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Research article

Geothermal energy as an initial factor in the process of life origin

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Abstract: Based on the concept of thermodynamic inversion (TI), the role and place of geothermal energy (including thermal and high-frequency fluctuation energy) in the process of the emergence of the biosphere is considered, and a comparison is made with an alternative solar power source. From the standpoint of the general thermodynamics of systems, the appearance of signs of a living state in nonliving organic systems means a transition from the prevalence of the entropy contribution in the system ($S_c > F_c$) to the relative prevalence of the free energy contribution ($S_c < F_c$). Such a transition can only occur in conditions far from equilibrium in the presence of different-rank oscillations of physical and chemical parameters in the environment (temperature, pressure, chemical, and electrical potentials, etc.). Their range must include high-frequency (short-period) oscillations that bring maximum energy to the prebiotic system. Such conditions exist in hydrothermal systems during the fluid migration to the surface. Five stages of the origin of primary living cells have been identified. In the initial stages (1–3), which occurred in the subsurface areas of hydrothermal systems, self-assembly of organic microsystems and their primary evolution to the level of protolife (subcells with a primary protein-synthesizing apparatus without DNA) occurred due to geothermal energy. With the exit of subcells on the surface in geothermal regions, life (as we know it) emerged due to the involvement of solar energy into the process: a cell growth cycle appeared and formed a genetic apparatus (4–5).

Keywords: origin of life; hydrothermal system; thermal energy; thermodynamics of systems; oscillations of parameters; first cells; sunlight

1. Introduction

There are two alternative energy sources that are used to explain the origin of life (OoL): solar and geothermal. The first one was proposed as a key factor in the very first hypotheses of the OoL on Earth put forward by A. Oparin in 1924 and J. Haldane in 1929. Subsequently, many chemical models of prebiological evolution were proposed, which were somehow connected with sunlight and the ocean as the maternal environment for the OoL [1–5]. In particular, the popular hypothesis of the RNA world suggests a moderate temperature of the environment for the OoL due to the low thermal stability of these macromolecules in vitro (up to 80–85°C). Such temperature values are considered as most probable for the ocean 3.6–3.9 billion years ago, when the simplest life on Earth was formed.

Geothermal energy was first considered as a key factor in a joint publication by J. Corliss *et al*. [6]. According to their hypothesis, the first microorganisms emerged in areas of hot springs on the ocean floor (the so-called “black smokers”) without the participation of sunlight. Additionally, there were many variations that developed these approaches [7–16]. According to the latest generalizations in this area, life originated either in hot springs on continents [17], in underwater hot vents at the bottom of the oceans [18], or in subsurface regions of hydrothermal systems [19].

Moreover, there are many variations that developed these approaches. One of the approaches to the emergence of life in a hydrothermal environment is the concept of thermodynamic inversion (TI), the starting point of which is a fundamental consideration of the transition of non-living organic microstructures into a living state from the standpoint of the general thermodynamics of systems [20–23]. In this article, it is presented in a conceptual form. This approach allows us to take a new look at the role and place of each of these types of energy in the process of the biosphere emergence.

2. Thermodynamic border between non-living and living systems

To date, many models of prebiotic systems have been proposed that are considered to be the predecessors of the primary living cells on Earth. Some models exhibit properties that are also characteristic of living cells. These include the presence of catalytic activity, the ability to selectively extract substances from the environment, and the ability to divide. However, all of them do not have the following key properties that demonstrate the activity of living systems (populations, cells) in the environment:

(1) The ability to boundless expansion (demands surplus free energy); and

(2) Purposeful behavior (demands surplus information)

The comparison of non-living and living systems from the thermodynamic point of view has been made on a basis of three universal notions - entropy, free energy, and information [21–23]. Free energy (F) is a measure of high-energy value (a part of the inner energy that can be converted into any kind of work). Information (I) is a value that reduces the uncertainty in a system’s state. Entropy (S) is both a measure of the low-energy value and a measure of disorganization [24,25]. There are strict formulas that use these values to calculate the change in free energy (Helmholtz or Gibbs) and the entropy in any process. The most general Helmholtz formula used in physics that includes these terms is the following:

$$F = U - TS,$$

where F is the free energy, U is the inner energy, T is the absolute temperature, and S is the entropy.

For example, this formula is suitable to calculate entropy changes in physical systems (in particular, in heat engines). The meaning of introducing temperature into this formula is that with its increase, the vibrations of atoms increase, which leads to an increase in disorder (that is, entropy) in the system. In living organisms, temperature is not a key parameter: the change in order / disorder in them is more related to other parameters that regulate biological organization. For this reason, the author uses more general terms to compare such fundamental types of natural systems as non-biological and biological: free energy contribution (F_c) and entropy contribution (S_c). At the same time, the physical meaning of these terms retains. Considering these types of natural systems from the point of view of their macrostate (i.e., through the Clausis approach), we can formulate the following thesis: the macrostate of a natural system is generally determined through the balance of contributions of free energy and entropy: "the total contribution of entropy (S_c) / the total contribution of free energy (F_c)" [21–23]. Of course, in any natural system, there are many microstates depending on a change in the S_c / F_c balance in its local areas due to the occurrence of various chemical reactions. Additionally, they have some influence on the existence of the system. However, within the given broad approach, microstates are treated as secondary factors and are not taken into consideration.

Considering the boundary between living and nonliving systems from the point of view of chemistry and thermodynamics, the following conclusion can be made: in the context of chemistry, biological and prebiotic chemical evolution themselves in the complexification of organic molecules and structures (Figure 1). From the point of view of the general thermodynamics of systems, the directions of evolution of chemical and biological systems are opposite. Being nonliving, chemical systems (including prebiotic ones) exist or evolve with a tendency to increase the entropy, which follows from the second law of thermodynamics. In the course of the evolution of the biosphere, the opposite tendency of living systems to concentrate free energy and information with a relative decrease in entropy manifests. Both of these tendencies are well known. However, their fundamental consideration in studying the issue of the origin of primary living cells leads to the conclusion that at the moment of the appearance of a living state in nonliving organic systems, a change of dominants occurs in them: a transition from the prevalence of entropy in the system to the relative prevalence of free energy and information. The author calls this transition a thermodynamic inversion [21].

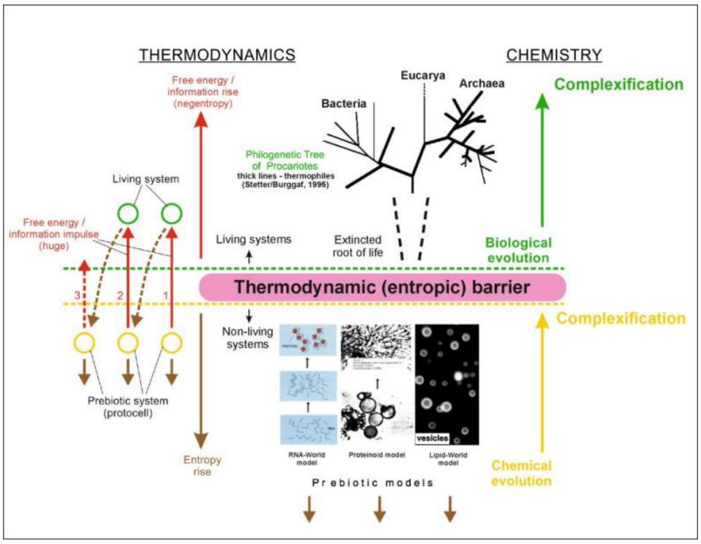

Figure 1. Entropic barrier between living (up) and non-living (down) systems.

Thus, there is the entropic barrier between chemical and biological systems, which manifests itself in the presence of a natural tendency of non-living systems to increase entropy in accordance with the 2nd law, which makes it impossible for organic systems to spontaneously transition to life only due to their chemical complexification. To implement it, a thermodynamic jump (inversion) is required: the inflow of a huge impulse of free energy into the network of prebiotic chemical reactions, which more than compensates for the tendency to increase the entropy in the system. In principle, this is the sole way that a prebiotic system can transition from existence with the dominance of entropy to existence with the dominance of free energy. Such an impulse can be generated with strong changes in the environment, that is, in conditions far from equilibrium in the presence of significant oscillations in physicochemical parameters (temperature, pressure, pH, concentrations of components, electrical potentials, etc.).

3. Key points of the TI concept

The concept of TI considers the transition of prebiotic organic microsystems into the original forms of life through a revolutionary change in the thermodynamic ratio (balance): "total contribution of entropy / total contribution of free energy" [21]. In the course of the transition, the ratio changes from positive to negative (negentropic). Accordingly, this transition should be carried out through the intermediate state (between "non-life" and life) with comparable contributions of free energy and entropy. Such a state maintains in an oscillatory mode in accordance with the succession: "a strong impulse of free energy - its exhaustion and increase in entropy - a new strong impulse of free energy".

In the framework of the TI concept, the border between non-life and life is defined through the inequality "total contribution of entropy S_c / total contribution of free energy F_c" in a system. The ratio between the contributions of free energy and entropy in a natural system can be different, and that is precisely what determines the thermodynamic type of the system (biological or non-biological). Three possible types of thermodynamic ratios (balance) are shown below:

For chemical evolution: $S_c > F_c$, the thermodynamic ratio is positive in non-living systems;

For biological evolution: $S_c < F_c$, the thermodynamic ratio is negative in living systems; and

For the intermediate state: $S_c \approx F_c$, the thermodynamic ratio is near zero.

Thus, a prebiotic system of any chemical composition in the intermediate state can either increasingly concentrate the free energy due to the incessant reorganization of the network of chemical reactions with a relative decrease in entropy (Figure 2, up) or return to the initial prebiotic state with an irreversible increase in entropy (Figure 2, down). In the first case, it shifts to an active existence in the environment and enters the beginning of biological evolution. In the second case, it transitions to a passive state.

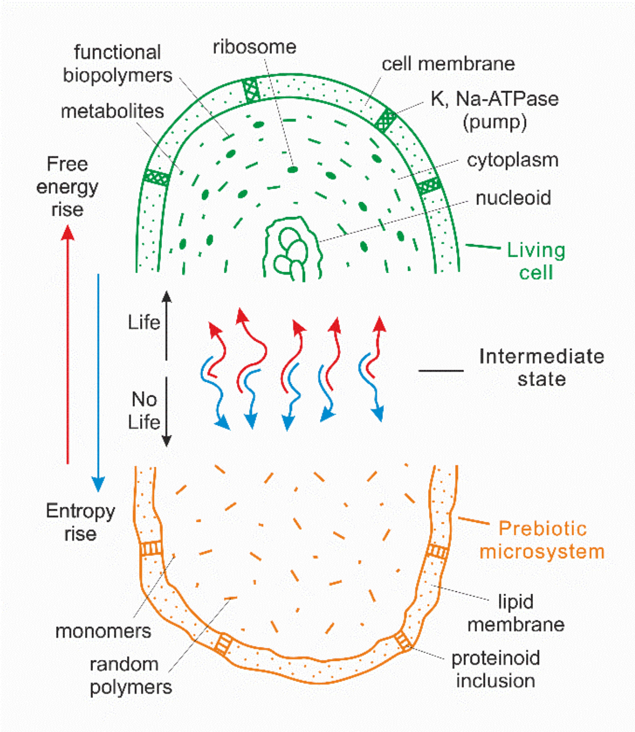

Figure 2. Schematic transition from a prebiotic microsystem to a simple prokaryotic microorganism. In the center: the intermediate state of the microsystem along the line of the entropic barrier, as shown in Figure 1; straight arrows – directions of relative increasing contribution of free energy/information (red) and entropy (blue); and writhing arrows - chemical and informational processes occurring in an oscillatory mode and leading to a relative increase in the contribution of free energy/information (red) and entropy (blue). In the lower part: the original prebiotic microsystem of schematic composition (yellow). In the upper part: a scheme of the simplest cell (green).

The negentropic balance of a living system ($S_c < F_c$) means that its total free energy includes two constituents: the first goes to fully compensate for the contribution of entropy, and the second is excessive, or supra-entropic. Thus, the main thermodynamic factor in the transition of a chemical (micro)system to life is not the total amount of free energy contained in it, but the presence of excessive supra-entropic free energy ($S_c < F_c$). This thesis connects the author's approach with Bauer's relational theory of biological thermodynamics, which states that there is a function in a living organism that creates a continuous nonequilibrium state, which is a generalized energy status of the cell. This function supports the ability to self-adapt and the ability to change its functions so that the system always gets anew the state of nonequilibrium [26–29]. Within the framework of the TI approach, it is the excessive part of free energy, which is outside the entropy pressure, that provides the generalized energy status of the cell associated with the function of a stable nonequilibrium state. There is no contradiction with the laws of physics and chemistry here - indeed, in a biological system there is a tendency towards equilibrium. However, due to their supra-entropic free energy, living organisms continuously do work to stop this tendency at a level above the thermodynamic barrier (Figure 1).

If the presented ideas really took place during the period of the biosphere emergence, then the periodic transitions of primary living systems to an active and then to a passive state should be laid at the foundation of the tree of life on Earth. Moreover, they should be traced throughout its entire evolution. Indeed, in the modern world of microorganisms, all populations without exception exist in two alternative states: (1) active (free-living forms); and (2) passive or anabiotic (resting forms). The transition to suspended animation begins with the onset of unfavorable conditions for the existence of a population; then, a consistent decrease in the metabolic activity of cells begins down to a resting or dormant form (anabiotic, in fact non-living state). The restoration starts with the establishment of favorable external conditions and proceeds in the opposite sequence of metabolic changes (Table 1) [30]. Thus, the described metabolic transitions must have been already laid down during the OoL period, and then maintained throughout the entire evolution of the biosphere. They have been preserved to this day in the reciprocating anabiotic process and are repeated every time a bacterial cell enters anabiosis and then exits from it. In any case, no one offers an alternative explanation for their appearance in the course of biological evolution.

Table 1. Succession of processes in the course of a cell acquiring a resting state and leaving it.

From: Kompanichenko V., El-Registan G. AIMS Geosciences, 2022, 8(3): 398–437. [30] Active existence of a bacterial cell (a free-living form)	
Transition to the anabiotic state ↓	Exit from the anabiotic state ↑
↓ A decrease in functional activity of the nucleic acids and enzymatic proteins.	↑ Appearance of the growth (cell) cycle, the genetic apparatus completely restores.
↓ A slowdown in the movement of lipids and enzymatic proteins in membranes, increase in microviscosity.	↑ Arising of the synthesis of enzymatic proteins, for which messenger RNA (“stored transcripts”) used.
↓ Further dehydration of the cell up to polycrystallization, loss of monovalent ions K^+, Na^+.	↑ The important functions (energy-giving, transport and barrier) of a cytoplasmic membrane start to recover.
↓ Cytoplasm of the cell obtains a glassy state at critically low residual amount of free water.	↑ After impact of stress-factors: an increase in respiratory activity, watering of the cytoplasm, entry of K^+, Na^+ ions into the cell.
This is the last stage.	*This is the initial stage.*
Passive existence of a bacterial cell: the state of anabiosis (resting form): intermediate state between non-life and life (a resting cell unable to counteract entropy, but remains memory of the previous living state)	

4. Environment for the OoL

It follows from the presented TI approach that the presence of multilevel (including high-frequency range) oscillations of physical and chemical parameters is a mandatory condition for the environment of the OoL. It is added as the fourth to the three generally accepted required conditions for the OoL (the presence of water, organic matter, and an energy source). Of the possible geological environments on Earth, only hydrothermal systems have a full set of all four conditions. They are considered by the author as a real environment suitable for the formation of primary populations of microorganisms. A significant number of scientists who work on the OoL problem are of the same opinion [8,16–18]. According to these approaches, geothermal energy was the main source of energy for the formation of primary living cells.

Concerning the hydrothermal origin of life, geothermal energy is commonly regarded as the thermal energy transferred by the heated fluid, which is considered as an alternative to solar power. The TI differs in that is uses a broader interpretation of the term "geothermal energy". In addition to the intrinsic thermal energy of the migrating fluid, an additional contribution to the transfer of geothermal energy to the surface is made through high-frequency (short-period) oscillations of the parameters (pressure, pH, chemical and electrical potentials, and others). They can be initiated by powerful geological phenomena, such as volcanic eruptions, earthquakes, and hydrothermal-explosive processes. In particular, different-rank fluctuations in pressure, temperature, and concentrations of chemical components in the context of the OoL were studied in the geothermal region of the Kamchatka Peninsula [15,21,31]. In fact, geothermal energy combines two of the above-mentioned factors for the OoL listed above: a source of (thermal) energy and high-frequency fluctuations of parameters. The latter can be considered as a factor of a type of external "pumping" factor that forces prebiotic systems to react and, under certain conditions, to evolve into a living state.

Additionally, the importance of cyclic gradients of temperature and other parameters in the OOL process has been considered in some other publications [12,17,32]. In particular, Spitzer and co-authors emphasized that the chemical evolution of the Earth is driven by the energies of cyclic (diurnal) disequilibria and the energies of hydrothermal vents [33]. They proposed an empirical program of experiments which involved complex chemical compositions with cyclic gradients of temperature, water activity, and electromagnetic radiation. In contrast to these approaches, smooth fluctuations of the physicochemical parameters in the environment (for example, diurnal temperature fluctuations in the ocean) were considered by the author as insufficient. As noted above, the TI concept substantiates the mandatory presence in the spectrum of parameter fluctuations of a high-frequency component with periods of less than 1 second, which brings the maximum energy to the prebiotic environment [22]. Only such intense oscillations can stimulate an effective (enhanced) response to periodic stress in organic microsystems and lead to the arising signs of a living state related with TI.

4.1. Stages of the origin of primary microorganisms

As noted above, based on the TI concept, periodic transitions of primary living systems (microorganisms, populations) to either an active or a passive state should be laid at the base of the tree of life on Earth and traced throughout the evolution of the biosphere. A logical consequence of this thesis is the hypothesis put forward, which states that the sequence of restoration of the metabolism of dormant cells in modern populations was initially formed during the development of the metabolism of primary living cells. Since then, this succession has been repeated with minor variations when all resting forms of bacteria and archaea exit from anabiosis (Table 1, right side). Based on this succession, and also taking the available data on the geology of hydrothermal systems, microbiology, and prebiotic chemistry into account, the following stages of the OoL in the oscillatory conditions of hydrothermal systems on the early Earth were reconstructed. They are described in detail in the works [23,30] and are briefly listed below. Once again, it should only be emphasized that the metabolic transformations in the distinguished stages generally follow the universal succession of the restoration of metabolism when a dormant cell exits from anabiosis, which is determined on a basis of a huge number of experimental studies in microbiology.

- *First stage*: *self-assembly of prebiotic microsystems*. The initial organic (prebiotic) microsystems involved in the process of the formation of primary life forms were multicomponent, which had a lipid membrane, probably with incorporated amino acids. The lipid membrane prevented the excessive loss of free energy by the prebiotic system, while the amino acid chains incorporated into it ensured an exchange with the environment (they were subsequently transformed into pumps that maintained, among other things, the K^+ / Na^+ balance in the forming cell). According to the TI concept, the self-assembly of microsystems proceeded in an oscillatory mode. At this stage, ATP and sugars were probably absent because of the high temperature of the medium (>100 ºC).

- *Second stage: formation of protocells.* The appearance of a weak energy-giving process of respiration in the microsystems facilitates concentrating the free energy in them. This begins by the electron transfer that supports redox reactions in the microsystems. An acceleration of the movement of lipids in membrane structures is associated with an increase in their fluidity. A tendency towards the concentration of (structural) information in clusters of microsystems is established. Then, “supra-entropic” information appears, which is related to the ability of the forming protocells to actively (intensified) respond to the oscillating conditions in the environment.

- *Third stage: formation of living subcells.* The synthesis of unsaturated fatty acids began; thus, a permeability barrier began to form, as well as the transport and energy-giving functions at the membrane. Simultaneously with the increase in the energy function of the membrane, the level of reactive oxygen species increased, for the neutralization of which a non-enzymatic antioxidant system of the subcell formed. At the same time, the foundation of the primary structure of the protein-synthesizing apparatus of the subcell took place, though the matrix synthesis of protein macromolecules was still absent. Energy equivalents (ATP) in the absence of biosynthesis have not yet been in demand.

- *Fourth stage (growth): emergence of primary living cells (progenotes).*

According to the given reconstruction, the fourth stage of growth in the OoL process, in principle, correlates with the initial stage of a modern cell transformation into a resting form during the anabiotic process. In the fourth stage, the formation of the growth cell cycle took place, which led to the appearance of the first living vegetative cells as constituent elements of the primary populations. The acid-base reactions of phosphates associated with the transfer of protons began to dominate in energy conversion processes and led to the widespread use of ADP and ATP. At this time, the genetic apparatus of the cell began to form as its informational basis. The targeted synthesis of enzymatic proteins that followed ensured an active cell metabolism.

- *Fifth stage:* This represents the early biological evolution of the initial prokaryotes to the oldest species of archaea and bacteria. According to the reconstruction by Woese [34], the evolution of progenotes up to prokaryotic cells proceeded through a significant rise of a level of the translational accuracy, an elongation of strings of both classes of biopolymers, the formation of DNA, and a genome.

These stages are shown schematically in Figure 3. Briefly, the stages can be designated as follows: Stage 1 – non-life; Stages 2 and 3 – protolife; and Stages 4 and 5 – life (as we know it). It follows from the figure that the energy for the formation of the primary “sparks” of life in prebiotic microsystems was geothermal (stages 1–3). Solar power was involved in the process of biological evolution starting from stage 4, when life (as we know it) was formed, with a cell growth cycle and a formed genetic apparatus.

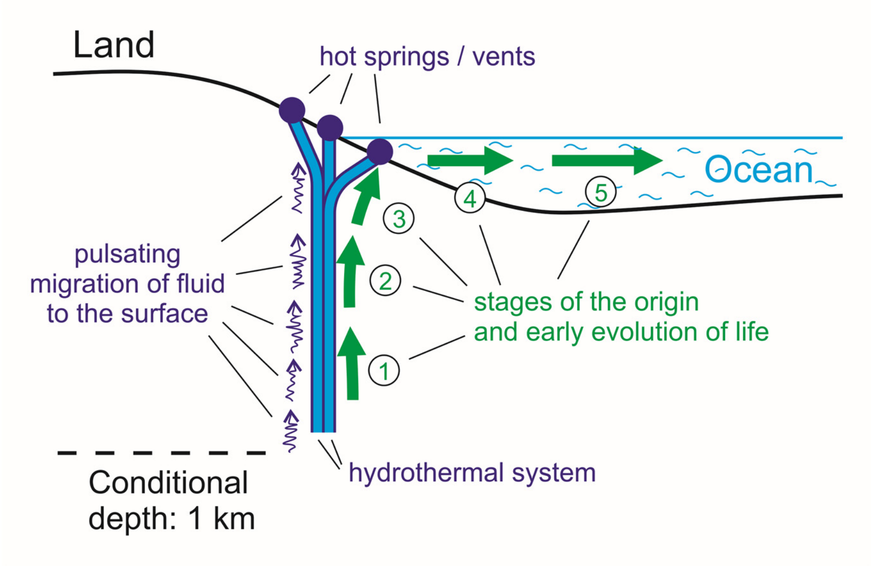

Figure 3. Scheme of the stages of origin and early evolution of biosphere.

4.2. Time of the stages of biosphere origin

The proposed reconstruction allows us to outline the parameters of evolutionary time during the period of the OoL at three levels. The first level is the "microscopic" level, in which clusters of organic microsystems in a transitional state between non-life and life appeared in some of the millions of cracks on the early Earth filled with migrating fluid (stages 1–2). Considering the need to stimulate this process with short-period (high-frequency) fluctuations in physicochemical parameters, such clusters could form over a period of time from several hours to several years. They appeared and disappeared as soon as the conditions in the crack changed. Clusters of such embryonic protolife could have appeared about 4 billion years ago, when the primary ocean condensed. In some cases, under exceptionally favorable geological conditions, such systems could evolve into more complex forms (approaching subcells) in large hydrothermal systems. This is the second level, which the author calls "local" (stage 3). The time span of the existence of such clusters in a certain place can be evaluated at several tens of thousands of years or less. For example, on the Kamchatka Peninsula, the existence of large hydrothermal systems with an area of tens of square kilometers (for example, Mutnovsky or Pauzhetsky) is 30–40 thousand years. The third level is "planetary", which covers the entire planet, including oceans and underground reservoirs in geothermal areas. This is life as we know it (from progenotes to prokaryotes) (stages 4–5); its formation took millions of years.

5. Conclusion

The key points of the TI concept are formulated as follows:

1. The intermediate state of the prebiotic system is maintained by oscillations around the entropy barrier with potential tendencies for development or degradation;

2. Chemical evolution turns into biological evolution when the prebiotic system begins to produce more free energy than entropy can compensate for through continuous reorganization in the network of chemical reactions; and

3. The transition of prebiotic systems into living cells occurred under the oscillatory conditions of a hydrothermal environment.

Within the framework of this approach, it is postulated that the significance and place of geothermal and solar energy in the process of biosphere formation are different. Geothermal energy includes thermal energy and the energy of short-period fluctuations of the physical and chemical parameters (both regular and irregular), which provided the start-up and initial phases of this process (stages 1–3), which took place in the subsurface areas of hydrothermal systems at the level of protolife. Solar power was included in providing the development of primary life forms after they came out with thermal fluid to the surface. The most favorable areas for further biological evolution seem to be the areas of hydrothermal vents in coastal areas of the planet and on continents near large bodies of water, where the conditions in the habitat were maximally diversified. In the deep-sea areas of the oceans, the large hydrostatic pressure of water should have prevented the development of high-frequency oscillations of the physical and chemical parameters (although they could have intensified as a result of volcanic eruptions and earthquakes). From this time, the formation and further evolution of life as we know it began, with a growth cycle of cells and the advanced genetic apparatus (stages 4–5).

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflicts of Interest

The author declares no conflict of interest.

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