

# Biosignature Preservation in Extreme Environments: Implications for Extraterrestrial Life Detection

Jelang Jelku D. Sangma<sup>1,2,3</sup> 

<sup>1</sup>Department of Food Science and Nutrition, University of Agricultural Sciences, GKVK, Bangalore, Karnataka, 560065, India

<sup>2</sup>AICRP-WIA, ICAR (CIWA), Bhubaneswar, College of Community Science, Central Agricultural University, Tura, Meghalaya - 794005, India

<sup>3</sup>Eudoxia Research University, 256 Chapman Road STE 105-4, New Castle, USA

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\*Corresponding Author: **Jelang Jelku D. Sangma** | Email Address: [jelang.jelku3@gmail.com](mailto:jelang.jelku3@gmail.com)

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## Abstract

The search for extra-terrestrial life depends largely on the identification and preservation of biosignatures, which are chemical, morphological, or isotopic indicators of biological activity, harsh planetary conditions such as radiation exposure, temperature extremes, oxidation, and geological disturbances can degrade or erase biological evidence over time. Earth's extreme environments—including polar ice regions, hyper-arid deserts, deep-sea hydrothermal systems, and subsurface habitats—serve as valuable analogs for studying how life survives and how biosignatures can persist under hostile conditions. Investigating preservation mechanisms such as mineral encapsulation, rapid sediment burial, salt entrapment, and cryogenic stabilization improves our understanding of where and how to search for life beyond Earth. These insights are especially important for ongoing and future missions targeting Mars and icy ocean worlds, where subsurface environments may offer protection for ancient or extant biological traces. Challenges remain in distinguishing genuine biosignatures from abiotic chemical signals and preventing contamination during exploration missions. Continued interdisciplinary research combining geology, chemistry, microbiology, and planetary science is essential for refining detection techniques. Understanding biosignature preservation processes ultimately strengthens strategies for identifying signs of life and guides future exploration efforts aimed at answering whether life exists elsewhere in the universe.

**Keywords:** Biosignatures, extreme environments, astrobiology, life detection, planetary exploration, extraterrestrial life.

## 1. Introduction

The quest to determine whether life exists beyond Earth remains one of the most compelling scientific endeavors of modern times. Advances in planetary exploration, astronomy, and astrobiology have revealed that many celestial bodies possess conditions that may once have supported—or may still support—biological processes. Yet, discovering life directly is extremely challenging, particularly because potential organisms may be microscopic, extinct, or hidden beneath hostile planetary surfaces. Consequently, scientists often rely on detecting biosignatures—measurable traces of biological activity—to infer the presence of life [1]. However, identifying such evidence is complicated by environmental processes that can alter, degrade, or completely erase biological traces over geological timescales. Earth itself provides a wide range of natural laboratories where life thrives under extreme conditions previously thought uninhabitable. These environments include polar ice sheets, deep subsurface rock formations, hydrothermal vents, acidic lakes, and hyper-arid deserts. Organisms inhabiting these environments, often called extremophiles, demonstrate remarkable resilience and reveal how life adapts to conditions similar to those found on other planets or moons.

More importantly, these regions allow scientists to study how biological materials are preserved—or destroyed—under extreme pressure, radiation, chemical stress, and temperature fluctuations [2]. By examining how microbial communities and their chemical footprints survive in such locations, researchers gain critical insights into where extraterrestrial biosignatures might be found and how long they could remain detectable.

Another major challenge lies in distinguishing genuine biological signals from abiotic processes that can produce similar chemical or structural patterns. Certain minerals or chemical reactions can mimic biological signatures, leading to potential misinterpretations. Therefore, understanding preservation environments is as important as identifying biosignatures themselves. Factors such as rapid burial, mineral encapsulation, freezing conditions, and low oxygen availability can significantly enhance preservation potential, while erosion, radiation exposure, and chemical oxidation can erase evidence over time. Knowledge of these processes helps refine exploration strategies for planetary missions, guiding scientists toward locations most likely to preserve ancient or extant life [3]. The study of biosignature preservation is therefore central to astrobiology. As missions increasingly target Mars, icy moons, and potentially habitable exoplanets, lessons learned from Earth's extreme environments become crucial in selecting

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landing sites, designing instruments, and interpreting results. Understanding not only where life might exist but also how its traces survive across vast timescales brings humanity closer to answering whether life is unique to Earth or a common phenomenon in the universe.

## 2. What Are Biosignatures?

Biosignatures are observable features or measurable properties that indicate past or present biological activity. They serve as indirect evidence of life when direct observation of living organisms is not possible. Biosignatures can take multiple forms, ranging from microscopic fossil structures to chemical imprints left by metabolic processes. Because life interacts with its environment in complex ways, biological activity often produces detectable changes in surrounding materials, atmospheric composition, or mineral formations. Understanding the variety and limitations of these indicators is essential for correctly interpreting potential signs of life on other planets. One major category of biosignatures involves chemical compounds produced or modified by living organisms. Organic molecules such as lipids, amino acids, pigments, and complex carbon-based polymers often originate from biological processes. Some of these molecules can persist long after organisms die, especially when protected by favorable environmental conditions. Certain patterns in molecular structure or distribution may suggest biological origin, although caution is necessary because some organic molecules can also form through non-biological chemical reactions. Consequently, researchers typically seek combinations of chemical indicators rather than relying on a single compound [4]. Isotopic biosignatures provide another powerful line of evidence. Biological processes frequently favor lighter isotopes of elements like carbon, nitrogen, or sulfur, resulting in characteristic isotopic ratios in biological materials and surrounding sediments. These isotopic signatures can remain preserved for billions of years within rock records, offering clues about ancient life on Earth and potentially on other planets. However, some geological processes can also produce similar isotope patterns, making contextual analysis essential.

Morphological biosignatures represent physical evidence of past organisms, such as microfossils, layered microbial structures, or mineral textures shaped by biological activity. These structures provide visual evidence of life but are often difficult to distinguish from non-biological formations, especially when altered by geological processes over long periods. At a planetary scale, atmospheric biosignatures may indicate biological activity through gases produced or maintained by life, such as oxygen or methane [5]. Detecting such signals in distant planetary atmospheres could suggest biological processes, although non-biological sources must always be carefully evaluated. Because each biosignature type has limitations, scientists rely on multiple lines of evidence combined with geological context to determine whether life once existed. Understanding how these biosignatures form and survive remains a crucial step in guiding future life-detection missions across the solar system and beyond.

## 3. Factors Affecting Biosignature Preservation

The preservation of biosignatures over long periods depends strongly on environmental and geological conditions. Even when life is abundant in a given environment, its traces may not survive long enough to be detected if conditions promote rapid degradation.

Therefore, understanding the factors that influence preservation is essential for identifying promising locations in the search for extraterrestrial life. Temperature plays a crucial role in determining preservation potential. High temperatures accelerate chemical reactions that break down organic molecules, leading to rapid decomposition of biological materials. On Earth, environments such as volcanic regions or deep geothermal zones rarely preserve organic remains for extended periods. In contrast, cold environments significantly slow chemical and biological processes, allowing organic matter to remain intact for thousands or even millions of years. Polar ice, permafrost regions, and permanently cold subsurface environments demonstrate how freezing conditions can effectively preserve microbial life and organic compounds. This understanding suggests that cold planetary environments, such as Martian polar regions or icy moons, may offer favorable preservation conditions [6]. Radiation exposure is another critical factor, especially on planetary surfaces lacking thick atmospheres or magnetic protection. Ultraviolet radiation and cosmic rays can damage organic molecules, disrupt cellular structures, and chemically alter biological materials. Over long periods, radiation can completely erase biosignatures at exposed surfaces. However, subsurface environments provide natural shielding, making buried sediments or underground habitats far more promising targets for detecting preserved life. Water availability influences preservation in complex ways. While water is essential for life, it also supports chemical reactions and microbial activity that decompose organic materials after death. Extremely dry environments, however, may inhibit decomposition and allow organic molecules to persist. For example, certain desert environments on Earth preserve organic remains due to minimal moisture and limited microbial activity [7]. Chemical conditions also play a major role. Oxidizing environments, such as those rich in reactive oxygen compounds, rapidly degrade organic molecules. In contrast, reducing environments with limited oxygen often preserve biological materials more effectively. Geological processes, including erosion, metamorphism, and tectonic activity, can further modify or destroy biosignatures, emphasizing the importance of locating relatively stable geological settings for exploration.

## 4. Earth's Extreme Environments as Analogs

Earth's extreme environments provide valuable insights into how life survives and how biosignatures may be preserved under conditions similar to those on other planetary bodies. These environments serve as natural testing grounds for studying survival mechanisms and preservation potential. Polar regions and permanently frozen environments are among the most important analogs. Microbial life trapped within ice or permafrost can remain dormant for thousands of years while preserving chemical and structural evidence of biological activity. Ice layers also shield organisms from radiation and slow decomposition. These characteristics are particularly relevant for Mars and icy moons, where frozen environments may preserve ancient biological traces beneath the surface [8]. Hyper-arid deserts offer another important comparison. In regions with extremely low rainfall, life persists in small, protected niches such as beneath rocks or within salt deposits. Organic materials degrade slowly due to limited moisture and reduced microbial recycling. These deserts resemble conditions expected on Mars, making them useful models for evaluating how life might survive and how its traces could remain preserved in dry planetary environments.

Deep-sea hydrothermal systems represent environments where life thrives without sunlight, relying instead on chemical energy sources. These ecosystems demonstrate that life can exist in extreme pressure and temperature conditions. Mineral deposits formed around hydrothermal vents often trap and preserve microbial structures, providing clues about possible preservation mechanisms in similar extraterrestrial settings [9]. Subsurface habitats also play a significant role in understanding preservation. Life existing deep within Earth's crust is protected from surface radiation, temperature extremes, and atmospheric fluctuations. This suggests that extra-terrestrial life, if present, may also be more likely found beneath planetary surfaces rather than in exposed regions.

Table: Biosignature Preservation Factors and Implications for Life Detection

Factor / Environment	Effect on Biosignature Preservation	Implication for Extraterrestrial Life Search
Low Temperature	Slows chemical and biological degradation, preserving organic material	Cold regions and icy bodies are promising targets
Radiation Exposure	Destroys organic molecules and damages biological structures	Subsurface exploration is more reliable than surface sampling
Low Water Activity	Reduces microbial decomposition and chemical alteration	Dry planetary environments may preserve ancient biosignatures
Oxidizing Conditions	Rapidly break down organic materials	Reduced or low-oxygen environments are better preservation sites
Rapid Burial	Protects biological remains from erosion and oxidation	Sedimentary deposits are prime exploration targets
Mineral Encapsulation	Traps and preserves microbial structures and chemicals	Silica and carbonate deposits may contain fossil evidence
Salt/Evaporite Deposits	Preserve microorganisms and organic molecules for long periods	Salt-rich planetary regions are high-priority sites
Frozen Environments	Maintain organic materials over long timescales	Polar and subsurface ice regions are key exploration zones
Subsurface Habitats	Shield biosignatures from radiation and surface damage	Drilling missions increase chances of detection

### 5. Preservation Mechanisms

Certain natural processes significantly enhance the preservation of biological materials. Understanding these mechanisms allows researchers to identify environments most likely to retain detectable biosignatures. Mineral encapsulation is one of the most effective preservation processes. Minerals such as silica, carbonate, or sulfate can rapidly precipitate around microorganisms, trapping cellular structures and protecting organic material from decay. Over time, this process can create fossilized remains that retain morphological details even after original biological material has degraded [10]. Salt and evaporite deposits also serve as powerful preservation environments. When water evaporates, dissolved salts crystallize and can entomb microorganisms and organic molecules. Salt crystals create stable environments that limit exposure to oxygen and moisture, allowing biological material to survive for extremely long periods. Such preservation has been observed in ancient terrestrial salt formations and may occur on other planets where evaporite minerals are present [5]. Rapid sediment burial is another important mechanism. When organisms are quickly covered by sediments, exposure to oxygen and scavenging organisms decreases, slowing decomposition. Fine-grained sediments, in particular, can preserve delicate biological structures, creating detailed fossil records. Freezing also provides effective preservation. Cryogenic environments drastically slow chemical reactions and microbial activity, allowing organic materials to remain stable for extended periods. Frozen conditions may therefore preserve biosignatures on planets or moons with long-term cold climates.

### 6. Challenges in Detecting Biosignatures

Despite advancements in technology and research, detecting biosignatures beyond Earth remains extremely challenging. One of the primary difficulties lies in distinguishing biological signals from abiotic processes that produce similar features. Many chemical reactions occurring without life can generate organic molecules or mineral patterns resembling biosignatures, leading to potential misinterpretation. Another major challenge is technological limitation. Robotic missions carry compact scientific instruments with limited sensitivity compared to laboratory equipment on Earth. These instruments must operate under harsh conditions while analyzing small samples, making detection of faint biological traces difficult. Contamination also poses a serious concern.

Spacecraft and equipment may inadvertently carry Earth-based microorganisms or organic materials, potentially confusing results. Strict planetary protection protocols are therefore necessary to prevent contamination of extraterrestrial environments and ensure scientific accuracy [5], geological alteration over billions of years may modify or erase biological evidence. Planetary surfaces exposed to meteorite impacts, volcanic activity, or erosion may no longer retain detectable traces of ancient life. As a result, scientists increasingly focus on subsurface exploration where preservation conditions are more favorable. Finally, interpreting results requires careful integration of geological, chemical, and environmental data. A single observation rarely proves biological origin; instead, multiple lines of evidence must converge to support claims of extra-terrestrial life.

### 11. Conclusion

The preservation of biosignatures remains one of the most critical factors in the ongoing search for extraterrestrial life. Studies of Earth's extreme environments reveal not only the remarkable adaptability of life but also the conditions under which biological evidence can survive across vast geological timescales. These environments demonstrate that even under severe temperature extremes, radiation exposure, or chemical stress, traces of biological activity can persist when protected by favorable preservation processes such as mineral encapsulation, rapid burial, or freezing conditions. A deeper understanding of these preservation mechanisms enhances our ability to select promising exploration sites and accurately interpret potential biosignatures detected on other planetary bodies. As future missions expand exploration of Mars, icy moons, and other potentially habitable worlds, insights gained from terrestrial analog environments will continue to refine life-detection strategies, integrating geological, chemical, and biological knowledge will bring humanity closer to resolving one of its most enduring questions: whether life exists beyond Earth.

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