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Review Article

Overview of Extremophiles and Geomicrobiology

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Abstract

The multidisciplinary study of how microorganisms interact with earth materials—such as soil, sediment, the atmosphere, the hydrosphere, minerals, and rocks—is known as geomicrobiology. The intersection of geology, biology, chemistry, and hydrology on the surface of the Earth is quantitatively dominated by microbes. The classical methods have been greatly expanded by contemporary molecular techniques. The use of new techniques has revealed connections between the geological and biological realms that were previously unknown. These habitats were disregarded in microbiology research for a long time. They are now recognized to have a variety of "extremophiles" within them. Many were unknown before. Biotechnology has advanced as a result of some of these. Others might have potential for the treatment of illnesses like cancer. Extreme settings are home to a diverse range of microorganisms. When compared to what is considered typical for humans, the adjective "extreme" is relative. High temperatures, high pressures, high concentrations of salt, low concentrations of nutrients, high concentrations of radiation, hazardous heavy metals, and poisonous substances (organic solvents) are examples of extreme settings. To explore the diversity of microorganisms in these habitats, both culture-dependent and culture-independent (molecular) approaches have been used. The novel diversity of extremophilic microorganisms has been uncovered by extensive worldwide research efforts. These organisms can thrive in harsh conditions because they have developed a number of structural and chemical adaptations. These bacteria' extreme-environment-functioning enzymes, or "extremozymes," have a number of biotechnological uses. Numerous applications are also being found for antibiotics, suitable solutes, and other substances that can be obtained from these microorganisms.

Key Words: Geomicrobiology, Extremophiles, Soil, Hydrosphere, Microbes, Geology, Hydrology

Introduction

The study of microbes' roles in the geologic past, from their first appearance on Earth some 4 eons ago to the present, as well as their current and anticipated future roles in some of the processes that are fundamental to geology 1, is known as geomicrobiology [1]. The discovery of microbial fossils in the geologic record that morphologically resemble modern microorganisms of geologic significance and pertinent biomarkers has led to the deduction of geomicrobial activities in the geologic past. Current geomicrobial activities that take place in environments akin to those thought to have existed in the geologic past have also been used to infer past geomicrobial activity. The structure and composition of rocks and minerals are impacted by the weathering actions of microorganisms, both biophysical and biochemical, which changes the speciation of metals and other mineral components. Whether they originate from anthropogenic or natural environmental sources, microorganisms play a crucial role in metal biogeochemistry. The influence of fungi on geological processes is known as "geomycology," which is a subset of "geomicrobiology" [2]. The primary focus of geomicrobiology is on prokaryotes; it is evident that fungi make up a sizable portion of the microbiota in a variety of rocks and mineral-based substrata; additionally, lichens, which are fungi that live in symbiosis with one or more photosynthetic partners, and lichens, which are fungi that are involved in many biogeochemical processes, are a major prokaryotic habitat that may extend to depths and temperatures where thermogenic-geosphere processes take place; and nearly all land plants seem to rely on mycorrhizal fungi, which are involved in metal mobilization from minerals, metal immobilization within biomass, and extracellular precipitation of mycogenic biominerals. The unexpected presence of prokaryotes in deep (kilometers) and ancient (>100 my) sediments can be attributed to the production of a variety of prokaryotic substrates from temperature stimulation of organic matter and minerals, according to sediment heating experiments used to mimic these temperature increases [3].

Materials and methods

Geomicrobial Activities

Geomicrobial activity types. Geomicrobial activities play a role in

1) mineral formation,

2) mineral degradation,

3) the movement of both organic and inorganic materials,

4) isotopic and chemical fractionation, and

5) the production and breakdown of fossil fuels. Weathering, bioleaching, and the creation and alteration of soil and sediment (diagenesis) are examples of microbial mineral degradation. To differing degrees, microbes play a role in the formation and breakdown of fossil fuels such as coal, petroleum, methane, and peat [3].

Certain geomicrobial activities can be used for profit in procedures like environmental bioremediation [3], biogas genesis, commercial tertiary petroleum recovery, and metal extraction from ores [3].

Physiological Processes Involved in Geomicrobial Activity

Different types of geomicrobial activity have varying physiological bases, which vary depending on the activity, the material being changed, and the organism or organisms involved [3]. Enzymatic oxidation or reduction of inorganic materials is a component of some geomicrobial activity. Mineral creation, mineral diagenesis, and mineral breakdown may be facilitated by these reactions, which are mostly facilitated by prokaryotic organisms. In other geomicrobial activities, both prokaryotes and eukaryotes play a significant role in the enzymatic synthesis or breakdown of naturally occurring organic carbon molecules. The enzymatic processes involved in such organic transformations are not limited to oxidations and/or reductions [4].

Although the term "mineralization" is occasionally used in microbial physiology to refer to the microbial breakdown of organic carbon to CO_2, it is solely used in this text to refer to the mineral production process. Certain geomicrobial activities may entail non-enzymatic reactions, such as the precipitation of heavy metals, the weathering and dissolution of minerals, or the mobilization of viscous petroleum hydrocarbons, wherein inorganic or organic products of microbial metabolism act as chemical reagents [4].

Thus, H_2S produced by sulphate-reducing bacteria can precipitate heavy metals. Microbially produced inorganic acids like H_2SO_4, HNO_3, and H_2CO_3, as well as organic acids like acetic, oxalic, lactic, propionic, butyric, and citric acids, as well as microbially produced bases like ammonia and amines, can weather carbonates, silicate and aluminosilicate minerals, and phosphate minerals. Microbially produced ligands can also mobilize metal components in some minerals, such as siderophores' ability to mobilize ferric iron. Microbially generated surface-active substances have the ability to emulsify and hence mobilize petroleum's water-insoluble components [4].

Growing bacteria' physical effects on the environment are responsible for a portion of geomicrobial activity. Therefore, by using oxygen in their respiration more quickly than it can be replenished by contact with air, developing bacteria have the potential to convert an aerobic environment into an anaerobic one [5]. On the other hand, by producing oxygen more quickly than the accompanying respiring organisms can use it, oxygenically photosynthesizing microorganisms (cyanobacteria, algae) can convert a quasi-anaerobic environment into an aerobic one. Microbes have the ability to change the pH of their surroundings, making it more or less suitable for other living things. Because of the pressure that their expanding biomass puts on the rock cracks, which causes them to enlarge, microbes thriving in these fissures may help break up the rock. Lastly, a combination of many of the aforementioned processes may result in some geomicrobial activity [6].

Conditions that Determine a Geomicrobial Attack

1.Direct enzymatic attack: Three requirements must be satisfied for a mineral to be directly attacked by an enzyme, which might be either oxidative or reductive. These conditions are [3];

i. One or more oxidizable or reducible mineral components are present.

ii. The cells that are engaged in the reduction or oxidation of a suitable mineral ingredient adhere to the surface of the mineral.

iii. The enzyme that can catalyze a mineral constituent's oxidation or reduction is found at the cell surface. This enzyme must come into contact with additional enzymes and electron carriers that are located beneath the cell surface in addition to the mineral surface. When a Gram-negative bacterium oxidizes minerals, electrons extracted from an oxidizable mineral constituent by the oxidase at the cell surface (outer membrane) are transferred to a terminal electron acceptor—oxygen in an aerobic process—by enzymes and electron carriers in the periplasm and plasma membrane below the cell surface [3].

When a Gram-negative bacterium reduces a mineral, electrons are transferred from an electron donor inside the cell to the reductase at the cell surface (outer membrane) in contact with the mineral. A suitable component of the mineral will be reduced in acting as a terminal electron acceptor thanks to the enzymes and electron carriers in the plasma membrane and periplasm below the cell surface. Because only prokaryotic microorganisms have representatives with oxidases or reductases at their cell surface that can interact with an oxidizable or reducible mineral, they are the only microbes that can directly attack minerals by enzymatic means.

Thus far, only Gram-negative bacteria—specifically, the aerobe Acidithiobacillus ferrooxidans, the facultative anaerobically growing Shewanella oneidensis MR-1, and the stringent anaerobe Geobacter sulfurreducens—have been found to possess such cell-surface-located enzymes. Gram-negative marine isolate strains BIII 32, BIII 41, and BIII 88 6 most likely also contain these enzymes. According to circumstantial evidence, Gram-positive Bacillus 29 and Bacillus GJ33 can decrease MnO_2 aerobically through a direct mechanism akin to that suggested for marine strain BIII 88. The assault mechanism used by Sulfolobus species and Acidianus brierleyi, which are members of the Archaea domain, is unknown despite the fact that they are known to target a variety of sulphide minerals, including pyrite (FeS_2), chalcopyrite ($FeCuS_2$), arsenopyrite (FeAsS), and nickel sulphide (NiS) [6].

2.Non-enzymatic attack: The reactive products of microbial metabolism are involved in the non-enzymatic assault of minerals by microorganisms. Below the cell envelope, in the cytoplasm of prokaryotes (Bacteria and Archaea) and in cell organelles and/or the cytoplasm of eukaryotes (fungi, algae, and lichens) are the microbial enzymes that are in charge of the production of metabolic products [6]. It is not necessary for the microbial cells to come into direct touch with the surface of the mineral being attacked in these cases of microbial attack. After being created inside cells, the reactive metabolic products are expelled into the bulk phase, where they can interact chemically—that is, without the need of enzymes—with a mineral that is vulnerable. The contact with the mineral can lead to either mineral diagenesis or mineral dissolution by oxidation, reduction, or acid/base assault, depending on the kind of metabolic product and mineral.

Complexation by a microbial metabolic product with that ability can also lead to mineral dissolution or diagenesis. Mineral assault might sometimes involve a mix of some of these reactions [4].

Extremophiles

Extremophiles are organisms that flourish in severe environments; polyextremophiles are organisms that survive in many extremes [7]. Sulfolobus acidocaldarius, an archaea that thrives at pH 3 and 80ºC, is an example of the latter. "Extremes" can be either geochemical (such as desiccation, salinity, pH, oxygen species, or redox potential) or physical (such as temperature, radiation, or pressure). An organism that flourishes in "extreme" circumstances is known as an extremophile. Since we relate it to human extremes, such as using oxygen, which is toxic to many creatures, the name "extremophile" is comparatively anthropocentric [1].

Scientists have been fascinated by the amazing creatures that live in harsh conditions for the past few decades. These creatures, referred to as extremophiles, flourish in environments that are unbearably unfriendly or even fatal to other terrestrial life forms. They flourish in a variety of environments that were once thought to be unsuitable for life, including extremely hot niches, ice, salt solutions, acidic and alkaline environments, and toxic waste, organic solvents, heavy metals, and a number of other environments. At pressures of up to 110 MPa, extremophiles have been discovered from extreme acid (pH 0) to extreme basic conditions (pH 12.8), from hydrothermal vents at 122 °C to freezing sea water at -20 °C, and from depths of 6.7 km inside the Earth's crust and over 10 km deep within the ocean. Numerous creatures have demonstrated that they not only can withstand the extreme environmental conditions examined, but that they frequently need them to survive [8].

Classification of Extremophiles

The following categories are based on the conditions under which they grow: psychrophiles (organisms that grow best at low temperatures), alkaliphiles and acidophiles (organisms that are best suited to acidic or basic pH values, respectively), barophiles (organisms that grow best under pressure), halophiles (organisms that require NaCl for growth), and thermophiles and hyperthermophiles (organisms growing at high or extremely high temperatures, respectively). Furthermore, because they have evolved to survive in environments where a variety of physicochemical parameters reach high values, these creatures are typically polyextremophiles. For instance, the deep ocean is typically cold, oligotrophic (having very little nutrients), and subjected to tremendous pressure; many hot springs are both acidic and alkaline simultaneously, and they are typically rich in metals [1].

Categories of Extremophiles

Extremophiles can be categorized into two main groups [9]:

a)creatures known as extremophiles, which need one or more harsh environments to thrive, and

b) Extremotolerant organisms are those that, although developing best under normal circumstances, can withstand excessive values of one or more physicochemical parameters [10].

Extremophiles are organisms that belong to the three realms of life: bacteria, archaea, and eukarya. Although microorganisms (of which a large percentage are archaea) make up the majority of extremophiles, this group also comprises multicellular organisms and eukaryotes like protists (such as algae, fungus, and protozoa) [10].

The primary group that can survive in harsh conditions is Archaea. Despite being less adaptable than bacteria and eukaryotes, members of this category are typically highly adept at adjusting to various harsh environments, and they commonly have extremophily records. Among the most halophilic, alkaliphilic, acidophilic, and hyperthermophilic microorganisms known are certain archaea. For instance, the genus Picrophilus (including Picrophilus torridus) has the most acidophilic organisms currently known, with the capacity to grow at a pH of 0.06 [11]. The archaeal Methanopyrus kandleri strain 116, on the other hand, grows at 122 °C (252 °F, the highest temperature ever recorded).

Cyanobacteria are the group of bacteria that are most suited to a variety of harsh environments. From Antarctic ice to continental hot springs, they frequently combine with other bacteria to form microbial mats. In addition to supporting high metal concentrations and surviving xerophilic environments (i.e., little water availability), cyanobacteria may grow in hypersaline and alkaline lakes and create endolithic communities in arid areas. However, settings with a pH of less than 5 to 6 are rarely home to cyanobacteria [11].

The most adaptable and ecologically successful evolutionary lineage among eukaryotes are fungus, either alone or in association with cyanobacteria or algae-forming lichens. Their ability to adapt to harsh conditions is good, with the exception of hyperthermophily. Acidic and metal-rich waters from mining areas, alkaline environments, hot and cold deserts, the deep ocean, and hypersaline areas like the Dead Sea are all home to fungi. However, the tardigrade, a minute invertebrate, is one of the most remarkable eukaryotic polyextremophiles in terms of its resilience to harsh circumstances. In their hibernation form, known as the tun state, tardigrades can withstand temperatures ranging from -272 °C (1 °C above absolute zero!) to 151 °C, vacuum conditions that cause severe dehydration, pressures of up to 6,000 atm, and exposure to X-rays and gamma rays. Additionally, even living tardigrades exhibit endurance to some harsh conditions, like extremely low temperatures and high radiation levels [9].

Extremophiles generally have a high level of phylogenetic variety, making them difficult to research. Only extremophiles are found in some orders or genera, while both extremophiles and non-extremophiles are found in other orders or genera. It is interesting to note that on the phylogenetic tree of life, extremophiles that have evolved to the same extreme circumstance may be widely distributed. This is true for several barophiles or psychrophiles, whose members can be found scattered throughout the three spheres of existence. Additionally, groups of creatures from the same biological family have evolved to adapt to a wide range of extremely or somewhat harsh environments [6]. The discipline has advanced significantly over the past few decades due to the rapid development of molecular biology tools, which have enabled us to examine fascinating questions about the nature of extremophiles with previously unheard-of accuracy. Specifically, the way we investigate extreme microbiology has been transformed by modern high-throughput DNA sequencing tools, which have revealed microbial communities with very high levels of complexity and diversity [6].

However, no other method can fully substitute a comprehensive understanding of the physiology of organisms in culture, which is necessary to supplement genomic or transcriptome research. Therefore, the best way to gain a better understanding of how microorganisms survive and function in such harsh conditions may be to combine improved classical methods of isolation/cultivation with contemporary culture-independent techniques [9]. Environments classified as moderate have a pH close to neutral, a temperature range of 20 to 40°C, an air pressure of 1 atm, and sufficient amounts of accessible salts, water, and nutrients. There are numerous severe settings in nature that are too harsh for regular life to exist, including deserts, ocean beds, saline and/or alkaline lakes, and acidic or hot springs. Extreme conditions are any environmental circumstances that are thought to be outside of the typical tolerable range [6]. However, a wide range of microorganisms can thrive under these conditions. These creatures, referred to as extremophiles, typically need extreme conditions for development and survival in addition to being able to withstand them. The microbial world is home to the majority of extremophiles. Compared to other living forms, bacteria can withstand a far wider variety of environmental extremes. Microbes can only thrive and reproduce at temperatures between -12° and above +100°C, pH values between 0 and 13, hydrostatic pressures up to 1400 atm, and saturated brine salt concentrations. Man-made severe circumstances, like cool-houses, steam-heated buildings, and acid mine waters, exist in addition to natural extreme situations [12].

Diversity of Microbes in Extreme Environments and their Adaptations

1. Psychrophiles: There have been reports of roughly 100 new species of both Gram-positive and Gram-negative bacteria from a variety of environments, including soil, sandstone, freshwater and marine lakes, sea ice, and seas. It has been reported that several species in the following genera are psychrophilic [1]: Alcaligenes, Alteromonas, Aquaspirillum, Arthobacter, Bacillus, Bacteroides, Brevibacterium, Gelidibacter, Methanococcoides, Methanogenium, Methanosarcina, Microbacterium, Micrococcus, Moritella, Octandecabacter, Phormidium, Photobacterium, Polaribacter, Polaromonas, Psychroserpens, Shewanella, and Vibrio. Only psychrophiles seem to be found in the genus Moritella. g-Proteobacteria, Shewanella, Photobacterium, Colwellia, Moritella, and Alteromonas haloplanktis are among the psychrophilic and barophilic bacteria that have been cultured. Leifsonia aurea, Sporosarcina macmurdoensis, and Kocuria polaris have been identified from Antarctica for the first time [9]. In Ace Lake, Antarctica, a permanently cold, anoxic hypolimnion yielded Methanococcoides burtonii, a psychrophilic and slightly halophilic methanogen [13]. This implies that members of the Archaea domain, the majority of which are members of the Crenarchaeota, are also able to lead psychrophilic lives and need closer proximity to both polar and temperate coastal waters [1].

Numerous isolates in any cold environment are psychrotrophs. Some species of Arthrobacter and Corynebacterium, as well as mesophilic bacteria like Bacillus megaterium and B. subtilis, are examples of psychrotrophs that have been isolated from food and dairy products. Caves in the Arctic, Lapland, the Pyrenees, the Alps, and Romania that are consistently cold have been shown to harbor psychrotrophic bacteria. Arthrobacter, Pseudomonas, and Flavobacterium were the genera that contained the majority of the organisms, with Arthrobacter accounting for nine of them [9].

Arthrobacter glacialis was similar to many of the psychrophiles that were isolated from the soils of these caves. Where snow melts and the snow surface turns red, green, or yellow, algae can be found. These snow algae are psychrotrophs for the most part. Chloromonas brevispina, C. pichinchae, C. rubroleosa, C. polyptera, and Chlamydomonas nivalis [4] are examples of snow algal flagellates. The troposphere and stratosphere, which have temperatures between -20°C and -40°C, are home to a wide variety of bacteria. Bacteria collected from 7000 meters above sea level were common soil types, and they could also be marine. Relatively high quantities of cobalamin, biotin, and niacin [1] may be caused by bacterial growth that takes place in clouds. However, it is necessary to validate the presence of psychrophiles in the atmosphere. Five main lineages of farmed obligatory psychrophilic bacteria and archaea were identified by a phylogenetic study of the SSU rRNA sequences of the cultivated psychrophiles: Crenarchaeota, Euryarchaeota, Flexibacter–Cytophaga–Bacteriida, Gram-positive bacteria, and proteobacteria. Moreover, it seems that mesophilic organisms that live in consistently frigid settings gave rise to psychrophiles [1].

Plate 1: Psychrophiles represented in all 3 domains of life [9]

Because of their exceptional capacity to endure and proliferate in cold environments, psychrophilic bacteria may provide ideal model organisms for comprehending the molecular underpinnings of low temperature adaptation. Several survival strategies, including the capacity to sense temperature [5], alter membrane fluidity, perform metabolic activities at low temperatures, and control gene expression at low temperatures, are necessary for their adaption to low temperatures. Psychrophiles, in contrast to mesophilic bacteria, have higher amounts of unsaturated fatty acids, which rise even more when the temperature drops. This helps them control membrane fluidity, which is a crucial cold adaption tactic. Because of their temperature-dependent production, carotenoids have also been demonstrated to control membrane fluidity [14, 15]. At low temperatures 10, 16, it was shown that psychrophiles may sustain transcription and translation and that cold active enzymes 12–14 were present. Additionally, research has shown that several genes were present and functioning at low temperatures [17]. Temperature perception has also been linked to differential phosphorylation of membrane proteins, most likely LPS21. The significance of LPS in cold adaptation is shown by recent research on how low temperatures alter its composition [18]. Polymeric compounds produced by sea-ice bacteria may act as cryoprotectants for the organisms and their enzymes. Psychrotrophs and psychrophiles, including Trichosporon pullulans, Bacillus psychrophilus, Aquaspirillum arcticum, and Arthrobacter globiformis, produce cold shock and cold-acclimation proteins, which serve as transcriptional enhancers and RNA-binding proteins, in reaction to abrupt changes in environmental temperature (cold shock) [18].

2.Thermophiles: Both prokaryotes and eukaryotes are among the many types of microbes that can grow at high temperatures. "A thermophile is an organism capable of living at temperatures at or near the maximum for the taxonomic group of which it is a part," Brock proposed as a definition 19. The benefit of this definition is that it highlights the taxonomic differences in thermophily among various organismal groups. Several thermophilic fungi from the Zygomycetes (Rhizomucor miehei, R. pusillus), Ascomycetes (Chaetomium thermophile, Thermoascus aurantiacus, Dactylomyces thermophilus, Melanocarpus albomyces, Talaromyces thermophilus, T. emersonii, Thielavia terrestris), Basidiomycetes (Phanerochaete chrysosporium), and Hyphomycetes (Acremonium alabamensis, A. thermophilum, Myceliophthora thermophila, Thermomyces lanuginosus, Scytalidium thermophilum, Malbranchea cinnamomea) have been isolated from composts, soils, bird nesting materials, wood chips, and numerous other sources [20, 21]. High temperatures are necessary for the growth of certain protozoa (Cothuria sp. Oxytricha falla, Cercosulcifer hamathensis, Tetrahymena pyriformis, Cyclidium citrullus, Naegleria fowleri, Chanthes exigua, Mougeotia sp., and Cyanidium caldarium) and algae [12]. Several bacteria and archaebacteria, which are capable of growth at elevated temperatures have been classified into moderate (Bacillus caldolyticus, Geobacillus stearothermophilus, Thermoactinomyces vulgaris, Clostridium thermohydrosulfuricum, Thermoanaerobacter ethanolicus, Thermoplasma acidophilum), extreme (Thermus aquaticus, T. thermophilus, Thermodesulfobacterium commune, Sulfolobus acidocaldarius, Thermomicrobium roseum, Sulfurococcus mirabilis, Thermotoga mritima) and hyperthermophiles (Methanoccus jannaschii, Acidianus infernos, Archaeoglobus profundus, Methanopyrus kandleri, Pyrobaculum islandicum, Pyrococcus furiosus, Pyrodictium occultum, Pyrolobus fumarii, Thermococcus littoralis, Ignicoccus islandicum, Nannoarchaeum equitans) – based on their optimum temperature requirements [9, 22, 23]. These have been separated from geothermally heated oil deposits and oil wells, composts, sun-heated soils, terrestrial hot springs, and undersea hydrothermal vents. In Bukreshwar, West Bengal, India, a hot spring's bacterial diversity was recently evaluated using a culture-independent method [24].

Green non-sulfur and low-GC Gram-positive bacteria from 16S rDNA clones, as well as g-proteobacteria and cyanobacteria, were found in the sediment samples. It was proposed that the initial phylotype co-branched with the iron reducer Shewanella. Samples of paper pulp and hot springs were used to extract strains of Geobacillus thermooleovorans that are extremely thermophilic. Recently, Kashefi and Lovely isolated an archaeal strain 121 from a water sample from the Mothra hydrothermal vent field (Northern Pacific field) that reduced Fe(III) to Fe(II). The strain's upper temperature limit was 121°C, the highest temperature limit ever recorded for a microbe. Many hyperthermophiles are chemolithotrophs, and the majority are anaerobic. Growth at high temperatures is not solely associated with any specific mechanism for energy generation or carbon utilization [26]. There is no one element that allows all thermophiles to thrive at high temperatures because lipids, nucleic acids, and proteins are typically heat-sensitive for all microbes. Compared to mesophiles, thermophiles have more saturated and straight-chain fatty acids in their membrane lipids. This gives thermophiles the proper amount of fluidity required for membrane function, enabling them to develop at higher temperatures. A paracrystalline surface layer (S-layer) made of protein or glycoprotein is present in many archaeal species, and it probably serves as an exterior barrier of defense. Hyperthermophiles have been found to contain histone-like proteins that bind DNA, which may shield DNA [20].

Additionally, reverse gyrase, a type 1 DNA topoisomerase that induces positive supercoiling and may stabilize DNA, is present in hyperthermophiles. As proteins start to denature, heat shock proteins, or chaperones, probably help stabilize and refold them. It is also known that certain proteins have a higher percentage of thermophilic amino acids (such as proline residues with fewer degrees of freedom), a higher degree of structure in hydrophobic cores, and a greater number of hydrogen bonds and salt bridges. It has been observed that thermostable proteins have a lower lysine content and a higher arginine content. Polyamines, intracellular potassium buildup, and solutes like 2,3-diphosphoglycerate can also help maintain protein stability. In the solfataras of Yellowstone National Park, sulfuric acid is produced by the oxidation of elemental sulfur or sulfuridic ores by the hyperthermophilic extreme acidophiles Sulfolobus, Sufurococcus, Desulfurolobus, and Acidianus, which have a pH optimal for growth at or below 3.0. Other microorganisms found in heated conditions include Stygiolobus sp., which decreases elemental sulphur, and Metallosphaera, which oxidizes sulphidic ores. From solfataric fields, Thermoplasma volcanicum, which develops at pH 2 and 55°C, has also been isolated. Self-heating coal trash piles were used to extract Thermoplasma acidophilum. While Bacillus acidocaldarius, Acidimicrobium ferroxidans, and Sulfobacillus sp. have been isolated from warm springs and hot springs, Thiobacillus caldus was isolated from hot acidic soils [20].

Two solfataric sites in northern Japan yielded the most extreme acidophiles (pH optimum 0.7), Picrophilus oshimae and P. torridus. In Yellowstone National Park, the red alga Cyanidium caldarium (pH opt. 2-3, 45°C) was found in colder streams and springs. Dunaliella acidophila is a green alga that can tolerate a pH range of 0 to 3. Acidic mine drainage fluids and mineral processing bioreactors are home to mesophilic and sulfur-oxidizing acidophiles such Thiobacillus ferrooxidans, T. thiooxidans, and Leptospirillum ferrooxidans [25].

Types of thermophiles [25]

i. Extreme thermophiles, or obligatory thermophiles, need extremely high temperatures to grow.

ii. Moderate thermophiles, or facultative thermophiles, may survive at both high and low temperatures (below 50 °C).

iii. The ideal temperature for hyperthermophiles, who are extremely extreme thermophiles, is higher than 80°C.

Plate 2: Pompei worm: The most heat tolerant animal on Earth [25]

3. Acidophiles: Acidophiles maintain a significant chemical proton gradient across the membrane because their internal pH stays close to neutral. The cells have a positive inner membrane potential due to phosphorylated groups of nucleic acids, metabolic intermediates, and amino acid side chains of proteins, which act as titrable groups. This intracellular net positive charge reduces the movement of protons into the cell. Consequently, the protonation of titrable groups and the production of a net intracellular positive charge are caused by the low intracellular pH. It is anticipated that Dunaliella acidophila's positive internal membrane potential and surface charge will lessen the amount of protons that enter the cells. Additionally, it overexpresses a strong cytoplasmic membrane H+-ATPase to promote cell efflux [25]. Because of its hydrophobic surroundings and high degree of intrinsic secondary structure, rusticyanin (an acid-stable electron carrier) of T. ferrooxidans has been shown to be acid stable. The acid stability of secreted proteins, including thermopsin (a protease of Sulfolobus acidocaldarius) and an a-amylase of Alicyclobacillus acidocaldarius, has been associated with a comparatively low degree of positive charge because it reduces electrostatic repulsion and protein folding [25].

4.Alkaliphiles: It has been possible to isolate alkaliphilic Gram-positive and endospore-forming Bacillus species from neutral soils, as well as non-sporing species of Aeromonas, Pseudomonas, Paracoccus, Micrococcus, Corynebacterium, and Actinopolyspora, as well as alkali-tolerant fungi. Ancyclobacterium sp. was identified from Kraft paper and board manufacturing effluents 27, the alkaliphilic Exiguobacterium aurantiacum was identified from man-made alkaline environments, such as potato processing waste. Aerobic species of Bacillus, Vibrio, Flavobacterium, Pseudomonas, and enterobacteria were found in Oman's calcium springs. Phototrophs like Cyanospira (Anabaenopsis) sp., Chlorococcum sp., and Pleurocapsa sp. frequently bloom in soda lakes. Lakes in East Africa are home to Spirulina platensis, while other lakes are home to Spirulina maxima. Spirulina has a higher photosynthetic productivity than most plants found on land [1].

Along with cyanobacteria, notable blooms of red-pigmented Ectothiorhodospira mobilis and E. vacuolata have been discovered in soda lakes. By using H2S as an electron donor in photosynthesis, they contribute significantly to the sulfur cycle in these lakes. There are also black anoxic lake sediments that are abundant in methanogens that use methylamines, like Methanohalophilus [28]. Different prokaryotic communities can be found in highly salty and alkaline settings, such as those found in the Rift Valley's Lake Magadi, California's Owens Lake, Egypt's Wadi Natrum Lake, a number of saline soda lakes, and soils in Tibet, Pakistan, India, and Russia. Numerous haloalkalophilic archaea, including Natronobacterium pharaonis, N. gregoryi, and Natronococcus occultus, are responsible for the lakes' frequent red coloration. Methylomicrobium alcaliphilum and Methylobacter alcaliphilus, two methanotrophs that are moderately haloalkaliphilic, have been identified in the sediment of Kenyan soda lakes and Lake Khadyn, respectively. In the water of Lake Magadi and Lake Khadyn, alkaliphilic spirochetes, including Spirochaeta alcalica and haloalkalophilic S. asiatica, have been isolated. Lake Magadi is home to the alkaliphilic sulphate-reducing bacterium Desulfonatronovibrio hydrogenovorans. Thermoanerobacter sp., Clostridium, and Thermopallium natronophilum were found in lake sediments as anaerobic alkalithermophiles [29].

The cytoplasm is kept neutral or slightly alkaline by alkaliphiles. H+/Na+ antiporters exchange sodium from the cytoplasm into the medium, which is necessary for the control of intracellular pH. Respiratory chain activity mediates electrogenic proton extrusion, and protons are returned to the cells by antiporters, which effectively transfer H+ into the cell at the price of Na+ export. In addition to regulating protons, entrance of Na+ into the cell is necessary for Na+-dependent pH regulation. A net sodium balance is maintained by the Na+-driven flagella rotation and the Na+-coupled solute symporter [30]. by symport and flagella rotation, the cell maintains appropriate Na+ levels while managing its internal pH by the joint action of antiporters and respiration. Higher pH values cause the peptidoglycan layer in alkaliphiles to cross-link more quickly, which could have a shielding effect by "tightening" the cell wall. Solute transport and flagella movement are powered by sodium gradients, while ATP production is not. Alkaliphiles have not been found to contain sodium-dependent ATP synthases. Additionally, it has been shown that the ATP synthases of alkaliphilic Bacillus species are solely proton translocating [31].

5.Barophiles: These organisms are highly sensitive to UV light, have no DNA repair mechanisms, grow in darkness, and inhabit high pressure habitats, deep ocean floors, and subterranean rocks. In 1996, 180 kinds of creatures were discovered in the Mariana trench, the deepest sea floor at 10,897 meters, many of which were extreme barophiles [31]. Deep-sea environments are likely to favor organisms that can grow under high pressure, at low and high temperatures, and with low and high levels of organic nutrients. At 10,500 meters below the surface of the ocean, deep-sea microorganisms have been identified and cultivated at >100 Mpa at 2°C and 40 Mpa above 100°C40. Numerous locales have yielded the isolation and identification of barophilic bacteria [32, 33]. The majority of bacteria that are both barophilic and barotolerant are members of g-Proteobacteria [34].

Since most of the filamentous fungi were common terrestrial fungi, it is probable that some of them have developed barotolerance [35]. A number of filamentous fungi were isolated from deep-sea calcareous deposits at 10 MPa pressure, which corresponds to 1000–3000 m depth. Deep-sea sediments at

0.1 MPa [36] have yielded non-sporulating filamentous fungus and yeasts. A few marine yeasts were cultured by Lorenz and Molitoris36 at pressures ranging from 20 to 40 MPa. Photobacterium, Shewanella, Colwellia, and Motiella are examples of psychrophilic, deep-sea, very barophilic bacteria that are members of the g-proteobacteria. The core of deep-sea hydrothermal ecosystems is the interfacial zone, where cold bottom seawater and vent fluids meet. Microbial communities can exist as microbial mats on surfaces that come into direct touch with the discharged vent fluids or as free-living populations linked to the vent fluids. Some of the vent animals use the bacteria as "grazing grounds" since they frequently develop thick mats [37].

Many specialized vent animals rely on chemosynthetic exo- and endo-symbiotic bacteria as their primary food supply. Hydrothermal vents are home to a wide variety of microorganisms that add to their rich biodiversity. It has been studied how pressure affects gene expression, proteins, and cell membranes. The membrane's relative levels of monounsaturation and polyunsaturation rise in response to high pressure. The amount of unsaturated fatty acids in the cell membrane of a barotolerant Alteromonas sp. was higher [38]. The consequences of the high pressure-induced increase in viscosity are offset by the increased unsaturation, which results in a more fluid membrane. Due to their great sensitivity to UV radiation, barophiles need environments that are dark or have less light, such those found in the deep water, in order to develop. As demonstrated by the DNA polymerases of the hyperthermophiles Pyrococcus strain ES4, P. furiosus, and Thermus aquaticus, whose thermal inactivation is lessened by hydrostatic pressure, pressure can stabilize proteins and postpone thermal denaturation. A pressure-regulated operon was discovered in a moderately barophilic Shewanella species, and it was cloned and sequenced. At varying pressures, this strain seemed to develop distinct DNA-binding proteins. Under varying pressures, Photobacterium SS9 produced two outer membrane proteins (porins) [39]. It is believed that the fluidity of the membrane regulates these cytoplasmic membrane proteins, which act as pressure sensors. It was discovered that the barophilic bacterium DB6705 40 has a pressure-regulated operon. The cytochrome-bd complex in the aerobic respiratory chain depends on the CydD protein, which is encoded by an ORF, indicating the apparent significance of membrane components in high-pressure adaptation [40].

6.Halophiles: Green algae of the genus Dunaliella (D. salina, D. parva, and D. viridis) are common at relatively high salinities (1–3.5 M NaCl). Polyols are the most common suitable solutes used by green algae (e.g., glycerol in D. salina). Numerous diatom species, including Amphora coffeaeformis, Nitzschia, and Navicula, have been discovered at 2M NaCl. For osmoregulation, certain diatoms store oligosaccharides and proline. Protozoa from saline settings, like Porodon utahensis and Fabrea salina, have been reported [39].

Yeast that is halotolerant Seawater was used to isolate Debaryomyces hansenii. In the Great Salt Lake, Cladosporium glycolicum was discovered growing on submerged wood. 26 fungal species representing 13 genera of Zygomycotina (Absidia glauca), Ascomycotina (Chaetomium aureum, C. flavigenum, Emericella nidulans, Eurotium amstelodami, Gymnoascella marismortui, and Thielavia terricola), and mitosporic fungi (Acremonium persicinum, Stachybotrys chartarum, and Ulocladium chlamydosporum) from the Dead Sea have been identified. Halophilic fungi, including Polypaecilum pisce and Basipetospora halophila, were isolated from salted fish [39].

Cyanobacteria make up the majority of planktonic biomass in hypersaline lakes. Aphanothece halophytica is a unicellular organism that can grow in a variety of salt conditions. The main suitable solute in this process is glycine betaine, which can be produced from choline or absorbed from the medium. Dactylococcopsis salina is another cyanobacterium that has been identified from the Great Salt Lake. From the green second layer of mats in hypersaline lakes, filamentous Microcoleus chthonoplastes, Phormidium ambiguum, Oscillatoria neglecta, O. limnetica, and O. salina have also been identified. Nevertheless, little research has been done on the variety of cyanobacteria found in hypersaline environments [39]. Grant [41] conducted a thorough analysis of the variety of halophilic bacteria and archaea. In hypersaline microbial mats, phototrophic bacteria are found in anaerobic but lit zones beneath the cyanobacterial layers. In order to create trehalose for use as an osmolyte, the moderately halophilic Chlorobium limnicola absorbs glycine betaine from the surroundings. For osmoprotection, Thiocapsa halophile produces N-acetylglutaminylglutamine amide and glycine betaine [41].

Aerobic Gram-negative organotrophic bacteria, such as Acinetobacter, Alteromonas, Deleya, Flavobacterium, Marinomonas, Pseudomonas, and Vibrio, are prevalent in medium-salinity brines. Though comparable species of the genera Marinococcus, Sporosarcina, Salinococcus, and Bacillus have been recovered from saline soils and salterns, aerobic heterotrophs are less prevalent in solar salterns than Gram-negative bacteria. The archaeal genera Haloarcula, Halobacterium, Haloferax, Halorubrum, Halococcus, Halobaculum, Haloterrigena, and Halorubrum are among the halobacteria found in neutral hypersaline waters worldwide. Foods that contain salt enhance the proteolytic Halobacterium salinarum [41].

7.Oligotrophs/oligophiles: An organism that can grow in a medium with 0.2–16.8 mg of dissolved organic carbon per liter is known as an oligotroph 6. The proportion of oligotrophs and eutrophs (copiotrophs) in natural ecosystems depends on each species' capacity to dominate its own habitat. No matter the growth phase, carbon source, or carbon content, the oligotrophic bacteria Sphingomonas sp. strain RB2256, which was isolated from Resurrection Bay, Alaska, maintained its ultramicrosize. Cycloclasticus oligotrophicus RB1, another oligotroph that was isolated from the Resurrection Bay, had characteristics in common with Sphingomonas, such as a single copy of the rRNA operon and a short genome. Oligotrophy seems to be a growth strategy that can be adopted and lost over time, but it is not inviolable. Oligophiles are abundant in nature, according to recent reports from studies looking into the diversity of these bacteria in Leh soils [42]. A substrate uptake system that can take in nutrients from its environment is one of the traits thought to be crucial for oligotrophic microorganisms [43]. As a result, oligotrophs should ideally have a high surface area to volume ratio, broad substrate specificity, high-affinity uptake mechanisms, and an innate resilience to environmental stressors including heat, hydrogen peroxide, and ethanol [4]. Several microorganisms that have evolved to low-nutrient conditions, such as Caulobacter, Hyphomicrobium, Prosthecomicrobium, Ancalomicrobium, Labrys, and Stella, develop appendages to improve their surfaces [43].

Extremophiles/Extremolytes Survival and defensive strategies

Thermophiles/carbohydrate

extremolytes/hydroxyectoine decrease of VLS in immunotoxin therapy; protection against oxidative protein degradation; and stabilization of enzymes against stress and freeze drying

Halophiles/ecotines UV protection for skin immune cells; stabilization of enzymes against drying, freezing, and heat; defense of the skin barrier against drying out and water loss; inhibition of the release of ceramides in human keratinocytes caused by UVA

Acidophiles/

Alkaliphiles The preservation of a circumneutral intracellular pH, continuous proton pumping into and out of the cytoplasm, acidic cell membrane polymers, passive control of the cytoplasmic polyamine pools, and low membrane permeability

Psychrophiles Cold-evolved enzyme translation; sections of protein structure that are more flexible; the presence of cold shock proteins and nucleic acid binding proteins; and a decrease in the arrangement of acyl chains in cell membranes

Barophiles Increasing amounts of unsaturated fatty acids, homeoviscous adaptability, and tightly packed lipid membranes; polyunsaturated fatty acids preserve membrane fluidity; strong DNA repair systems; Heat shock is present in highly conserved pressure-regulated operons.

Table 1: Showing Major Extremophiles

The table below shows the survival and defensive strategies in major extremophiles to thrive under extreme environmental conditions Source [43]

Economic Potential of Extremophiles

Protein folding knowledge is among the fundamental molecular biology facts that extremophiles have contributed. There are two ways that evolutionary biology has benefited. Phylogenetic enlightenment has increased due to the discovery of entire new species in the quest to identify the most severe of extremophiles. Second, survival in certain harsh settings has evolved several times, which has led to a new understanding of need vs chance in evolutionary pathways, particularly at the molecular level [44]. The ice-binding antifreeze proteins, for instance, are evolutionarily convergent; the Antarctic notothenioid fish's protein evolved from a pancreatic protease that resembles trypsinogen. Chemical syntheses, laundry detergents, pharmaceuticals, and agriculture are just a few of the multibillion-dollar sectors that have become enamored with extremeophiles. The European Commission has provided funding for this field's technological development, training, and commercialization [45].

Extremophile-derived enzymes, or "extremozymes," have potential applications in a variety of fields. They can be used directly or as inspiration to modify enzymes obtained from mesophiles. Though experiments have shown that aqueous/organic and nonaqueous media allow for the alteration of reaction equilibria and enzyme selectivity, paving the possibility for the synthesis of new chemicals, the reaction medium is typically aqueous. Because extremophiles require exacting growing conditions, it is frequently more cost-effective to express the gene in a more manageable host organism, such E. coli [46]. Taq polymerase, the key enzyme in the popular polymerase chain reaction (PCR), is the quintessential example of an enzyme generated from extremophiles in biotechnology. The thermophilic bacteria Thermus aquaticus, which was found in Yellowstone National Park in 1969, Wyoming [47], is the source of Taq polymerase. Promega Corporation has sold DNA polymerases derived from various thermophiles as a high-fidelity PCR product; each has unique benefits [48, 49].

There are industrial uses for other extremophiles. Polyunsaturated fatty acids, for instance, are produced by some Antarctic bacteria and are a necessary component of the diets of many aquaculture species, including Atlantic salmon. Rotifers, a food source for fish larvae, are enriched with the bacteria. An issue in cold seas [50] is the potential for Antarctic microbes to bioremediate waters after oil spills. D. salina is utilized extensively in the commercial manufacture of glycerol, which it produces to balance external osmotic pressure, and b-carotenes, which it produces in reaction to sun radiation. Through biotechnology and bioremediation, extremophiles may indirectly improve human health. Marketing dried Dunaliella as a dietary supplement, mainly as an antioxidant, is one example of a direct use. Potential use for antifreeze proteins as cryoprotectants for frozen organs [12].

Conclusion

The study of microbes' roles in the geologic past, from their first appearance on Earth some 4 eons ago to the present, as well as their current and anticipated future roles in some of the processes that are fundamental to geology, is known as geomicrobiology. The discovery of microbial fossils in the geologic record that morphologically resemble modern microorganisms of geologic significance and pertinent biomarkers has led to the deduction of geomicrobial activities in the geologic past. The physiological underpinnings of various geomicrobial activity types vary depending on the activity type, the material being changed, and the organism or organisms involved. Enzymatic reductions or oxidations of inorganic materials are a part of some geomicrobial activity. Prokaryotic organisms are primarily responsible for these processes, which can aid in the creation, diagenesis, and degradation of minerals. Prokaryotes and eukaryotes both play a significant role in the enzymatic synthesis or breakdown of naturally occurring organic carbon molecules, which is another type of geomicrobial activity. In addition to oxidations and/or reductions, these organic transformations entail a wide variety of additional enzyme processes.

Extremophiles are organisms that flourish in harsh environments; polyextremophiles are organisms that thrive in many extremes. Sulfolobus acidocaldarius, an archaea that thrives at pH 3 and 80ºC, is an example of the latter. "Extremes" can be either geochemical (such as desiccation, salinity, pH, oxygen species, or redox potential) or physical (such as temperature, radiation, or pressure). An organism that flourishes in "extreme" circumstances is known as an extremophile. Since we compare it to human extremes—for example, we use oxygen, even though it is toxic to many organisms—the term "extremophile" is comparatively anthropocentric. More research seminars and studies on this subject should be promoted in order to educate the public about its significance to humanity.

Availability of Data and Materials

The authors declare consent for all available data present in this study.

Conflict of Interest

The authors declare no conflicts of interest. The authors alone are responsible for the content and the writing of the paper.

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