

Before Life: A Planet Full of Chemistry

QTC-020 · From Quarks to Consciousness

The Universe, Life, and How We Found Out

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Epistemic profile: Current scientific interpretation

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Article Abstract

Before biology, Earth was not chemically empty. Atmosphere, rocks, meteorites, ultraviolet light, lightning, impacts and hydrothermal flow continually made, destroyed and redistributed organic compounds. The central difficulty was not merely obtaining ingredients, but concentrating compatible ones and linking reactions before dilution or degradation erased the result. This article separates experimental possibility from historical proof. Miller made amino acids, not life; meteorites delivered organics, not organisms; minerals and vents catalyze selected reactions without supplying a complete pathway. Surface wet-dry cycles, porous hydrothermal systems and mineral interfaces each solve different parts of the problem and create different liabilities. No single cradle has won. The evidence instead supports a planet containing many connected chemical laboratories—and an unfinished question about when productive chemistry became evolution.

In 60 Seconds

Prebiotic chemistry asks what non-biological processes could operate before inherited evolution. Experiments show several robust pieces. Electrical discharges make amino acids from selected gas mixtures; ultraviolet light drives useful photoredox networks; meteorites carry amino acids and sugars; impact shocks can synthesize organics. Yet ingredients dispersed through an ocean are not a pathway. Evaporation, freezing, wet-dry cycles, mineral adsorption, thermophoresis and microscopic pores can concentrate molecules, while clays and metal sulfides catalyze particular reactions. Each mechanism also creates losses: ultraviolet light destroys products, minerals can trap them, salts disrupt membranes, heat accelerates decomposition, and every transfer between environments dilutes material. Surface pools offer dehydration and repeated cycling. Alkaline hydrothermal systems offer sustained pH and redox gradients. Neither has reproduced a continuous, geologically supplied route to heredity. Laboratory success therefore answers a conditional question—what chemistry can occur here?—not the historical question of what did occur. QTC-020 maps that distinction and stops before chemical systems begin to evolve, the boundary taken up by QTC-021.

Why This Question Matters

Origin-of-life stories often turn an evocative place into an answer: a spark flask, a warm pond, a clay surface or an alkaline vent. The evidence is more demanding and more fertile. Different environments supply different functions, and their weaknesses matter as much as their celebrated reactions. Following inputs, energy, concentration, catalysis, degradation and transport prevents a laboratory product from becoming a historical certainty. It also reveals a deeper possibility: the relevant unit

may not have been one cradle at all, but a connected planetary network whose stages must still be demonstrated rather than narrated.

1. A Planet Before Biology

The Question

If a flask produces one ingredient of life, what exactly has been shown? It establishes a chemical possibility under controlled conditions. The larger claim—that the early Earth supplied, concentrated and connected those conditions—must be earned independently.

Prebiotic chemistry is chemistry before biology in the explanatory sense: reactions that do not require cells, enzymes or inherited instructions. It does not name a single era whose beginning and end are preserved in rock, nor a recipe already known to lead to life.[1,11,12] Researchers can reconstruct possible feedstocks and environments, test reactions and compare products with geological constraints. The task is historical as well as chemical. A molecule made without biology today could have been irrelevant four billion years ago if its reagents never met, its concentration stayed too low or its lifetime was too short.

This creates a crucial hierarchy of evidence. An experiment first establishes that specified inputs, apparatus, energy and timing produce a specified output. A second question asks whether early Earth could supply each condition. A third asks whether the product would accumulate beside the products and catalysts needed next.[1,12,14,31] Only then does a reaction become part of a historical pathway. The phrase 'prebiotically plausible' is therefore conditional: plausible under an atmospheric model, lake chemistry, vent composition or irradiation history that must itself be defended.[12,14,16] It is not a certificate that the reaction happened.

The laboratory record is already impressive. Experiments have made amino acids, nucleobases, sugars, activated nucleotides, short polymers, amphiphilic compartments and connected precursor networks.[1,11,12,18,24] None has recreated the origin of life. That is not a dismissal; it locates the achievement. Building blocks are not automatically a system, compartments are not automatically cells, and a network that runs once is not automatically capable of heredity. QTC-021 will examine the missing transition to persistence, variation and selection. This article stays with the planet that supplied chemical opportunities before that threshold.

Five functions organize the comparison. A setting needs ingredients; an energy source able to drive some reactions; a way to concentrate matter; surfaces, gradients or catalysts that shape rates; and cycles or transport that connect steps.[14,17,25,29,34] The list is not a new origin theory. It is a way to expose hidden assumptions. A hydrothermal pore can concentrate and energize; a wet-dry shoreline can concentrate and cycle; a mineral can catalyze one step while binding the product too tightly for the next. Each proposed advantage generates a liability that belongs in the same sentence.

Early Earth offered many settings at once. Impacts crossed atmosphere and ocean; rain and rivers moved solutes across rock; hydrothermal circulation connected crust and seawater; aerosols and meteorites added external material.[10,21,25,33,34] These environments could compete, cooperate or occur in sequence. But drawing arrows among them is not yet chemistry. Every arrow requires travel time, survival, flux and concentration. The first stage of the investigation is simpler: identify what material the planet and Solar System could place on the table.

Where That Leaves Us

Prebiotic chemistry begins with disciplined modesty: a reaction is real under the conditions that produced it, while its place in Earth history remains a separate claim. Ingredients, energy, concentration, catalysis and connection provide the audit trail. The next question follows the ingredients themselves—from atmospheric gases and volcanic plumes to impact shocks and carbon-rich stones arriving from space.

2. Ingredients From Air, Rock, and Space

The Question

The famous spark flask is often remembered as either a triumph that created life or a failure that used the wrong atmosphere. It was neither. It was a decisive experiment whose result and historical reach must be described at different scales.

In 1953 Stanley Miller circulated water past methane, ammonia and hydrogen, sent electrical sparks through the gases and collected organic products. Paper chromatography revealed amino acids, including glycine and alanine.[1] The published paper was Miller's. Harold Urey provided the theoretical and institutional setting and supervised the doctoral work, but did not appear as coauthor. That distinction preserves both agency and influence without renaming the experiment. More importantly, the apparatus produced amino acids, not proteins, cells or life. Its enduring force was methodological: a claim about primordial chemistry could be moved from speculation into a flask with recoverable products.

The gas mixture was a hypothesis, not a sample of ancient air. Hadean zircon measurements later placed magma oxygen fugacity near the fayalite-magnetite-quartz buffer, which makes a persistently, globally methane-ammonia-rich atmosphere from later volcanic outgassing difficult to sustain.[2] Mantle redox does not determine every atmospheric interval, especially during accretion and giant impacts, but it breaks the simplest retelling. Neutral CO₂-N₂ mixtures can still yield organics under electrical discharge when hydrogen or other reductants participate, generally with different efficiencies and products.[3] 'The atmosphere was wrong' is therefore as crude as 'the experiment recreated Earth.'

Local environments enlarge the range. In 2008 Johnson and colleagues reanalysed archived samples from Miller's volcanic apparatus and detected more amino acids than the original methods had resolved.[4] Parker and colleagues later examined a 1958 H₂S-rich discharge sample and reported 23 amino acids and four amines.[5] These experiments support chemically reducing volcanic plumes or sulfur-rich zones even if the average atmosphere was less reducing. They do not establish that such a plume hosted the origin. The correction is geographical: a global atmospheric average need not erase transient local reactors.

Space supplied another stream. The Murchison meteorite contained amino acids and hydrocarbons with evidence for extraterrestrial origin; later analyses found sugar-related compounds, and carbonaceous meteorites have yielded ribose and other sugars under stringent contamination and isotope controls.[6,8,9] Some meteoritic alpha-methyl amino acids show modest L-enantiomeric excesses, proving that abiotic processes can create molecular asymmetry before biology.[7] None of this means organisms arrived in meteorites. The defensible claim is narrower and important: early Earth's organic inventory was not limited to what its atmosphere made.

Impacts did more than deliver. Shock experiments using carbon, nitrogen, iron and water-bearing materials produced fatty acids, amines and glycine under simulated oceanic-impact conditions.[10] Natural impacts would also vaporize, oxidize and bury material, so recovery products cannot be multiplied directly by crater counts. Atmosphere, volcanoes, meteorites and shocks instead form a portfolio of sources whose proportions changed over time. Once ingredients existed, a harder balance appeared. The energy that makes a molecule can destroy it, and a source that spreads products globally can leave each one too dilute to use.

Where That Leaves Us

Miller's experiment survives the atmospheric correction because its deepest result was conditional and experimental: simple gases can become amino acids when energy flows through an appropriate mixture. Volcanic zones, meteorites and impacts widen the supply without delivering life. Supply alone now yields to a sharper problem—how energy can drive useful chemistry while preventing its own products from being erased.

3. Energy That Makes and Breaks Molecules

A chemical reaction needs more than ingredients. It needs a path across an activation barrier and a continuing thermodynamic reason to proceed. Miller used electrical discharge; early Earth also offered ultraviolet photons, impact shocks, geothermal heat and persistent redox or pH differences.[1,10,13,31] These sources are not interchangeable currencies. A photon has a wavelength, a discharge has a spectrum, a shock has pressure and cooling history, and a gradient needs a mechanism that couples flow to reaction. Saying that a young planet was 'full of energy' explains no product until those particulars are supplied.

Lightning makes the point. Electrical discharges fragment stable gases and let reactive radicals recombine into organics, but yields change steeply with atmospheric oxidation state and available hydrogen.[1,3,4] The collector in a spark experiment also protects soluble products by moving them away from further discharge. A natural atmosphere offers rainout, aerosols, oceans and rock surfaces instead. Estimating production therefore requires discharge frequency, gas composition, product destruction and removal together. The same flash can begin a synthetic sequence and erase another molecule before either reaches a useful reservoir.

Ultraviolet light supplies a more spatially continuous test. Ritson and Sutherland used photoredox chemistry to make simple sugars from HCN-derived feedstocks; Patel and colleagues connected photochemistry to precursors of RNA, amino acids and lipids; later work mapped sulfite and ferrocyanide routes.[13–15] Rimmer and colleagues compared productive light chemistry with competing dark reactions under wavelength-dependent irradiation.[16] These results show that photons can select pathways rather than merely heat a mixture. They also make the environment more demanding: water depth, haze, mineral shielding, time of day and absorber concentration decide which photons arrive.

Light is double-edged because photochemistry has no intention. It can generate hydrated electrons and useful radicals, cleave unstable by-products, destroy desired products or exhaust a sensitizer.[13–16] A plausible setting may therefore need exposed phases for synthesis and shaded, buried or dark phases for preservation. Cycling can turn the contradiction into a mechanism, but only if the

compounds survive transport between phases. The important variable is net accumulation after the full light-dark history, not a maximum yield measured at the most favorable instant.

Gradients differ from pulses. Where alkaline, hydrogen-rich water meets a more acidic, CO₂-bearing ocean across mineral barriers, pH and redox differences can persist as long as flow continues.[29–31] They store free energy in spatial separation. Yet a gradient does no chemical work unless charges or molecules cross through a catalytic pathway. Heat likewise accelerates both synthesis and decomposition; ribose, for example, decomposes rapidly at high temperature under measured neutral conditions.[35] Energy solves activation only when concentration, catalysis and preservation solve the losses. That requirement leads from sources to places where matter can stop dispersing.

Where That Leaves Us

Energy is not a magic ingredient but a timed, filtered interaction between matter and environment. Discharges, photons, shocks, heat and gradients each open reactions while also accelerating loss. Any origin scenario must therefore report a net chemical budget after destruction and transport. Surface water cycles provide the clearest next test: can repeated concentration and drying make dilution itself temporarily reversible?

4. Surface Pools: Concentration by Cycles

The phrase 'primordial soup' hides a physical problem. A global ocean is an excellent solvent and an enormous diluter. Reactions that join monomers often release water, so abundant water can favor the reverse reaction. Local hydrology changes the arithmetic. Evaporation shrinks volume; freezing rejects many solutes into brines; seepage removes water; rainfall resets the mixture. [17,20,33] None guarantees useful chemistry, because salts and inhibitors concentrate too. But a fluctuating pool converts a static concentration problem into a sequence whose dry and wet phases can perform different tasks.

Phosphate illustrates how location matters. Calcium in ordinary waters tends to remove phosphate into poorly soluble minerals. Toner and Catling combined experiments and modelling to show that carbonate-rich lakes can suppress dissolved calcium through carbonate precipitation and thereby allow phosphate to reach high concentrations under suitable evaporation.[17] The result is not 'all lakes solve phosphate.' It requires carbonate alkalinity, hydrologic balance and sources of phosphate. Its value lies in replacing a planet-wide shortage with a testable class of local waters.

Wet-dry experiments have joined reactions that are difficult in permanent dilute water. Rajamani and colleagues produced RNA-like polymers from mononucleotides in lipid-assisted cycles; Forsythe and colleagues drove ester-mediated amide bond formation with repeated drying; Becker and colleagues maintained continuous synthesis of canonical and non-canonical nucleosides across cycles.[18–20] These are different systems, not one complete pathway. Together they establish a physical principle: water activity and concentration can oscillate, allowing dehydration chemistry during dry phases and dispersion, folding or encapsulation during wet phases.

Membranes make the water chemistry visible. Milshteyn and colleagues tested selected amphiphilic compounds in samples from a hydrothermal hot spring and in seawater. Vesicles assembled in the hot-spring water but not in the tested seawater, where salts and divalent ions interfered.[21] This does not ban all marine compartments; different lipids and marine

microenvironments behave differently. It does show why 'water was present' is too weak. Ionic composition can decide whether the same organic molecules become a boundary or remain dispersed.

Models of warm little ponds combine meteoritic delivery, degradation, seepage and repeated drying to calculate when nucleobases might accumulate.[33] The fluctuating-hydrothermal-pool hypothesis extends the setting to membranes and combinatorial selection across coupled phases.[34] Both make predictions, but exposed land area, pond abundance, rainfall, ultraviolet exposure and feedstock continuity remain uncertain. A surface scenario gains dehydration and cycling while accepting vulnerability to desiccation, photolysis and interrupted supply. Its strongest claim is not that Darwin's warm pond was right. It is that a changing shoreline can act as a chemical machine.

Where That Leaves Us

Surface pools turn geography into a reagent. Evaporation, freezing and wet-dry cycling can concentrate solutes, change water activity and alternate synthesis with rehydration; lake chemistry can even release phosphate from a global-looking bottleneck. The price is exposure and uncertain continuity. A contrasting environment moves the reactor below water, replacing atmospheric cycles with mineral walls, flowing gradients and microscopic pores.

5. Hydrothermal Vents: Gradients and Pores

The Question

The words 'hydrothermal vent' can evoke a scorching black smoker, yet origin models often mean cooler alkaline flow through porous mineral barriers. Temperature, pH, salinity, minerals and mixing differ enough that evidence for one vent cannot be assigned to all.

Hydrothermal systems replace the filling and emptying of a pool with continuous flow through rock. Russell, Hall and Turner grew iron-sulfide chimneys in the laboratory by bringing appropriate solutions together, demonstrating that precipitation can build thin-walled, compartmented structures.[26] Russell and colleagues later proposed that catalytic iron-sulfide membranes at alkaline vents could separate hydrogen-rich hydrothermal fluid from a more acidic CO₂-bearing ocean.[27] The proposal joined three functions: mineral catalysis, microscopic compartments and a persistent electrochemical gradient. It was a hypothesis with experimental handles, not a fossilized first cell.

The attractive energy source is geochemical disequilibrium. Serpentinization and related water-rock reactions can generate hydrogen; mixing with oceanic carbon dioxide creates redox potential, while a pH difference stores proton-motive free energy.[27,29,31] Modern cells exploit proton gradients, but resemblance does not prove direct continuity. The prebiotic question is whether an inorganic barrier can couple those separated half-reactions without enzymes. It must also remain permeable enough for feedstocks and products to move while retaining enough separation to preserve the gradient.

Individual reactions now exist. Huber and Wächtershäuser formed activated acetic-acid derivatives from carbon monoxide and methyl sulfide on iron-nickel sulfides.[28] Herschy and colleagues detected carbon reduction products in an origin-of-life reactor designed to simulate alkaline vent conditions.[29] Barge and colleagues showed that iron oxyhydroxide redox state, pH

and temperature controlled reductive amination of pyruvate to alanine.[30] Each result demonstrates a catalytic possibility in a defined mineral system. None supplies the whole carbon-fixation sequence, feedstock provenance, product escape and recurrence in one apparatus.

Hudson and colleagues isolated a particularly informative step. In a microfluidic device, a pH gradient across freshly precipitated Fe(Ni)S coupled hydrogen oxidation to CO₂ reduction at room temperature and moderate pressure. Isotope labelling confirmed formate, reported at about 1.5 micromolar; reducing the gradient, removing hydrogen or eliminating the precipitate gave no detectable product.[31] The controls establish the gradient's causal role in that reaction. They do not turn micromolar formate into metabolism. Precision about the small product is what makes the experiment important rather than weak.

The liabilities are equally physical. Hot water accelerates decomposition of sugars and other intermediates; seawater ions can disrupt fatty-acid compartments; open flow can dilute products; mineral precipitates age and clog; early ocean composition and vent flux remain uncertain. [21,25,32,35] Thermophoresis in pores offers one countermeasure, but its efficiency depends on geometry and temperature difference.[25] 'Vents destroy organics' is too broad, as is 'vents solve metabolism.' Cooler porous systems can provide gradients and concentration, but every claimed pathway still needs a compatible chemical budget.

Where That Leaves Us

Alkaline hydrothermal systems turn continuous flow into gradients, compartments and mineral catalysis. Controlled reactors now demonstrate selected carbon and amino-acid reactions, including gradient-driven formate at micromolar scale, but not a living metabolism. Their weaknesses—heat, salts, dilution and uncertain continuity—lead naturally to the surfaces themselves. Minerals can edit chemistry wherever water and rock meet, not only at vents.

6. Minerals as Chemical Editors

A dissolved molecule samples three-dimensional water; an adsorbed molecule is held near neighbors on a two-dimensional surface. That change can raise local concentration, orient reactive groups and alter activation barriers. It can also immobilize a molecule or make hydrolysis easier. 'Minerals catalyzed the origin' therefore compresses selection, concentration and loss into one flattering verb. The useful question is comparative: which mineral face, charge and fluid composition changes which reaction, and can the product leave in a form available to the next step?

Montmorillonite clay supplies the classic polymer example. Ferris and colleagues showed that activated nucleotides form longer RNA-like oligomers on mineral surfaces than in corresponding solution chemistry.[22] The clay did not manufacture the activated monomers, and product sequences reflected the reaction system rather than biological information. The experiment established surface-assisted bond formation. Historical use would require compatible activation chemistry, repeated monomer supply and a release or transfer mechanism before adsorption became a trap.

Minerals can protect as well as join. Ricardo and colleagues found that borate stabilized ribose in formose reaction mixtures, limiting rearrangement and decomposition.[23] That result addresses one notorious instability without solving the entire sugar problem. Early Earth still had to supply

borate at the same place as sugar precursors, then move stabilized ribose into activation and nucleotide chemistry. A mineral solution to one bottleneck can create a geographical requirement for the next. This is why end-to-end pathways are harder than a catalogue of individually successful reactions.

Surfaces can also connect compartments to polymers. Hanczyc, Fujikawa and Szostak reported that montmorillonite accelerated fatty-acid micelle conversion into vesicles; clay particles with adsorbed RNA could become encapsulated.[24] The experiment links three often separated modules—mineral catalysis, nucleic-acid adsorption and membrane assembly—without claiming a complete protocell. Encapsulation alone does not produce reproduction or selection, but it shows that a mineral need not remain outside a boundary. Particles can carry chemistry into a compartment while helping the compartment form.

Pore-scale physics extends the role beyond molecular adsorption. Baaske and colleagues used thermal gradients and convection in simulated hydrothermal pores to accumulate nucleotides by orders of magnitude.[25] Geometry, molecular diffusion, flow and temperature created the concentration effect; a generic hot ocean would not. Together these experiments suggest that minerals edit chemistry by selecting locations and residence times as well as reactions. They can concentrate, stabilize, catalyze, encapsulate or sequester. The sign of the net effect belongs to the entire mixture, which becomes decisive when several molecular families must operate together.

Where That Leaves Us

Minerals are not a universal solution but a library of selective interfaces. Clay can lengthen activated oligomers and enter vesicles; borate can stabilize ribose; pores can accumulate nucleotides. Every benefit is conditional on fluid, feedstock and release. The next hurdle is therefore integration: whether independently successful syntheses of bases, sugars, amino-acid and lipid precursors can coexist as a network rather than a museum of reactions.

7. From Building Blocks to Networks

The Question

Suppose one experiment makes a nucleobase, another a sugar and a third a membrane. The inventory has grown, but the historical problem has not been solved until their reagents, salts, temperatures and timing can share a sequence without destroying one another.

Early synthesis studies often began with one celebrated molecule. Oró heated concentrated hydrogen cyanide and obtained adenine, showing that five small HCN units can assemble into a purine base under selected conditions.[11] The route was conceptually powerful because it connected a simple carbon-nitrogen feedstock to a biological component. Its historical burden remained concentration: where was enough HCN produced, protected and gathered? Adenine is also only one base, and a base without sugar, phosphate, activation and a compatible assembly route does not become RNA.

Powner, Gerland and Sutherland changed the architecture of the ribonucleotide problem. Rather than synthesize ribose and a pyrimidine base separately and force them together, they used a sequence in which smaller precursors converged on activated pyrimidine ribonucleotides.[12] Ultraviolet irradiation helped destroy unwanted stereoisomers while supporting the productive

route. The achievement was not merely another component; it showed that a famously difficult bond could be avoided by choosing a different path. Yet reagent order, phosphate, pH changes and irradiation still need an environmental choreography.

Systems chemistry pushes several branches toward common inputs. Ritson and Sutherland produced simple sugars through HCN-derived photoredox chemistry.[13] Patel and colleagues reported a cyanosulfidic network leading to precursors of ribonucleotides, amino acids and lipids; Xu and colleagues expanded photochemical reductive homologation using sulfite and ferrocyanide.[14,15] Shared feedstocks reduce the implausibility of entirely separate chemical worlds. They do not prove that every branch ran simultaneously. A common stream can still split into environments with incompatible pH, metal ions or photon exposure.

Chirality adds a different integration problem. Cronin and Pizzarello measured modest L-enantiomeric excesses in particular meteoritic alpha-methyl amino acids.[7] The result establishes that abiotic Solar System chemistry can break mirror symmetry before life. It does not supply the near-homochirality used by biological proteins and nucleic acids, nor show how an extraterrestrial excess transfers to other molecular families. Amplification, selection and preservation remain mechanisms to demonstrate. The correct lesson is possibility of a bias, not a solved origin of handedness.

A network must work in time as well as in a reaction diagram. Salts that help phosphorylation can disrupt fatty-acid membranes; ultraviolet light that selects one product can destroy another; heat that speeds synthesis shortens sugar lifetime; minerals that concentrate monomers can retain polymers.[16,20,21,23,35] Sequential environments can relax simultaneous compatibility, but they add transport, dilution and preservation. The relevant experimental goal is therefore not a single perfect flask. It is a continuous or cycled system with mass balance, realistic inputs and products that remain available for the next transformation.

Where That Leaves Us

Systems chemistry replaces the shopping list with compatibility. Adenine, activated pyrimidine nucleotides and shared precursor networks show that route design can bypass old bottlenecks; meteoritic asymmetry shows that abiotic bias is possible. But every successful branch still carries environmental conditions into the next. The final assessment must compare whole settings and connected sequences without promoting the most vivid experiment into a unique birthplace.

8. No Single Cradle Has Won

The leading environments solve different equations. Surface pools concentrate through evaporation and use wet-dry cycles for dehydration chemistry. Alkaline hydrothermal systems maintain redox and pH gradients and provide pores. Mineral interfaces adsorb, orient and catalyze. Meteorites and atmospheric or impact chemistry widen the inputs.[9,17,25,31,34] None has demonstrated every required function, and no experiment can recover a unique location simply by succeeding. The correct comparison asks which bottleneck is solved, which new one appears and whether the full material flow closes.

Earth supplied broad opportunity early. Jack Hills zircons record crust-water interaction by about 4.4 billion years ago, implying liquid water and differentiated crust while the planet was still young.[36] They do not preserve a warm pond, an alkaline vent or an origin date. Geological

context is most useful as a filter: exposed land cannot be assumed without evidence; a vent composition must follow water-rock reactions; an atmospheric feedstock must survive photochemistry. The archive constrains stage design more often than it identifies the historical stage.

Chemical lifetime sharpens that filter. Larralde, Robertson and Miller measured ribose half-lives of about 73 minutes at pH 7 and 100°C and 44 years at pH 7 and 0°C.[35] Those numbers do not disprove an RNA-related origin, because synthesis, stabilization, cooling or rapid use can outrun loss. They do forbid a timeless arrow labelled 'ribose accumulates' across all environments. Rates are part of plausibility. A compound that exists analytically may be absent functionally if its destruction is faster than its supply.

Connected environments remain plausible and demanding. An impact product could rain into a carbonate lake, a wet-dry cycle could form oligomers, and groundwater could carry them toward mineral pores. Each transfer may also oxidize, adsorb, hydrolyze or dilute the cargo. [10,20,25,33,34] A multi-stage story becomes stronger only when fluxes and survival are quantified. Otherwise it gains flexibility by moving every difficulty to a new place. The planet-wide network is a research programme, not a loophole through which incompatible experiments automatically cooperate.

What has been established is substantial: abiotic routes make diverse organics; local settings concentrate them; light, minerals and gradients select reactions; simple compartments assemble under some water chemistries.[1,9,12,17,21,24,31] What remains absent is a geologically supplied, continuous transition from those processes to open-ended heredity. That absence does not make life's emergence supernatural or unknowable. It identifies the next experimental boundary. QTC-020 ends with chemistry becoming organized enough to persist. QTC-021 begins when persistence can vary, reproduce and undergo selection.

Where That Leaves Us

Before life, Earth was already a network of chemical reactors. Air, space, rock, light, water cycles, minerals and hydrothermal flow supplied complementary possibilities, each bounded by losses and historical uncertainty. No cradle has earned exclusivity, and no isolated reaction has crossed the biological threshold. The next article asks what additional organization lets chemistry retain differences long enough for evolution to begin.

What We Know, and How

- Electrical discharge, ultraviolet photochemistry and impact shocks can synthesize organic compounds from selected simple inputs.[1,3,10,13–16]
- Carbonaceous meteorites contain extraterrestrial amino acids, sugar-related compounds and ribose.[6–9]
- Wet-dry cycles, mineral adsorption, thermophoresis and pores can concentrate or join relevant molecules in experiments.[17–25]
- Mineral catalysts and pH or redox gradients drive selected carbon and amino-acid reactions in controlled hydrothermal systems.[26–31]
- No experiment has yet produced a continuous, geologically supplied transition from simple feedstocks to open-ended heredity.[12,24,31,34]

What We Still Don't Know

- Which early-Earth environments produced the largest useful fluxes rather than the largest isolated laboratory yields.
- How compatible feedstocks accumulated together while destructive salts, ultraviolet light, heat and hydrolysis were controlled.
- Whether surface pools, hydrothermal pores, ice and mineral interfaces acted as alternatives, partners or stages in a sequence.
- How molecular chirality was amplified and maintained across different precursor families.
- What experimentally reproducible transition converted productive chemistry into persistent heredity and evolution.

What Could Change Our Minds

- A geological archive that directly links a specific early environment with diagnostic prebiotic products and reaction conditions.
- Continuous experiments showing that a proposed environment supplies feedstocks, concentration, energy, catalysis and preservation together.
- Mass-balanced transport experiments demonstrating that products survive transfer through a proposed multi-environment sequence.
- Independent replication that removes a key product or pathway under realistic impurities, salts, ultraviolet spectra or temperature cycles.
- A reproducible system in which geochemically bounded inputs generate compartments with heritable variation and sustained selection.

If You Remember Only One Thing

Before life, Earth offered many chemical reactors, not one proven cradle. Experiments establish possible reactions; history requires compatible ingredients, energy, concentration, preservation and transport to operate together before heredity begins.

Related Articles

- QTC-016 — How to Build a Planet
- QTC-019 — Earth's Thermostat
- QTC-021 — When Chemistry Began to Evolve

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