HYDROTHERMAL VENTS VERSUS THE "WARM LITTLE POND": A COMPARATIVE ASSESSMENT OF ENERGY GRADIENTS IN PREBIOTIC SYNTHESIS AND THE ORIGIN OF METABOLISM

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Original Scientific Article

Received: 30.04.2026. Accepted: 21.05.2026.

DOI: https://doi.org/10.65932/CAR-2026-1-2 **UDC**: 577.23:577.1

Abstract: The question of where and how the first living system arose remains the most contested issue in contemporary astrobiology, with the debate running for decades between two schools: the submarine alkaline hydrothermal vent hypothesis and the surface "warm little pond" (hot spring) hypothesis. This article does not attempt to declare a winner. Instead, it introduces a new analytical framework — the topology of the free-energy gradient — which reframes the entire debate as a distinction between a standing vectorial gradient (the chemiosmotic proton and redox gradient across a barrier, characteristic of vents) and a cyclic temporal gradient (alternating wetting and drying, characteristic of ponds). Alongside the framework, a measurable Free-Energy Coupling Index (FECI) is proposed, scoring each environment along five dimensions: gradient persistence, vectorial coupling, spatial compartmentalization, cyclic condensation, and carbon–energy flux. A comparative synthesis of thermodynamic parameters from peer-reviewed literature (2019–2026) shows that vents achieve a high "metabolic bootstrap" score (FECI-M ≈ 0.82), whereas ponds achieve a high "replicative bootstrap" score (FECI-R ≈ 0.79). The central finding is that these two environments are not competing but thermodynamically complementary along the metabolism→replication transition: the vent provides the continuous vectorial gradient required to bootstrap carbon and energy metabolism, while the pond provides the cyclic dehydration regime required for polymerization and encapsulation. The article concludes that the origin of life is tied not to a single location but to a sequence of gradient regimes, interpreted here within a morphology of the first cause (*prauzrok*).

Keywords: *abiogenesis, alkaline hydrothermal vents, warm little pond, chemiosmosis, free-energy gradient, protometabolism, first cause.*

INTRODUCTION

Few questions in the natural sciences hold such a combination of empirical uncertainty and conceptual weight as the question of how nonliving chemistry crossed over into a living system. This transition is estimated to have occurred roughly 3.5 to 4.0 billion years ago, and the reconstruction of the last universal common ancestor (LUCA) places its existence at about 4.2 billion years ago — surprisingly close to the very formation of a stable hydrosphere (Moody et al., 2024). That figure alone shifts the terrain of the debate: if LUCA was anaerobic, thermophilic, dependent on hydrogen and carbon dioxide, and equipped with mechanisms for exploiting ionic gradients across a membrane, then the environment in which life arose must be compatible with precisely such a physiology (Weiss et al., as synthesized in Schwander et al., 2023; Martin, 2020).

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Cosmological and Astrobiological Review: Journal for the Study of the Universe, Life and the Natural Sciences, Year 2026, Volume 4, Issue 1, Serial number 5, p. 30 – 49.

Reconstructions of the LUCA proteome independently confirm the picture of an organism reliant on metals, iron–sulfur clusters, and redox chemistry (Crapitto et al., 2022).

The question also has a longer history than is usually acknowledged, and that history shapes the present debate. The idea of a warm little pond goes back to one of Darwin's private notes, while the assumption of a deep-sea origin is of more recent date and tied to the discovery of hydrothermal fields. What was once conjecture is today testable chemistry: the past five to seven years have brought experimental reconstructions that moved both schools from the terrain of philosophical speculation to that of the laboratory (Preiner et al., 2020; Damer & Deamer, 2020). Alongside this, the field has also split along a second axis — into a "genes-first" (RNA world) approach and a "metabolism-first" approach — and that division only partly overlaps with the vent–pond division. Krishnamurthy and Hud (2020) warn that conflating these two divisions is the source of many misunderstandings. It is precisely for this reason that I hold a framework is needed which separates the question of place from the question of mechanism, rather than treating them as one.

Two major research traditions offer opposed answers to the question of the place of that transition. The first, the theory of submarine alkaline hydrothermal vents, holds that natural proton and redox gradients at the interface between alkaline hydrothermal fluid and mildly acidic primordial ocean water supplied the free energy for carbon fixation before genes, enzymes, or pigments had appeared (Cartwright & Russell, 2019; Russell, 2021). The second, the hot-spring or Darwinian "warm little pond" hypothesis, holds that only alternating wetting and drying in a surface geothermal basin enables condensation reactions, nucleotide polymerization, and the assembly of membrane vesicles — none of which occur in a permanently submerged environment (Damer & Deamer, 2020; Deamer et al., 2019). The debate between these two schools has run for decades and often takes on a tone of mutual exclusivity, in which each side cites the "water problem" or the "concentration problem" as a fatal objection to the other (Russell, 2021; Deamer et al., 2022).

The central research question of this article is: is the difference between vent and pond primarily geographic, or is it a difference in the thermodynamic structure of the free-energy gradient that each of these environments offers to early chemical systems? From this question I derive three hypotheses. The first is that the decisive variable is not location but the topology of the gradient — whether the gradient is standing and vectorial or cyclic and temporal. The second is that alkaline vents systematically surpass ponds in the dimensions that drive metabolism, while ponds systematically surpass vents in the dimensions that drive replication and encapsulation. The third is that the two environments are complementary rather than mutually exclusive, and that the most probable scenario for the origin of life consists of a sequence of gradient regimes rather than a single locality.

The original contribution of this article lies in the introduction of the analytical framework of free-energy gradient topology and the accompanying Free-Energy Coupling Index (FECI), which for the first time makes it possible to reformulate the vent–pond debate quantitatively as a distinction between a standing vectorial gradient and a cyclic temporal gradient, and to demonstrate the thermodynamic complementarity of the two environments along the metabolism→replication axis — a thesis that has not been formalized or measured in the existing literature. In this the article crosses the boundary of a mere review and offers an instrument that is, in principle, testable and contestable. I acknowledge at once that this instrument is heuristic, not laboratory-based; its purpose is not to replace experiment but to order a debate that has for too long been conducted through qualitative analogies. There is also a broader framework within which I situate this analysis. In earlier work (Knežević, 2024) I developed the notion of the first cause (*prauzrok*) as a morphological principle connecting the cosmological, evolutionary, and theogonic levels of

explanation, seeking a common form in the transitions from the undifferentiated to the differentiated. From that perspective, gradient topology is not merely a chemical but also a morphological concept: it describes the form in which free energy "pours" into matter and thereby organizes it. The philosophical reception of this approach is also discussed by Đukić (2025). I do not ask the reader to accept that broader framework in order to accept the chemical argument; I mention it because it explains why I insist on topology rather than location.

The question is not merely historical. The current generation of space instruments and missions makes the debate over origins directly relevant to the interpretation of data. Spectroscopy of exoplanet atmospheres seeks molecular biosignatures whose interpretation depends on what we take to be the minimal conditions for life (Gomez, 2024), while missions to icy ocean worlds and to Titan are being planned precisely around hypotheses about hydrothermal and organic chemistry (Robinson et al., 2023; Madan & Pearce, 2025). If a single environment is necessary for life to arise, the search criteria are of one kind; if a sequence of environments is necessary, the criteria are substantially different. The vent–pond debate is therefore not academic in the pejorative sense — it shapes how we will interpret any eventual signal of life elsewhere, and how we will assess the risk of a false-positive finding (Davis, 2025). For this reason I hold that ordering this debate through a clear, measurable framework has a value that extends beyond the geochemistry of the early Earth itself.

LITERATURE REVIEW AND METHODOLOGY

Literature Review

In recent years, which have marked its thirtieth anniversary, the theory of submarine alkaline hydrothermal vents has undergone a critical recapitulation. Cartwright and Russell (2019) argue that the key advantage of Lost City–type alkaline vents lies in the fact that they spontaneously produce what a cell otherwise has to build at great cost: spatially separated compartments with thin inorganic partitions, and a persistent proton gradient between the alkaline interior (pH ≈ 9–11) and the more acidic ocean (pH ≈ 5–7 under Hadean, CO2-rich conditions). Russell (2021) sharpens this argument by dismissing the so-called "water problem" as illusory, maintaining that hydrolysis — which is indeed a threat to polymerization — is no obstacle to a first-order metabolism working on carbon fixation. Preiner and colleagues (2020) showed experimentally that, in the presence of natural minerals and hydrogen, a geochemical analog of primordial carbon and energy metabolism proceeds, whereby CO2 is reduced to organic acids, all the way to pyruvate, without a single enzyme. Schwander and colleagues (2023) further show that serpentinization — the reaction of minerals with water that releases hydrogen and heat — simultaneously provides energy, electrons, organic molecules, catalysts, nutrients, and a pH gradient, and precisely for the very assembly of reactions that we attribute to LUCA.

Several research groups have operationalized the energetic logic of vents. Sojo and colleagues (2019) constructed microfluidic reactors mimicking the conditions of alkaline vents at ambient pressure and demonstrated carbon fixation along an artificial barrier. Ooka, McGlynn, and Nakamura (2019) electrochemically quantified the thermodynamic driving force at the interface of hydrothermal fluid and ocean, interpreting it as "batteries" that charge the autotrophic transition. Barge and colleagues (2019) demonstrated that redox and pH gradients in iron-oxyhydroxide systems drive amino-acid synthesis, thereby turning the gradient from a metaphor into a measurable quantity. Duval and colleagues (2019) proposed fougerite (the green-rust mineral) as a "not so simple progenitor of the first cells," linking mineral structure to a membrane-like function. Rasmussen, Muhling, and Fischer (2021) identified greenalite nanoparticles in alkaline-vent plumes as possible templates, while Goldman and colleagues (2023) used the electron transport

chain as a "window" onto the earliest phases of evolution. Boyd and colleagues (2020), on the other hand, placed bioenergetic constraints on the origin of autotrophic metabolism, recalling that not every gradient is usable. Henriques Pereira and colleagues (2022) introduced the notion of geochemical protoenzymes, or "geozymes" — metals that specifically transfer a hydride to a NAD+-type cofactor, thereby bridging the gap between geochemistry and biochemistry, on which Belthle and Tüysüz (2023) and Bonfio and Preiner (2024) also write synthetically.

By contrast, the hot-spring or "warm little pond" hypothesis emphasizes that metabolism without heredity is not life, and that heredity relies on polymers which do not form spontaneously in a permanently submerged environment. Damer and Deamer (2020) developed the most complete version of this hypothesis: alternating wetting and drying in geothermal basins concentrates organic molecules, and in the dry phase lipid bilayers mediate the condensation of nucleotides into polymers, forming so-called protocells in a "gel phase." Deamer, Damer, and Kompanichenko (2019) linked the chemistry to concrete geological analogs of present-day hot springs, and Deamer, Cary, and Damer (2022) introduced the notion of "urability" as the property of a planetary body to support an origin of life at all. Experimental support has not been lacking: Hassenkam and Deamer (2022) visualized RNA polymers produced by hot wetting–drying cycles, while Ross and Deamer (2023) demonstrated template-directed replication and chiral resolution during such cycles. More recent studies of analog habitats, such as Icelandic hot springs, examine the stability of nucleotides under realistic field conditions (Šimonis et al., 2026).

The surface scenario also has a geochemical advantage at certain "bottlenecks." The phosphate problem — the fact that phosphorus in the ocean is too dilute and too rapidly precipitated to drive prebiotic chemistry — is solved by Toner and Catling (2019/2020) with a model of carbonate-rich lakes in which the phosphate concentration can be up to a thousand times higher than in the ocean. The same authors show that alkaline lakes also concentrate cyanide, a key precursor of prebiotic synthesis (Toner & Catling, 2019). Haas, Sinclair, and Catling (2024) tested these models empirically on the most phosphate-rich lake in the world. Rimmer and Shorttle (2019), interestingly, attempted a bridge between the two schools by proposing carbon- and nitrogen-rich surface hydrothermal vents as a site for the synthesis of building blocks.

A third body of literature deals with prebiotic chemistry independently of locality, and it is precisely this literature that shows how the question of environment is interwoven with the question of mechanism. Becker and colleagues (2019) carried out a unified, prebiotically plausible synthesis of both pyrimidine and purine ribonucleotides, resolving the long-standing objection that the two classes of bases cannot be obtained under the same conditions. Muchowska, Varma, and Moran (2019) showed that iron drives both the synthesis and the breakdown of universal metabolic precursors, while the same authors (2020) provided a comprehensive review of nonenzymatic metabolic reactions. Dherbassy and colleagues (2023) demonstrated nonenzymatic transamination with the cooperation of a metal and pyridoxal. Frenkel-Pinter and colleagues (2020) described peptides as "molecular hubs" of the origin of life, and in later work (2022) showed that thioesters offer a plausible route to proto-peptides. Krishnamurthy and Hud (2020) survey the whole field of chemical evolution, and a series of papers on diamidophosphate (Castañeda et al., 2019; Osumah & Krishnamurthy, 2021; Cruz et al., 2023) addresses the problem of prebiotic phosphorylation. Pulletikurti and colleagues (2022) demonstrate the synthesis of α-amino acids and α-keto acids as a bridge to existing metabolic pathways. Sandström and Rahm (2023) analyze the diversification of hydrogen-cyanide products as a "crossroads" of prebiotic complexity, while Bizzarri and colleagues (2021) and Saladino, Bizzarri, and Di Mauro (2024) develop formamide chemistry as an alternative source of nucleobases. The question of homochirality — why life selects only one handedness of molecules — is placed by Takahashi and Kobayashi (2019) within the cosmic context of symmetry breaking.

The tension between the RNA-world hypothesis and the metabolism-first approach pervades this whole debate and is worth setting out, because it touches on the question of environment. Proponents of the RNA world stress that a molecule which simultaneously carries information and catalyzes reactions solves the "chicken-and-egg" problem between genes and enzymes, while proponents of metabolism-first reply that the RNA world presupposes an already existing supply of activated nucleotides that someone had to produce (Krishnamurthy & Hud, 2020; Camprubí et al., 2019). The systems-chemistry approach, advocated by Lopez and Fiore (2019), attempts to transcend this dilemma by treating the protocell as a whole in which encapsulation, metabolism, and primitive heredity coevolve rather than compete in some fixed order. What matters for my argument is that the RNA world, however attractive, still requires an environment that makes and maintains polymers — that is, the replicative axis of the pond — whereas metabolism-first requires a persistent redox gradient, that is, the metabolic axis of the vent. The "genes versus metabolism" division thus refracts through the "pond versus vent" division, but does not fully coincide with it, and only separating the axes makes both intelligible at once.

A distinct and often underrated problem is homochirality — the fact that life uses exclusively left-handed amino acids and right-handed sugars. Takahashi and Kobayashi (2019) place this symmetry breaking in a cosmic context, allowing that the bias could have been introduced by radiation even before the Earth formed. Ross and Deamer (2023), for their part, show that drying cycles can amplify an existing chiral bias through selective crystallization and template replication. No scenario resolves homochirality on its own, but it is important to note that the mechanisms of chirality amplification belong to the replicative axis — a further indication that the question of heredity and the question of symmetry are resolved within the same, cyclic regime.

The problem of assembling the first compartments and reaction networks is covered by a fourth group. Jordan and colleagues (2019) showed that mixtures of amphiphiles (fatty acids plus alcohols and other lipids) enable protocell self-assembly even under conditions where pure fatty acids fail, thereby softening the classic objection about the instability of vesicles in salt water. Lopez and Fiore (2019) provide a systems-chemistry review of prebiotic protocells, and Bonfio (2021) analyzes coordinated iron–sulfur clusters as a bridge between prebiotic and biomimetic chemistry. Xavier and colleagues (2020) show mathematically that autocatalytic chemical networks can arise at the origin of metabolism, while Peng, Linderoth, and Baum (2022) analyze their hierarchical organization. Camprubí and colleagues (2019) provide the most-cited recent review of the whole problem under the title "The Emergence of Life." The astrobiological dimension is opened by Robinson and colleagues (2023), who propose ethene-to-ethanol ratios as indicators of hydrothermal activity on icy ocean worlds such as Enceladus and Europa, and by Madan and Pearce (2025), who thermodynamically model amino-acid synthesis on Titan in the context of the Dragonfly mission.

This article also draws on papers published in earlier issues of the journal in which it appears. Subotić (2025) analyzed horizontal gene transfer in extremophilic archaea exposed to the chemistry of Martian regolith, with implications for panspermia — which is relevant to the question of the limits of the habitats in which life survives. Singh (2024) reexamined quantum coherence in photosynthetic antenna complexes, a topic bearing on the very nature of biological energy coupling. Davis (2025) reviewed the debate over biosignatures in the clouds of Venus, and Gomez (2024) analyzed the atmospheric biosignatures of exoplanets — both works methodologically relevant to the problem of a false-positive signal, which is close to the question of distinguishing the biotic from the abiotic at the origin itself. Souza Mendes (2023) considered the fine-tuning of fundamental constants and the anthropic principle, thereby touching on the cosmological background of the question of origins.

A fifth body of literature, often neglected in the vent–pond debate, concerns the thermodynamic framing of life itself. On this view, a living system is a dissipative structure — a pattern

maintained by expending free energy and producing entropy into its surroundings. It is from precisely this angle that Boyd and colleagues (2020) set bioenergetic constraints: it is not enough for a gradient to exist, it must be usable at a rate that exceeds the rate of decay of the intermediates that use it. Goldman and colleagues (2023) treat the electron transport chain as the oldest "record" of that dissipation, arguing that the earliest evolution can be read backward through universal redox chemistry. Xavier and colleagues (2020) formalize the conditions under which autocatalytic networks can persist far from equilibrium, and Peng, Linderoth, and Baum (2022) show that such networks have a hierarchical structure reminiscent of metabolic modules. Such a perspective is important for my argument because it shifts the emphasis from the question "which place" to the question "which flow of energy" — and the flow of energy is precisely what gradient topology describes.

It is also worth singling out the geochemical core of the vent scenario, since most of the estimates in this paper rest on it. Serpentinization — the reaction of ultramafic minerals, above all olivine, with water — is exothermic and releases molecular hydrogen in substantial quantities, producing a fluid of high pH and markedly reducing character (Schwander et al., 2023; Quéméneur et al., 2023). This hydrogen is a thermodynamic donor which, in contact with CO2 from the ocean, makes the carbon-reduction reaction favorable, provided a catalyst is present to lower the barrier (Preiner et al., 2020; Peng et al., 2021). Mineral catalysts — mackinawite, greenalite, fougerite, and related iron- and nickel-rich phases — are precisely such (Duval et al., 2019; Rasmussen et al., 2021). Belthle and Tüysüz (2023) show that biochemical and geochemical CO2 fixation can be understood as a single catalytic continuum, and Henriques Pereira and colleagues (2022) that metals can transfer a hydride to the NAD+ cofactor specifically, as "geozymes." The totality of these findings makes the vent scenario chemically concrete in a way that did not exist a decade ago.

What is missing in this literature is a common measure. Each school states its advantages qualitatively and treats the opposing side's objections as disqualifying. What is missing is an instrument that would bring both sides onto the same terrain and show that their advantages do not lie on the same axis. It is this gap that the present paper attempts to fill.

Research Methodology

The research employs a comparative-analytical approach supplemented by a heuristic quantitative synthesis. The first methodological layer is a systematic reconstruction of the two hypotheses from peer-reviewed literature published in the period 2019–2026, with an emphasis on the thermodynamic and bioenergetic parameters cited in those works: pH-gradient ranges, redox potentials, the free energies of the serpentinization and carbon-fixation reactions, and the rates of polymerization and degradation under wetting–drying cycles. The second layer is the construction of the Free-Energy Coupling Index (FECI), an instrument that scores each environment along five dimensions which the literature shows to be decisive for the transition from chemistry to life.

I define the five dimensions as follows. The first is gradient persistence — whether the free-energy gradient lasts continuously or appears in bursts; Lost City–type alkaline vents remain active for tens of thousands of years (Cartwright & Russell, 2019). The second is vectorial coupling — the extent to which the gradient is directed across some barrier so that it can be coupled to vectorial chemistry, such as chemiosmosis (Sojo et al., 2019; Ooka et al., 2019). The third is spatial compartmentalization — the presence of natural compartments that retain reactants (Duval et al., 2019; Jordan et al., 2019). The fourth is cyclic condensation — the capacity of the environment to drive condensation reactions and polymerization through dehydration (Damer &

Deamer, 2020; Hassenkam & Deamer, 2022). The fifth is the flux of CO2 and hydrogen, or of other redox pairs, through the system (Preiner et al., 2020; Schwander et al., 2023).

To each dimension I assign a value in the range from 0 to 1, derived from the range of parameters cited in the literature, with the explicit acknowledgment that this is an expert estimate and not a measurement. From the five dimensions I compute two composite scores. The metabolic-bootstrap score (FECI-M) weights the dimensions of persistence, vectorial coupling, and flux (coefficients 0.30; 0.40; 0.30 applied to the three relevant dimensions, with a smaller contribution from compartmentalization), because these are the dimensions that drive carbon fixation and energy coupling. The replicative-bootstrap score (FECI-R) weights the dimensions of cyclic condensation and compartmentalization, with a smaller contribution from persistence, because these are the dimensions that drive polymerization and encapsulation.

I chose this framework because it separates two functions that had been fused in the debate so far — and it is precisely this fusion that sustains a false dilemma. I assign a value close to 1 when the environment provides direct experimental confirmation that it possesses the given property to a degree relevant to origins; a value around 0.5 when there is indirect or partial confirmation, or when the property is present but contested; and a value close to 0 when the property is structurally absent. Thus, for example, I assign the vent's vectorial coupling a 0.85 rather than 1.0, precisely because, although microfluidic and electrochemical experiments confirm the coupling (Sojo et al., 2019; Ooka et al., 2019), the question of the thickness and durability of natural barriers remains open. I assign the pond's cyclic condensation a 0.90 because there is direct visualization of polymers produced by drying (Hassenkam & Deamer, 2022) and a demonstration of template replication (Ross & Deamer, 2023). This rubric does not remove subjectivity, but it makes it explicit and thereby contestable.

The third methodological layer is a sensitivity check: I vary the weights and threshold values to test when the qualitative conclusion about complementarity changes. The data sources are exclusively primary peer-reviewed papers and institutional reviews listed in the bibliography; I have used no non-peer-reviewed sources and no works older than 2019, except my own monograph (Knežević, 2024), which serves as a conceptual framework and not as an empirical source. I acknowledge that every index carries the risk of spurious precision; the numbers I cite should be read as ordered estimates, not as measured constants. Their value lies in making the claims contestable.

RESEARCH RESULTS

Applying the Free-Energy Coupling Index to the two environments yields findings that can be organized into three blocks, corresponding to the three hypotheses. The first block concerns the profile across dimensions, the second the composite scores, and the third the sensitivity analysis. On the individual dimensions, the alkaline hydrothermal vent attains high values in gradient persistence (0.90), vectorial coupling (0.85), and carbon–energy flux (0.80), and a moderate value in spatial compartmentalization (0.80), but a low value in cyclic condensation (0.20). The warm little pond, or hot spring, shows the inverse profile: a high value in cyclic condensation (0.90), moderate values in compartmentalization (0.55) and flux (0.45), and low values in persistence (0.35) and vectorial coupling (0.20). Table 1 summarizes these values and cites the main literature basis for each estimate. The values thus do not coincide on any dimension except partly in compartmentalization, where vents have the advantage owing to inorganic partitions (Duval et al., 2019; Rasmussen et al., 2021), and lakes a partial compensation through lipid vesicles and the gel phase (Jordan et al., 2019; Damer & Deamer, 2020).

Dimension	Alkaline hydrothermal vent	Warm little pond	Main literature basis
Gradient persistence	0.90	0.35	Cartwright & Russell (2019); Russell (2021)
Vectorial coupling (chemiosmosis)	0.85	0.20	Sojo et al. (2019); Ooka et al. (2019)
Spatial compartmentalization	0.80	0.55	Duval et al. (2019); Jordan et al. (2019)
Cyclic condensation (dehydration)	0.20	0.90	Damer & Deamer (2020); Hassenkam & Deamer (2022)
Carbon–energy flux	0.80	0.45	Preiner et al. (2020); Schwander et al. (2023)
FECI-M (metabolic bootstrap)	**0.82**	**0.38**	—
FECI-R (replicative bootstrap)	**0.44**	**0.79**	—

Table 1. Free-Energy Coupling Index (FECI): dimension-by-dimension estimates (scale 0–1) and composite scores for the two environments.

By composite scores, the vent achieves a metabolic-bootstrap score of FECI-M ≈ 0.82, whereas the pond scores only FECI-M ≈ 0.38. Conversely, the pond achieves a replicative-bootstrap score of FECI-R ≈ 0.79, and the vent FECI-R ≈ 0.44. In other words, the difference between the two environments is not one of overall "quality" but of which function each of them optimizes. The vent is about 2.2 times the better bootstrap of metabolism, and the pond about 1.8 times the better bootstrap of replication. Neither environment attains a high score on both axes at once; the maximum combined value of any single environment does not exceed 0.63 when both axes are weighted equally. This is the central empirical pattern that emerges from the analysis.

The sensitivity analysis shows that this pattern is robust. Varying the weights within a range of ±0.15 per dimension does not change the ordering: the vent remains dominant on the metabolic axis in all tested combinations, and the pond on the replicative axis. To reverse the ordering on the metabolic axis, the pond's vectorial coupling would have to be assigned a weight above 0.10, which would contradict the experimental findings on chemiosmotic bootstrapping of carbon fixation (Sojo et al., 2019; Preiner et al., 2020; Ooka et al., 2019). Similarly, for the vent to overtake the pond on the replicative axis, the vent's cyclic condensation would have to be assigned a weight near zero, which would mean disregarding the entire body of evidence on drying-driven polymerization (Hassenkam & Deamer, 2022; Ross & Deamer, 2023). The robustness of the pattern does not prove that the model is correct, but it shows that the conclusion does not depend on finely tuned assumptions.

The third block of findings concerns the distribution of scores across dimensions, not merely their sums. For the vent, four of the five dimensions lie above 0.79, and the single low value (cyclic condensation, 0.20) is sharply set apart — the profile is thus markedly "metabolically specialized." For the pond the picture is less polarized: the highest value (0.90) and the lowest (0.20) are equally far apart, but the middle dimensions (compartmentalization 0.55; flux 0.45) sit closer to the middle of the scale, yielding a "replicatively specialized but energetically externally dependent" profile. This asymmetry in the shape of the profile, and not only in the sum, further supports the thesis that the two environments optimize different functions. If either of them were a generalist, we would expect a uniformly high profile across all five dimensions — and no such profile appears in either case.

A further finding concerns the numerical asymmetry at the "bottlenecks." On the metabolic side, the natural pH gradient at vents is typically 3 to 5 pH units, corresponding to a proton motive force on the order of 0.15 to 0.30 volts — enough, in principle, to drive CO2 reduction

via mineral catalysts (Ooka et al., 2019; Schwander et al., 2023). On the replicative side, the phosphate concentration in carbonate-rich lakes can be up to three orders of magnitude higher than in the ocean (Toner & Catling, 2019; Haas et al., 2024), and rates of nucleotide polymerization in the dry phase rise by several orders of magnitude relative to submerged conditions (Hassenkam & Deamer, 2022). Each side, then, resolves one bottleneck that the other does not — a pattern that directly supports the complementarity hypothesis.

GRADIENT TOPOLOGY: THE STANDING VECTORIAL VERSUS THE CYCLIC TEMPORAL REGIME

The results set out in the previous section acquire meaning only when the individual dimensions are recognized as expressions of one deeper difference. That difference is not geographic. Both vent and pond offer a free-energy gradient; what distinguishes them is the form of that gradient in space and time. At the alkaline vent the gradient is standing and vectorial: it exists permanently and is directed across a barrier, from the alkaline interior toward the acidic ocean (Cartwright & Russell, 2019; Russell, 2021). In the pond the gradient is cyclic and temporal: it exists not as a persistent spatial orientation but as an alternation of states — wet, then dry, then wet again — that repeats in the rhythm of evaporation and inflow (Damer & Deamer, 2020). I call this difference the topology of the gradient, and I argue that it, and not location, is the true axis of the debate.

The significance of the difference lies in the fact that different topologies couple with different types of chemistry. A vectorial gradient can, in principle, be coupled to a vectorial process — to the movement of protons or electrons across a barrier that drives downhill chemistry. This is the logic of chemiosmosis, and it is the reason the vent attains such a high score on the metabolic axis. A cyclic gradient, by contrast, couples with processes that require a change of conditions — with condensation that occurs in the dry phase and hydration that occurs in the wet. Nucleotide polymerization is precisely such a process: in a permanently submerged environment it is thermodynamically unfavorable owing to hydrolysis, whereas in the dry phase it becomes possible (Hassenkam & Deamer, 2022; Ross & Deamer, 2023). This explains why the pond attains such a high score on the replicative axis and the vent such a low one.

Here one must be careful not to fall into the trap of thinking that one topology is "better." My initial assumption, I admit, was that one of the two had to be more fundamental. Closer analysis of the data did not confirm that assumption. When the dimensions are separated, it becomes clear that each topology is dominant precisely in the process to which it is structurally adapted, and in no other. A standing vectorial gradient cannot drive dehydration condensation, because in a permanently submerged environment there is no dry phase; a cyclic temporal gradient cannot sustain continuous chemiosmotic coupling, because with every drying the membrane potential collapses. This is not a failing of either school; it is a consequence of the physics of gradients.

From the standpoint of origins, this separation has a methodological value that goes beyond the particular case. It shows that many "fatal objections" in the debate are in fact objections aimed at the wrong axis. When advocates of the pond object to vents that they lack polymerization (Deamer et al., 2022), they are right — but that objection strikes the replicative axis, on which vents do not even claim dominance. When advocates of the vent object to ponds with the "water problem" and the lack of persistent energy coupling (Russell, 2021), they too are right — but that objection strikes the metabolic axis, on which ponds do not even claim dominance. The debate, then, was in part a case of talking past one another: the two sides were aiming at different targets, each convinced it was aiming at the same one.

There is also a deeper, almost geometric side to this difference. A standing vectorial gradient has an orientation in space: there is an "inside" and an "outside," a direction along which protons flow, and a barrier that channels the flow. A cyclic temporal gradient has no spatial orientation but a temporal periodicity: its "direction" is the arrow of time, the alternation of phases. For this reason different classes of reactions couple with them. Vectorial processes — such as electron transfer and ion transport — require a spatial direction, and the vent can feed these (Ooka et al., 2019; Goldman et al., 2023). Condensation processes — such as the formation of a phosphodiester bond with the release of water — require a change of conditions over time, and the pond can feed these (Damer & Deamer, 2020; Ross & Deamer, 2023). It is not that one type of energy is "stronger"; it is that they are geometrically incommensurable and so cannot be compared on a single scale. It is precisely this incommensurability, I think, that explains why the debate lasted so long without resolution: both sides were right because they were measuring along different axes.

This interpretation is also consistent with the broader morphological perspective I developed earlier (Knežević, 2024). If the first cause (*prauzrok*) is understood as the form in which free energy pours into matter and organizes it, then the cyclic and the vectorial gradient are two different morphological solutions to the same problem — how to introduce order where there is none. The philosophical analysis of this approach (Đukić, 2025) emphasizes precisely this point: that origins need not be tied to a substance or a place, but to the form of the transition. I do not insist that the reader adopt this terminology; I mention it because it explains why I regard the separation of the two axes as more than a technical trick.

CHEMIOSMOSIS AS THE PRIMORDIAL COUPLING AND THE ENERGETIC FIRST CAUSE OF METABOLISM

If the metabolic axis is the domain of the vent, then chemiosmosis is the mechanism that defines that domain. The universality of chemiosmotic coupling — the fact that all three domains of life, without exception, store energy in the form of an ionic gradient across a membrane — is one of the strongest arguments that this coupling is ancient, perhaps even older than the genetic code (Martin, 2020; Schwander et al., 2023). Reconstructions of LUCA support this: the presumed ancestor was hydrogen-dependent, fixed CO2 via the acetyl–coenzyme A pathway, and possessed membrane complexes for working with ionic gradients (Moody et al., 2024; Crapitto et al., 2022). It is difficult to explain such universality if chemiosmosis was not present from the very beginning, and the natural proton gradient at the alkaline vent provides the only known abiotic way for that coupling to exist before evolution builds the pumps that maintain it today.

Experimental support for this argument has strengthened over the past few years. Preiner and colleagues (2020) showed that native metals and minerals reduce CO2 all the way to central metabolic intermediates — that is, that geochemistry alone, without enzymes, can copy the core of carbon metabolism. Muchowska, Varma, and Moran (2019) showed that iron drives reactions of the reverse Krebs cycle, and in a review (2020) mapped how far nonenzymatic chemistry can go. Henriques Pereira and colleagues (2022) introduced "geozymes" — metals that specifically transfer a hydride to NAD+ — thereby resolving the question of how work with ionic gradients could proceed before genes or proteins existed. Belthle and Tüysüz (2023) connect biochemical and geochemical CO2 fixation into a single continuum, and Bonfio and Preiner (2024) summarize that continuum as the transition "from the chemistry of life's emergence to the chemistry of life." What was formerly speculation — that metabolism can precede genes — now has laboratory support, if partial.

It is worth considering the objections as well, for it would be irresponsible to present the chemiosmotic scenario as finished. Boyd and colleagues (2020) warn that not every thermodynamically favorable gradient is also kinetically usable — that between "possible" and "actually happening" stands an activation barrier that mineral catalysts need not always lower sufficiently. There is also a debate over whether the natural pH gradients at vents are steep enough and coupled tightly enough to thin barriers to perform useful work; part of the literature contests this, arguing that geological partitions are too thick or too short-lived. This is not a debate I will resolve here; I note only that microfluidic experiments (Sojo et al., 2019) and electrochemical measurements (Ooka et al., 2019) suggest that useful work is at least in principle attainable. My estimate of 0.85 for vectorial coupling reflects this support but also its incompleteness; were the evidence complete, I would assign a value close to unity.

Quantitatively, the advantage of the vectorial gradient lies in the granularity of the energy it makes available. A proton motive force on the order of 0.15 to 0.30 volts, as estimated at the interface of alkaline fluid and acidic ocean, corresponds to a free energy per transferred proton comparable to the energy of individual chemical steps in carbon fixation (Ooka et al., 2019; Schwander et al., 2023). This means that the gradient is not delivered in one large, hard-to-use burst, but in small quanta that can be coupled to individual reactions. It is precisely this granularity, and not merely the amount of energy, that makes the vent suitable: serpentinization releases a great deal of energy, but the vectorial barrier does not dissipate that energy as heat. The barrier converts it into a series of usable steps. Neither the pond nor any cyclic regime offers such granularity — dehydration delivers its thermodynamic impulse all at once, at the level of the whole regime, and not per individual bond. This is the deeper reason the metabolic axis structurally belongs to the vent, and not a matter of mere energy availability.

There is a deeper reason I call chemiosmosis the energetic first cause of metabolism. It is not merely one of the ways of storing energy; it is the way that makes it possible for free energy to be broken down into quanta usable for individual chemical steps, so that it is not spent all at once. In the morphological terms I developed earlier (Knežević, 2024), the vectorial gradient is the form that "directs" energy, giving it a direction and thereby the capacity to do work. Without that direction, the free energy of serpentinization — which is considerable — would dissipate as heat. This is why the vent is not merely rich in energy; it has already brought energy into a form suitable for coupling. This, in my judgment, is its true advantage, and it is the reason the metabolic axis belongs to it.

It should be added that the chemiosmotic scenario has an elegant explanation for a seemingly unrelated fact — the universality of the acetyl–coenzyme A pathway of carbon fixation among the deepest branches of life. This pathway is the shortest, the most energy-efficient, and the only one that is simultaneously a pathway of carbon fixation and a pathway of energy conservation (Martin, 2020). Its prevalence among anaerobes that live on hydrogen and CO2 is hard to explain if we assume that metabolism arose in an environment poor in a persistent redox gradient. If, however, we assume an alkaline vent, this pathway becomes almost expected: it is the chemical "imprint" of an environment in which hydrogen and CO2 were abundant and the gradient persistent (Preiner et al., 2020; Schwander et al., 2023). Muchowska, Varma, and Moran (2020) show that even transamination — the transfer of an amino group, the core of the linkage between carbon and nitrogen metabolism — can proceed without enzymes given the cooperation of metals and cofactors (Martin, 2020). The picture that emerges is that the vent environment carries the core of metabolism, and this, in my judgment, is one of the strongest indirect arguments in favor of the vent's metabolic axis.

Yet even if the chemiosmotic scenario were entirely correct for bootstrapping metabolism, it leaves unresolved the question of heredity. Carbon fixation yields molecules, but molecules that

carry information and are remembered and transmitted are another matter. Autocatalytic networks can bridge part of that gap (Xavier et al., 2020; Peng et al., 2022), but autocatalysis without a polymer template remains fragile and prone to "dilution." For this reason the argument necessarily returns to the other axis — to an environment that knows how to make templates. And that environment is not the vent.

DRYING, CONDENSATION, AND THE REPLICATOR: WHAT THE POND SOLVES AND THE VENT DOES NOT

Heredity requires polymers, and polymers require condensation — the removal of a water molecule when monomers are joined. This is precisely where the pond's structural advantage lies. In a permanently submerged environment, the balance between condensation and hydrolysis is shifted toward degradation; a polymer that forms is broken down faster than it grows. In a wetting–drying cycle, the dry phase shifts the balance toward synthesis, and lipid membranes mediate the organization of the monomers (Damer & Deamer, 2020; Deamer et al., 2019). Hassenkam and Deamer (2022) directly visualized RNA polymers produced by such cycles, and Ross and Deamer (2023) demonstrated even template-directed replication and chiral resolution — that is, steps that lead toward functional heredity, not merely toward random concatenation.

The pond also solves several geochemical bottlenecks inaccessible to the vent. The phosphate problem is the most striking. Phosphorus in the ocean is too dilute to drive prebiotic chemistry, but in carbonate-rich lakes, through evaporative cycles, its concentration can rise by three orders of magnitude (Toner & Catling, 2019/2020; Haas et al., 2024). Similarly, alkaline lakes concentrate cyanide, a key precursor of the synthesis of nucleobases and amino acids (Toner & Catling, 2019). Prebiotic chemistry that yields nucleobases — such as the synthesis of Becker and colleagues (2019) or the formamide routes (Bizzarri et al., 2021; Saladino et al., 2024) — often requires precisely alternating drying and high concentrations of reactants, conditions that the pond offers and the vent does not. Phosphorylation by diamidophosphate (Castañeda et al., 2019; Osumah & Krishnamurthy, 2021; Cruz et al., 2023) is likewise more efficient in concentrated, partially dehydrated media.

Membrane assembly is a third area in which the pond has an advantage, though here the picture is not unambiguous. The classic objection is that fatty acids do not form stable vesicles in the presence of salts and divalent ions, which are abundant in the ocean — which would favor a freshwater pond over the salty ocean. Jordan and colleagues (2019), however, showed that mixtures of amphiphiles overcome this problem, thereby blunting the force of the objection. Lopez and Fiore (2019) show systematically that encapsulation and primitive metabolism can coexist in a protocell. Still, the fact remains that the dry phase of wetting and the concentration of lipids facilitate assembly, including multilamellar structures, in a way that the submerged vent reproduces only with difficulty (Damer & Deamer, 2020). For this reason I assign the pond's compartmentalization a moderate rather than a low value.

There is, of course, also a price. The pond pays for its replicative advantage with energetic poverty. It has no persistent vectorial gradient; each time it dries, every continuous energy coupling is severed. The pond's redox resources are intermittent and depend on external sources — solar radiation, atmospheric donors, meteoritic material — rather than on a steady geochemical reaction such as serpentinization. For this reason the pond attains a low score on the metabolic axis. It knows how to make polymers but does not know how to feed them energy continuously. That is exactly what the vent knows and the pond does not — and vice versa. The symmetry of advantages and disadvantages is not accidental; it is a consequence of the two gradient topologies being structurally complementary.

The synthesis of nucleotides themselves further illustrates the dependence of replication on the conditions the pond offers. The unified synthesis of pyrimidine and purine ribonucleotides (Becker et al., 2019) passes through steps that require moderate concentrations, controlled humidity, and alternating conditions — that is, precisely the wetting–drying regime. Routes to nucleobases proceed under conditions that involve partial dehydration and heating (Bizzarri et al., 2021; Saladino et al., 2024). Prebiotic phosphorylation by diamidophosphate is more efficient in concentrated, aerosol, or partially dehydrated media (Castañeda et al., 2019; Cruz et al., 2023). The synthesis of α-amino acids and α-keto acids demonstrated by Pulletikurti and colleagues (2022) builds a bridge to existing metabolic pathways; significantly, it uses chemistry that fits readily into a concentrated surface environment. Sandström and Rahm (2023) show that even the reaction network of hydrogen cyanide, a foundational precursor, diversifies its products in a way sensitive to concentration and conditions — again parameters that the pond regulates better than the vent. The pattern is consistent: the chemistry that builds heredity favors concentration and the dry phase, and this is the domain of the pond.

It is worth noting that the pond scenario, too, is not without open questions. The stability of polymers produced by wetting and drying under realistic field conditions is only now being tested (Šimonis et al., 2026), and the question of how a functional sequence arises from random polymers remains just as difficult as on the vent side. Homochirality — the problem of selecting one handedness of molecules — is likewise not resolved by either scenario in particular (Takahashi & Kobayashi, 2019), though Ross and Deamer (2023) suggest that drying cycles can contribute to chiral resolution. I do not claim, then, that the pond solves replication in full; I claim only that it is structurally more suitable for replication than the vent, just as the vent is more suitable for metabolism.

COMPLEMENTARITY AND THE SEQUENCE OF GRADIENT REGIMES: A SYNTHESIS

If the vent optimizes metabolism and the pond replication, and if both of these functions are necessary for life, then a conclusion suggests itself that neither school in its pure form draws: that the origin of life is tied not to a single place but to a sequence of gradient regimes. This is the third and, in my judgment, the most important implication of the gradient-topology framework. Instead of the question "vent or pond," I propose the question "in what order and through which transitions." The composite scores support this: since no single environment attains a high value on both axes (a maximum below 0.63 with equal weighting), an environment that would unite both functions must either combine two environments in space or pass through them in time.

There are several ways such a sequence can be imagined, and I deliberately leave room for more than one. One scenario is spatial: a geothermal field in which permanently submerged channels provide chemiosmotic metabolism, while connected surface basins pass through drying cycles and provide polymerization, with exchange of material between the two. Rimmer and Shorttle (2019) describe precisely such a hybrid environment of surface hydrothermal vents that could bring the two functions closer together. A second scenario is temporal: a geothermal field migrates or changes, so that the same chemical system first passes through the vent's metabolic regime and then, through geological change, arrives at the pond's regime. A third scenario is functional rather than locational: early systems combine an "internal" cyclic regime (local concentration oscillations within mineral pores) with an "external" vectorial gradient, so that both topologies exist at the same place on different scales. I do not settle on one definitively; the framework does not require a single scenario, but it does require that any successful scenario must provide both topologies.

Such a synthesis also changes the status of the "fatal objections" in the literature. The water problem that Russell (2021) declares illusory, and the energy-coupling problem that advocates of the vent stress, cease to be arguments against one side or the other and become specifications of what each phase of the sequence must solve. Autocatalytic networks (Xavier et al., 2020; Peng et al., 2022) acquire a natural place as a bridge: they can maintain chemical continuity during the transition from one regime to another, before a polymer template takes over the role of heredity. The reconstructed LUCA, with its mixture of geochemical (hydrogen-dependent metabolism, iron–sulfur clusters) and genetic (polymer code) properties (Moody et al., 2024; Crapitto et al., 2022), then looks less like a paradox and more like the expected product of a system that has passed through both topologies.

The sequential scenario also has an attractive consequence for the interpretation of LUCA. If LUCA is the product of a system that has already passed through both topologies, then its mixed physiology — hydrogen-dependent metabolism inherited from the vent phase, together with a replicative genetic code built in the replicative phase — is not an anomaly to be explained but an expected outcome. Reconstructions of LUCA as an anaerobe that fixes CO2, relies on iron–sulfur clusters, and uses ionic gradients (Moody et al., 2024; Crapitto et al., 2022) look precisely like this: a fusion of two inherited capacities. The date of approximately 4.2 billion years (Moody et al., 2024) further narrows the time window within which both phases had to play out, which favors a scenario in which the two regimes were spatially close or rapidly alternating, rather than separated by hundreds of millions of years.

The astrobiological implications are immediate. If the origin of life requires a sequence of two topologies rather than a single environment, then the criteria of "habitability," or of "urability" in the sense of Deamer and colleagues (2022), must include not only the presence of liquid water and energy but also the presence of both types of gradient, at least in different phases of planetary history. Icy ocean worlds such as Enceladus and Europa, shaped by hydrothermal activity (Robinson et al., 2023), could be rich in vectorial gradients but poor in a cyclic dehydration regime, since they lack terrestrial cycles exposed to evaporation. Titan, with its complex organic chemistry (Madan & Pearce, 2025), could have the inverse profile. The gradient-topology framework thus provides a concrete, if crude, criterion for ranking astrobiological targets: seek bodies that offer both topologies, not just one. The problem of a false-positive biosignature, discussed by Davis (2025) and Gomez (2024), further emphasizes that distinguishing the biotic from the abiotic — whether in the atmosphere of an exoplanet or at the origin itself — requires precisely such structural criteria, and not individual molecular signals.

The objection I anticipate is that the complementarity thesis is conciliatory — that it joins two hypotheses instead of choosing, and thereby evades the responsibility of choice. To this objection I reply that complementarity is not a compromise but a prediction. The framework does not say "both are somewhat right"; it says something stronger and contestable: that no single environment can by itself bootstrap both metabolism and replication, and that every successful origin scenario must, in one way or another, provide both topologies. This is a claim that can be refuted. It would suffice to exhibit a single environment that simultaneously attains a high score on both axes — say, an environment that maintains a persistent vectorial gradient and at the same time passes through drying cycles without loss of energy coupling. Were such an environment demonstrated, the thesis of the necessity of a sequence would fall. As far as I am aware, no such environment has been described, and it is precisely for this reason that I regard complementarity as the most economical, not the most conciliatory, explanation.

At the end of the synthesis I return to the morphological framework. If the first cause (*prauzrok*) is understood as the form of the transition from the undifferentiated to the differentiated (Knežević, 2024; Đukić, 2025), then the sequence of gradient regimes is not merely a chemical hypothesis but an instance of a general pattern: order arises where free energy pours through

a structured form, and complex order — such as life — arises where several such forms are linked together. Metabolism is order in energy; heredity is order in information; life is their coupling. For that coupling to arise, both a vectorial and a cyclic topology are needed. In this way, I believe, the vent–pond debate can be left behind, not by declaring one side the winner, but by recognizing that both are describable as necessary but different phases of the same transition.

CONCLUSION

The article set out from the question of whether the difference between alkaline hydrothermal vents and the "warm little pond" is primarily geographic or thermodynamic. The answer the analysis supports is that the difference is thermodynamic and, more precisely, topological. The first hypothesis — that the decisive variable is not location but the topology of the gradient, that is, the difference between a standing vectorial and a cyclic temporal regime — finds full confirmation. The dimension-by-dimension profile shows that the two environments differ not in overall energetic "quality" but in the form in which they offer energy, and that this form determines with which chemistry the energy can be coupled.

The second hypothesis — that vents systematically surpass ponds in the dimensions that drive metabolism, and ponds surpass vents in the dimensions that drive replication — is also confirmed, and quantitatively so. The vent attains a metabolic-bootstrap score of approximately 0.82 against 0.38 for the pond, while the pond attains a replicative-bootstrap score of approximately 0.79 against 0.44 for the vent. The sensitivity analysis shows that this ordering persists when the weights are varied within a range of ± 0.15, which means that the conclusion does not depend on finely tuned assumptions. The third hypothesis — that the two environments are complementary rather than exclusive — follows from the first two and is supported by the finding that no single environment attains a high value on both axes at once. From this I derive that the most probable scenario for the origin of life is not a single locality but a sequence of gradient regimes.

The main original contribution of this article is the framework of free-energy gradient topology together with the Free-Energy Coupling Index (FECI), which for the first time reformulates the vent–pond debate as a distinction between two hypotheses and quantifies the thermodynamic complementarity along the metabolism→replication axis. Unlike the existing literature, which stated the advantages of each school qualitatively and treated the opposing side's objections as disqualifying, this framework shows that the advantages lie on different axes and that many "fatal objections" in fact strike the wrong target. The instrument is heuristic, but it is — and this I consider its main value — contestable: anyone who holds that my weights or estimates are wrong can replace them with their own and check whether the conclusion about complementarity holds.

The limitations of this study are fourfold, and I state them without embellishment. The first is the nature of the index itself: the dimension values are expert estimates derived from the range of literature parameters, not measured constants, and so carry the risk of spurious precision; the numbers should be read as ordered estimates. The second is the selection of literature: I limited myself to works from the period 2019–2026, whereby I may have omitted older findings that would change particular estimates, although I made that decision deliberately in order to retain currency. The third is the lack of independent verification of the weights: the entire framework was constructed by a single author, and I present the weights without inter-rater verification of the coding, a weakness I would like to remedy in further work by including several independent assessors. The fourth is the conceptual boldness of the framework: connecting a chemical argument to the morphological notion of the first cause (*prauzrok*) goes beyond the usual bounds of astrobiology and is, I admit, contestable; I mention it because I hold that it explains the structure of the argument, but I acknowledge that the chemical part of the paper stands without it as well.

For future research I see three directions. The first is empirical calibration of the index: measuring the actual values of the five dimensions in laboratory analogs and in the field, whereby estimates would be replaced by data. The second is the construction of an explicit model of the sequence — spatial or temporal — that would show how chemical continuity is carried from the metabolic to the replicative regime without loss of continuity, with autocatalytic networks as a bridge (Xavier et al., 2020; Peng et al., 2022). The third is astrobiological application: a systematic ranking of planetary bodies by how far they offer both topologies, as a complement to existing urability criteria (Deamer et al., 2022; Robinson et al., 2023). There remains an open question, which I cannot resolve here, of whether the sequence of two topologies is truly necessary or merely sufficient — whether there exists, somewhere, a single environment that unites both. Until such an environment is demonstrated, complementarity remains the most economical explanation.

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HIDROTERMALNI IZVORI NASPRAM „TOPLOG MALOG JEZERCA": UPOREDNA PROCJENA ENERGETSKIH GRADIJENATA U PREBIOTIČKOJ SINTEZI I PORIJEKLU METABOLIZMA

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Originalni naučni članak

Primljeno: 30.04.2026. Prihvaćeno: 21.05.2026.

DOI: https://doi.org/10.65932/CAR-2026-1-2 **UDK**: 577.23:577.1

Sažetak: Pitanje o tome gdje je i kako nastao prvi živi sistem ostaje najspornija tačka savremene astrobiologije, a rasprava se već decenijama vodi između dvije škole: hipoteze o submarinskim alkalnim hidrotermalnim izvorima i hipoteze o površinskom „toplom malom jezercu", odnosno vrelim izvorima na kopnu. Članak ne pokušava da izabere pobjednika. Umjesto toga, uvodi se nov analitički okvir — topologija slobodnoenergetskog gradijenta — koji preformuliše cijelu raspravu kao razliku između stajaćeg vektorskog gradijenta (hemiozmotski, protonski i redoks gradijent na membrani, karakterističan za izvore) i cikličnog vremenskog gradijenta (naizmjenično vlaženje i sušenje, karakteristično za jezerca). Uz okvir se predlaže i mjerljivi Indeks slobodnoenergetske sprege (ISES), koji svako okruženje ocjenjuje duž pet dimenzija: perzistencija gradijenta, vektorska sprega, prostorna kompartmentalizacija, ciklična kondenzacija i fluks ugljenika i energije. Komparativna sinteza termodinamičkih parametara iz recenzovane literature (2019–2026) pokazuje da izvori postižu visoku vrijednost „metaboličkog pokretanja" (ISES-M ≈ 0,82), dok jezerca postižu visoku vrijednost „replikativnog pokretanja" (ISES-R ≈ 0,79). Ključni nalaz jeste da ova dva okruženja nisu konkurentska nego termodinamički komplementarna duž prelaza metabolizam→replikacija: izvor obezbjeđuje kontinuirani vektorski gradijent nužan za pokretanje ugljeničnog i energetskog metabolizma, a jezerce obezbjeđuje ciklični dehidratacioni režim nužan za polimerizaciju i inkapsulaciju. Rad zaključuje da porijeklo života nije vezano za jedno mjesto nego za sekvencu gradijentnih režima, i tu sekvencu tumači u okviru morfologije prauzroka.

Ključne riječi: *abiogeneza, alkalni hidrotermalni izvori, toplo malo jezerce, hemiozmoza, slobodnoenergetski gradijent, protometabolizam, prauzrok.*