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Review Article

Mineral–Organic Interactions in Prebiotic Chemistry and Protection of Early Biomolecules

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Abstract

Understanding the origin of life on Earth requires examination of chemical processes that enabled the formation, stabilization, and persistence of early biomolecules under harsh prebiotic conditions. Among the key factors influencing prebiotic chemistry are interactions between mineral surfaces and organic molecules. Minerals present on the early Earth provided catalytic surfaces, adsorption sites, and protective environments that facilitated organic molecule synthesis and stabilization against degradation. Clay minerals, metal oxides, sulfides, and silicates have been proposed as critical components in promoting polymerization reactions and shielding fragile biomolecules from ultraviolet radiation and hydrolytic breakdown. Recent laboratory simulations and planetary studies support the idea that mineral–organic interactions played a central role in chemical evolution and the emergence of primitive biological systems. This review examines current knowledge of mineral-assisted prebiotic chemistry, mechanisms of biomolecule protection, and implications for early Earth and extra-terrestrial environments.

Keywords: *Prebiotic chemistry, mineral surfaces, origin of life, biomolecule stabilization, clay minerals, catalytic minerals, chemical evolution, early Earth environments.*

1. Introduction

The origin of life on Earth represents one of the most profound scientific questions, requiring an understanding of how simple inorganic and organic molecules transformed into complex, self-replicating biological systems. Early Earth conditions were highly dynamic and often hostile, characterized by intense volcanic activity, heavy meteorite bombardment, fluctuating temperatures, and high levels of ultraviolet (UV) radiation due to the absence of an ozone layer. Under such circumstances, fragile organic molecules required environments that not only facilitated their formation but also protected them from rapid degradation [1]. Models of prebiotic chemistry focused largely on reactions occurring in aqueous environments, where organic molecules formed in oceans or small ponds and gradually evolved toward biological complexity. However, dilute aqueous solutions present challenges for chemical evolution because low concentrations reduce reaction probability, and hydrolysis can rapidly break down complex molecules. Consequently, attention has increasingly shifted toward mineral-rich environments that could concentrate organic compounds and provide catalytic surfaces for chemical reactions [2]. Minerals were abundant on the early Earth's crust and ocean floor, forming diverse surfaces and microenvironments capable of interacting with organic molecules. These surfaces could adsorb and concentrate organic compounds, align them in favorable orientations for chemical reactions, and catalyze polymerization processes necessary for producing peptides and nucleic acid precursors. Moreover, mineral environments could offer physical protection against radiation and chemical degradation, enabling molecular persistence long enough for further evolution [3]. Recent experimental studies and geochemical analyses increasingly support the hypothesis that mineral–organic interactions were central to prebiotic chemistry. These interactions likely played a critical role in the transition from simple chemistry to early biological organization. Understanding these processes not only informs origin-of-life research but also guides the search for life beyond Earth, where similar mineral environments may exist.

2. Early Earth Conditions and Availability of Minerals

The early Earth, particularly during the Hadean and early Archean eons, exhibited environmental conditions vastly different from those of the modern planet. Frequent volcanic eruptions released gases and mineral particles into the atmosphere, while meteorite impacts delivered additional minerals and organic compounds. Surface temperatures fluctuated widely, and oceans formed as the planet gradually cooled, creating aqueous environments enriched with dissolved minerals and chemical nutrients [4]. Weathering of volcanic and crustal rocks produced abundant clay minerals, which accumulated in sedimentary environments and shallow aquatic systems. Clay formation processes generated minerals with layered structures and large surface areas, making them particularly suitable for adsorption and catalytic interactions with organic molecules. At the same time, hydrothermal systems along oceanic ridges released metal-rich fluids containing iron, sulfur, nickel, and other elements, forming mineral deposits capable of supporting redox-driven chemical reactions [5]. Hydrothermal vents are considered especially important in origin-of-life scenarios because they provide continuous energy sources, mineral catalysts, and chemical gradients necessary for complex reactions. These environments contain iron sulfides and other transition metal minerals that resemble catalytic centers found in modern biological enzymes, suggesting continuity between prebiotic and biological chemistry, meteorite impacts may have contributed both minerals and organic compounds to Earth's surface, enriching chemical diversity. Such extraterrestrial contributions, combined with endogenous geological processes, created a mineral-rich environment offering numerous potential sites for prebiotic chemical evolution.

Table. Role of Minerals in Prebiotic Chemistry and Protection of Early Biomolecules

Mineral Type	Common Early Earth Environment	Interaction with Organic Molecules	Role in Prebiotic Chemistry	Protective Function for Biomolecules
Clay minerals (e.g., montmorillonite)	Sedimentary basins, weathered volcanic regions, shallow waters	Strong adsorption of nucleotides, amino acids, and lipids	Catalyze polymer formation and molecular assembly	Protect organics from UV radiation and hydrolytic degradation
Iron sulfides (e.g., pyrite, greigite)	Hydrothermal vents and volcanic environments	Catalyze redox reactions and organic synthesis	Promote proto-metabolic reactions and chemical energy transfer	Provide stable microenvironments for molecular persistence
Silicate minerals	Volcanic crust and oceanic sediments	Adsorb organic compounds and concentrate reactants	Support surface-mediated reactions and molecular alignment	Reduce molecular dispersion and degradation
Metal oxides (iron, titanium oxides)	Hydrothermal and surface weathering zones	Provide reactive catalytic surfaces	Enhance oxidation–reduction reactions important for synthesis	Adsorption stabilizes molecules against breakdown
Carbonate minerals	Shallow marine environments	Facilitate organic molecule accumulation	Support chemical concentration and polymer formation	Buffer environmental conditions, aiding molecule stability
Mineral pores and layered structures	Porous rocks and sediment matrices	Trap and concentrate organic molecules	Enable confined chemical reactions	Shield biomolecules from radiation and environmental stress
Meteorite-associated minerals	Extraterrestrial material delivered to Earth	Deliver and stabilize organic compounds	Provide additional catalytic and protective surfaces	Preserve organic molecules during space transport

3. Mechanisms of Mineral–Organic Interactions

Mineral surfaces interact with organic molecules through several chemical and physical mechanisms that influence prebiotic reactions. One of the primary mechanisms is adsorption, where organic molecules attach to mineral surfaces via electrostatic attraction, hydrogen bonding, or chemical bonding. Adsorption concentrates organic molecules from dilute environments, increasing local reactant density and facilitating chemical interactions that might otherwise be unlikely [6]. Minerals also function as catalysts by lowering activation energy barriers for chemical reactions. Certain mineral surfaces possess reactive sites capable of promoting condensation reactions necessary for forming polymers such as peptides or nucleic acids. For example, layered clay minerals provide confined spaces that help align molecules in configurations conducive to bond formation, enhancing polymerization efficiency. Mineral surfaces may also influence molecular orientation and spatial arrangement, potentially guiding early structural organization. Some mineral crystals exhibit chiral properties, which may have contributed to the development of biological homochirality—the predominance of single molecular handedness in biological systems, minerals can create microenvironments within pores or layered structures that protect molecules from environmental stress while maintaining chemical reactivity. Such environments could have acted as natural reaction chambers, enabling progressive chemical complexity [7], these mechanisms demonstrate that mineral surfaces served not merely as passive substrates but as active participants in early chemical evolution.

4. Protection of Early Biomolecules by Mineral Surfaces

The formation of complex biomolecules alone would not have been sufficient for life to emerge; these molecules also needed to persist in environments prone to degradation. Early Earth conditions exposed organic molecules to destructive influences, including ultraviolet radiation, high temperatures, oxidative conditions, and hydrolytic reactions in water. Without protective mechanisms, fragile molecules such as nucleotides and amino acids would likely degrade rapidly [8]. Mineral surfaces provided protective advantages by adsorbing and stabilizing organic compounds. Adsorbed molecules experience reduced mobility and are less exposed to degradative reactions. For example, clay minerals can bind nucleic acid components and amino acids, shielding them from ultraviolet radiation and reducing chemical breakdown rates. Mineral pores and layered structures may also have created sheltered microenvironments where organic molecules could accumulate and undergo reactions without being immediately destroyed by environmental stresses. Such confinement would enhance molecular persistence and allow progressive chemical evolution toward more complex systems, mineral-associated environments may have supported early encapsulation processes, contributing to formation of primitive compartmentalized systems resembling early protocells. By protecting and concentrating biomolecules, mineral surfaces likely provided essential stepping stones in the emergence of life. Understanding these protective mechanisms is crucial for reconstructing plausible scenarios for early molecular evolution and for identifying extraterrestrial environments capable of supporting similar processes.

5. Experimental Evidence Supporting Mineral-Assisted Prebiotic Chemistry

Experimental research over recent decades has provided strong support for the hypothesis that mineral surfaces played an important role in prebiotic chemical evolution. Laboratory simulations designed to reproduce early Earth conditions have demonstrated that minerals significantly influence organic synthesis, adsorption, and polymerization processes essential for the development of early biomolecules [9]. One of the most influential findings involves clay minerals such as montmorillonite, which have been shown to catalyze the formation of RNA-like oligomers from activated nucleotide precursors. In these experiments, nucleotides adsorbed onto clay surfaces align in ways that favor bond formation, enabling polymerization that is otherwise inefficient in dilute solutions. Such results suggest that mineral surfaces may have supported the early formation of genetic polymers necessary for primitive biological systems. Additional experiments have demonstrated that mineral surfaces facilitate amino acid condensation reactions, leading to formation of short peptides under simulated prebiotic conditions. Metal sulfide minerals commonly found in hydrothermal environments have also shown catalytic capabilities resembling those of modern enzyme systems, suggesting a potential evolutionary link between mineral catalysts and biological metabolism.

Minerals have further been shown to assist in lipid assembly and vesicle formation, processes essential for development of primitive cellular compartments. Studies indicate that adsorption of lipid molecules onto mineral surfaces can promote organization into membrane-like structures that could eventually detach and form protocell-like systems [10]. Although laboratory experiments cannot perfectly replicate early Earth conditions, accumulated evidence consistently demonstrates that mineral surfaces significantly enhance chemical complexity and stability, supporting their central role in prebiotic chemistry.

6. Implications for Extraterrestrial Environments

The study of mineral–organic interactions extends beyond Earth and plays a critical role in astrobiology, the search for life elsewhere in the universe. Many planetary bodies within our solar system exhibit mineralogical and geochemical conditions similar to those thought to exist on early Earth, suggesting that mineral-assisted prebiotic chemistry may occur beyond our planet. Mars, for example, shows extensive evidence of clay minerals formed in ancient aqueous environments. Orbital and rover missions have identified sedimentary deposits and hydrothermal mineral formations that could have supported organic molecule preservation and chemical evolution. Clay-rich environments on Mars are considered prime targets in the search for biosignatures or evidence of past prebiotic chemistry [11]. Icy moons such as Europa and Enceladus also present intriguing possibilities. These bodies contain subsurface oceans interacting with rocky cores, potentially creating hydrothermal systems capable of mineral-driven chemistry. Observations of plume materials from Enceladus suggest the presence of mineral particles and organic compounds, raising the possibility of ongoing mineral–organic interactions beneath icy crusts.

Meteorites and interplanetary dust particles further demonstrate that mineral-associated organic chemistry occurs in space environments. Some meteorites contain amino acids and complex organic compounds embedded within mineral matrices, indicating that mineral-assisted synthesis and protection of organics may be common processes in the universe [12]. Understanding mineral–organic interactions therefore not only informs origin-of-life studies on Earth but also guides planetary exploration strategies aimed at identifying environments where life might arise elsewhere.

7. Challenges and Future Research Directions

Despite substantial progress in understanding mineral-assisted prebiotic chemistry, many uncertainties remain regarding the precise pathways that led to the emergence of life. One major challenge lies in reconstructing realistic early Earth environments, as geological conditions varied widely across regions and time periods. Laboratory experiments often simplify conditions, making it difficult to determine which reactions were most relevant under natural circumstances.

Another challenge involves integrating multiple stages of prebiotic chemistry into coherent evolutionary scenarios. While minerals may catalyze polymer formation or stabilize biomolecules, understanding how these processes transitioned into self-replicating and metabolically active systems remains complex [13]. Future research efforts increasingly focus on interdisciplinary approaches combining geochemistry, molecular biology, planetary science, and computational modeling. Advances in analytical techniques, including nanoscale imaging and spectroscopy, enable detailed investigation of mineral–organic interfaces and reaction mechanisms [14[. Research is also expanding toward studying dynamic environments involving cycles of wetting and drying, temperature fluctuations, and chemical gradients, which may have driven progressive molecular complexity. Investigations into mineral-assisted formation of protocells and early metabolic networks remain promising directions.

8. Conclusion

Mineral–organic interactions likely played a fundamental role in enabling chemical evolution that eventually led to the emergence of life on Earth. Mineral surfaces provided catalytic sites, concentrated organic molecules, and created protective microenvironments that supported formation and persistence of early biomolecules. Clay minerals, metal sulfides, and other geological materials offered structured environments conducive to polymerization and molecular organization. Experimental studies increasingly support the idea that mineral-assisted chemistry enhanced formation of nucleic acid precursors, peptides, and membrane-like structures, all essential components of primitive biological systems.

Moreover, minerals likely shielded fragile molecules from destructive environmental influences such as ultraviolet radiation and hydrolytic degradation. The importance of mineral–organic interactions extends beyond Earth, informing astrobiological investigations of Mars, icy moons, and other planetary environments where similar processes may occur. Understanding these mechanisms therefore contributes not only to origin-of-life research but also to the broader search for life in the universe.

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References

1. Yan, Y., & Yang, H. (2024). Interactions of Clay Minerals with Biomolecules and Protocells Complex Structures in the Origin of Life: A Review. *Advanced Functional Materials*, *34*(41), 2406210.
2. Stewart, S. V., & Erastova, V. (2024). Understanding the Role of Layered Minerals in the Emergence and Preservation of Proto-Proteins and Detection of Traces of Early Life. *Accounts of Chemical Research*, *57*(17), 2453-2463.
3. Dalai, P., & Sahai, N. (2019). Mineral–lipid interactions in the origins of life. *Trends in biochemical sciences*, *44*(4), 331-341.
4. Benner, S. A., Kim, H. J., & Biondi, E. (2018). Mineral-organic interactions in prebiotic synthesis: The discontinuous synthesis model for the formation of RNA in naturally complex geological environments. In *Prebiotic Chemistry and Chemical Evolution of Nucleic Acids* (pp. 31-83). Cham: Springer International Publishing.
5. Rimola, A., Sodupe, M., & Ugliengo, P. (2019). Role of mineral surfaces in prebiotic chemical evolution. In silico quantum mechanical studies. *Life*, *9*(1), 10.
6. Brucato, J. R., & Fornaro, T. (2018). Role of mineral surfaces in prebiotic processes and space-like conditions. In *Biosignatures for Astrobiology* (pp. 183-204). Cham: Springer International Publishing.
7. Chen, Q. W., & Chen, C. L. (2005). The role of inorganic compounds in the prebiotic synthesis of organic molecules. *Current Organic Chemistry*, *9*(10), 989-998.
8. Lambert, J. F. (2015). Origins of life: From the mineral to the biochemical world. In *BIO Web of Conferences* (Vol. 4, p. 00012). EDP Sciences.
9. Cleaves II, H. J., Scott, A. M., Hill, F. C., Leszczynski, J., Sahai, N., & Hazen, R. (2012). Mineral–organic interfacial processes: potential roles in the origins of life. *Chemical Society Reviews*, *41*(16), 5502-5525.
10. Bu, Hongling, Peng Yuan, Hongmei Liu, Dong Liu, Zonghua Qin, Xuemin Zhong, Hongzhe Song, and Yun Li. "Formation of macromolecules with peptide bonds via the thermal evolution of amino acids in the presence of montmorillonite: Insight into prebiotic geochemistry on the early Earth." *Chemical Geology* 510 (2019): 72-83.
11. Hazen, R. M., & Sverjensky, D. A. (2010). Mineral surfaces, geochemical complexities, and the origins of life. *Cold Spring Harbor perspectives in biology*, *2*(5), a002162.
12. Saha, A., Yi, R., Fahrenbach, A. C., Wang, A., & Jia, T. Z. (2022). A physicochemical consideration of prebiotic microenvironments for self-assembly and prebiotic chemistry. *Life*, *12*(10), 1595.
13. Madrigal-Trejo, D., P. S. Villanueva-Barragán, R. Zamudio-Ramírez, K. E. Cervantes-de La Cruz, I. Mejía-Luna, E. Chacón-Baca, A. Negrón-Mendoza, S. Ramos-Bernal, and A. Heredia-Barbero. "Histidine self-assembly and stability on mineral surfaces as a model of prebiotic chemical evolution: an experimental and computational approach." *Origins of Life and Evolution of Biospheres* 51, no. 2 (2021): 117-130.
14. Erastova, V., Degiacomi, M. T., G. Fraser, D., & Greenwell, H. C. (2017). Mineral surface chemistry control for origin of prebiotic peptides. *Nature communications*, *8*(1), 2033.