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Article

Calcium Carbonate as a Potential Template for the Origin of Life: Coupled Inorganic−Organic Geochemistry of Travertine Deposit from Puga Hot Spring

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Cite This: https://doi.org/10.1021/acsearthspacechem.5c00127

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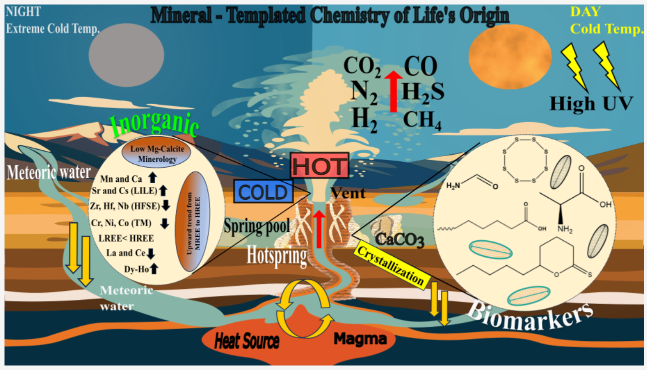

ABSTRACT: Unraveling life's origin involves finding environments that can form and preserve organic molecules, with hydrothermal systems offering a likely setting. Terrestrial mineral deposits in the form of silicates and carbonates may have functioned as natural reactors that facilitated early prebiotic chemical reactions. At lab scale, calcium carbonate ($CaCO_3$) surfaces accelerate key prebiotic reactions, yet natural sites focusing on organic preservation associated with $CaCO_3$ remain limited. This study shows that $CaCO_3$ can actively concentrate and stabilize organic molecules under extreme conditions. In this work, we present the first empirical demonstration that Puga, Ladakh's hot-spring travertine, hosts prebiotic molecules, serving as a natural template for mineral-driven organic reactions. X-ray diffraction showed C−O lattice distortions in calcite linked to biogenic input, while molecular analysis identified carbonate bands with organic groups. Biomarker analysis detected trapped biomarkers including traces of β-alanine derivatives (amino propanoic acid), pyran-2-thione, TMS-derivatized formamide, cyclooctasulfur (S_8), and hexadecenoic methyl ester (fatty acid). Stable-isotopic signatures of travertine yielded $\delta^{18}O_{carb} \sim -24‰$ VPDB and $\delta^{13}C_{carb} \sim -5‰$ VPDB. Elemental geochemistry indicated low-temperature hydrothermal enrichment in large-ion lithophiles and depletion of high-field-strength elements. We hypothesized a four-step conceptual model emphasizing travertine's dual role in preserving inorganic tracers and organic precursors. Findings reveal that cold ambient conditions synergize with hydrothermal processes to host and concentrate prebiotic molecules within calcic matrices. Rapid CO_2 degassing and cooling of vent fluids in a colder external environment trigger low-Mg calcite precipitation, encapsulating diatoms and organic moieties, offering new insights into mineral scaffolds that could have triggered early-life reactions.

KEYWORDS: *prebiotic geochemistry, Ladakh, biomarkers, Martian analogue, mineralogical analysis, molecular analysis, major trace and rare earth elements*

1. INTRODUCTION

The coevolution of minerals and microbes has played a pivotal role in Earth's history, with biological activity directly influencing the formation of many rock types. It is also increasingly evident that mineral substrates may have offered a foundation for the emergence of life.[1] Among these, calcium carbonate minerals stand out as reactive surfaces capable of concentrating and stabilizing organic precursors. Yet, the natural environments in which they may trap and preserve such prebiotic compounds remain largely underexplored. Laboratory studies have demonstrated that calcite can catalyze peptide bond formation and nucleoside phosphorylation under conditions simulating early Earth.[2−6] Moreover, recent findings show that simple inorganic ions like Ca^{2+} can facilitate the chiral selection and polymerization of α-hydroxy acid monomers, crucial steps in the development of biological homochirality.[7] These insights position calcium carbonate as a promising geomaterial for detecting traces of early life.[8]

Researchers have shown that, alongside calcium carbonate, silicate-based minerals, especially silica and silica−carbonate compounds, can effectively preserve organic molecules under conditions thought to resemble early Earth. Experiments reveal that when Fe^{3+} ions are embedded in silica colloids, they help

Received: April 29, 2025
Revised: June 4, 2025
Accepted: June 5, 2025