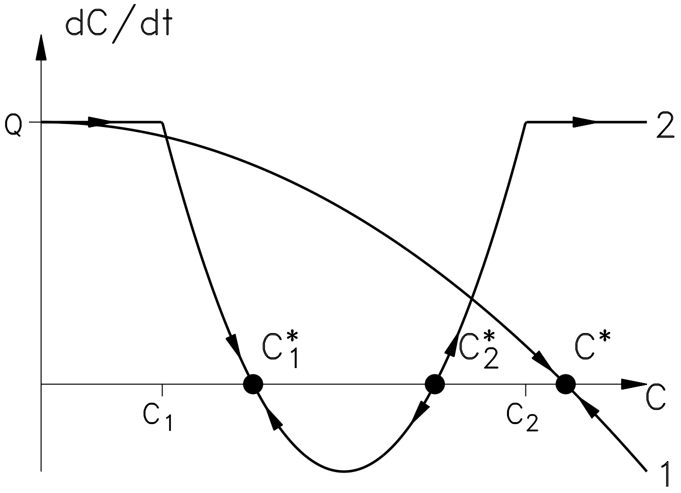

Figure 1 System phase portraits: (1) the planet surface is weathered, only weathering takes carbon out of the atmosphere; (2) the planet is covered by "green cover" with an unimodal temperature function.

Earth area taken over by the continents. We assume that $S(t)$ and $p(t)$ are the given functions of "slow" time. Then the simplest zero-dimensional model of such sort of planetary skin can be presented in the form:

$$\begin{aligned} T &\approx \left(\frac{S[(1-\alpha_q-(\alpha_p-\alpha_q)p)(1+\rho)]}{\sigma(C)}\right)^{1/4}, \\ \frac{dC}{dt} &= Q-\beta(T)pf_c(C) \end{aligned}$$

where ρ is the coefficient of spatial correlation between $\lambda = 1-\alpha(x)$ and $S(x)$, x is spatial co-ordinate that reflect a spatial interposition of skin and "free" surface on the Globe. The value $\beta(T)$ describes dependence of the rate, with which the skin takes carbon out of the atmosphere, on the temperature. $Q(t)$ is the inflow of carbon from the mantle (volcanism).

Let us consider different candidates for the role of active cover, which can actively regulate the Earth temperature.

a) "planet with weathering": For this process $\beta = \beta_w \sim \exp(\delta T), f_c \sim \sqrt{C}$. The phase portrait of the system described by (1) is shown in Fig. 1. There is only one stable equilibrium C^*, which "floats" in slow time. It is the solution of equation $\beta[T(C^*, p)]pf_c(C^*) = Q$. It is obvious that corresponding to C^* the temperature T^* can get into the tolerable interval $[T_1, T_2]$ only accidentally.

b) "planet with vegetation" ("green cover"): In this case $\beta = \beta_\nu$ is a finite unimodal function within the interval $[T_1, T_2]$ and $\beta \equiv 0$ outside of

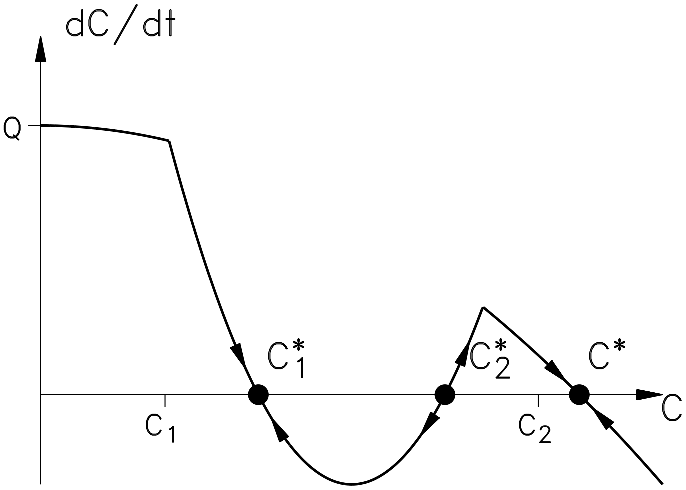

Figure 2 A system phase portrait: the planet cover is a combination of "chemical" (weathering) and "biological" (vegetation) covers. It is assumed that chemical and biological pumps work simultaneously.

it. The function f_c is a monotonous increase function with saturation. The corresponding phase portrait is also shown in Fig. 1. There are two "slow floating" equilibria: stable with lower temperature, C_1^*, and unstable with higher one, C_2^*. Since then this means that the "green cover" can maintain the equilibrium temperature $T(C_1^*)$ belonging to the tolerable interval and lying in its low part, but the stability domain of the equilibrium is very small. Its upper boundary is $C_2^* < C_2$ which corresponds to $T(C_2^*) < T_2$, i.e., it lies lower than the upper tolerable temperature.

c) "planet with vegetation + weathering": The best results in the sense of stability and maintenance of the tolerable interval for life can give the combination of "chemical" (like weathering crust) and "biological" (like vegetation) covers. Let us assume that chemical and biological pumps work simultaneously. Then the equation for atmosphere carbon is written as

$$\frac{dC}{dt} = Q/p - [\beta_\nu(T) f_c^\nu(C) + \beta_w(T) f_c^w(C)]. \tag{1.1}$$

From its phase portrait (Fig. 2) one can see that the system behaviour became more complicated, where this complexity depends on the value of bifurcation parameter Q/p. Let us consider its slow evolution from large to small values. When Q/p was large (high volcanism, small continental area that corresponds to the early Earth history), only one already stable equilibrium exists. A leading role plays here the weathering. The area of continents increases, the volcanism decreases, the value of bifurcation

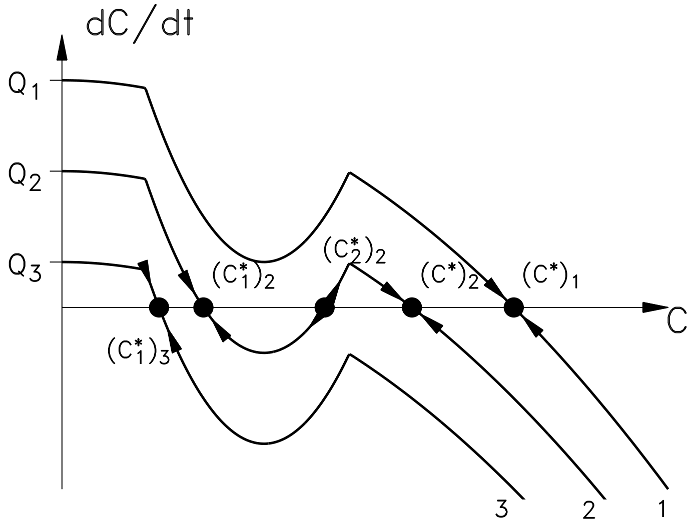

Figure 3 The planet cover is a combination of "chemical" (weathering) and "biological" (vegetation) covers. Phase portraits are considered for three values of carbon inflow from the mantle into the atmosphere: $Q_1 > Q_2 > Q_3$
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parameter Q/p also decreases. In the system arises an interesting transition regime with three equilibria: two are stable and one (intermediate) is unstable. If the first stable equilibrium corresponds to lower temperature lying within the tolerable interval then the second stable equilibrium corresponds to higher temperature lying outside of it. In order to shift it even if to the high border of the tolerable interval we additionally have to manipulate the cover albedo and its relative area. At last, let us consider the case with low value of Q/p when the volcanism is small and the continental area is large (present time). One equilibrium with tolerable temperature only is stable. The main role in the regulation of the Earth temperature plays the vegetation. Further decrease in Q/p takes the stable temperature outside of tolerable limits. The biosphere would be finished, the Earth would be transformed into an "ice desert".

d) **"planet - chameleon":** At the beginning the skin of planet had been "lunar" colour with $\alpha = 0.07$ that did not differ from the oceanic albedo ($0.07 - 0.10$). The radiation temperature of this planet was equal to 275 K. The mantle degassing can rise the planetary temperature up to 60°C–70°C. If the new atmosphere contains H_2O, CO_2, NH_3, H_2S, S_2, HCl then an optical (not chemical) result of interaction between these gases and the matter of "lunar" surface was, as a rule, the increase in albedo. The analogous result will be assuming that the atmosphere contains a sufficient amount of oxygen to oxygenate surface rocks. For instance, the albedo

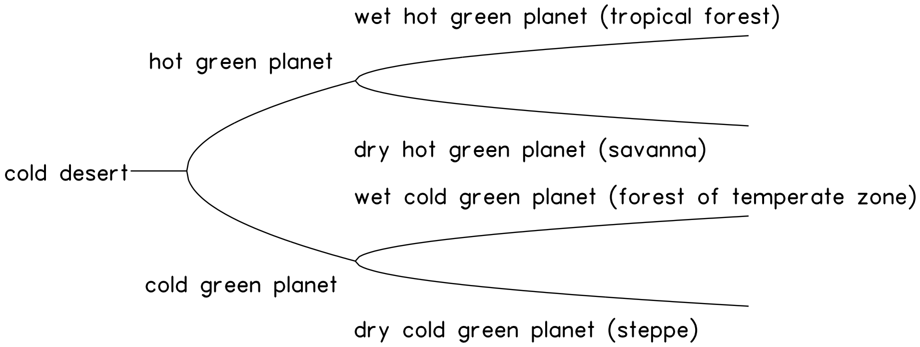

Figure 4 A bifurcation diagram of the system "climate + biosphere".

> of red sands is equal to 0.2. The finale stages of weathering are carbonates and sands with $\alpha = 0.3 - 0.4$. A rise of living skin of green colour (cyanobacterial mats, vascular plants, etc.) also increased the albedo up to $\alpha = 0.12 - 0.22$. All these processes led to one result: drop of initial temperature of the planet shifting it to tolerable values for life. On the other hand, if the planet was initially covered by snow then the vegetation arised and its further propagation increased the temperature also shifting it to tolerable values.

Revenons à nos moutons and keeping in mind our question we can answer that the truth lies, as usually, in the middle: in order to get into the tolerable life interval we need a suitable combination of abiotic factors. But after the life has been arisen, it can maintain the global thermostat for its self-existence.

COMPLEX NON-LINEAR BEHAVIOUR OF PLANET COVERED BY "GREEN COVER"

Let us consider the following model (in details it is described in (Svirezhev & von Bloh, 1998), when a typical example of active cover is the vegetation (surface biota), which is a main component of the biosphere. It changes the planetary albedo and influences the atmosphere composition trough the global carbon and hydrological cycles that leads to the change of climate. In turn, the dynamics of vegetation depends on the climate and the concentration of atmospheric CO_2. The system has the following bifurcation parameters:

1. The total amount of carbon. In the course of a "slow" planetary evolution (characteristic time $\approx 10^5$–10^6 years) this value, involved in the "crust - biosphere" cycle, has been changed by the processes of silicate-rock weathering and volcanism. The latter is directly connected with the tectonic activity and continental dynamics.

2. The total amount of water.

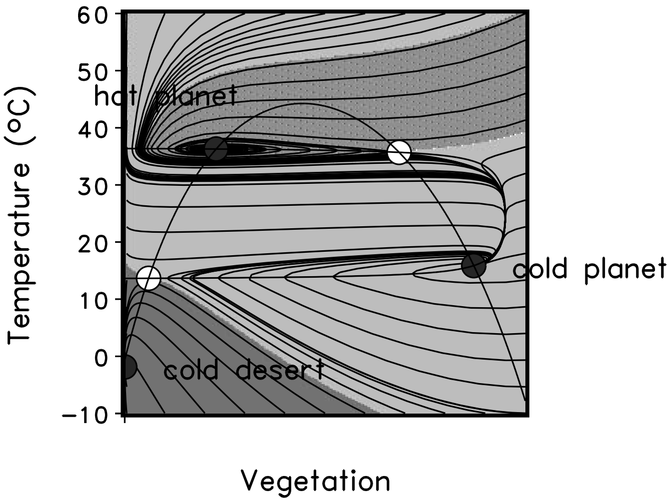

Figure 5 A phase portrait of the system "climate + biosphere" (projection onto the plane (temperature, vegetation).

3. The product $P_m\tau$, where P_m is a "potential" productivity of global vegetation and τ is a residence-time of carbon in biota. A "slow" dynamics of this parameter is closely connected with the evolution of carbon transformers and oxygen producers: from microorganisms to vascular trees.

What kind of bifurcation is possible in this system (Svirezhev, 1999)? We can observe the change of the planet's "status" from "a cold (ice) desert" either to "a cold green planet" or to "a hot green planet" (first bifurcation). Then either "a wet hot" planet, covered by tropical rain forest, or "a dry hot" planet (savanna) develops from hot green planet as a result of second bifurcation. Analogously, either "a wet cold" (temperate forest) or "a dry cold" (steppe) planet arise from green cold planet (Fig. 4). In this figure the bifurcation diagram is presented as a branching structure depending on one general value. Really, it depends on all three bifurcation parameters.

We shall consider the system with two causal loops: (1) vegetation ⇒ albedo ⇒ temperature ⇒ vegetation, (2) vegetation ⇔ atmosphere carbon ⇒ temperature ⇒ vegetation. In this case the system can have up to five different equilibria: three of them are stable and two others are unstable. The projection of its phase portrait onto the plane (T, N) where T is the temperature and N is the density of biomass is shown in Fig. 5.

There are four attractive domains corresponding to the following equilibria:

1. "cold desert" when the planet has no vegetation and the planetary temperature is less than $-3°\mathrm{C}$.

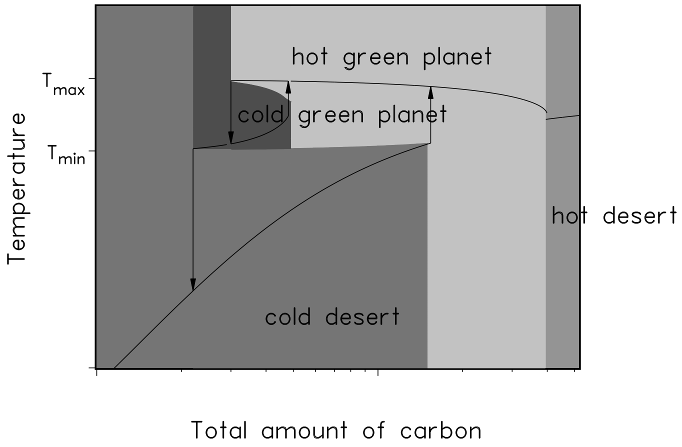

Figure 6 Bifurcation diagram of the "climate + biosphere" system. Black lines indicate trajectories of the evolution for either decreasing or increasing carbon. Gray-shaded areas denote the basis of attraction of the stable equilibria.

2. "cold green planet" with a rich vegetation and relatively low temperature, approximately equal to the current Earth's temperature, 15°C.

3. "hot green planet" with a poor vegetation and relatively high temperature, higher than 30°C; that is typical for Earth's hot deserts.

4. "hot desert" is a lifeless planet, its temperature is higher than the upper boundary of the tolerable interval ($> 60°$C).

Let us consider the evolution of the system topology when the total amount of carbon, A, slowly decreases. Fig. 6 plots the temperatures of the different equilibria as a function of A where the black lines indicate trajectories of the evolution for either decreasing or increasing carbon. Gray-shaded areas are the so-called basins of attraction, i.e. the set of initial conditions, starting in which trajectories come to the same stable equilibrium. The area denoted as the "cold desert" is the solution without vegetation on the planet. The equilibrium temperature lies below the lower tolerable temperature T_1, while the "hot desert" marks a solution with a temperature, which is too hot for the vegetation. The "hot green planet" and "cold green planet" are the non-trivial solutions with low and high vegetation densities, respectively.

Two hysteresis loops can be identified. Starting with the "hot desert" the planet evolves in the following way: hot desert ⇒ hot green planet ⇒ cold green planet ⇒ cold desert. The transition "hot green planet ⇒ cold green planet" is accompanied by almost an explosive increase in vegetation biomass 8–10 times. Starting from the cold desert, however, a different path is realized: cold desert ⇒ hot green planet ⇒ hot desert. This means that a current state of the coupled climate-biosphere system depends on its history. The change from one to another equilibrium is done in a non-continuous way. The arrows in the diagram indicate non-continuous transitions. The rise of the hot green planet from the hot desert only is a continuous process.

CYANOBACTERIAL MATS AND ZAVARZIN'S EARLY BIOSPHERE APPROACH

Let us consider our planet at early stages of its history (2 – 3 aeons ago) when one large and flat continent only was surrounded by mountains (Zharkov, 2000), so there was no contact between the continent and the slightly acid (pH = 4 – 5) ocean. This entire "saucer" was fulfilled by shallow water-body systems of intercontinental seas and lakes, which were ideal niches for Cyanobacter microbial mats (CBM). All this forms a special type of active cover, which consists of photosynthesising prokaryotic communities: CBM. This system can be considered as some first stage of the biosphere succession: the biosphere of CBM or Zavarzin's biosphere (Zavarzin, 1984). Namely this system has played a main role (as a predecessor) in the formation of the contemporary Phanerozoic biosphere and atmosphere. If assuming that contemporary CBM are analogues of those ancient ones then we can say that the CBM were optimally adapted to their ecological niche. Using results of the work of Gerasimenko & Zavarzin (1994) we distinguish the properties, which may play an adaptive and regulating role.

1. Their productivity was very high (as by contemporary tropical rain forest). For instance, under sub-optimal conditions (salinity $\sim$ 16–21%, $T^0 \approx$ 40–45°C), the annual gross production and destruction of CBM is equal to 1.6 kgC/m^2 and 1.1 kgC/m^2 , correspondingly. Their difference is equal to 0.5 kgC/m^2. Although the destruction in CBM are mostly anaerobic but the production of oxygen by photosynthesis is proportional to this difference so that one square meter of CBM produces 1.3 kg O_2 per year.

2. CBM were covered by mucopolysaccharide films ("mucus"). A sandwich from 2 m of water and 2 mm of mucus guaranteed practically the full defense from UV radiation. Diffusion in mucus is the same as in pure water, mucus fibers within CBM are very good light-conductors, due to this the light and nutrients are transported to the whole volume of CBM.

3. Due to the high species diversity of organisms, which form the mat, a full use of visible spectrum was attained.

4. CBM create conditions for $CaCO_3$ formation, since over a mat the pH = 8.4 – 9.6 and the concentration of HCO_3 is equal to 280 mg/l, while under a mat the pH decreases to 7 and the concentration of HCO_3 is equal to 915 mg/l.

CBM have a perfect structure organisation: light conductors, calcium and gypsum quasi-skeleton, their “shark skin” adjusted external water flows increasing the nutrients transport, etc. .

Considering the scenario in which the area of intercontinental seas covered by CBM was 10^7 km^2 ($\sim 6\%$ of the contemporary continental area), we assume that all water, which was degassed from the mantle, is concentrated in the contemporary hydrosphere, 1.64×10^{24} g. All degassing nitrogen is concentrated in the atmosphere, 4.1×10^{21} g. If we test the composition of volcanic gases of the different origin (Voitkevich & Bessonov, 1986) then the best approximation will be the emission of Iceland geysers and fumaroles: 99.4% H_2O, 0.33% C in the form of CO_2, 0.05% N_2. In accordance with these assumptions we get the estimations for N_2: 0.825×10^{21} g, and for carbon (in the form of CO_2): 5.445×10^{21} g. In order to remove all this carbon dioxide 10^7 m^2 of CBM have to work one million years. 1.45×10^{22} g oxygen will be produced by photosynthetic mats. The most part of oxygen is spent for the oxidation of FeO, CO, SO_2 and H_2. The contemporary atmosphere contains 1.1×10^{21} g.

Certainly, this is some extreme estimation under conditions very close to optimal ones. Substantively, the process of the atmosphere CO_2 “grazing” by CBM occurred much slower.

In accordance with Ronov’s estimation (Budyko et al., 1985) the stratisphere contain 9.8×10^{22} g C. This value is 18 times higher than the estimation, which was mentioned above. In order to get a better consistency of these estimations we can either increase the percentage of N_2 (~ 5 times) and C ($\sim$18 times) in volcanic emanations or decrease the total amount of degassed water.

Let us consider the following thermodynamic model: a flow of mixed gases with the concentrations corresponding to volcanic emanations passes through an active membrane with properties of CBM. The process is isothermic and isobaric: $T^0 = 50^\circ$C, pressure = 5 bar. Using the methods of non-linear thermodynamics we calculated the equilibrium atmosphere, which was established behind membrane: 1% of CO_2 and 8% of O_2.

When as a result of intensive orographic processes the depth of intercontinental seas has begun to increase, this was a reason of massive ruin of CBM since their density was ~ 1.39 g/cm^3. The biosphere of the CBM has perished as the contemporary (Phanerozoic) biosphere (the biosphere of vascular plants), which has appeared about 0.6 billion years ago, would perish about 0.6 billion years after (Franck et al., 2000).

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