Planetary analog sites in the Indian subcontinent and the Indian Ocean: Underexplored environments suited for astrobiological and space research

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Abstract

The central objective of astrobiology is to evaluate the habitability of other planetary bodies and given the high cost and logistical complexity of space missions, preliminary investigations of planetary analog sites are a critical step in supporting and de-risking future exploration efforts. Planetary analog sites are extreme environments on Earth that exhibit one or more environmental, geological, geochemical, or biological characteristics that are analogous to conditions expected on other planetary bodies. Understanding how life persists in planetary analog sites is essential for advancing our knowledge of extraterrestrial habitability. They provide valuable opportunities to study life's resilience and to test life-detection instruments in realistic settings. In this review, we present the first comprehensive synthesis of over 30 planetary analog field sites located across the Indian subcontinent and the surrounding Indian Ocean region. These include high-altitude glaciers, alkaline lakes, hypersaline basins, hot springs, and cold desert ecosystems. Although these environments remain largely underexplored in the context of astrobiology, they exhibit strong environmental parallels to planetary conditions and offer significant potential for advancing microbial ecology, biosignature detection, and geobiological research. As the scientific community prepares for the next generation of deep space missions focused on the search for life beyond Earth, we call for a broader geographical and conceptual inclusion of analog sites. By highlighting the environmental diversity and scientific value of these under-characterized regions in South Asia and their marine periphery, this review contributes a vital and previously underrepresented perspective to planetary analog research. This review fills a critical gap in the global planetary analog landscape and aims to stimulate interdisciplinary investigations across planetary science, microbiology, and life-detection technology development.

Introduction

Astrobiology explores fundamental questions about the origin, evolution, distribution, and future of life on Earth and beyond (Chyba and Hand 2005). The search for life outside Earth begins with identifying and characterizing potentially habitable environments within our Solar System bodies such as Mars, Europa, and Enceladus, as well as on exoplanets orbiting distant stars (McKay 2022; Kane et al. 2021). This search is informed by our understanding of how life first emerged and evolved on Earth. Early life thrived in environments we now call "extreme," is a designation that reflects an anthropocentric perspective, since these conditions represent physiologically normal habitats for the microorganisms that inhabit them (Rothschild and Mancinelli 2001; Horneck et al. 2010; Merino et al. 2019). In extreme environments, microbes can tap into inorganic compounds such as iron, sulfur, or hydrogen for energy, in absence of sunlight and underscoring the possibility of life in dark subsurface habitats beyond Earth (Canfield et al. 2006). Moreover, microbes can exploit a wide range of electron donors and acceptors, enabling them to drive diverse metabolic pathways and thrive across varied environmental conditions (Froelich et al. 1979). Physicochemical extremes, including high radiation, hypersalinity, pressure variations, and nutrient-poor terrains, still persist on Earth today, delineating the outer limits of habitability (Merino et al. 2019; Coleine and Delgado-Baquerizo 2022). Such environments serve as planetary analogues, offering natural laboratories to investigate microbial survival, biosignature preservation, and the potential for life on other worlds. They also play a critical role in developing and validating life-detection instruments, refining scientific methodologies, and supporting mission planning through terrain and environmental simulations (Léveillé 2009; Martins et al. 2017). In recent years, the concept of planetary analogues has expanded beyond purely "geological analogues" to include "functional analogues." These may involve natural sites or engineered platforms selected for their relevance to specific scientific or operational goals, such as petrology, mineralogy, biological processes, or engineering compatibility (Foucher et al. 2021). This broader classification enables a more strategic integration of analogue environments across mission phases; from instrumentation development to in-situ exploration and post-mission data interpretation

International space agencies have prioritized a range of terrestrial field sites as astrobiological analogues (Supplementary Table 1) for planetary bodies such as Mars, Venus, Lunar, and Icy Moons (Europa and Enceladus). For Mars, Venus, and other rocky planets, hyperarid deserts and volcanic terrains provide valuable parallels. The Atacama Desert in Chile, one of the driest places on Earth, mirrors the UV-intense, desiccated surface of Mars and is critical for studying microbial survival and biosignature stability (Azua-Bustos et al. 2022; Lebre et al. 2017; Visscher et al. 2020). Likewise, Death Valley (Farr 2004; Douglas et al. 2008), the Tibetan Plateau (Liu et al., 2022; Sun et al., 2018), and the McMurdo Dry Valleys in Antarctica offer Mars-like extremes of aridity, cold, and low atmospheric pressure (Salvatore and Levy 2021). Hydrothermal and volcanic sites, such as the Iberian Pyritic Belt in Spain (Amils et al. 2007; 2014; Gómez et al. 2011), the Dallol geothermal field in Ethiopia (Cavalazzi et al. 2019), Icelandic volcanoes (Voigt et al., 2025; Fagents and Thordarson, 2007), and the basalt flows of Kīlauea, Hawaii (Bergsten et al., 2021; D'Incecco et al., 2024; Seelos et al., 2010), recreate acidic and mineral-rich terrains comparable to past Martian hydrothermal systems and Venusian volcanism. The Manicouagan impact crater in Canada further contributes insights into impact-generated habitats relevant to Mars and icy bodies (Spray et al. 2010; Cloutis et al. 2015). Svalbard in Norway provides permafrost landscapes and logistical isolation that make it an effective analog for Mars surface exploration and lunar habitation scenarios (Kołodziejczyk et al., 2025; Hauber et al., 2011). For icy moons, subglacial and deep-sea hydrothermal environments offer compelling parallels. Lake Vostok in Antarctica (Cassaro et al. 2021), the Strýtan hydrothermal vents in Iceland (Twing et al. 2022), and seafloor systems such as Gakkel Ridge (Ramirez-Llodra et al. 2023), Lost City (Amador et al. 2017), Juan de Fuca (Kelley et al. 2012; Osinski et al. 2006), and the Mariana Trench (Preston and Dartnell 2014) simulate energy-rich, water–rock interactions in subsurface oceans where life may persist (Gaidos et al. 1999; Barge and White 2017; Martin and McMinn 2018; German et al. 2022). Despite global progress in analogue research, geologically diverse regions remain underexplored. The Indian subcontinent and adjoining Indian Ocean basin, shaped by complex tectonics and unique environmental extremes (Valdiya 2016), represent promising yet overlooked additions to the planetary analogue inventory. Incorporating these sites would broaden the global scope of astrobiology, expand analogue functions, and deepen our understanding of habitability across a wider spectrum of planetary environments.

The Indian subcontinent and the adjoining Indian Ocean, with their tectonic complexity, encompass diverse geological settings that offer valuable opportunities for testing hypotheses on the origin and resilience of life in extraterrestrial environments (Figure 1 and 2). Yet, despite hosting numerous extreme habitats, these regions remain underexplored in astrobiological research. This gap stems from limited integration of regional geology with planetary science, fragmented interdisciplinary collaborations, and significant practical challenges. Many sites are remote and difficult to access, while sustained field-based studies are constrained by limited economic resources. Additionally, anthropogenic activity and contamination in some areas complicate the preservation of pristine conditions for analogue research. However, these geological field sites retain high relevance, as their tectonic, mineralogical, and geochemical attributes preserve natural extremes that provide valuable parallels to planetary environments (Supplementary Table 2,3, and 4; Figure 1 and 2). The tectonic collision between the Indian and Eurasian Plates, around 50 Ma (Molnar and Tapponnier 1977; Jain 2014; Wu et al. 2023), gave rise to the Himalayas and exposing stratigraphic sequences spanning from the Archean geological time (4 Ga), including some of the oldest continental crusts preserved in the Dharwar and Singhbhum cratons (Dey and Moyen 2020b) and the ophiolitic sequences (Bhat et al. 2022), ideal for Early Earth investigations. High-altitude glacial systems, such as Ladakh, Sikkim, and the Hindu Kush-Himalayan ranges, mimics the Martian and/or early Earth Environments (Pandey et al. 2020; Schopf et al. 2008; Armstrong 2010). Dinodhar hill (Kachchh) and Alaldari Valley (Maharashtra) offer parallels to fluvial activity on Martian surfaces (Chavan et al. 2022). Hyper-arid zones, such as the Thar Desert may simulate Martian surface desiccation and dust dynamics (Khormali and Monger 2020; Sarkar et al. 2019). The hypersaline Sambhar lake (Sarkar et al. 2023; Sinha and Raymahashay 2004a) and the Lonar soda lake (Paul Antony et al. 2013) present analogs to evaporitic basins on Mars (Mancinelli et al. 2004). Additionally, geothermal springs scattered across the Deccan Traps and the Himalayan region (Das et al. 2022; Tamburello et al. 2022), along with the deep-sea hydrothermal vents spread across the Indian Ocean (Dick 2019a), may provide windows into subsurface microbial life processes relevant to ocean worlds.

This review aims to foreground these underexplored Indian field sites within global analogue research by systematically evaluating their planetary and functional relevance. We highlight their capacity to inform biosignature detection, expand the range of habitability scenarios, and support the development of mission-relevant technologies. Establishing the Indian subcontinent and adjoining Indian Ocean as integral components of the planetary analogue framework will broaden astrobiology's geographic scope and enrich its experimental and operational dimensions.

The Indian Plate

The Indian Plate, composed of Archean cratons, Proterozoic mobile belts, Phanerozoic sedimentary basins, large igneous provinces, and tectonically active regions such as the Himalayas, preserves a geological record that spans from the Archean to the present (Chaudhuri et al. 2018), hosting extreme environments as listed in Supplementary Table 2 (Figure 3, 4). The Archean cratons (dating between 3.6 and 2.5 Ga), including the Dharwar, Singhbhum, Bastar, Aravalli, and Bundelkhand cratons, are dominated by rocks that preserve the earliest continental crust and provide critical insights into early Earth processes. Stromatolites and banded iron formations within these cratons (Beukes et al. 2008; Mukhopadhyay et al. 2025; Dey and Moyen 2020a) may have records of microbial life in an anoxic world. The younger Proterozoic mobile belts (dated 2.5 - 0.5 Ga), include the Aravalli–Delhi Belt, the Eastern Ghats Mobile Belt, and the Central Indian Tectonic Zone, that document ocean closures, continental collisions, crustal reworking, Great Oxidation Event (2.4 Ga), and the Neoproterozoic Oxygenation Event (0.5 billion years ago) (Kaiho et al. 2024; Olejarz et al. 2021; Chen et al. 2022). Glaciogenic deposits within these belts preserve evidence of microbial life survival during Snowball Earth episodes (Hoffman et al. 2017). In addition, Precambrian alluvial successions, which formed before the appearance of land plants, retains microbial textures and mineralogical signatures that illuminate early surface processes and offer potential extraterrestrial analogs (Chakraborty et al. 2022). From an astrobiological perspective, these Precambrian records are particularly valuable because they reflect microbial ecosystems under low-oxygen atmospheres, conditions that may resemble those of other habitable planets or moons.

The Phanerozoic era (beginning about 0.5 Ga to the present) brought extensive sedimentation across Gondwana basins. Beginning in the Late Carboniferous and Jurassic, these basins preserve fluvial sandstones, coal beds, and fossiliferous strata that chronicle terrestrial ecosystem evolution during Gondwana's breakup (Chakraborty et al. 2019). Along the northern margin of the plate, the Tethyan Himalayan Basin accumulated marine sediments from the Cambrian to the Eocene, recording the history of the vanished Tethys Ocean (Liu and Einsele 1994; Jiang et al. 2016). Fossils and organic molecules in these sediments, including kerogen, hopanes, and steranes (Brocks and Summons 2003), provide benchmarks for biosignature interpretation. Phanerozoic strata also record redox variability, ranging from anoxic to sulfidic to oxic conditions, which directly influences biosignature preservation (Sperling et al. 2021). Their lacustrine (Michalski et al. 2022), fluvial (Cardenas et al. 2022), deltaic (Di Achille and Hynek 2010; De Toffoli et al. 2021), and evaporitic environments (Kite and Conway 2024) serve as planetary analogs for sedimentary environments identified on Mars. While Phanerozoic basins refine biosignature detection methods in post-vegetation ecosystems, Precambrian archives remain the closest parallels to microbial worlds that may exist on other planets.

In Cenozoic era, the Deccan Traps (emplaced about 66 Ma) form one of Earth's largest flood basalt provinces and are linked to mantle plume activity and the end-Cretaceous mass extinction (Sen et al. 2009; Beane et al. 1986; Mishra et al. 2024). Deccan basalts, with their basaltic stratigraphy, alteration patterns, and mineralogy, serve as analogs for Martian terrains such as Mawrth Vallis (Craig et al., 2017; Bhattacharya et al., 2016; Greenberger et al., 2012). Their porosity and fracture networks host endolithic and subsurface microbial communities that exploit iron- and sulfur-based chemoautotrophy (Dutta et al. 2019; 2018; Jungbluth et al. 2016). Such systems offer parallels to potential subsurface life on Mars, where rock–water interactions and redox gradients may sustain habitability.

Altogether, the Indian Plate encompasses extreme environments shaped by tectonics, climate, and deep time. From Archean cratons and Proterozoic mobile belts to Phanerozoic basins and Cenozoic flood basalts, these natural laboratories preserve biosignatures, track planetary environmental transitions, and provide Earth analogs for diverse extraterrestrial settings, from early Mars to the subsurface oceans of icy moons such as Europa and Enceladus. Studying biosignatures in these terrestrial settings will allow us to constrain what types of biosignatures might form, survive, or degrade in Martian equivalents, particularly in clay-rich (Bishop et al. 2018; Gainey et al. 2017; Ehlmann et al. 2008) or iron-rich sediments (Kizovski et al. 2025; Ehlmann and Edwards 2014).

Soda and hypersaline Lakes

Soda lakes, characterized by high concentrations of sodium, carbonate, and bicarbonate ions, result in highly alkaline waters. These systems are often endorheic, with no fluvial outflow accumulating salts over geological time with persistent high-pH environments on Earth (Boros and Kolpakova 2018; Kempe and Kazmierczak 2011). These lakes supports diverse and robust microbial communities adapted to extreme alkalinity (Dimitry Y Sorokin et al. 2015; Jones et al. 1998; Sorokin et al. 2014; Sorokin and Kuenen 2005; Zorz et al. 2019). Globally, they serve as natural laboratories for early Earth and potentially habitable environments on other planets (Cohen et al. 2024; Ventosa 2004). Some of the most well-known soda lakes include Lake Magadi and Lake Natron in East Africa (Deocampo and Renaut 2016), Big Soda and Mono Lake in California (Cloern et al. 1983; Honke et al. 2019; Kharaka et al. 1984), the Kulunda Steppe lakes in Russia (Meyer et al. 2008), and lakes of the Cariboo plateau in Canada (Renaut 1990). They support dense populations of alkaliphilic and halophilic microbes, including cyanobacteria, sulfur-oxidizing bacteria, and alkaliphilic archaea (Jeilu et al. 2022; Cloern et al. 1983; Humayoun et al. 2003; Rojas et al. 2018; Foti et al. 2008; Dimitry Y. Sorokin et al. 2015; Zorz et al. 2019). Many of these microbes thrive on anaerobic metabolisms such as fermentation, methanogenesis, denitrification, metal respiration, arsenate reduction. The presence of layered microbial mats, carbonate precipitates, and microbialites in these systems provides insights into potential biosignature preservation, making soda lakes key field sites for astrobiological studies.

In the Indian subcontinent, soda lakes are less extensively studied. Notable examples include Lonar Crater Lake, formed by a meteorite impact (Fredriksson et al. 1973). It hosts microbial communities adapted to both alkaline and saline conditions, including cyanobacteria, purple sulfur bacteria, and archaea (Paul Antony et al. 2013). The combination of high pH, basaltic geology, and impact-driven hydrology makes Lonar Lake a key planetary analog for Mars (Pandey et al. 2019), where alkaline brines and volcanic terrains are thought to occur. Another significant site is Sambhar Lake in Rajasthan, which is India's largest inland saline lake and exhibits moderate alkalinity (Sinha and Raymahashay 2004b). Although it is primarily known for its salt production and avian biodiversity, the lake's fluctuating hydrology and hypersaline conditions make it a potentially interesting site for studying microbial adaptation in alkaline brines (Sahay et al. 2012; Pal et al. 2020). Both lakes are valuable for exploring alkaline geochemistry, microbial adaptation, prebiotic chemistry, and biosignature preservation in extreme saline–alkaline settings.

Dust Storms of Arid Desert

The hot, arid regions of the Thar and Cholistan Deserts serve as valuable terrestrial analogues for planetary research, particularly for understanding Martian surface processes including dust storms (Wang and Richardson 2015; Leovy et al. 1973). These deserts are characterized by intense solar radiation, extreme temperature fluctuations and low water availability. In Thar desert, the frequent occurrence of mineral dust storms, reducing visibility, modifying sediment textures, and driving extensive aeolian transport (Middleton et al. 1986; Jain et al. 2025). These airborne dust influences planetary climate, habitability, and the remote detection of biosignatures (Boutle et al. 2020). These dust storms provide an opportunity to evaluate how dust loading, particle composition, and scattering properties affect remote sensing signals, thereby refining strategies for biosignature detection on Mars and other planetary surfaces. While the physical dynamics of dust storms are similar on Earth and Mars, their compositions differ. Rajasthan dust contains up to 10% iron oxides (Mishra and Tripathi, 2008), whereas Martian dust is estimated at about 22% (Berger et al., 2016), due to higher iron content. Dust storms may also transport microbial cells, as demonstrated in other desert systems (Yamaguchi et al. 2012; González-Toril et al. 2020), raising questions about microbial survival during atmospheric transit and even the potential for interplanetary dispersal (Barberán et al., 2015; Amato et al., 2023). However, airborne microbial communities in these deserts remain unstudied, with most research focused on soils, dunes, and rock surfaces (Rao et al., 2016; Parihar et al., 2022; Fatima et al., 2019). Developing predictive models and deploying automated samplers before dust events, or collecting post-storm deposited dust, may provide a way forward in addressing this gap.

Microbial communities in the Thar and Cholistan exhibit adaptations such as spore formation, UV-protective pigments, DNA repair mechanisms, and metabolic flexibility, which enable survival under nutrient-poor and water-limited conditions. These traits, along with the preservation of organic compounds in dry sediments, make the region a natural laboratory for refining life-detection strategies relevant to Mars and other planetary bodies. Lastly, the geomorphology of the Thar, with its active dune fields, evaporite crusts, and silicate-rich sediments, also provides a natural test bed for rover mobility, autonomous navigation, and remote sensing systems designed for planetary exploration.

Natural caves and unused mines

Natural cave environments provide stable temperatures, radiation shielding, and protection from extreme weather and micrometeorite impacts, making them valuable analogues for Martian habitats (Blank, 2018; Boston et al., 2001; Léveillé & Datta, 2010). Many terrestrial caves form in karst landscapes, where groundwater dissolves soluble rocks such as limestone, dolomite, and gypsum (Waele and Gutiérrez 2022). On Mars and the Moon, extensive cave networks, including lava tubes and pit craters, have been identified, with some lunar caves maintaining stable temperatures suitable for habitation (Sauro et al. 2020). Earth-based caves thus serve as planetary analogues and provide opportunities to investigate biosignature preservation, microbial–mineral interactions, and the ecological impacts of long-term darkness. They host diverse extremophilic microorganisms, many relying on chemolithoautotrophy and minimal nutrients (Gabriel and Northup, 2013; Zhu et al., 2022; Turrini et al., 2024). Lava tubes, in particular, are also useful for testing robotic exploration technologies (Morrell et al. 2024). Globally, several caves hold astrobiological significance. The Movile Cave in Romania, an oxygen-poor ecosystem, sustains microbial communities based on sulfur and ammonium chemolithotrophy as well as methanogenesis, methanotrophy, and methylotrophy (Hutchens et al., 2004; Chen et al., 2009; Wischer et al., 2015). Lechuguilla Cave in New Mexico harbors antibiotic-resistant microbes preserved in pristine conditions, providing insights into the evolution of the deep biosphere (Cunningham et al. 1995). The Frasassi Caves in Italy support sulfur-cycling microbial mats that exemplify metabolisms relevant to extreme environments (Macalady et al. 2006; 2007). In the Indian subcontinent, Borra Caves, Krem Phyllut, Mawsmai, and Kotumsar Cave (Chhattisgarh) offer promising settings for astrobiological research (Baskar and Baskar 2022; Baskar et al. 2009; 2011).

Beyond natural caves, unused or decommissioned mines provide valuable subsurface laboratories for astrobiology. Deep underground environments replicate conditions relevant to planetary interiors, with high pressure, limited nutrients, and absence of sunlight. Around the world, several mines have been repurposed: the Sanford Underground Research Facility in South Dakota, converted from the Homestake gold mine, now hosts experiments in physics and subsurface biology (Heise and J. 2015; Osburn et al. 2014; Jangir et al. 2019; Osburn et al. 2019; Rowe et al. 2021); the Boulby Underground Laboratory in the UK supports planetary science and microbiology research in a potash mine (Wadsworth et al. 2020; Cockell et al. 2019; Payler et al. 2019); the Canadian Underground Research Laboratory revealed biofilm-associated minerals in granite (Brown et al. 1994); the Soudan mine has yielded diverse iron-oxidizing and -reducing microbes (Hsu et al. 2024; Badalamenti et al. 2016; Edwards et al. 2006); and deep mines in South Africa have produced groundbreaking discoveries of microbial taxa thriving in high-pressure conditions (Gihring et al. 2006; Onstott et al. 1997). Similar opportunities also exist in India. The Kolar Gold Fields in the Dharwar Archean craton (Siddaiah and Rajamani 1989; Reddy et al. 2017), sections of the Paleoproterozoic regions hosted in Jaduguda uranium mines in the Singhbhum shear zone (Pal et al. 2011), the Zawar zinc mines in Rajasthan, and the Malanjkhand copper mine in Madhya Pradesh (Pandey et al. 2007; Equeenuddin et al. 2017; Sikka 1989) expose diverse lithologies and complex geochemical settings. These environments are ideal for investigating extremophile microbial communities, biogeochemical cycling, and biosignature preservation. Repurposing such sites as underground laboratories would enable studies of water–rock–microbe interactions, radiation shielding strategies, and life-support simulations.

Mud Volcanoes

Mud volcanoes (MVs) are dynamic features of compressional tectonic regimes that occur in both marine (Napoli et al. 2025) and terrestrial settings (Milkov 2000). They vent fluids and fine-grained sediments dominated by methane, along with CO_2 and other hydrocarbons (Mazzini and Etiope 2017), and display diverse morphologies ranging from low mud flows to steep cones (Kopf 2002; Dimitrov 2002). MVs transport clay-rich sediments, rock fragments, and subsurface microorganisms from the deep subsurface to the surface, providing opportunities to study extremophiles and their metabolic networks in fluid- and mineral-rich habitats (Ijiri et al., 2018; Lee et al., 2018a; Rajendran et al., 2025). While extensive research on marine MVs revealed necessary syntrophic interaction for microbial survival, between anaerobic methanotrophs (ANMEs) and their sulfate-reducing partners, representative of Early Earth scenarios (Orphan et al. 2001; Lösekann et al. 2007; Pachiadaki et al.

2011; Lee et al. 2018b; Omoregie et al. 2008; Ruff et al. 2019; Niemann et al. 2006), the terrestrial MV's have recently gained traction (Miyake et al. 2023; Merkel et al. 2021; Tu et al. 2017). Terrestrial MV's provide a more accessible systems critical for understanding the limits of Earth's deep biosphere and for interpreting methane emissions and mud-like morphologies on Mars and other worlds (Krýza et al. 2025; Komatsu et al. 2016; Skinner and Mazzini 2009; Hosein et al. 2014).

Prominent terrestrial MVs occur across the Makran accretionary prism, including the Hingol complex, Gwadar, Ormara, and Lasbela regions, where large cones such as Chandragup I (~90 m) episodically discharge methane-rich fluids and fine sediments (Delisle et al. 2002; Kassi et al. 2014). In the northern Andaman forearc basin, regional compression, overpressured shales, and mass-transport deposits control MV formation (Ankush et al. 2024; Ray et al. 2013; Kumar et al. 2021). Terrestrial MVs in the Andaman Islands actively emit methane-rich gases, water, and mud breccia, with occasional eruptions triggered by seismic activity (Chaudhuri et al. 2012). Microbial studies in the Andaman and Nicobar MVs have so far catalogued broad bacterial groups and heterotrophic communities (Amaresan et al., 2018; Meena et al., 2023; Manna et al., 2021, but targeted enrichment of extremophiles adapted to reduced, methane- and hydrocarbon-rich conditions remains limited.

The Himalayan Range

The Himalayan and adjoining mountain ranges, collectively known as the Third Pole, form the highest terrain on Earth (Altitude: 4 km, Area: ~595000 km^2) hosts extreme environments including glaciers, natural caves, geothermal springs, saline ecosystems, and ophiolites (Supplementary Table 3; Figure 3, 4). The origin of the Himalayan range lies in the ongoing collision between the Indian and Eurasian plates, beginning around 50 Ma ago, which uplifted the Tethys Ocean floor and produced the world's tallest mountains. This tectonic setting preserves fragments of ancient oceanic lithosphere in the form of ophiolites, which are emplaced sections of oceanic crust and mantle typically found within suture zones (Kelemen et al. 2023; Coleman 1977; Dickinson 1971). Ophiolites are frequently composed of peridotite, gabbro, and basalt, displaying evidence of alteration by seawater. Serpentinization of ultramafic rocks in ophiolites, results in generation of hydrogen, methane, and other reduced compounds that provide chemical energy for microbial life (Klein et al. 2013; McCollom and Bach 2009; Moody 1976). These processes are central to understanding how water–rock interactions sustained early life on Earth (Schwander et al. 2023) and how biosignatures might be preserved in mineralized fractures, offering analogues for habitable environments on Mars (Emran et al. 2025; Schulte et al. 2006; Oze and Sharma 2005) and icy moons such as Europa and Enceladus (Holm et al. 2015; Taubner et al. 2018; Guo and Eiler 2007). The well-preserved Oman (Semail) Ophiolite remains the most complete section of oceanic lithosphere exposed on land, making it a global benchmark for studying oceanic crust formation, alteration, and serpentinite-hosted microbial ecosystems (Rempfert et al. 2023; Lima-Zaloumis et al. 2022; Rempfert et al. 2017; Fones et al. 2019). Across South Asia, ophiolite remnants of the Neo-Tethys Ocean occur along the Indus Suture Zone in Ladakh and Pakistan, the Indo–Myanmar ranges, the Indus–Tsangpo belt in Tibet, and the Andaman Islands (Villalobos-Orchard et al. 2025; Bhat et al. 2022; Ullah et al. 2020; 2023; Jalil et al. 2023; Pedersen et al. 2010). Some sites report hydrocarbon-rich fluids with measurable methane (Das et al. 2017; Sachan et al. 2007). Yet, microbiological investigations across these ophiolites remain sparse, highlighting the need for systematic studies to assess their role as planetary analogues for habitability.

The Himalayan cryosphere contains the largest ice volume outside the polar regions (Bolch et al., 2012). It hosts valley and cirque glaciers, ice caps, glacial lakes, permafrost zones, and alpine wetlands shaped by interactions among tectonics, topography, and climate. Glacier-fed lakes and streams are significant carbon sources, emitting up to 1746 ± 139 mg C m^{-2} d^{-1} and 1960 ± 176 mg C m^{-2} d^{-1}, respectively, largely through dissolved inorganic carbon fluxes (Shukla et al. 2023). These emissions, along with CO_2 degassing from geothermal hot springs, estimated at $1.5 \pm 1.0 \times 10^{11}$ mol yr^{-1} (Pradhan and Sen 2024), derive primarily from deep metamorphic and mantle processes. As glacial lakes continue to expand rapidly, these environments provide valuable sites to study microbial survival, metabolism, and biosignature production in cold, carbon-rich, UV-exposed settings analogous to early Earth and icy planetary bodies. Despite their importance, microbial processes driving carbon cycling in these systems remain poorly characterized. Glaciers, permafrost, and subglacial zones are considered as planetary analogues to icy habitats on Mars, Europa, and Enceladus (Garcia-Lopez and Cid 2017). Microorganisms in these environments are polyextremophiles, tolerating low temperatures (Margesin and Miteva, 2011; Cavicchioli, 2016), high radiation (Zhang et al. 2023), desiccation (Brenning and Trombotto 2006), nutrient limitation and surviving by metabolizing sulfur, methane, and iron under subglacial conditions independent of sunlight (Anesio et al. 2017; Bourquin et al. 2022). Himalayan glaciers (Stres et al. 2013; Venkatachalam et al. 2015; Rafiq et al. 2017; Kumar et al. 2019; Dhakar and Pandey 2020; Singh et al. 2024) and rivers (Paudel Adhikari et al. 2019; Suyal et al. 2022) host diverse psychrophilic microbes, some capable of degrading complex substrates (Sanyal et al. 2018; Ali et al. 2025), offering insights into biosignature preservation and prebiotic chemistry under cryogenic conditions.

Geothermal systems (hot springs) further expand the Himalayan analogue landscape. The hot springs, characterized by high pH from carbonate-rich fluids, support thermophilic and chemotrophic microbial communities and are considered plausible sites for prebiotic chemistry. On Mars, mineralogical evidence of carbonates, phyllosilicates, and silica suggests that alkaline fluids once existed (Hurowitz et al. 2023). Terrestrial examples include the Puga (Roy et al. 2020; Mondal et al. 2022), Chumathang (Anu et al. 2024), Panamik (Mondal et al. 2022; Choudhary et al. 2024; Anu et al. 2024) geothermal hot springs, which host diverse phototrophs and chemotrophs, providing an analogue for initial investigations on biosignature studies (Ansari et al. 2025). Terrestrial hot springs, with wet–dry cycling, are more conducive to prebiotic polymerization than deep-sea vents (Westall et al. 2018; Des Marais and Walter 2019; Deamer and Georgiou 2015). In addition, underexplored Himalayan alkaline lakes such as Tso Kar, Kyagar Tso, and Tso Moriri provide further opportunities to investigate biosignature preservation in brine-rich systems (Pandey et al. 2020).

Together, ophiolites, glaciers, permafrost, and geothermal systems of the Himalayas constitute a diverse natural laboratory. These environments allow investigation of water–rock reactions, carbon fluxes, microbial adaptations, and biosignature preservation under extreme conditions, offering analogues highly relevant to early Earth and potentially habitable planetary settings.

The Indian Ocean

The Indian Ocean formed during the breakup of Gondwana in the Mesozoic, with seafloor spreading initiating along the Carlsberg and Central Indian ridges around 140–120 Ma (Gaina et al. 2007; 2015), hosts many deep sea vents and trenches for exploration (Supplementary Table 4; Figure 3). Its rock record preserves key tectonic and magmatic features, including slow- to ultra-slow spreading ridges, fracture zones, seamount chains, and thick sedimentary sequences influenced by the Himalaya and monsoonal systems. Together, these archives document the evolution of oceanic lithosphere, plate reorganization, and paleoceanographic change across the Cenozoic. Within the Indian Ocean, oxygen-depleted habitats, including oxygen minimum zones, hadal trenches, hydrothermal systems, and cold seeps, provide valuable analogues for extraterrestrial environments.

Deep sea hydrothermal vents found along mid-ocean ridges, where tectonic plates diverge, allow seawater to circulate through fractured crust and interact with underlying magma. These environments replicate extreme conditions expected on icy moons such as Europa and Enceladus, including high pressure, low temperature, absence of sunlight, and chemical energy derived from water–rock interactions (McClain et al. 2022; Aguzzi et al. 2024). They serve as natural laboratories for evaluating biosignature production and strategies for life detection in extraterrestrial oceans (George 2020; German et al. 2022) as they sustain microbial communities reliant on chemosynthesis rather than photosynthesis (Ricci and Greening 2024; Sogin et al. 2020; Dick 2019b), Evidence from the Galileo mission (Zimmer et al. 2000) and the Cassini mission (Barge and Rodriguez 2021), supported by subsequent studies (Barge and White 2017; Glass et al. 2022), indicates that hydrothermal activity may occur within the subsurface oceans of Europa and Enceladus, creating conditions capable of supporting methanogenesis (Holden and Sistu 2023; Lyu et al. 2018), while the ongoing Europa Clipper mission seeks to assess Europa's subsurface ocean directly (Roberts et al. 2023). The Indian Ocean Ridge System, subdivided into the Central (CIR), Southwest (SWIR), and Southeast Indian Ridge (SEIR), is a slow- to ultra-slow spreading system hosting diverse vent fields. Since their first discovery in 2001 (Van Dover et al. 2001), notable sites include Kairei, Edmond (Van Dover et al. 2001), Solitaire, Dodo (Nakamura et al. 2012), and Onnuri (Lim et al. 2022) on the CIR; Mount Jourdanne (Münch et al. 2001), Longqi (Tao et al. 2012), Duanqiao (Yang et al. 2017), Tiancheng (Zhou et al. 2018), Old City (Lecoeuvre et al. 2021), and Carlsberg ridge (Qiu et al. 2021; Liang et al. 2023; Cai et al. 2024) on the SWIR; and Pelagia (Han et al. 2018) on the SEIR. These fields exhibit variable geology, from basaltic to ultramafic hosts, supporting rich mineral formations including massive sulfides, iron-oxyhydroxides, barite, and talc (Perez et al. 2021; van der Most et al. 2023; Thomas et al. 2024; Ta et al. 2024). Microbial studies using isolations, 16S rRNA sequencing, and metagenomics reveal assemblages adapted to vent-specific gradients in fluids, chimneys, and plumes (Li et al. 2016; Huang et al. 2023; Adam-Beyer et al. 2023; Namirimu et al. 2022; Wee et al. 2021; Bai et al. 2021; Han et al. 2018; Ding et al. 2017; La Duc et al. 2007). Thermophiles and chemolithoautotrophs drive sulfur, iron, and methane cycling (Zhong et al. 2022; Cao et al. 2014; Surya Prakash et al. 2025; Wee et al. 2021), while symbiotic communities support endemic fauna such as Rimicaris shrimp and Scaly-foot snails (Bai et al. 2021; Methou et al. 2022). These ecosystems highlight metabolic diversity relevant to potential chemolithotrophic life on icy moons.

Deep-sea trenches develop at convergent margins where one tectonic plate is subducted beneath another, creating the deepest depressions on Earth's seafloor. Hadal trenches (Jamieson et al. 2010; Jamieson 2020), at depths greater than 6,000 meters, offer additional insights into microbial survival under extreme hydrostatic pressure, low temperature, and limited nutrients (Tyler 2003; Jørgensen and Boetius 2007). Redox stratification within trench sediments produces distinct oxic, nitrogenous, and ferruginous zones (Luo et al. 2018; Schauberger et al. 2021), and pressure effects may even induce anaerobic metabolism in otherwise oxic conditions (Yang et al. 2024). Until today, the Mariana Trench remains the most studied hadal site, with work on geomorphology, geochemistry, microbial adaptations, and autonomous sampling technologies revealing that nearly 89% of recovered microbial taxa remain unclassified (Dietrich et al. 1978; Kato et al. 1998; Tarn et al. 2016; Nunoura et al. 2018; Liu et al. 2019; Li et al. 2021; Xiao et al. 2025).. Other key trenches include the Japan, Izu–Ogasawara (Hiraoka et al. 2020; Arakawa et al. 2005), and Kermadec systems (Zhang et al. 2024). Recent discoveries in the Kuril–Kamchatka and Aleutian Trenches revealed chemosynthetic communities spanning 2,500 km at depths exceeding 9,000 m (Peng et al. 2025). The Indian Ocean hosts the Java Trench, that reaches hadal depths and has remained largely unsampled for decades (Jamieson 2020). A 2019 expedition using a full-depth submersible revealed diverse habitats and microbial-associated features, including putative chemolithoautotrophic bacterial mats, underscoring the urgent need for targeted exploration of this trench to understand extreme microbial ecosystems better (Jamieson et al. 2022).

To maximize the astrobiological relevance of deep-sea research, Earth-based studies must be explicitly linked with models of extraterrestrial hydrothermal environments. Laboratory pressure reactors simulating icy moon conditions allow controlled investigations of microbial survival, metabolism, and biosignature production. Observations of plume chemistry and dynamics at Earth's vents may also refine strategies for remote sensing of plumes on icy moons. Expanded exploration of Indian Ocean environments with autonomous submersibles and robotic platforms will not only deepen understanding of microbial survival strategies and biogeochemical processes but also provide critical test beds for technologies being developed for space missions (Feng et al., 2022; O'Neill, 2021; Liang et al., 2021).

Extreme Environments as Planetary Analogues for Habitability

Life, as currently understood, requires fundamental physicochemical conditions that support processes such as metabolism, growth, and reproduction (Falkowski et al. 2008). These requirements are largely derived from Earth, where microbial life represents the earliest and most adaptable form of biology (Nealson and Conrad 1999). Although extraterrestrial life may differ in its chemistry, it is still expected to follow universal principles (Benner 2010; Cockell et al. 2016; Hoehler 2007a; McKay 2022; Méndez et al. 2021). The most critical requirement is the presence of a solvent. On Earth, the unique properties of water, including polarity, heat capacity, and its ability to dissolve diverse compounds, make it indispensable for sustaining life. Therefore, planetary bodies and exoplanets that host liquid water, even transiently, are considered prime targets for exoplanet research (Kite and Ford 2018; Goldblatt 2015). Another essential requirement is the availability of key elements such as carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur (CHNOPS), which form the backbone of biomolecules (Rossetto and Mansy 2022). Microorganisms derive energy and assimilate essential elements for growth and reproduction from their geochemical environment through redox-active compounds that exist in chemical disequilibrium (Hoehler 2007b). This concept holds particular significance in astrobiology, as it implies that planets or moons exhibiting active water–rock interactions may provide the chemical energy necessary to sustain life in environments devoid of sunlight.

Earth's extreme environments illustrate these possibilities. Microorganisms in deserts, deep crustal rocks, hypersaline lakes, and hydrothermal systems (Figure 3) exploit chemical energy from compounds such as iron, sulfur, or hydrogen. Their ability to persist under conditions of high radiation, desiccation, or pressure demonstrates the plausibility of life in dark subsurface habitats on early Earth, Mars, Icy worlds (Europa, or Enceladus) (Figure 4). These adaptations expand our understanding of habitability and provide models for biosignature preservation in energy-limited settings. Beyond informing the search for life, microbial strategies are increasingly relevant to space exploration itself. Insights from analogue studies guide planetary protection policies and inform the design of life-detection instruments. They also highlight how biology might contribute to sustaining long-duration missions. Microorganisms capable of extracting metals from regolith, producing oxygen, or recycling resources could support in-situ resource utilization (ISRU) on the Moon, Mars, and beyond (Santomartino et al. 2023; Koehle et al. 2023; Cockell et al. 2024). Testing these processes under planetary analogue conditions on Earth enables the development of sustainable and adaptable bioengineering strategies for off-world survival. Integrating such biology–geology systems into exploration frameworks is therefore critical for both advancing astrobiology and meeting the practical challenges of human spaceflight.

Scientific Gaps from the Indian Astrobiology Perspective

From an astrobiological standpoint, extreme environments across the Indian subcontinent and the Indian Ocean remain underexplored despite their relevance as planetary analogues (Figure 2). Microbial life has been reported from glaciers, geothermal springs, alkaline lakes, hydrothermal vents, permafrost zones, and impact structures such as Lonar crater, yet systematic insights into their ecological roles and astrobiological significance are still limited. In many of these habitats, the physiology and metabolic strategies of extremophiles capable of withstanding high pressure, temperature, salinity, or acidity remain poorly characterized. Subsurface environments, including permafrost layers, subglacial sediments, and deep-sea trenches, are particularly neglected, even though they closely resemble shielded niches that could exist on Mars, Europa, or other planetary bodies.

Key research gaps arise from methodological limitations. Most studies rely on isolated sampling campaigns and culture-based approaches, offering only a partial view of microbial diversity. The limited use of advanced molecular techniques such as metagenomics, metatranscriptomics, and metabolomics restricts our understanding of functional capabilities and ecological dynamics (Clark et al., 2023; Jansson and Baker, 2016; Krassowski et al., 2020). Without long-term monitoring, the response of microbial communities to seasonal or episodic environmental fluctuations also remains unresolved (Nguyen et al. 2021; Gunnigle et al. 2017; Whitaker and Banfield 2005). Another critical gap lies in the study of biosignature preservation. While pigments, lipids, isotopic signals, and biominerals provide promising targets, little is known about how these markers persist under the unique geochemical and physical conditions of Indian extreme environments (Barge et al. 2022; Campbell et al. 2015; Hays et al. 2017; Moore et al. 2022; Summons et al. 2011). Addressing these gaps is essential for developing effective life-detection strategies for future planetary missions.

Preservation of these geological sites is equally critical. Many analogue sites, in and around Indian subcontinent and the Indian ocean, are increasingly threatened by unregulated geotourism, microbial contamination, and anthropogenic alteration of fragile mineralogical and geochemical gradients (Dowling 2010; Santos and Brilha 2023). Extreme environments, as sensitive indicators of environmental change, respond rapidly to shifts in temperature, precipitation, and chemical fluxes. Protecting their integrity is therefore essential not only for advancing astrobiology but also for sustaining long-term ecological and climate monitoring. Linking planetary exploration with Earth's analogue sites underscores a dual responsibility: advancing scientific discovery while safeguarding irreplaceable natural heritage from irreversible human impact.

Realizing the full potential of these environments requires coordinated interdisciplinary research that integrates geomicrobiology, geochemistry, planetary science, and remote sensing. Establishing long-term observatories, deploying in situ analytical tools, and fostering regional and international collaborations will be vital for building a robust framework for analogue research. Beyond their astrobiological value, these sites serve as natural laboratories for studying early Earth conditions and biogeochemical cycling of carbon, sulfur, and methane under natural constraints, thereby informing both planetary exploration and climate science.

Challenges in Studying Analog Sites hosted in the Indian subcontinent

Astrobiologically motivated geomicrobiological research in planetary analogue sites faces several challenges that affect both sampling and data interpretation. Foremost are accessibility and logistical constraints. High-altitude regions such as Ladakh and remote geothermal zones in the Himalayas often require specialized transport, acclimatization, and multiple administrative permissions. These limitations reduce the frequency and duration of field campaigns, restricting the resolution of temporal and spatial microbial assessments. Environmental heterogeneity and seasonal variability further complicate the identification of representative sampling windows. A hybrid strategy that combines targeted seasonal expeditions with autonomous in situ monitoring could help overcome these limitations. Portable analytical tools, remote sensing platforms, and sentinel sensor networks can extend temporal coverage, while standardized low-impact sampling protocols preserve site integrity and ensure reproducibility. Long-term collaborations with local institutions and authorities are also essential to streamline permitting and enable sustained access.

Addressing these concerns requires strict contamination control, including not only sterile or UV-sterilized tools but also comprehensive use of field blanks and negative controls. Establishing restricted-access research zones can further reduce human disturbance, while multi-seasonal monitoring of physicochemical parameters (pH, salinity, redox, mineral composition) coupled with high-resolution molecular profiling (e.g., shotgun metagenomics, amplicon sequencing) will help establish reliable baselines. Incorporating computational decontamination pipelines (Murray et al.

2015; Schmieder and Edwards 2011; Lu and Salzberg 2018) can then separate indigenous microbial signals from transient contaminants. Closely related to this challenge is the lack of standardized procedures for aseptic sampling, in situ preservation, and metadata reporting, which limits reproducibility and cross-site comparisons. Developing unified protocols aligned with international standards such as MIxS (Field et al. 2011) and Darwin Core (Wieczorek et al. 2012) is therefore critical. This can be achieved through interdisciplinary workshops that bring together planetary scientists, geomicrobiologists, and geochemists to co-design context-specific methods, followed by pilot testing across diverse analogue sites. Publishing the resulting framework as an open-access, modular protocol, with training modules and field-ready checklists, would promote consistency, enhance data comparability, and support long-term multi-site analysis.

Finally, the establishment of dedicated infrastructure near key analogue sites, such as field stations, environmental monitoring platforms, and sample repositories, would strengthen the research ecosystem. Policy support is needed to designate protected analogue research zones, ensuring both long-term access and preservation of site integrity. Together, these measures would allow planetary analogue environments to be studied with the rigor required for astrobiological relevance, positioning them as critical contributors to global efforts in understanding habitability, biosignature preservation, and planetary exploration.

Future perspectives

The Indian subcontinent and its adjoining oceans host an exceptional diversity of extreme environments, ranging from high-altitude cold deserts and geothermal springs in the Himalayas to hypersaline lagoons, deep caves, submarine hydrothermal systems, and cold seeps along the Indian Ocean ridges. These settings serve as valuable planetary analogues, offering insights into habitability and biosignature preservation beyond Earth. To harness this potential, the Indian Space Research Organisation (ISRO), alongside global space agencies, should prioritize the systematic identification and designation of analogue sites across the region.

A key step forward would be the establishment of dedicated planetary analogue observatories at strategically selected field sites. These observatories could combine in situ measurements, autonomous sensors, and remote sensing data to generate multi-scale datasets that capture both short-term variability and long-term climatic and geological trends. Emerging technologies, including portable genomic sequencers, autonomous loggers, underwater drones, and satellite-linked sensor networks, can help overcome logistical constraints and expand monitoring capacity. Integrating

ISRO's Earth observation capabilities with international datasets would further enable high-resolution mapping of extreme habitats and microbial community dynamics. Fostering interdisciplinary investigations that connect microbiologists, planetary scientists, oceanographers, and geochemists will help cultivate the expertise necessary for research across varied environments. Moreover, collaborative frameworks among universities, research institutes, government agencies, and space organizations will streamline fieldsite access, share infrastructure, and coordinate long-term field campaigns. Embedding these efforts within open-access data-sharing platforms will amplify the international visibility of Indian research while promoting responsible stewardship of fragile terrestrial and marine analogue sites.

In the long term, the Indian subcontinent and Indian Ocean would emerge as a global hub for planetary analogue science, directly supporting exploration of the Moon, Mars, and icy worlds. These environments provide natural laboratories for testing life-detection technologies, validating sample handling protocols, and refining hypotheses about life's adaptability under extreme conditions. By aligning national priorities with international astrobiology roadmaps and coupling exploration with conservation, India will be well-positioned to make a distinctive contribution to the search for life beyond Earth while safeguarding its own unique analogue environments.

Author Contributions

Conceptualization: Y.J.; Methodology: Y.J. and S.D.; Validation: Y.J. and S.D.; Formal analysis: Y.J. and S.D.; Resources: Y.J.; Data curation: Y.J. and S.D.; Writing (original draft, review, and editing): Y.J.; Visualization: S.D.; Supervision: Y.J.

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Figures

Figure 1: Planetary analog environments across the Indian subcontinent and the Indian ocean basins that represent planetary bodies of astrobiological interest.

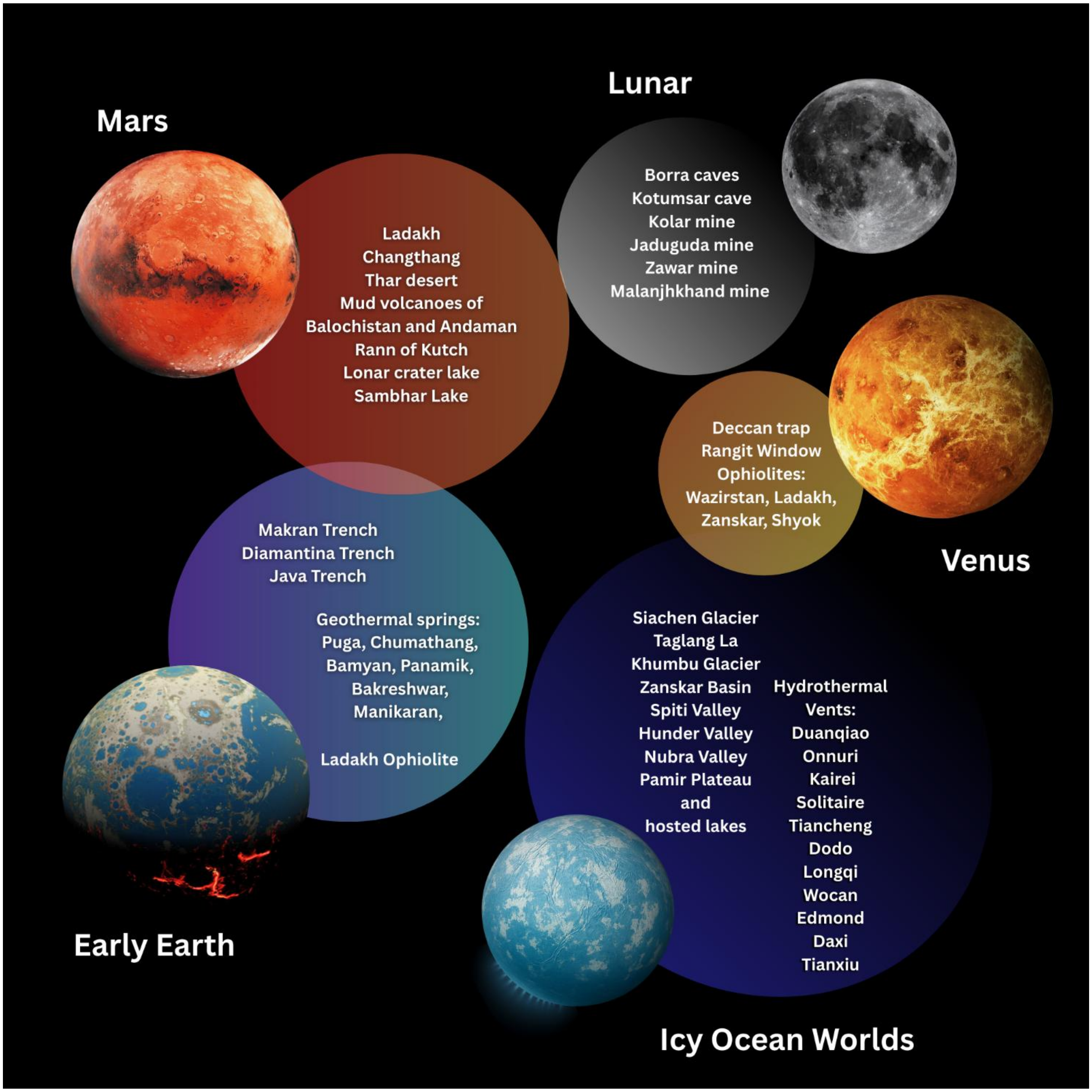


Figure 2. Schematic representation of extreme environments across the Indian subcontinent and the Indian Ocean that serve as planetary analogues. Terrestrial ecosystems include mud volcanoes, saline habitats, desert sandstorms, glaciers, ophiolites, geothermal springs, high-altitude lakes, and natural caves and mines. Marine ecosystems of the Indian Ocean remain relatively underexplored, with documented sites including deep-sea hydrothermal vents and subsurface trenches. This figure is adapted and inspired by Merino et al. (2019).

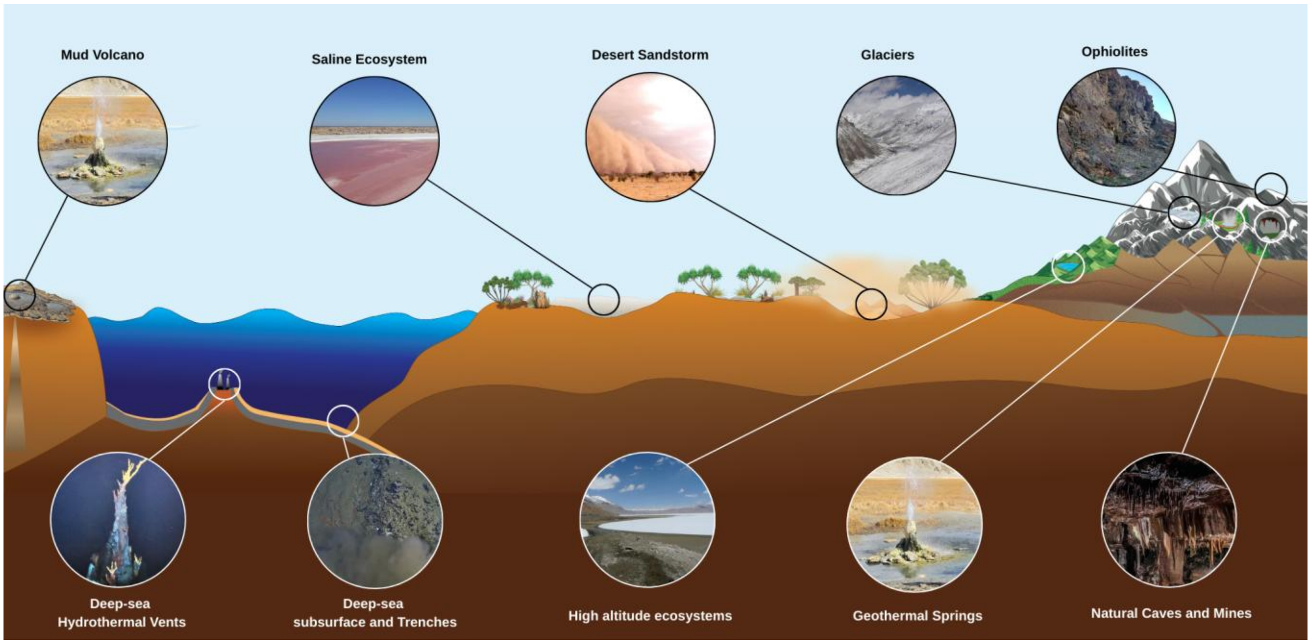


Figure 3: Geographic distribution of extreme environments, that can serve as planetary analogues, overlaid on a hypsometric map of the Indian subcontinent and adjoining Indian Ocean. The left panel illustrates the regional distribution of terrestrial and marine sites across diverse ecosystems, while the right panel provides a detailed view of the Himalaya and Tibetan Plateau, highlighting clusters of high-altitude and glacial environments. The underlying topography and bathymetry emphasize the environmental gradients that shape the diversity of analogue sites. Geological base map compiled from GEBCO Compilation Group (2025).

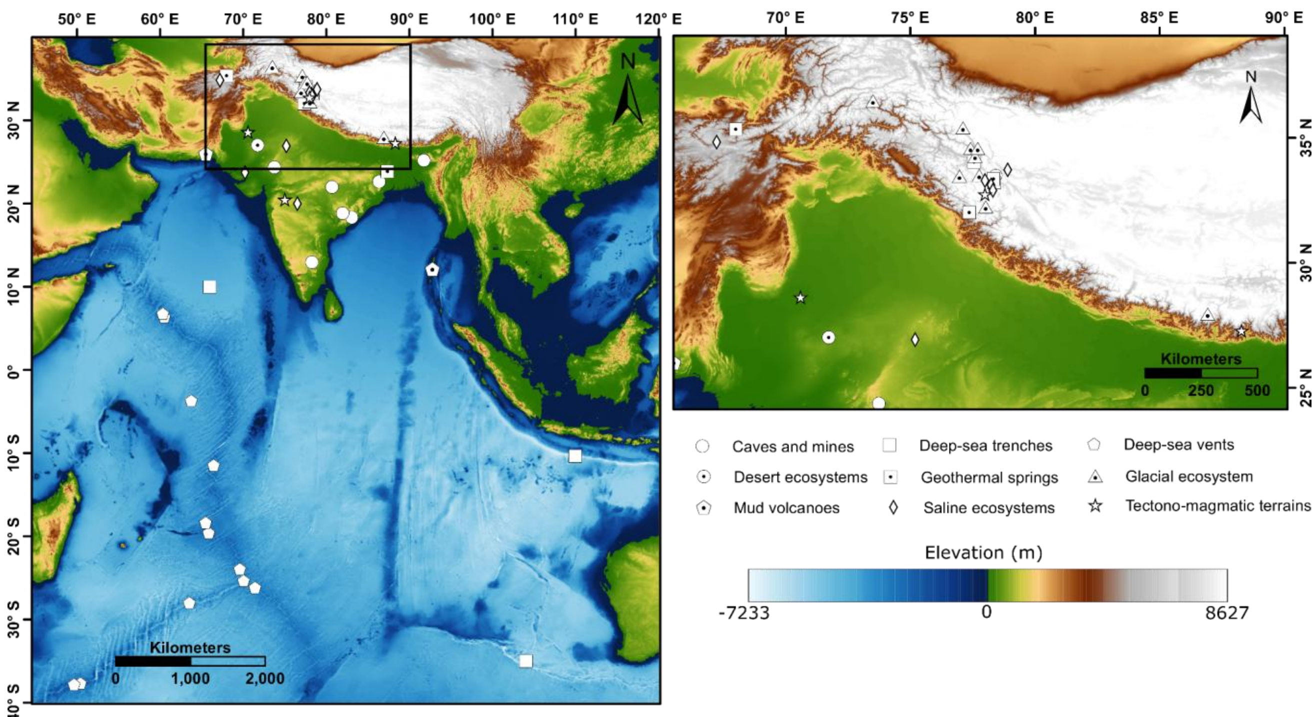
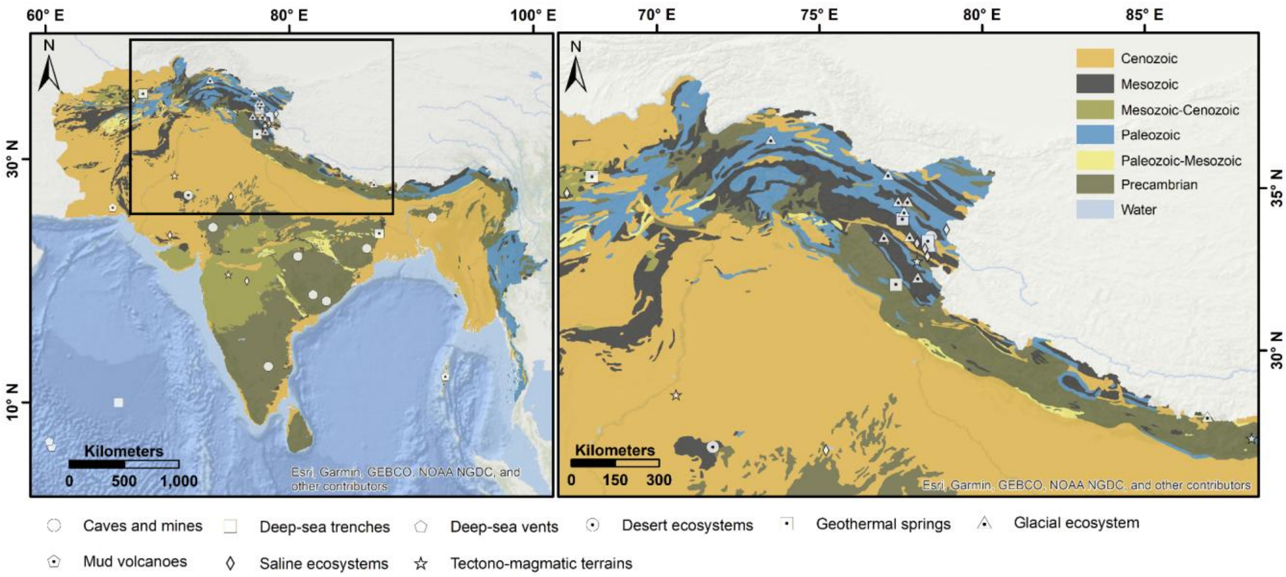


Figure 4: Geographic distribution of extreme environments, that can serve as planetary analogues, overlaid on a generalized geological map of the bed rock of the Indian subcontinent. The underlying geological framework (Cenozoic, Mesozoic, Paleozoic, and Precambrian units) highlights the lithological diversity associated with these analogue sites. Geological base map compiled from Wandrey, C.J., 1998, *Geologic map of South Asia (geo8ag)*.



References

Achyuthan, Hema, and Chris Eastoe. 1999. "Mineralogy and Isotopic Composition of Pyrites-Bearing Ejects from a Mud Volcano, Baratang, Andaman Islands." *Journal of the Geological Society of India* 53 (3): 329–34. https://doi.org/10.17491/jgsi/1999/530305.

Adam-Beyer, Nicole, Katja Laufer-Meiser, Sebastian Fuchs, et al. 2023. "Microbial Ecosystem Assessment and Hydrogen Oxidation Potential of Newly Discovered Vent Systems from the Central and South-East Indian Ridge." *Frontiers in Microbiology* 14 (October). https://doi.org/10.3389/fmicb.2023.1173613.

Aguzzi, Jacopo, Javier Cuadros, Lewis Dartnell, et al. 2024. "Marine Science Can Contribute to the Search for Extra-Terrestrial Life." *Life* 14 (6): 6. https://doi.org/10.3390/life14060676.

Ali, Ahmad, Phuntsog Dolma, Tatiana A. Vishnivetskaya, Tsewang Namgail, Tundup Dolma, and Archana Chauhan. 2025. "Exploring Prokaryotic Diversity in Permafrost-Affected Soils of Ladakh's Changthang Region and Its Geochemical Drivers." *Scientific Reports* 15 (1): 15388. https://doi.org/10.1038/s41598-025-94542-9.

Amador, Elena S., Joshua L. Bandfield, William J. Brazelton, and Deborah Kelley. 2017. "The Lost City Hydrothermal Field: A Spectroscopic and Astrobiological Analogue for Nili Fossae, Mars." *Astrobiology* 17 (11): 1138–60. https://doi.org/10.1089/ast.2016.1606.

Amaresan, N., Krishna Kumar, G. Venkadesaperumal, and N. Ch. Srivathsa. 2018. "Microbial Community Level Physiological Profiles of Active Mud Volcano Soils in Andaman and Nicobar Islands." *National Academy Science Letters* 41 (3): 161–64. https://doi.org/10.1007/s40009-018-0632-3.

Amato, Pierre, Frederic Mathonat, Leslie Nuñez Lopez, et al. 2023. "The Aeromicrobiome: The Selective and Dynamic Outer-Layer of the Earth's Microbiome." *Frontiers in Microbiology* 14 (May). https://doi.org/10.3389/fmicb.2023.1186847.

Amils, Ricardo, David Fernández-Remolar, and The IPBSL Team. 2014. "Río Tinto: A Geochemical and Mineralogical Terrestrial Analogue of Mars." *Life* 4 (3): 511–34. https://doi.org/10.3390/life4030511.

Amils, Ricardo, Elena González-Toril, David Fernández-Remolar, et al. 2007. "Extreme Environments as Mars Terrestrial Analogs: The Rio Tinto Case." *Planetary and Space Science*, Planet Mars II, vol. 55 (3): 370–81. https://doi.org/10.1016/j.pss.2006.02.006.

Anesio, Alexandre M., Stefanie Lutz, Nathan A. M. Chrismas, and Liane G. Benning. 2017. "The Microbiome of Glaciers and Ice Sheets." *Npj Biofilms and Microbiomes* 3 (1): 10. https://doi.org/10.1038/s41522-017-0019-0.

Ankush, P. Dewangan, and G. Sriram. 2024. "Methane Gas Flares in the Forearc Basin of the Andaman-Nicobar Subduction Zone." *Frontiers in Earth Science* 12 (April). https://doi.org/10.3389/feart.2024.1334942.

Ansari, Arif H., Veeru Kant Singh, Pankaj Kumar, et al. 2023. "Hydrogeochemistry, Geothermometry, and Sourcing of High Dissolved Boron, Tungsten, and Chlorine

Concentrations in the Trans-Himalayan Hotsprings of Ladakh, India." *Hydrology* 10 (6): 118. https://doi.org/10.3390/hydrology10060118.

Ansari, Arif Husain, Arunaditya Das, Nasreen Ghazi Ansari, and Archana Sonker. 2025. "Tracing Early Life on Mars: Lessons from Organics Produced in High-Altitude Hotsprings of Ladakh." *Progress in Earth and Planetary Science* 12 (1): 49. https://doi.org/10.1186/s40645-025-00699-2.

Anu, Kumari, Shalini Kumari, Geetanjli Choudhary, and Sarita Devi. 2024. "Microbial Diversity Analysis of Chumathang Geothermal Spring, Ladakh, India." *Brazilian Journal of Microbiology* 55 (2): 1545–55. https://doi.org/10.1007/s42770-024-01284-3.

Arakawa, S, M Mori, L Li, et al. 2005. "Cold-Seep Microbial Communities Are More Abundant at Deeper Depths in the Japan Trench Land Slope." *Journal of Japanese Society for Extremophiles* 4 (2): 50–55. https://doi.org/10.3118/jjse.4.50.

Armstrong, Richard L. 2010. *The Glaciers of the Hindu Kush-Himalayan Region: A Summary of the Science Regarding Glacier Melt/Retreat in the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan Mountain Ranges*. Technical. International Centre for Integrated Mountain Development (ICIMOD). CIRES/NSIDC, University of Colorado,. https://lib.icimod.org/records/nk11c-esz23.

Azua-Bustos, Armando, Carlos González-Silva, and Alberto G. Fairén. 2022. "The Atacama Desert in Northern Chile as an Analog Model of Mars." *Frontiers in Astronomy and Space Sciences* 8 (January). https://doi.org/10.3389/fspas.2021.810426.

Badalamenti, Jonathan P., Zarath M. Summers, Chi Ho Chan, Jeffrey A. Gralnick, and Daniel R. Bond. 2016. "Isolation and Genomic Characterization of 'Desulfuromonas Soudanensis WTL', a Metal- and Electrode-Respiring Bacterium from Anoxic Deep Subsurface Brine." *Frontiers in Microbiology* 7 (June). https://doi.org/10.3389/fmicb.2016.00913.

Bai, Shijie, Hengchao Xu, and Xiaotong Peng. 2021. "Microbial Communities of the Hydrothermal Scaly-Foot Snails From Kairei and Longqi Vent Fields." *Frontiers in Marine Science* 8 (October). https://doi.org/10.3389/fmars.2021.764000.

Barberán, Albert, Joshua Ladau, Jonathan W. Leff, et al. 2015. "Continental-Scale Distributions of Dust-Associated Bacteria and Fungi." *Proceedings of the National Academy of Sciences* 112 (18): 5756–61. https://doi.org/10.1073/pnas.1420815112.

Barge, Laura M., and Laura E. Rodriguez. 2021. "Life on Enceladus? It Depends on Its Origin." *Nature Astronomy* 5 (8): 740–41. https://doi.org/10.1038/s41550-021-01382-4.

Barge, Laura M., Laura E. Rodriguez, Jessica M. Weber, and Bethany P. Theiling. 2022. "Determining the 'Biosignature Threshold' for Life Detection on Biotic, Abiotic, or Prebiotic Worlds." *Astrobiology* 22 (4): 481–93. https://doi.org/10.1089/ast.2021.0079.

Barge, Laura M., and Lauren M. White. 2017. "Experimentally Testing Hydrothermal Vent Origin of Life on Enceladus and Other Icy/Ocean Worlds." *Astrobiology* 17 (9): 820–33. https://doi.org/10.1089/ast.2016.1633.

Baskar, Sushmitha, R. Baskar, Natuschka Lee, and P. K. Theophilus. 2009. “Speleothems from Mawsmai and Krem Phyllut Caves, Meghalaya, India: Some Evidences on Biogenic Activities.” *Environmental Geology* 57 (5): 1169–86. https://doi.org/10.1007/s00254-008-1413-y.

Baskar, Sushmitha, and Ramanathan Baskar. 2022. “Studies on Geomicrobiology in Some Indian Caves.” *Journal of the Geological Society of India* 98 (10): 1380–84. https://doi.org/10.1007/s12594-022-2185-9.

Baskar, Sushmitha, Ramanathan Baskar, Vinod Chandra Tewari, et al. 2011. “Cave Geomicrobiology in India: Status and Prospects.” In *STROMATOLITES: Interaction of Microbes with Sediments*, edited by Vinod Tewari and Joseph Seckbach. Cellular Origin, Life in Extreme Habitats and Astrobiology. Springer Netherlands. https://doi.org/10.1007/978-94-007-0397-1_24.

Beane, J. E., C. A. Turner, P. R. Hooper, K. V. Subbarao, and J. N. Walsh. 1986. “Stratigraphy, Composition and Form of the Deccan Basalts, Western Ghats, India.” *Bulletin of Volcanology* 48 (1): 61–83. https://doi.org/10.1007/BF01073513.

Benner, Steven A. 2010. “Defining Life.” *Astrobiology* 10 (10): 1021–30. https://doi.org/10.1089/ast.2010.0524.

Berger, Jeff A., Mariek E. Schmidt, Ralf Gellert, et al. 2016. “A Global Mars Dust Composition Refined by the Alpha-Particle X-Ray Spectrometer in Gale Crater.” *Geophysical Research Letters* 43 (1): 67–75. https://doi.org/10.1002/2015GL066675.

Bergsten, Pauline, Pauline Vannier, Alexandra María Klonowski, et al. 2021. “Basalt-Hosted Microbial Communities in the Subsurface of the Young Volcanic Island of Surtsey, Iceland.” *Frontiers in Microbiology* 12 (September). https://doi.org/10.3389/fmicb.2021.728977.

Beukes, Nicolas J., Joydip Mukhopadhyay, and Jens Gutzmer. 2008. “Genesis of High-Grade Iron Ores of the Archean Iron Ore Group around Noamundi, India.” *Economic Geology* 103 (2): 365–86. https://doi.org/10.2113/gsecongeo.103.2.365.

Bhat, Irfan Maqbool, Hiredya Chauhan, Reyaz Ahmad Dar, and Talat Ahmad. 2022. “Ladakh Himalayan Ophiolites (LHO): A Geological Heritage of Northwestern India.” *Geoheritage* 15 (1): 2. https://doi.org/10.1007/s12371-022-00764-y.

Bhattacharya, Satadru, Souvik Mitra, Saibal Gupta, et al. 2016. “Jarosite Occurrence in the Deccan Volcanic Province of Kachchh, Western India: Spectroscopic Studies on a Martian Analog Locality.” *Journal of Geophysical Research: Planets* 121 (3): 402–31. https://doi.org/10.1002/2015JE004949.

Bishop, Janice L., Alberto G. Fairén, Joseph R. Michalski, et al. 2018. “Surface Clay Formation during Short-Term Warmer and Wetter Conditions on a Largely Cold Ancient Mars.” *Nature Astronomy* 2 (3): 206–13. https://doi.org/10.1038/s41550-017-0377-9.

Biswas, Sanjib K., Kotha Mahender, and Gaurav D. Chauhan. 2022. *Field Guide Book of Geology of Kutch (Kachchh) Basin, Gujarat, India*. Springer Geology. Springer International Publishing. https://doi.org/10.1007/978-3-030-87470-4.

Blank, J. 2018. "Planetary Caves as Astrobiology Targets." 2018 (December): P21H-3428. https://ui.adsabs.harvard.edu/abs/2018AGUFM.P21H3428B.

Bolch, T., A. Kulkarni, A. Kääb, et al. 2012. "The State and Fate of Himalayan Glaciers." *Science* 336 (6079): 310–14. https://doi.org/10.1126/science.1215828.

Boros, Emil, and Marina Kolpakova. 2018. "A Review of the Defining Chemical Properties of Soda Lakes and Pans: An Assessment on a Large Geographic Scale of Eurasian Inland Saline Surface Waters." *PLOS ONE* 13 (8): e0202205. https://doi.org/10.1371/journal.pone.0202205.

Boston, P.J., M.N. Spilde, D.E. Northup, et al. 2001. "Cave Biosignature Suites: Microbes, Minerals, and Mars." *Astrobiology* 1 (1): 25–55. https://doi.org/10.1089/153110701750137413.

Bourquin, Massimo, Susheel Bhanu Busi, Stilianos Fodelianakis, et al. 2022. "The Microbiome of Cryospheric Ecosystems." *Nature Communications* 13 (1): 3087. https://doi.org/10.1038/s41467-022-30816-4.

Boutle, Ian A., Manoj Joshi, F. Hugo Lambert, et al. 2020. "Mineral Dust Increases the Habitability of Terrestrial Planets but Confounds Biomarker Detection." *Nature Communications* 11 (1): 2731. https://doi.org/10.1038/s41467-020-16543-8.

Brenning, Alexander, and Dario Trombotto. 2006. "Logistic Regression Modeling of Rock Glacier and Glacier Distribution: Topographic and Climatic Controls in the Semi-Arid Andes." *Geomorphology* 81 (1): 141–54. https://doi.org/10.1016/j.geomorph.2006.04.003.

Brocks, J. J., and R. E. Summons. 2003. "8.03 - Sedimentary Hydrocarbons, Biomarkers for Early Life." In *Treatise on Geochemistry*, edited by Heinrich D. Holland and Karl K. Turekian. Pergamon. https://doi.org/10.1016/B0-08-043751-6/08127-5.

Brown, D. Ann, D. Choudari Kamineni, Jerzy A. Sawicki, and Terry J. Beveridge. 1994. "Minerals Associated with Biofilms Occurring on Exposed Rock in a Granitic Underground Research Laboratory." *Applied and Environmental Microbiology* 60 (9): 3182–91. https://doi.org/10.1128/aem.60.9.3182-3191.1994.

Cai, Yiyang, Xiqiu Han, Sven Petersen, Yejian Wang, Zhongyan Qiu, and Ming Yang. 2024. "Mineralization of Sulfide Mound at Wocan-1 Hydrothermal Field Based on Geological Mapping, Mineralogy and Sulfur Isotope Studies, Carlsberg Ridge, Northwest Indian Ocean." *Ore Geology Reviews* 171 (August): 106180. https://doi.org/10.1016/j.oregeorev.2024.106180.

Campbell, Kathleen A., Bridget Y. Lynne, Kim M. Handley, et al. 2015. "Tracing Biosignature Preservation of Geothermally Silicified Microbial Textures into the Geological Record." *Astrobiology* 15 (10): 858–82. https://doi.org/10.1089/ast.2015.1307.

Canfield, Don E, Minik T Rosing, and Christian Bjerrum. 2006. "Early Anaerobic Metabolisms." *Philosophical Transactions of the Royal Society B: Biological Sciences* 361 (1474): 1819–36. https://doi.org/10.1098/rstb.2006.1906.

Cao, Huiluo, Yong Wang, On On Lee, Xiang Zeng, Zongze Shao, and Pei-Yuan Qian. 2014. "Microbial Sulfur Cycle in Two Hydrothermal Chimneys on the Southwest Indian Ridge." *mBio* 5 (1): 10.1128/mbio.00980-13. https://doi.org/10.1128/mbio.00980-13.

Cardenas, Benjamin T., Michael P. Lamb, and John P. Grotzinger. 2022. “Martian Landscapes of Fluvial Ridges Carved from Ancient Sedimentary Basin Fill.” *Nature Geoscience* 15 (11): 871–77. https://doi.org/10.1038/s41561-022-01058-2.

Cassaro, Alessia, Claudia Pacelli, Lorenzo Aureli, Ilaria Catanzaro, Patrick Leo, and Silvano Onofri. 2021. “Antarctica as a Reservoir of Planetary Analogue Environments.” *Extremophiles* 25 (5): 437–58. https://doi.org/10.1007/s00792-021-01245-w.

Cavalazzi, B., R. Barbieri, F. Gómez, et al. 2019. “The Dallol Geothermal Area, Northern Afar (Ethiopia)—An Exceptional Planetary Field Analog on Earth.” *Astrobiology* 19 (4): 553–78. https://doi.org/10.1089/ast.2018.1926.

Cavicchioli, Ricardo. 2016. “On the Concept of a Psychrophile.” *The ISME Journal* 10 (4): 793–95. https://doi.org/10.1038/ismej.2015.160.

Chakraborty, Partha Pratim, Rahul Bailwal, Pritam P. Paul, and Aditi Sharma. 2022. “Alluvial Sedimentary Records in Indian Precambrian Basins: Implications Toward Unique Precambrian Sedimentary Environment?” *Frontiers in Earth Science* 10 (July). https://doi.org/10.3389/feart.2022.892717.

Chakraborty, Partha Pratim, Sampat K. Tandon, and Subhojit Saha. 2019. “Development of Phanerozoic Sedimentary Basins of India.” *Journal of Asian Earth Sciences* 184 (October): 103991. https://doi.org/10.1016/j.jseaes.2019.103991.

Chandra, Rakesh, Nazia Kowser, Michael E. Brookfield, Manavalan Satyanarayanan, and Daniel Stöckli. 2023. “Nature of the Shyok (Northern) Suture Zone between India and Asia: Petrology, Geochemistry and Origin of the Tirit Granitoids and Associated Dykes (Nubra Valley Ladakh Himalaya, NW India).” *Geological Magazine* 160 (5): 1020–39. https://doi.org/10.1017/S0016756823000134.

Chaudhuri, Hirok, Debasis Ghose, Rakesh K. Bhandari, Prasanta Sen, and Bikash Sinha. 2012. “A Geochemical Approach to Earthquake Reconnaissance at the Baratang Mud Volcano, Andaman and Nicobar Islands.” *Journal of Asian Earth Sciences* 46 (March): 52–60. https://doi.org/10.1016/j.jseaes.2011.10.007.

Chaudhuri, Trisrota, Yusheng Wan, Rajat Mazumder, Mingzhu Ma, and Dunyi Liu. 2018. “Evidence of Enriched, Hadean Mantle Reservoir from 4.2-4.0 Ga Zircon Xenocrysts from Paleoarchean TTGs of the Singhbhum Craton, Eastern India.” *Scientific Reports* 8 (1): 7069. https://doi.org/10.1038/s41598-018-25494-6.

Chavan, Anil, Vivek Bhore, and Subhash Bhandari. 2022. “Terrestrial Martian Analogues from the Indian Subcontinent: Implications for Hydrological Activity on Mars.” *Icarus* 385 (October): 115118. https://doi.org/10.1016/j.icarus.2022.115118.

Chen, Guoxiong, Qiuming Cheng, Timothy W. Lyons, et al. 2022. “Reconstructing Earth’s Atmospheric Oxygenation History Using Machine Learning.” *Nature Communications* 13 (1): 5862. https://doi.org/10.1038/s41467-022-33388-5.

Chen, Yin, Liqin Wu, Rich Boden, et al. 2009. "Life without Light: Microbial Diversity and Evidence of Sulfur- and Ammonium-Based Chemolithotrophy in Movile Cave." *The ISME Journal* 3 (9): 1093–104. https://doi.org/10.1038/ismej.2009.57.

Chen, Yuanqing, Sinan Xu, Weining Liu, et al. 2024. "Assessing Biogeochemical Controls on Porewater Dissolved Inorganic Carbon Cycling in the Gas Hydrate-Bearing Sediments of the Makran Accretionary Wedge, Northeastern Arabian Sea off Pakistan." *Frontiers in Marine Science* 10 (January). https://doi.org/10.3389/fmars.2023.1181921.

Choudhary, Geetanjli, Shalini Kumari, Kumari Anu, and Sarita Devi. 2024. "Deciphering the Microbial Communities of Alkaline Hot Spring in Panamik, Ladakh, India Using a High-Throughput Sequencing Approach." *Brazilian Journal of Microbiology* 55 (2): 1465–76. https://doi.org/10.1007/s42770-024-01346-6.

Chyba, Christopher F., and Kevin P. Hand. 2005. "Astrobiology: The Study of the Living Universe." *Annual Review of Astronomy and Astrophysics* 43 (Volume 43, 2005): 31–74. https://doi.org/10.1146/annurev.astro.43.051804.102202.

Clark, M. S., J. I. Hoffman, L. S. Peck, et al. 2023. "Multi-Omics for Studying and Understanding Polar Life." *Nature Communications* 14 (1): 7451. https://doi.org/10.1038/s41467-023-43209-y.

Cloern, James E., Brian E. Cole, and Ronald S. Oremland. 1983. "Seasonal Changes in the Chemistry and Biology of a Meromictic Lake (Big Soda Lake, Nevada, U.S.A.)." *Hydrobiologia* 105 (1): 195–206. https://doi.org/10.1007/BF00025188.

Cloutis, Edward A., Paul Mann, Matthew R. M. Izawa, et al. 2015. "The Canadian Space Agency Planetary Analogue Materials Suite." *Planetary and Space Science* 119 (December): 155–72. https://doi.org/10.1016/j.pss.2015.09.001.

Cockell, Charles S., John Holt, Jim Campbell, et al. 2019. "Subsurface Scientific Exploration of Extraterrestrial Environments (MINAR 5): Analogue Science, Technology and Education in the Boulby Mine, UK." *International Journal of Astrobiology* 18 (2): 157–82. https://doi.org/10.1017/S1473550418000186.

Cockell, Charles S., Mark Simons, Julie Castillo-Rogez, et al. 2024. "Sustained and Comparative Habitability beyond Earth." *Nature Astronomy* 8 (1): 30–38. https://doi.org/10.1038/s41550-023-02158-8.

Cockell, C.S., T. Bush, C. Bryce, et al. 2016. "Habitability: A Review." *Astrobiology* 16 (1): 89–117. https://doi.org/10.1089/ast.2015.1295.

Cohen, Zachary R, Dian Ding, Lijun Zhou, et al. 2024. "Natural Soda Lakes Provide Compatible Conditions for RNA and Membrane Function That Could Have Enabled the Origin of Life." *PNAS Nexus* 3 (3): pgae084. https://doi.org/10.1093/pnasnexus/pgae084.

Coleine, Claudia, and Manuel Delgado-Baquerizo. 2022. "Unearthing Terrestrial Extreme Microbiomes for Searching Terrestrial-like Life in the Solar System." *Trends in Microbiology* 30 (11): 1101–15. https://doi.org/10.1016/j.tim.2022.04.002.

Coleman, Robert G. 1977. *Ophiolites: Ancient Oceanic Lithosphere?* Edited by P. J. Wyllie, W. Von Engelhardt, and T. Hahn. Vol. 12. Minerals and Rocks. Springer. https://doi.org/10.1007/978-3-642-66673-5.

Craig, Patricia, Vincent Chevrier, M. R. G. Sayyed, and R. Islam. 2017. "Spectral Analysis of Deccan Intrabasaltic Bole Beds: Implications for the Formation and Alteration of Phyllosilicates on Mars." *Planetary and Space Science* 135 (January): 55–63. https://doi.org/10.1016/j.pss.2016.11.008.

Cunningham, K. I., D. E. Northup, R. M. Pollastro, W. G. Wright, and E. J. LaRock. 1995. "Bacteria, Fungi and Biokarst in Lechuguilla Cave, Carlsbad Caverns National Park, New Mexico." *Environmental Geology* 25 (1): 2–8. https://doi.org/10.1007/BF01061824.

Das, Prasenjit, K. Maya, and D. Padmalal. 2022. "Hydrogeochemistry of the Indian Thermal Springs: Current Status." *Earth-Science Reviews* 224 (January): 103890. https://doi.org/10.1016/j.earscirev.2021.103890.

Das, S., A.R. Basu, and B.K. Mukherjee. 2017. "In Situ Peridotitic Diamond in Indus Ophiolite Sourced from Hydrocarbon Fluids in the Mantle Transition Zone." *Geology* 45 (8): 755–58. https://doi.org/10.1130/G39100.1.

De Toffoli, B., A.-C. Plesa, E. Hauber, and D. Breuer. 2021. "Delta Deposits on Mars: A Global Perspective." *Geophysical Research Letters* 48 (17): e2021GL094271. https://doi.org/10.1029/2021GL094271.

Deamer, David W., and Christos D. Georgiou. 2015. "Hydrothermal Conditions and the Origin of Cellular Life." *Astrobiology* 15 (12): 1091–95. https://doi.org/10.1089/ast.2015.1338.

Delisle, G., U. Von Rad, H. Andruleit, C. Von Daniels, A. Tabrez, and A. Inam. 2002. "Active Mud Volcanoes On- and Offshore Eastern Makran, Pakistan." *International Journal of Earth Sciences* 91 (1): 93–110. https://doi.org/10.1007/s005310100203.

Deocampo, Daniel M., and Robin W. Renaut. 2016. "Geochemistry of African Soda Lakes." In *Soda Lakes of East Africa*, edited by Michael Schagerl. Springer International Publishing. https://doi.org/10.1007/978-3-319-28622-8_4.

Des Marais, David J., and Malcolm R. Walter. 2019. "Terrestrial Hot Spring Systems: Introduction." *Astrobiology* 19 (12): 1419–32. https://doi.org/10.1089/ast.2018.1976.

Dey, Alosree, Koushik Sen, and Manish A. Mamtani. 2023. "Lattice Preferred Orientation of Quartz in Granitic Gneisses from Tso Morari Crystalline Complex, Eastern Ladakh, Trans-Himalaya: Evaluating Effect of Dauphiné Twin in Dynamic Recrystallization during Exhumation." *Geological Magazine* 160 (8): 1556–77. https://doi.org/10.1017/S0016756823000560.

Dey, Sukanta, and Jean-François Moyen. 2020a. "Archean Granitoids of India: Windows into Early Earth Tectonics – an Introduction." *Geological Society, London, Special Publications* 489 (1): 1–13. https://doi.org/10.1144/SP489-2020-155.

Dey, Sukanta, and Jean-François Moyen. 2020b. "Archean Granitoids of India: Windows into Early Earth Tectonics – an Introduction." In *Archean Granitoids of India: Windows into Early Earth*

Tectonics, edited by S. Dey and J.-F. Moyen, vol. 489. Geological Society of London. https://doi.org/10.1144/SP489-2020-155.

Dhakar, Kusum, and Anita Pandey. 2020. “Microbial Ecology from the Himalayan Cryosphere Perspective.” *Microorganisms* 8 (2): 2. https://doi.org/10.3390/microorganisms8020257.

Di Achille, Gaetano, and Brian M. Hynek. 2010. “Ancient Ocean on Mars Supported by Global Distribution of Deltas and Valleys.” *Nature Geoscience* 3 (7): 459–63. https://doi.org/10.1038/ngeo891.

Dick, Gregory J. 2019a. “The Microbiomes of Deep-Sea Hydrothermal Vents: Distributed Globally, Shaped Locally.” *Nature Reviews Microbiology* 17 (5): 271–83. https://doi.org/10.1038/s41579-019-0160-2.

Dick, Gregory J. 2019b. “The Microbiomes of Deep-Sea Hydrothermal Vents: Distributed Globally, Shaped Locally.” *Nature Reviews Microbiology* 17 (5): 271–83. https://doi.org/10.1038/s41579-019-0160-2.

Dickinson, William R. 1971. “Plate Tectonics in Geologic History.” *Science* 174 (4005): 107–13. https://doi.org/10.1126/science.174.4005.107.

Dietrich, V., R. Emmermann, R. Oberhänsli, and H. Puchelt. 1978. “Geochemistry of Basaltic and Gabbroic Rocks from the West Mariana Basin and the Mariana Trench.” *Earth and Planetary Science Letters* 39 (1): 127–44. https://doi.org/10.1016/0012-821X(78)90149-8.

Dimitrov, Lyobomir I. 2002. “Mud Volcanoes—the Most Important Pathway for Degassing Deeply Buried Sediments.” *Earth-Science Reviews* 59 (1): 49–76. https://doi.org/10.1016/S0012-8252(02)00069-7.

D’Incecco, P., J. Filiberto, J. B. Garvin, et al. 2024. “The Analogs for VENus’ GEologically Recent Surfaces (AVENGERS) Initiative: Updates and New Target Areas.” Paper presented at 55th Lunar and Planetary Science Conference (LPSC), The Woodlands, TX. March 11. https://ntrs.nasa.gov/citations/20240000304.

Ding, Jian, Yu Zhang, Han Wang, Huahua Jian, Hao Leng, and Xiang Xiao. 2017. “Microbial Community Structure of Deep-Sea Hydrothermal Vents on the Ultraslow Spreading Southwest Indian Ridge.” *Frontiers in Microbiology* 8 (June). https://doi.org/10.3389/fmicb.2017.01012.

Douglas, Susanne, William Abbey, Randall Mielke, Pamela Conrad, and Isik Kanik. 2008. “Textural and Mineralogical Biosignatures in an Unusual Microbialite from Death Valley, California.” *Icarus*, Saturn’s Icy Satellites from Cassini, vol. 193 (2): 620–36. https://doi.org/10.1016/j.icarus.2007.08.019.

Dowling, Ross K. 2010. *Geotourism : The Tourism of Geology and Landscape*. 1–260.

Dutta, Avishek, Srimanti Dutta Gupta, Abhishek Gupta, et al. 2018. “Exploration of Deep Terrestrial Subsurface Microbiome in Late Cretaceous Deccan Traps and Underlying Archean Basement, India.” *Scientific Reports* 8 (1): 17459. https://doi.org/10.1038/s41598-018-35940-0.

Dutta, Avishek, Pinaki Sar, Jayeeta Sarkar, et al. 2019. “Archaeal Communities in Deep Terrestrial Subsurface Underneath the Deccan Traps, India.” *Frontiers in Microbiology* 10 (July). https://doi.org/10.3389/fmicb.2019.01362.

Edwards, Robert A., Beltran Rodriguez-Brito, Linda Wegley, et al. 2006. “Using Pyrosequencing to Shed Light on Deep Mine Microbial Ecology.” *BMC Genomics* 7 (1): 57. https://doi.org/10.1186/1471-2164-7-57.

Ehlmann, Bethany L., and Christopher S. Edwards. 2014. “Mineralogy of the Martian Surface.” *Annual Review of Earth and Planetary Sciences* 42 (Volume 42, 2014): 291–315. https://doi.org/10.1146/annurev-earth-060313-055024.

Ehlmann, Bethany L., John F. Mustard, Caleb I. Fassett, et al. 2008. “Clay Minerals in Delta Deposits and Organic Preservation Potential on Mars.” *Nature Geoscience* 1 (6): 355–58. https://doi.org/10.1038/ngeo207.

Emran, A., J. D. Tarnas, and K. M. Stack. 2025. “Global Distribution of Serpentine on Mars.” *Geophysical Research Letters* 52 (2): e2024GL110630. https://doi.org/10.1029/2024GL110630.

Equeenuddin, Sk. Md., Abhijit Panda, Vishal Singh, Prafulla Kumar Sahoo, Subhashis Sahu, and Sumit Kumar Basantray. 2017. “Geochemical Appraisal of Mine Discharge and Tailing at Malanjkhand Copper Mine, India.” *Journal of the Geological Society of India* 90 (2): 209–16. https://doi.org/10.1007/s12594-017-0701-0.

Fagents, Sarah A., and Thorvaldur Thordarson. 2007. “Rootless Volcanic Cones in Iceland and on Mars.” In *The Geology of Mars: Evidence from Earth-Based Analogs*, edited by Mary Chapman. Cambridge Planetary Science. Cambridge University Press. https://doi.org/10.1017/CBO9780511536014.007.

Falkowski, Paul G., Tom Fenchel, and Edward F. Delong. 2008. “The Microbial Engines That Drive Earth’s Biogeochemical Cycles.” *Science* 320 (5879): 1034–39. https://doi.org/10.1126/science.1153213.

Farr, Tom G. 2004. “Terrestrial Analogs to Mars: The NRC Community Decadal Report.” *Planetary and Space Science*, Exploring Mars Surface and its Earth Analogues, vol. 52 (1): 3–10. https://doi.org/10.1016/j.pss.2003.08.004.

Fatima, Adeela, Usman Aftab, Khaled A. Shaaban, Jon S. Thorson, and Imran Sajid. 2019. “Spore Forming Actinobacterial Diversity of Cholistan Desert Pakistan: Polyphasic Taxonomy, Antimicrobial Potential and Chemical Profiling.” *BMC Microbiology* 19 (1): 49. https://doi.org/10.1186/s12866-019-1414-x.

Feng, Jing-Chun, Jianzhen Liang, Yanpeng Cai, Si Zhang, Jingchuan Xue, and Zhifeng Yang. 2022. “Deep-Sea Organisms Research Oriented by Deep-Sea Technologies Development.” *Science Bulletin* 67 (17): 1802–16. https://doi.org/10.1016/j.scib.2022.07.016.

Field, Dawn, Linda Amaral-Zettler, Guy Cochrane, et al. 2011. “The Genomic Standards Consortium.” *PLOS Biology* 9 (6): e1001088. https://doi.org/10.1371/journal.pbio.1001088.

Fischer, D., H. Sahling, K. Nöthen, G. Bohrmann, M. Zabel, and S. Kasten. 2012. “Interaction between Hydrocarbon Seepage, Chemosynthetic Communities, and Bottom Water Redox at Cold Seeps of the Makran Accretionary Prism: Insights from Habitat-Specific Pore Water Sampling and Modeling.” *Biogeosciences* 9 (6): 2013–31. https://doi.org/10.5194/bg-9-2013-2012.

Fones, Elizabeth M., Daniel R. Colman, Emily A. Kraus, et al. 2019. “Physiological Adaptations to Serpentinization in the Samail Ophiolite, Oman.” *The ISME Journal* 13 (7): 1750–62. https://doi.org/10.1038/s41396-019-0391-2.

Foti, Mirjam J., Dimitry Yu. Sorokin, Elena E. Zacharova, Nicolai V. Pimenov, J. Gijs Kuenen, and Gerard Muyzer. 2008. “Bacterial Diversity and Activity along a Salinity Gradient in Soda Lakes of the Kulunda Steppe (Altai, Russia).” *Extremophiles* 12 (1): 133–45. https://doi.org/10.1007/s00792-007-0117-7.

Foucher, F., K. Hickman-Lewis, A. Hutzler, et al. 2021. “Definition and Use of Functional Analogues in Planetary Exploration.” *Planetary and Space Science* 197 (March): 105162. https://doi.org/10.1016/j.pss.2021.105162.

Fredriksson, K., A. Dube, D. J. Milton, and M. S. Balasundaram. 1973. “Maloof.” *Science* 180 (4088): 862–64. https://doi.org/10.1126/science.180.4088.862.

Froelich, P. N., G. P. Klinkhammer, M. L. Bender, et al. 1979. “Early Oxidation of Organic Matter in Pelagic Sediments of the Eastern Equatorial Atlantic: Suboxic Diagenesis.” *Geochimica et Cosmochimica Acta* 43 (7): 1075–90. https://doi.org/10.1016/0016-7037(79)90095-4.

Gabriel, C. Riquelme, and Diana E. Northup. 2013. “Microbial Ecology: Caves as an Extreme Habitat.” In *Cave Microbiomes: A Novel Resource for Drug Discovery*, edited by Naowarat Cheeptham. Springer. https://doi.org/10.1007/978-1-4614-5206-5_5.

Gaidos, Eric J., Kenneth H. Nealson, and Joseph L. Kirschvink. 1999. “Life in Ice-Covered Oceans.” *Science* 284 (5420): 1631–33. https://doi.org/10.1126/science.284.5420.1631.

Gaina, Carmen, Douwe J. J. van Hinsbergen, and Wim Spakman. 2015. “Tectonic Interactions between India and Arabia since the Jurassic Reconstructed from Marine Geophysics, Ophiolite Geology, and Seismic Tomography.” *Tectonics* 34 (5): 875–906. https://doi.org/10.1002/2014TC003780.

Gaina, Carmen, R. Dietmar Müller, Belinda Brown, Takemi Ishihara, and Sergey Ivanov. 2007. “Breakup and Early Seafloor Spreading between India and Antarctica.” *Geophysical Journal International* 170 (1): 151–69. https://doi.org/10.1111/j.1365-246X.2007.03450.x.

Gainey, Seth R., Elisabeth M. Hausrath, Christopher T. Adcock, et al. 2017. “Clay Mineral Formation under Oxidized Conditions and Implications for Paleoenvironments and Organic Preservation on Mars.” *Nature Communications* 8 (1): 1230. https://doi.org/10.1038/s41467-017-01235-7.

Garcia-Lopez, Eva, and Cristina Cid. 2017. “Glaciers and Ice Sheets As Analog Environments of Potentially Habitable Icy Worlds.” *Frontiers in Microbiology* 8 (July). https://doi.org/10.3389/fmicb.2017.01407.

Garry Singla, Birendra P. Singh, Om. N. Bhargava, Ramanpreet Kaur, and Stanzin Stopden. 2021. "Trilobites of the Middle Wuliuan (Miaolingian) from the Kunzam La (Parahio) Formation of the Sumna River Section, Spiti, Himalaya, and Its Biostratigraphic Significance." *Stratigraphy and Geological Correlation* 29 (1): 8–20. https://doi.org/10.1134/S086959382101007X.

George, Robert Y. 2020. "Extremophilic Life in Our Oceans as Models for Astrobiology." In *Extremophiles as Astrobiological Models*. John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119593096.ch7.

GEBCO Compilation Group (2025) GEBCO 2025 Grid (doi:10.5285/37c52e96-24ea-67ce-e063-7086abc05f29)

German, Christopher R., Donna K. Blackman, Andrew T. Fisher, et al. 2022. "Ocean System Science to Inform the Exploration of Ocean Worlds." *Oceanography* 35 (1): 16–22.

Gihring, T. M., D. P. Moser, L.-H. Lin, et al. 2006. "The Distribution of Microbial Taxa in the Subsurface Water of the Kalahari Shield, South Africa." *Geomicrobiology Journal* 23 (6): 415–30. https://doi.org/10.1080/01490450600875696.

Glass, Jennifer B., Heidi M. Dierssen, Christopher R. Glein, Britney E. Schmidt, and Dale P. Winebrenner. 2022. "Defining and Characterizing Habitable Environments in Ocean World Systems." *Oceanography* 35 (1): 30–38. https://doi.org/10.5670/oceanog.2021.414.

Goldblatt, Colin. 2015. "Habitability of Waterworlds: Runaway Greenhouses, Atmospheric Expansion, and Multiple Climate States of Pure Water Atmospheres." *Astrobiology* 15 (5): 362–70. https://doi.org/10.1089/ast.2014.1268.

Gómez, F., N. Walter, R. Amils, et al. 2011. "Multidisciplinary Integrated Field Campaign to an Acidic Martian Earth Analogue with Astrobiological Interest: Rio Tinto." *International Journal of Astrobiology* 10 (3): 291–305. https://doi.org/10.1017/S147355041100005X.

González-Toril, Elena, Susana Osuna, Daniel Viúdez-Moreiras, et al. 2020. "Impacts of Saharan Dust Intrusions on Bacterial Communities of the Low Troposphere." *Scientific Reports* 10 (1): 6837. https://doi.org/10.1038/s41598-020-63797-9.

Gopal, B., M. Chauhan, and D. P. Zutshi. 2002. "High Altitude Lakes of Ladakh: Changes since the Yale North India Expedition." *SIL Proceedings, 1922-2010* 28 (2): 519–23. https://doi.org/10.1080/03680770.2001.11901771.

Greenberger, R. N., J. F. Mustard, P. S. Kumar, M. D. Dyar, E. A. Breves, and E. C. Sklute. 2012. "Low Temperature Aqueous Alteration of Basalt: Mineral Assemblages of Deccan Basalts and Implications for Mars." *Journal of Geophysical Research: Planets* 117 (E11). https://doi.org/10.1029/2012JE004127.

Gunnigle, Eoin, Aline Frossard, Jean-Baptiste Ramond, Leandro Guerrero, Mary Seely, and Don A. Cowan. 2017. "Diel-Scale Temporal Dynamics Recorded for Bacterial Groups in Namib Desert Soil." *Scientific Reports* 7 (1): 40189. https://doi.org/10.1038/srep40189.

Guo, Weifu, and John M. Eiler. 2007. "Temperatures of Aqueous Alteration and Evidence for Methane Generation on the Parent Bodies of the CM Chondrites." *Geochimica et Cosmochimica Acta* 71 (22): 5565–75. https://doi.org/10.1016/j.gca.2007.07.029.

Han, Yuchen, Giorgio Gonnella, Nicole Adam, et al. 2018. "Hydrothermal Chimneys Host Habitat-Specific Microbial Communities: Analogues for Studying the Possible Impact of Mining Seafloor Massive Sulfide Deposits." *Scientific Reports* 8 (1): 10386. https://doi.org/10.1038/s41598-018-28613-5.

Harinarayana, T., K. K. Abdul Azeez, D. N. Murthy, et al. 2006. "Exploration of Geothermal Structure in Puga Geothermal Field, Ladakh Himalayas, India by Magnetotelluric Studies." *Journal of Applied Geophysics*, Electrical and Electromagnetic Studies in Geothermally Active Regions, vol. 58 (4): 280–95. https://doi.org/10.1016/j.jappgeo.2005.05.005.

Hauber, E., D. Reiss, M. Ulrich, et al. 2011. "Landscape Evolution in Martian Mid-Latitude Regions: Insights from Analogous Periglacial Landforms in Svalbard." In *Martian Geomorphology*, edited by M. R. Balme, A. S. Bargery, C. J. Gallagher, and S. Gupta, vol. 356. Geological Society of London. https://doi.org/10.1144/SP356.7.

Hays, Lindsay E., Heather V. Graham, David J. Des Marais, et al. 2017. "Biosignature Preservation and Detection in Mars Analog Environments." *Astrobiology* 17 (4): 363–400. https://doi.org/10.1089/ast.2016.1627.

Heise, Jaret and J. 2015. "The Sanford Underground Research Facility at Homestake." *Journal of Physics: Conference Series, Volume 606, Issue 1, Article Id. 012015 (2015).* 606 (1). https://doi.org/10.1088/1742-6596/606/1/012015.

Hiraoka, Satoshi, Miho Hirai, Yohei Matsui, et al. 2020. "Microbial Community and Geochemical Analyses of Trans-Trench Sediments for Understanding the Roles of Hadal Environments." *The ISME Journal* 14 (3): 740–56. https://doi.org/10.1038/s41396-019-0564-z.

Hoehler, Tori M. 2007a. "An Energy Balance Concept for Habitability." *Astrobiology* 7 (6): 824–38. https://doi.org/10.1089/ast.2006.0095.

Hoehler, Tori M. 2007b. "An Energy Balance Concept for Habitability." *Astrobiology* 7 (6): 824–38. https://doi.org/10.1089/ast.2006.0095.

Hoffman, Paul F., Dorian S. Abbot, Yosef Ashkenazy, et al. 2017. "Snowball Earth Climate Dynamics and Cryogenian Geology-Geobiology." *Science Advances* 3 (11): e1600983. https://doi.org/10.1126/sciadv.1600983.

Holden, James F., and Harita Sistu. 2023. "Formate and Hydrogen in Hydrothermal Vents and Their Use by Extremely Thermophilic Methanogens and Heterotrophs." *Frontiers in Microbiology* 14 (March). https://doi.org/10.3389/fmicb.2023.1093018.

Holm, N.G., C. Oze, O. Mousis, J.H. Waite, and A. Guilbert-Lepoutre. 2015. "Serpentinization and the Formation of H2 and CH4 on Celestial Bodies (Planets, Moons, Comets)." *Astrobiology* 15 (7): 587–600. https://doi.org/10.1089/ast.2014.1188.

Honke, J. S., J. S. Pigati, J. Wilson, et al. 2019. “Late Quaternary Paleohydrology of Desert Wetlands and Pluvial Lakes in the Soda Lake Basin, Central Mojave Desert, California (USA).” *Quaternary Science Reviews* 216 (July): 89–106. https://doi.org/10.1016/j.quascirev.2019.05.021.

Horneck, Gerda, David M. Klaus, and Rocco L. Mancinelli. 2010. “Space Microbiology.” *Microbiology and Molecular Biology Reviews* 74 (1): 121–56. https://doi.org/10.1128/mmbr.00016-09.

Hosein, Riad, Shirin Haque, and Denise M. Beckles. 2014. “Mud Volcanoes of Trinidad as Astrobiological Analogs for Martian Environments.” *Life* 4 (4): 566–85. https://doi.org/10.3390/life4040566.

Hsu, David, Jack R. Flynn, Christopher J. Schuler, et al. 2024. “Isolation and Genomic Analysis of ‘Metallumcola Ferriviriculae’ MK1, a Gram-Positive, Fe(III)-Reducing Bacterium from the Soudan Underground Mine, an Iron-Rich Martian Analog Site.” *Applied and Environmental Microbiology* 90 (8): e00044-24. https://doi.org/10.1128/aem.00044-24.

Huang, Jing, Ping Chen, Yaxin Zhu, et al. 2023. “Biogeography and Potential Ecological Functions of Prokaryotes in the Hydrothermal and Non-Hydrothermal Field Sediments of the Indian Ocean Ridges.” *Frontiers in Marine Science* 9 (January). https://doi.org/10.3389/fmars.2022.1072569.

Humayoun, Shaheen B., Nasreen Bano, and James T. Hollibaugh. 2003. “Depth Distribution of Microbial Diversity in Mono Lake, a Meromictic Soda Lake in California.” *Applied and Environmental Microbiology* 69 (2): 1030–42. https://doi.org/10.1128/AEM.69.2.1030-1042.2003.

Hurowitz, Joel A., David C. Catling, and Woodward W. Fischer. 2023. “High Carbonate Alkalinity Lakes on Mars and Their Potential Role in an Origin of Life Beyond Earth.” *Elements* 19 (1): 37–44. https://doi.org/10.2138/gselements.19.1.37.

Husain, Mohd Suhail, Rashid Umar, and Shamshaad Ahmad. 2020. “A Comparative Study of Springs and Groundwater Chemistry of Beas and Parbati Valley, Kullu District, Himachal Pradesh, India.” *HydroResearch* 3 (January): 32–47. https://doi.org/10.1016/j.hydres.2020.04.003.

Hutchens, Elena, Stefan Radajewski, Marc G. Dumont, Ian R. McDonald, and J. Colin Murrell. 2004. “Analysis of Methanotrophic Bacteria in Movile Cave by Stable Isotope Probing.” *Environmental Microbiology* 6 (2): 111–20. https://doi.org/10.1046/j.1462-2920.2003.00543.x.

Ijiri, Akira, Fumio Inagaki, Yusuke Kubo, et al. 2018. “Deep-Biosphere Methane Production Stimulated by Geofluids in the Nankai Accretionary Complex.” *Science Advances* 4 (6): eaao4631. https://doi.org/10.1126/sciadv.aao4631.

Jain, A. K. 2014. “When Did India–Asia Collide and Make the Himalaya?” *Current Science* 106 (2): 254–66.

Jain, Madhavi, Pallavi Saxena, and Saurabh Sonwani. 2025. “Characteristics, Dynamics, and Impact of the Thar Desert Dust Storms on Air Quality over Northern India.” *Natural Hazards* 121 (5): 5589–619. https://doi.org/10.1007/s11069-024-07003-3.

Jalil, Raham, Olivier Alard, Bruce Schaefer, et al. 2023. “Geochemistry of Waziristan Ophiolite Complex, Pakistan: Implications for Petrogenesis and Tectonic Setting.” *Minerals* 13 (3): 311. https://doi.org/10.3390/min13030311.

Jamieson, Alan J. 2020. “The Five Deeps Expedition and an Update of Full Ocean Depth Exploration and Explorers.” *Marine Technology Society Journal* 54 (1): 6–12. https://doi.org/10.4031/MTSJ.54.1.1.

Jamieson, Alan J., Toyonobu Fujii, Daniel J. Mayor, Martin Solan, and Imants G. Priede. 2010. “Hadal Trenches: The Ecology of the Deepest Places on Earth.” *Trends in Ecology & Evolution* 25 (3): 190–97. https://doi.org/10.1016/j.tree.2009.09.009.

Jamieson, Alan J., Heather A. Stewart, Johanna N. J. Weston, Patrick Lahey, and Victor L. Vescovo. 2022. “Hadal Biodiversity, Habitats and Potential Chemosynthesis in the Java Trench, Eastern Indian Ocean.” *Frontiers in Marine Science* 9 (March). https://doi.org/10.3389/fmars.2022.856992.

Jangir, Yamini, Amruta A. Karbelkar, Nicole M. Beedle, et al. 2019. “In Situ Electrochemical Studies of the Terrestrial Deep Subsurface Biosphere at the Sanford Underground Research Facility, South Dakota, USA.” *Frontiers in Energy Research* 7. https://www.frontiersin.org/articles/10.3389/fenrg.2019.00121.

Jansson, Janet K., and Erin S. Baker. 2016. “A Multi-Omic Future for Microbiome Studies.” *Nature Microbiology* 1 (5): 5. https://doi.org/10.1038/nmicrobiol.2016.49.

Jawadi, Hussain Ali, Hasan Ali Malistani, Mohammad Anvar Moheghy, and Jay Sagin. 2021. “Essential Trace Elements and Arsenic in Thermal Springs, Afghanistan.” *Water* 13 (2): 134. https://doi.org/10.3390/w13020134.

Jeilu, Oliyad, Amare Gessesse, Addis Simachew, Eva Johansson, and Erik Alexandersson. 2022. “Prokaryotic and Eukaryotic Microbial Diversity from Three Soda Lakes in the East African Rift Valley Determined by Amplicon Sequencing.” *Frontiers in Microbiology* 13 (December). https://doi.org/10.3389/fmicb.2022.999876.

Jiang, Tian, Jonathan C. Aitchison, and Xiaoqiao Wan. 2016. “The Youngest Marine Deposits Preserved in Southern Tibet and Disappearance of the Tethyan Ocean.” *Gondwana Research* 32 (April): 64–75. https://doi.org/10.1016/j.gr.2015.01.015.

Jones, B. E., William D. Grant, A. W. Duckworth, and G. G. Owenson. 1998. “Microbial Diversity of Soda Lakes.” *Extremophiles* 2 (3): 191–200. https://doi.org/10.1007/s007920050060.

Jørgensen, Bo Barker, and Antje Boetius. 2007. “Feast and Famine — Microbial Life in the Deep-Sea Bed.” *Nature Reviews Microbiology* 5 (10): 770–81. https://doi.org/10.1038/nrmicro1745.

Jungbluth, Sean P, Robert M Bowers, Huei-Ting Lin, James P Cowen, and Michael S Rappé. 2016. “Novel Microbial Assemblages Inhabiting Crustal Fluids within Mid-Ocean Ridge Flank

Subsurface Basalt." *The ISME Journal* 10 (8): 2033–47. https://doi.org/10.1038/ismej.2015.248.

Kaiho, Kunio, Atena Shizuya, Minori Kikuchi, et al. 2024. "Oxygen Increase and the Pacing of Early Animal Evolution." *Global and Planetary Change* 233 (February): 104364. https://doi.org/10.1016/j.gloplacha.2024.104364.

Kane, Stephen R., Giada N. Arney, Paul K. Byrne, et al. 2021. "The Fundamental Connections between the Solar System and Exoplanetary Science." *Journal of Geophysical Research: Planets* 126 (2): e2020JE006643. https://doi.org/10.1029/2020JE006643.

Kassi, Akhtar M., Shuhab D. Khan, Huseyin Bayraktar, and Aimal K. Kasi. 2014. "Newly Discovered Mud Volcanoes in the Coastal Belt of Makran, Pakistan—Tectonic Implications." *Arabian Journal of Geosciences* 7: 4899–909. https://doi.org/10.1007/s12517-013-1135-7.

Kato, Chiaki, Lina Li, Yuichi Nogi, Yuka Nakamura, Jin Tamaoka, and Koki Horikoshi. 1998. "Extremely Barophilic Bacteria Isolated from the Mariana Trench, Challenger Deep, at a Depth of 11,000 Meters." *Applied and Environmental Microbiology* 64 (4): 1510–13. https://doi.org/10.1128/AEM.64.4.1510-1513.1998.

Kelemen, Peter B., Jürg M. Matter, Damon A. H. Teagle, et al. 2023. "Preface: Special Issue on Ophiolites and Oceanic Lithosphere." *Journal of Geophysical Research: Solid Earth* 128 (4): e2023JB026677. https://doi.org/10.1029/2023JB026677.

Kelley, Deborah S., Suzanne M. Carbotte, David W. Caress, et al. 2012. "Endeavour Segment of the Juan de Fuca Ridge: ONE OF THE MOST REMARKABLE PLACES ON EARTH." *Oceanography* 25 (1): 44–61.

Kempe, Stephan, and Jozef Kazmierczak. 2011. "Soda Lakes." In *Encyclopedia of Geobiology*. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-9212-1_191.

Kharaka, Yousif K., Stephen W. Robinson, Leroy M. Law, and William W. Carothers. 1984. "Hydrogeochemistry of Big Soda Lake, Nevada: An Alkaline Meromictic Desert Lake." *Geochimica et Cosmochimica Acta* 48 (4): 823–35. https://doi.org/10.1016/0016-7037(84)90104-2.

Khormali, Farhad, and Curtis Monger. 2020. "Hot Desert Soils—Global Distribution and Unique Characteristics." *Geoderma Regional* 23 (December): e00330. https://doi.org/10.1016/j.geodrs.2020.e00330.

Kirkbride, Martin P., Sophie C. Sherriff, Ann V. Rowan, et al. 2023. "Provenance and Transport of Supraglacial Debris Revealed by Variations in Debris Geochemistry on Khumbu Glacier, Nepal Himalaya." *Earth Surface Processes and Landforms* 48 (14): 2737–53. https://doi.org/10.1002/esp.5657.

Kite, Edwin S., and Susan Conway. 2024. "Geological Evidence for Multiple Climate Transitions on Early Mars." *Nature Geoscience* 17 (1): 10–19. https://doi.org/10.1038/s41561-023-01349-2.

Kite, Edwin S., and Eric B. Ford. 2018. "Habitability of Exoplanet Waterworlds." *The Astrophysical Journal* 864 (1): 75. https://doi.org/10.3847/1538-4357/aad6e0.

Kizovski, T. V., M. E. Schmidt, L. O'Neil, et al. 2025. "Fe-Phosphates in Jezero Crater as Evidence for an Ancient Habitable Environment on Mars." *Nature Communications* 16 (1): 6470. https://doi.org/10.1038/s41467-025-60026-7.

Klein, Frieder, Wolfgang Bach, and Thomas M. McCollom. 2013. "Compositional Controls on Hydrogen Generation during Serpentinization of Ultramafic Rocks." *Lithos*, Serpentinites from mid-oceanic ridges to subduction, vol. 178 (September): 55–69. https://doi.org/10.1016/j.lithos.2013.03.008.

Koehle, Allison P., Stephanie L. Brumwell, Emily P. Seto, Anne M. Lynch, and Camilla Urbaniak. 2023. "Microbial Applications for Sustainable Space Exploration beyond Low Earth Orbit." *Npj Microgravity* 9 (1): 1. https://doi.org/10.1038/s41526-023-00285-0.

Kołodziejczyk, Agata Maria, Marek Lewandowski, Adam Nawrot, and Ireneusz Sobota. 2025. "Polar Stations as Testing Platforms for Space Analogue Simulations – Case Study for Polish Potential." *Arctic, Antarctic, and Alpine Research* 57 (1): 2439123. https://doi.org/10.1080/15230430.2024.2439123.

Komatsu, Goro, Chris H. Okubo, James J. Wray, et al. 2016. "Small Edifice Features in Chryse Planitia, Mars: Assessment of a Mud Volcano Hypothesis." *Icarus* 268 (April): 56–75. https://doi.org/10.1016/j.icarus.2015.12.032.

Kopf, Achim J. 2002. "Significance of Mud Volcanism." *Reviews of Geophysics* 40 (2): 2-1-2–52. https://doi.org/10.1029/2000RG000093.

Krassowski, Michal, Vivek Das, Sangram K. Sahu, and Biswapriya B. Misra. 2020. "State of the Field in Multi-Omics Research: From Computational Needs to Data Mining and Sharing." *Frontiers in Genetics* 11. https://www.frontiersin.org/articles/10.3389/fgene.2020.610798.

Krýza, Ondřej, Petr Brož, Mark G. Fox-Powell, et al. 2025. "Small Amounts of Dissolved Salts Increase the Mobility of Mud Flows on Mars and Other Extraterrestrial Bodies." *Communications Earth & Environment* 6 (1): 116. https://doi.org/10.1038/s43247-025-02110-w.

Kumar, Alok, Jyotiranjan S. Ray, P. E. Binusarma, et al. 2021. "Origin of Breccia in Mud Volcanoes of the Andaman Accretionary Prism: Implications for Forearc Processes." *Chemical Geology* 586 (December): 120595. https://doi.org/10.1016/j.chemgeo.2021.120595.

Kumar, Saurabh, Deep Chandra Suyal, Amit Yadav, Yogesh Shouche, and Reeta Goel. 2019. "Microbial Diversity and Soil Physiochemical Characteristic of Higher Altitude." *PLOS ONE* 14 (3): e0213844. https://doi.org/10.1371/journal.pone.0213844.

Kumari, Shalini, Geetanjli Choudhary, Kumari Anu, and Sarita Devi. 2024. "Metagenomics Insight into Puga Geothermal Geyser Located in Himalayan Geothermal Belt (Trans-Himalayan Plateau) Ladakh, India." *Brazilian Journal of Microbiology* 55 (3): 2321–34. https://doi.org/10.1007/s42770-024-01408-9.

La Duc, Myron T., James N. Benardini, Michael J. Kempf, David A. Newcombe, Michael Lubarsky, and Kasthuri Venkateswaran. 2007. "Microbial Diversity of Indian Ocean Hydrothermal Vent

Plumes: Microbes Tolerant of Desiccation, Peroxide Exposure, and Ultraviolet and γ-Irradiation.” *Astrobiology* 7 (2): 416–31. https://doi.org/10.1089/ast.2006.0060.

Lakhan, Nongmaithem, Athokpam Krishnakanta Singh, Birendra Pratap Singh, et al. 2020. “Zircon U–Pb Geochronology, Mineral and Whole-Rock Geochemistry of the Khardung Volcanics, Ladakh Himalaya, India: Implications for Late Cretaceous to Palaeogene Continental Arc Magmatism.” *Geological Journal* 55 (5): 3297–320. https://doi.org/10.1002/gj.3594.

Lebre, Pedro H., Pieter De Maayer, and Don A. Cowan. 2017. “Xerotolerant Bacteria: Surviving through a Dry Spell.” *Nature Reviews Microbiology* 15 (5): 285–96. https://doi.org/10.1038/nrmicro.2017.16.

Lecoeuvre, Aurélien, Bénédicte Ménez, Mathilde Cannat, Valérie Chavagnac, and Emmanuelle Gérard. 2021. “Microbial Ecology of the Newly Discovered Serpentinite-Hosted Old City Hydrothermal Field (Southwest Indian Ridge).” *The ISME Journal* 15 (3): 818–32. https://doi.org/10.1038/s41396-020-00816-7.

Lee, Dong-Hun, Jung-Hyun Kim, Yung Mi Lee, et al. 2018a. “Biogeochemical Evidence of Anaerobic Methane Oxidation on Active Submarine Mud Volcanoes on the Continental Slope of the Canadian Beaufort Sea.” *Biogeosciences* 15 (24): 7419–33. https://doi.org/10.5194/bg-15-7419-2018.

Lee, Dong-Hun, Jung-Hyun Kim, Yung Mi Lee, et al. 2018b. “Biogeochemical Evidence of Anaerobic Methane Oxidation on Active Submarine Mud Volcanoes on the Continental Slope of the Canadian Beaufort Sea.” *Biogeosciences* 15 (24): 7419–33. https://doi.org/10.5194/bg-15-7419-2018.

Leovy, C. E., R. W. Zurek, and J. B. Pollack. 1973. “Mechanisms for Mars Dust Storms.” Journal of the Atmospheric Sciences. *Journal of the Atmospheric Sciences* 30 (5): 749–62. https://doi.org/10.1175/1520-0469(1973)030%253C0749:MFMDS%253E2.0.CO;2.

Léveillé, Richard. 2009. “Validation of Astrobiology Technologies and Instrument Operations in Terrestrial Analogue Environments.” *Comptes Rendus Palevol*, Traces de vie présente ou passé: quels indices, signatures ou marqueurs?, vol. 8 (7): 637–48. https://doi.org/10.1016/j.crpv.2009.03.005.

Léveillé, Richard J., and Saugata Datta. 2010. “Lava Tubes and Basaltic Caves as Astrobiological Targets on Earth and Mars: A Review.” *Planetary and Space Science*, Exploring other worlds by exploring our own: The role of terrestrial analogue studies in planetary exploration, vol. 58 (4): 592–98. https://doi.org/10.1016/j.pss.2009.06.004.

Li, Guorui, Xiangping Chen, Fanghao Zhou, et al. 2021. “Self-Powered Soft Robot in the Mariana Trench.” *Nature* 591 (7848): 66–71. https://doi.org/10.1038/s41586-020-03153-z.

Li, Jiangtao, Huaiyang Zhou, Jiasong Fang, Zijun Wu, and Xiaotong Peng. 2016. “Microbial Distribution in a Hydrothermal Plume of the Southwest Indian Ridge.” *Geomicrobiology Journal* 33 (5): 401–15. https://doi.org/10.1080/01490451.2015.1048393.

Liang, Jianzhen, Jing-Chun Feng, Si Zhang, et al. 2021. “Role of Deep-Sea Equipment in Promoting the Forefront of Studies on Life in Extreme Environments.” *iScience* 24 (11). https://doi.org/10.1016/j.isci.2021.103299.

Liang, Jin, Chunhui Tao, Xiangxin Wang, et al. 2023. “Geological Context and Vents Morphology in the Ultramafic-Hosted Tianxiu Field, Carlsberg Ridge.” *Acta Oceanologica Sinica* 42 (9): 62–70. https://doi.org/10.1007/s13131-023-2157-y.

Lim, Dhongil, Jihun Kim, Wonnyon Kim, et al. 2022. “Characterization of Geochemistry in Hydrothermal Sediments From the Newly Discovered Onnuri Vent Field in the Middle Region of the Central Indian Ridge.” *Frontiers in Marine Science* 9 (February). https://doi.org/10.3389/fmars.2022.810949.

Lima-Zaloumis, Jon, Anna Neubeck, Magnus Ivarsson, et al. 2022. “Microbial Biosignature Preservation in Carbonated Serpentine from the Samail Ophiolite, Oman.” *Communications Earth & Environment* 3 (1): 231. https://doi.org/10.1038/s43247-022-00551-1.

Liu, Guanghua, and G. Einsele. 1994. “Sedimentary History of the Tethyan Basin in the Tibetan Himalayas.” *Geologische Rundschau* 83 (1): 32–61. https://doi.org/10.1007/BF00211893.

Liu, Jiwen, Yanfen Zheng, Heyu Lin, et al. 2019. “Proliferation of Hydrocarbon-Degrading Microbes at the Bottom of the Mariana Trench.” *Microbiome* 7 (1): 47. https://doi.org/10.1186/s40168-019-0652-3.

Liu, Li, Haiyun Liu, Wensi Zhang, et al. 2022. “Microbial Diversity and Adaptive Strategies in the Mars-like Qaidam Basin, North Tibetan Plateau, China.” *Environmental Microbiology Reports* 14 (6): 873–85. https://doi.org/10.1111/1758-2229.13111.

Liu, Xiao-Qiang, Chuan-Lin Zhang, Xiao-Shu Hao, Haibo Zou, Hai-Xiang Zhao, and Xian-Tao Ye. 2020. “Early Cretaceous Granitoids in the Southern Pamir: Implications for the Meso-Tethys Evolution of the Pamir Plateau.” *Lithos* 362–363 (June): 105492. https://doi.org/10.1016/j.lithos.2020.105492.

Lone, Ihsan Ullah, Meenal Mishra, Sachin Kr. Tiwary, and Rakesh Chandra. 2022. “Recognition of Shyok Ophiolites of NW Ladakh Trans-Himalaya as a Geoheritage: Importance to Himalayan Orogeny and Remnant of Tethyan Oceanic Lithosphere.” *Geoheritage* 15 (1): 3. https://doi.org/10.1007/s12371-022-00763-z.

Lösekann, Tina, Katrin Knittel, Thierry Nadalig, et al. 2007. “Diversity and Abundance of Aerobic and Anaerobic Methane Oxidizers at the Haakon Mosby Mud Volcano, Barents Sea.” *Applied and Environmental Microbiology* 73 (10): 3348–62. https://doi.org/10.1128/AEM.00016-07.

Lu, Jennifer, and Steven L. Salzberg. 2018. “Removing Contaminants from Databases of Draft Genomes.” *PLOS Computational Biology* 14 (6): e1006277. https://doi.org/10.1371/journal.pcbi.1006277.

Luo, Min, Thomas J. Algeo, Hongpeng Tong, et al. 2018. “More Reducing Bottom-Water Redox Conditions during the Last Glacial Maximum in the Southern Challenger Deep (Mariana Trench, Western Pacific) Driven by Enhanced Productivity.” *Deep Sea Research Part II: Topical Studies in Oceanography*, Exploring the Hadal Zone: Recent Advances in Hadal

Science and Technology, vol. 155 (September): 70–82. https://doi.org/10.1016/j.dsr2.2017.01.006.

Lyu, Zhe, Nana Shao, Taiwo Akinyemi, and William B. Whitman. 2018. "Methanogenesis." *Current Biology* 28 (13): R727–32. https://doi.org/10.1016/j.cub.2018.05.021.

Macalady, Jennifer L., Daniel S. Jones, and Ezra H. Lyon. 2007. "Extremely Acidic, Pendulous Cave Wall Biofilms from the Frasassi Cave System, Italy." *Environmental Microbiology* 9 (6): 1402–14. https://doi.org/10.1111/j.1462-2920.2007.01256.x.

Macalady, Jennifer L., Ezra H. Lyon, Bess Koffman, et al. 2006. "Dominant Microbial Populations in Limestone-Corroding Stream Biofilms, Frasassi Cave System, Italy." *Applied and Environmental Microbiology* 72 (8): 5596–609. https://doi.org/10.1128/AEM.00715-06.

Majumdar, R. K, N Majumdar, and A. L Mukherjee. 2000. "Geoelectric Investigations in Bakreswar Geothermal Area, West Bengal, India." *Journal of Applied Geophysics* 45 (3): 187–202. https://doi.org/10.1016/S0926-9851(00)00028-8.

Maloof, Adam C., Sarah T. Stewart, Benjamin P. Weiss, et al. 2010. "Geology of Lonar Crater, India." *GSA Bulletin* 122 (1–2): 109–26. https://doi.org/10.1130/B26474.1.

Mancinelli, R. L., T. F. Fahlen, R. Landheim, and M. R. Klovstad. 2004. "Brines and Evaporites: Analogs for Martian Life." *Advances in Space Research*, Space Life Sciences: Search for Signatures of Life, and Space Flight Environmental Effects on the Nervous System, vol. 33 (8): 1244–46. https://doi.org/10.1016/j.asr.2003.08.034.

Mandal, Anirban, Gyana Ranjan Tripathy, Vineet Goswami, Lukáš Ackerman, Suraj K. Parcha, and Rakesh Chandra. 2021. "Re–Os and Sr Isotopic Study of Permian–Triassic Sedimentary Rocks from the Himalaya: Shale Chronology and Carbonate Diagenesis." *Minerals* 11 (4): 417. https://doi.org/10.3390/min11040417.

Manna, Sanjib Kumar, Basanta Kumar Das, Bimal Prasanna Mohanty, et al. 2021. "Exploration of Heterotrophic Bacterial Diversity in Sediments of the Mud Volcano in the Andaman and Nicobar Islands, India." *Environmental Nanotechnology, Monitoring & Management* 16 (December): 100465. https://doi.org/10.1016/j.enmm.2021.100465.

Margesin, Rosa, and Vanya Miteva. 2011. "Diversity and Ecology of Psychrophilic Microorganisms." *Research in Microbiology* 162 (3): 346–61. https://doi.org/10.1016/j.resmic.2010.12.004.

Martin, Andrew, and Andrew McMinn. 2018. "Sea Ice, Extremophiles and Life on Extra-Terrestrial Ocean Worlds." *International Journal of Astrobiology* 17 (1): 1–16. https://doi.org/10.1017/S1473550416000483.

Martin, C. R., N. J. Van Buer, H. Matchette-Downes, et al. 2025. "The Geology of the Shyok Suture Zone: Evidence for Cretaceous Extension of the Southern Eurasian Margin and Eocene India–Eurasia Collision." *Journal of the Geological Society* 182 (2): jgs2024-082. https://doi.org/10.1144/jgs2024-082.

Martins, Zita, Hervé Cottin, Julia Michelle Kotler, et al. 2017. “Earth as a Tool for Astrobiology—A European Perspective.” *Space Science Reviews* 209 (1): 43–81. https://doi.org/10.1007/s11214-017-0369-1.

Mazzini, Adriano, and Giuseppe Etiope. 2017. “Mud Volcanism: An Updated Review.” *Earth-Science Reviews* 168 (May): 81–112. https://doi.org/10.1016/j.earscirev.2017.03.001.

McClain, Craig R., S. River Bryant, Granger Hanks, and Marshall W. Bowles. 2022. “Extremophiles in Earth’s Deep Seas: A View Toward Life in Exo-Oceans.” *Astrobiology* 22 (8): 1009–28. https://doi.org/10.1089/ast.2021.0120.

McCollom, Thomas M., and Wolfgang Bach. 2009. “Thermodynamic Constraints on Hydrogen Generation during Serpentinization of Ultramafic Rocks.” *Geochimica et Cosmochimica Acta* 73 (3): 856–75. https://doi.org/10.1016/j.gca.2008.10.032.

McKay, Christopher P. 2022. “Chapter 7 - Habitability in the Solar System beyond the Earth and the Search for Life.” In *New Frontiers in Astrobiology*, edited by Rebecca Thombre and Parag Vaishampayan. Elsevier. https://doi.org/10.1016/B978-0-12-824162-2.00006-3.

Meena, Balakrishnan, Lawrance Anburajan, Karankal Aryamol, Nambali Valsalan Vinithkumar, and Gopal Dharani. 2023. “Studies on Biodiversity and Bioprospecting of Active Mud Volcano Associated Bacteria and Actinobacteria from Baratang, Andaman Islands, India.” *Systems Microbiology and Biomanufacturing* 3 (2): 339–57. https://doi.org/10.1007/s43393-022-00118-3.

Méndez, Abel, Edgard G. Rivera-Valentín, Dirk Schulze-Makuch, et al. 2021. “Habitability Models for Astrobiology.” *Astrobiology* 21 (8): 1017–27. https://doi.org/10.1089/ast.2020.2342.

Merino, Nancy, Heidi S. Aronson, Diana P. Bojanova, et al. 2019. “Living at the Extremes: Extremophiles and the Limits of Life in a Planetary Context.” *Frontiers in Microbiology* 10 (April). https://doi.org/10.3389/fmicb.2019.00780.

Merkel, Alexander Y., Nikolay A. Chernyh, Nikolai V. Pimenov, Elizaveta A. Bonch-Osmolovskaya, and Alexander I. Slobodkin. 2021. “Diversity and Metabolic Potential of the Terrestrial Mud Volcano Microbial Community with a High Abundance of Archaea Mediating the Anaerobic Oxidation of Methane.” *Life* 11 (9): 953. https://doi.org/10.3390/life11090953.

Methou, Pierre, Masanari Hikosaka, Chong Chen, et al. 2022. “Symbiont Community Composition in Rimicaris Kairei Shrimps from Indian Ocean Vents with Notes on Mineralogy.” *Applied and Environmental Microbiology* 88 (8): e00185-22. https://doi.org/10.1128/aem.00185-22.

Meyer, Burghard Christian, Vera Schreiner, Elena N. Smolentseva, and Boris A. Smolentsev. 2008. “Indicators of Desertification in the Kulunda Steppe in the South of Western Siberia.” *Archives of Agronomy and Soil Science* 54 (6): 585–603. https://doi.org/10.1080/03650340802342268.

Michalski, Joseph R., Timothy A. Goudge, Sean A. Crowe, Javier Cuadros, John F. Mustard, and Sarah Stewart Johnson. 2022. “Geological Diversity and Microbiological Potential of Lakes on Mars.” *Nature Astronomy* 6 (10): 1133–41. https://doi.org/10.1038/s41550-022-01743-7.

Middleton, Nicholas John, Andrew S. Goudie, and Gordon L. Wells. 1986. “The Frequency and Source Areas of Dust Storms.” In *Aeolian Geomorphology*. Routledge.

Milkov, A. V. 2000. “Worldwide Distribution of Submarine Mud Volcanoes and Associated Gas Hydrates.” *Marine Geology* 167 (1): 29–42. https://doi.org/10.1016/S0025-3227(00)00022-0.

Mishra, S. K., and S. N. Tripathi. 2008. “Modeling Optical Properties of Mineral Dust over the Indian Desert.” *Journal of Geophysical Research: Atmospheres* 113 (D23). https://doi.org/10.1029/2008JD010048.

Mishra, Shreya, Mahi Bansal, Vandana Prasad, et al. 2024. “Did the Deccan Volcanism Impact the Indian Flora during the Maastrichtian?” *Earth-Science Reviews* 258 (November): 104950. https://doi.org/10.1016/j.earscirev.2024.104950.

Miyake, Nori, Ryo Ishimaru, Goro Komatsu, and Takafumi Matsui. 2023. “Characterization of Archaeal and Bacterial Communities Thriving in Methane-Seeping on-Land Mud Volcanoes, Niigata, Japan.” *International Microbiology* 26 (2): 191–204. https://doi.org/10.1007/s10123-022-00288-z.

Molnar, Peter, and Paul Tapponnier. 1977. “The Collision between India and Eurasia.” *Scientific American* 236 (4): 30–41.

Mondal, Nibendu, Aditya Peketi, Tarunendu Mapder, et al. 2022. “Indus and Nubra Valley Hot Springs Affirm the Geomicrobiological Specialties of Trans-Himalayan Hydrothermal Systems.” *Journal of Earth System Science* 131 (1): 12. https://doi.org/10.1007/s12040-021-01757-1.

Moody, Judith B. 1976. “Serpentinization: A Review.” *Lithos* 9 (2): 125–38. https://doi.org/10.1016/0024-4937(76)90030-X.

Moore, Kelsey R., Throdore M. Present, Frank Pavia, et al. 2022. “Biosignature Preservation Aided By Organic-Cation Interactions In Proterozoic Tidal Environments.” *PALAIOS* 37 (9): 486–98. https://doi.org/10.2110/palo.2022.017.

Morrell, Benjamin J., Maira Saboia da Silva, Marcel Kaufmann, et al. 2024. “Robotic Exploration of Martian Caves: Evaluating Operational Concepts through Analog Experiments in Lava Tubes.” *Acta Astronautica* 223 (October): 741–58. https://doi.org/10.1016/j.actaastro.2024.07.041.

Most, Naomi van der, Pei-Yuan Qian, Yan Gao, and Sabine Gollner. 2023. “Active Hydrothermal Vent Ecosystems in the Indian Ocean Are in Need of Protection.” *Frontiers in Marine Science* 9 (January). https://doi.org/10.3389/fmars.2022.1067912.

Mouchot, Nicolas, Lies Loncke, Geoffroy Mahieux, et al. 2010. “Recent Sedimentary Processes along the Makran Trench (Makran Active Margin, off Pakistan).” *Marine Geology* 271 (1): 17–31. https://doi.org/10.1016/j.margeo.2010.01.006.

Mukhopadhyay, Joydip, Rebeun Ngobeli, Gautam Ghosh, and Marlina A. Elburg. 2025. “Age of the Western Iron Ore Group, India, and Implications for Pre-GOE Oxygenation of Oceans at the Twilight of Archean-Proterozoic Transition.” *Scientific Reports* 15 (1): 13951. https://doi.org/10.1038/s41598-025-97611-1.

Münch, Ute, Claude Lalou, Peter Halbach, and Hiromi Fujimoto. 2001. “Relict Hydrothermal Events along the Super-Slow Southwest Indian Spreading Ridge near 63°56′E—Mineralogy, Chemistry and Chronology of Sulfide Samples.” *Chemical Geology* 177 (3): 341–49. https://doi.org/10.1016/S0009-2541(00)00418-6.

Murray, Dáithí C., Megan L. Coghlan, and Michael Bunce. 2015. “From Benchtop to Desktop: Important Considerations When Designing Amplicon Sequencing Workflows.” *PLOS ONE* 10 (4): e0124671. https://doi.org/10.1371/journal.pone.0124671.

Nakamura, Kentaro, Hiromi Watanabe, Junichi Miyazaki, et al. 2012. “Discovery of New Hydrothermal Activity and Chemosynthetic Fauna on the Central Indian Ridge at 18°–20°S.” *PLOS ONE* 7 (3): e32965. https://doi.org/10.1371/journal.pone.0032965.

Namirimu, Teddy, Yun Jae Kim, Mi-Jeong Park, Dhongil Lim, Jung-Hyun Lee, and Kae Kyoung Kwon. 2022. “Microbial Community Structure and Functional Potential of Deep-Sea Sediments on Low Activity Hydrothermal Area in the Central Indian Ridge.” *Frontiers in Marine Science* 9 (February). https://doi.org/10.3389/fmars.2022.784807.

Napoli, Simone, Daniele Spatola, Daniele Casalbore, Luigi Lombardo, Hakan Tanyas, and Francesco Latino Chiocci. 2025. “Comprehensive Global Inventory of Submarine Mud Volcanoes.” *Scientific Data* 12 (1): 382. https://doi.org/10.1038/s41597-025-04726-1.

Nealson, Kenneth H., and Pamela G. Conrad. 1999. “Life: Past, Present and Future.” *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 354 (1392): 1923–39. https://doi.org/10.1098/rstb.1999.0532.

Nguyen, Jen, Juanita Lara-Gutiérrez, and Roman Stocker. 2021. “Environmental Fluctuations and Their Effects on Microbial Communities, Populations and Individuals.” *FEMS Microbiology Reviews* 45 (4): fuaa068. https://doi.org/10.1093/femsre/fuaa068.

Niemann, H., J. Duarte, C. Hensen, et al. 2006. “Microbial Methane Turnover at Mud Volcanoes of the Gulf of Cadiz.” *Geochimica et Cosmochimica Acta* 70 (21): 5336–55. https://doi.org/10.1016/j.gca.2006.08.010.

Nunoura, Takuro, Manabu Nishizawa, Miho Hirai, et al. 2018. “Microbial Diversity in Sediments from the Bottom of the Challenger Deep, the Mariana Trench.” *Microbes and Environments* 33 (2): 186–94. https://doi.org/10.1264/jsme2.ME17194.

Olejarz, Jason, Yoh Iwasa, Andrew H. Knoll, and Martin A. Nowak. 2021. “The Great Oxygenation Event as a Consequence of Ecological Dynamics Modulated by Planetary Change.” *Nature Communications* 12 (1): 3985. https://doi.org/10.1038/s41467-021-23286-7.

Omoregie, Enoma O., Vincent Mastalerz, Gert de Lange, et al. 2008. “Biogeochemistry and Community Composition of Iron- and Sulfur-Precipitating Microbial Mats at the Chefren Mud Volcano (Nile Deep Sea Fan, Eastern Mediterranean).” *Applied and Environmental Microbiology* 74 (10): 3198–215. https://doi.org/10.1128/AEM.01751-07.

O’Neill, Ian J. 2021. “Robotic Navigation Tech Will Explore the Deep Ocean - NASA.” Nasa.gov. May 14. https://www.nasa.gov/centers-and-facilities/jpl/robotic-navigation-tech-will-explore-the-deep-ocean/.

Onstott, Tullis C., K. Tobin, H. Dong, et al. 1997. “Deep Gold Mines of South Africa: Windows into the Subsurface Biosphere.” *Instruments, Methods, and Missions for the Investigation of Extraterrestrial Microorganisms* 3111 (July): 344–57. https://doi.org/10.1117/12.278789.

Orphan, V. J., K.-U. Hinrichs, W. Ussler, et al. 2001. “Comparative Analysis of Methane-Oxidizing Archaea and Sulfate-Reducing Bacteria in Anoxic Marine Sediments.” *Applied and Environmental Microbiology* 67 (4): 1922–34. https://doi.org/10.1128/AEM.67.4.1922-1934.2001.

Osburn, Magdalena R., Brittany Kruger, Andrew L. Masterson, Caitlin P. Casar, and Jan P. Amend. 2019. “Establishment of the Deep Mine Microbial Observatory (DeMMO), South Dakota, USA, a Geochemically Stable Portal Into the Deep Subsurface.” *Frontiers in Earth Science* 7 (July). https://doi.org/10.3389/feart.2019.00196.

Osburn, Magdalena R., Douglas E. LaRowe, Lily M. Momper, and Jan P. Amend. 2014. “Chemolithotrophy in the Continental Deep Subsurface: Sanford Underground Research Facility (SURF), USA.” *Frontiers in Microbiology* 5 (November): 610. https://doi.org/10.3389/FMICB.2014.00610.

Osinski, Gordon, Richard Léveillé, Alain Berinstain, Martin Lebeuf, and Matthew Bamsey. 2006. “Terrestrial Analogues to Mars and the Moon:: Canada’s Role.” *Geoscience Canada* 33 (4): 175–88.

Oze, Christopher, and Mukul Sharma. 2005. “Have Olivine, Will Gas: Serpentinization and the Abiogenic Production of Methane on Mars.” *Geophysical Research Letters* 32 (10). https://doi.org/10.1029/2005GL022691.

Pachiadaki, Maria G., Argyri Kallionaki, Anke Dählmann, Gert J. De Lange, and Konstantinos Ar. Kormas. 2011. “Diversity and Spatial Distribution of Prokaryotic Communities Along A Sediment Vertical Profile of A Deep-Sea Mud Volcano.” *Microbial Ecology* 62 (3): 655–68. https://doi.org/10.1007/s00248-011-9855-2.

Pal, Dipak C, Surajit Sarkar, Biswajit Mishra, and A K Sarangi. 2011. “Chemical and Sulphur Isotope Compositions of Pyrite in the Jaduguda U (–Cu–Fe) Deposit, Singhbhum Shear Zone, Eastern India: Implications for Sulphide Mineralization.” *Journal of Earth System Science* 120 (3): 475–88. https://doi.org/10.1007/s12040-011-0080-7.

Pal, Srikanta, Raju Biswas, Arijit Misra, et al. 2020. “Poorly Known Microbial Taxa Dominate the Microbiome of Hypersaline Sambhar Lake Salterns in India.” *Extremophiles* 24 (6): 875–85. https://doi.org/10.1007/s00792-020-01201-0.

Pandey, Piyush Kant, Richa Sharma, Manju Roy, and Madhurima Pandey. 2007. “Toxic Mine Drainage from Asia’s Biggest Copper Mine at Malanjkhand, India.” *Environmental Geochemistry and Health* 29 (3): 237–48. https://doi.org/10.1007/s10653-006-9079-4.

Pandey, Siddharth, Annalea Beattie, Jennifer Blank, Steven Hobbs, and Jonathan Clarke. 2019. “Lonar Crater in India as an Analogue for Mars Astrobiology Studies (Screen 2).” March 1, 141–55. https://ui.adsabs.harvard.edu/abs/2019absc.conf41155P.

Pandey, Siddharth, Jonathan Clarke, Preeti Nema, et al. 2020. “Ladakh: Diverse, High-Altitude Extreme Environments for off-Earth Analogue and Astrobiology Research.” *International Journal of Astrobiology* 19 (1): 78–98. https://doi.org/10.1017/S1473550419000119.

Parihar, Jagdish, Suraj P. Parihar, Prashanth Suravajhala, and Ashima Bagaria. 2022. “Spatial Metagenomic Analysis in Understanding the Microbial Diversity of Thar Desert.” *Biology* 11 (3): 3. https://doi.org/10.3390/biology11030461.

Paudel Adhikari, Namita, Yongqin Liu, Keshao Liu, et al. 2019. “Bacterial Community Composition and Diversity in Koshi River, the Largest River of Nepal.” *Ecological Indicators* 104 (September): 501–11. https://doi.org/10.1016/j.ecolind.2019.05.009.

Paul Antony, Chakkiath, Deepak Kumaresan, Sindy Hunger, Harold L Drake, J Colin Murrell, and Yogesh S Shouche. 2013. “Microbiology of Lonar Lake and Other Soda Lakes.” *The ISME Journal* 7 (3): 468–76. https://doi.org/10.1038/ismej.2012.137.

Payler, Samuel J., Jennifer F. Biddle, Barbara Sherwood Lollar, et al. 2019. “An Ionic Limit to Life in the Deep Subsurface.” *Frontiers in Microbiology* 10 (March). https://doi.org/10.3389/fmicb.2019.00426.

Pedersen, R.B., M.P. Searle, A. Carter, and P.C. Bandopadhyay. 2010. “U–Pb Zircon Age of the Andaman Ophiolite: Implications for the Beginning of Subduction beneath the Andaman–Sumatra Arc.” *Journal of the Geological Society* 167 (6): 1105–12. https://doi.org/10.1144/0016-76492009-151.

Peng, Xiaotong, Mengran Du, Andrey Gebruk, et al. 2025. “Flourishing Chemosynthetic Life at the Greatest Depths of Hadal Trenches.” *Nature*, July 30, 1–7. https://doi.org/10.1038/s41586-025-09317-z.

Perez, Maëva, Jin Sun, Qinzeng Xu, and Pei-Yuan Qian. 2021. “Structure and Connectivity of Hydrothermal Vent Communities Along the Mid-Ocean Ridges in the West Indian Ocean: A Review.” *Frontiers in Marine Science* 8 (October). https://doi.org/10.3389/fmars.2021.744874.

Pradhan, Samyak, and Indra Sekhar Sen. 2024. “Metamorphic CO2 Fluxes Offset the Net Geological Carbon Sink in the Himalayan-Tibetan Orogen.” *Earth and Planetary Science Letters* 647 (December): 119018. https://doi.org/10.1016/j.epsl.2024.119018.

Preston, Louisa J., and Lewis R. Dartnell. 2014. “Planetary Habitability: Lessons Learned from Terrestrial Analogues.” *International Journal of Astrobiology* 13 (1): 81–98. https://doi.org/10.1017/S1473550413000396.

Qiu, Zhongyan, Xiqiu Han, Mou Li, et al. 2021. “The Temporal Variability of Hydrothermal Activity of Wocan Hydrothermal Field, Carlsberg Ridge, Northwest Indian Ocean.” *Ore Geology Reviews* 132 (May): 103999. https://doi.org/10.1016/j.oregeorev.2021.103999.

Rafiq, Muhammad, Muhammad Hayat, Alexandre M. Anesio, et al. 2017. “Recovery of Metallo-Tolerant and Antibiotic Resistant Psychrophilic Bacteria from Siachen Glacier, Pakistan.” *PLOS ONE* 12 (7): e0178180. https://doi.org/10.1371/journal.pone.0178180.

Rajendran, Senthil Kumar, Suprokash Koner, Bashir Hussain, et al. 2025. “Mud Volcanoes and Microbial Communities: Unraveling the Mysteries of Formation, Features, and Occurrence.” *Journal of Asian Earth Sciences* 290 (August): 106635. https://doi.org/10.1016/j.jseaes.2025.106635.

Ramirez-Llodra, Eva, Claudio Argentino, Maria Baker, et al. 2023. “Hot Vents Beneath an Icy Ocean: The Aurora Vent Field, Gakkel Ridge, Revealed.” *Oceanography* 36 (1): 6–17.

Rao, Subramanya, Yuki Chan, Donnabella C. Bugler-Lacap, Ashish Bhatnagar, Monica Bhatnagar, and Stephen B. Pointing. 2016. “Microbial Diversity in Soil, Sand Dune and Rock Substrates of the Thar Monsoon Desert, India.” *Indian Journal of Microbiology* 56 (1): 35–45. https://doi.org/10.1007/s12088-015-0549-1.

Rathour, Rashmi, Juhi Gupta, Arti Mishra, Aparna C. Rajeev, Christopher L. Dupont, and Indu Shekhar Thakur. 2020. “A Comparative Metagenomic Study Reveals Microbial Diversity and Their Role in the Biogeochemical Cycling of Pangong Lake.” *Science of The Total Environment* 731 (August): 139074. https://doi.org/10.1016/j.scitotenv.2020.139074.

Ray, Jyotiranjan S., Alok Kumar, A. K. Sudheer, et al. 2013. “Origin of Gases and Water in Mud Volcanoes of Andaman Accretionary Prism: Implications for Fluid Migration in Forearcs.” *Chemical Geology* 347 (June): 102–13. https://doi.org/10.1016/j.chemgeo.2013.03.015.

Reddy, K. Umesha, C. Ningappa, and J. Sannappa. 2017. “Natural Radioactivity Level in Soils around Kolar Gold Fields, Kolar District, Karnataka, India.” *Journal of Radioanalytical and Nuclear Chemistry* 314 (3): 2037–45. https://doi.org/10.1007/s10967-017-5545-y.

Rempfert, Kaitlin R., Hannah M. Miller, Nicolas Bompard, et al. 2017. “Geological and Geochemical Controls on Subsurface Microbial Life in the Samail Ophiolite, Oman.” *Frontiers in Microbiology* 8 (February). https://doi.org/10.3389/fmicb.2017.00056.

Rempfert, Kaitlin R., Daniel B. Nothaft, Emily A. Kraus, et al. 2023. “Subsurface Biogeochemical Cycling of Nitrogen in the Actively Serpentinizing Samail Ophiolite, Oman.” *Frontiers in Microbiology* 14 (April). https://doi.org/10.3389/fmicb.2023.1139633.

Renaut, Robin W. 1990. “Recent Carbonate Sedimentation and Brine Evolution in the Saline Lake Basins of the Cariboo Plateau, British Columbia, Canada.” *Hydrobiologia* 197 (1): 67–81. https://doi.org/10.1007/BF00026939.

Ricci, Francesco, and Chris Greening. 2024. “Chemosynthesis: A Neglected Foundation of Marine Ecology and Biogeochemistry.” *Trends in Microbiology* 32 (7): 631–39. https://doi.org/10.1016/j.tim.2023.11.013.

Roberts, James H., William B. McKinnon, Catherine M. Elder, et al. 2023. “Exploring the Interior of Europa with the Europa Clipper.” *Space Science Reviews* 219 (6): 46. https://doi.org/10.1007/s11214-023-00990-y.

Rojas, Patricia, Nuria Rodríguez, Vicenta de la Fuente, Daniel Sánchez-Mata, Ricardo Amils, and José L. Sanz. 2018. “Microbial Diversity Associated with the Anaerobic Sediments of a Soda Lake (Mono Lake, California, USA).” *Canadian Journal of Microbiology* 64 (6): 385–92. https://doi.org/10.1139/cjm-2017-0657.

Rossetto, Daniele, and Sheref S. Mansy. 2022. “Metals Are Integral to Life as We Know It.” *Frontiers in Cell and Developmental Biology* 10 (March). https://doi.org/10.3389/fcell.2022.864830.

Rothschild, Lynn J., and Rocco L. Mancinelli. 2001. “Life in Extreme Environments.” *Nature* 409 (6823): 1092–101. https://doi.org/10.1038/35059215.

Rowe, Annette R., Karla Abuyen, Bonita R. Lam, et al. 2021. “Electrochemical Evidence for in Situ Microbial Activity at the Deep Mine Microbial Observatory (DeMMO), South Dakota, USA.” *Geobiology* 19 (2): 173–88. https://doi.org/10.1111/gbi.12420.

Roy, Chayan, Moidu Jameela Rameez, Prabir Kumar Haldar, et al. 2020. “Microbiome and Ecology of a Hot Spring-Microbialite System on the Trans-Himalayan Plateau.” *Scientific Reports* 10 (1): 5917. https://doi.org/10.1038/s41598-020-62797-z.

Ruff, S E, J Felden, H R Gruber-Vodicka, et al. 2019. “In Situ Development of a Methanotrophic Microbiome in Deep-Sea Sediments.” *The ISME Journal* 13 (1): 197–213. https://doi.org/10.1038/s41396-018-0263-1.

Sachan, Himanshu K., Barun K. Mukherjee, and Robert J. Bodnar. 2007. “Preservation of Methane Generated during Serpentinization of Upper Mantle Rocks: Evidence from Fluid Inclusions in the Nidar Ophiolite, Indus Suture Zone, Ladakh (India).” *Earth and Planetary Science Letters* 257 (1): 47–59. https://doi.org/10.1016/j.epsl.2007.02.023.

Sagwal, Sumit, Anil Kumar, Choudhurimayum Pankaj Sharma, Pradeep Srivastava, Shravi Agarwal, and Ravi Bhushan. 2023. “Late-Holocene Hydrological Variability from the NW Himalaya and Southwestern Tibetan Plateau: Paleo-Salinity Records from Pangong Tso.” *The Holocene* 33 (7): 842–59. https://doi.org/10.1177/09596836231163486.

Sahay, Harmesh, Sahil Mahfooz, Atul K. Singh, et al. 2012. “Exploration and Characterization of Agriculturally and Industrially Important Haloalkaliphilic Bacteria from Environmental Samples of Hypersaline Sambhar Lake, India.” *World Journal of Microbiology and Biotechnology* 28 (11): 3207–17. https://doi.org/10.1007/s11274-012-1131-1.

Saktura, Wanchese M., Solomon Buckman, Allen P. Nutman, Jessica Walsh, and George Murray. 2023. “Magmatic Records from the Karakoram Terrane: U–Pb Zircon Ages from Granites and Modern Sediments in the Nubra Valley, NW Himalaya.” *Journal of Asian Earth Sciences* 255 (October): 105771. https://doi.org/10.1016/j.jseaes.2023.105771.

Salvatore, Mark R., and Joseph S. Levy. 2021. “Chapter 11 - The McMurdo Dry Valleys of Antarctica: A Geological, Environmental, and Ecological Analog to the Martian Surface and near Surface.” In *Mars Geological Enigmas*, edited by Richard J. Soare, Susan J. Conway, Jean-Pierre Williams, and Dorothy Z. Oehler. Elsevier. https://doi.org/10.1016/B978-0-12-820245-6.00011-2.

Salwan, Richa, Arvind Gulati, and Ramesh Chand Kasana. 2010. “Phylogenetic Diversity of Alkaline Protease-Producing Psychrotrophic Bacteria from Glacier and Cold Environments of Lahaul and Spiti, India.” *Journal of Basic Microbiology* 50 (2): 150–59. https://doi.org/10.1002/jobm.200800400.

Santomartino, Rosa, Nils J. H. Averesch, Marufa Bhuiyan, et al. 2023. “Toward Sustainable Space Exploration: A Roadmap for Harnessing the Power of Microorganisms.” *Nature Communications* 14 (1): 1391. https://doi.org/10.1038/s41467-023-37070-2.

Santos, Priscila L. A., and José Brilha. 2023. “A Review on Tourism Carrying Capacity Assessment and a Proposal for Its Application on Geological Sites.” *Geoheritage* 15 (2): 47. https://doi.org/10.1007/s12371-023-00810-3.

Sanyal, Aritri, Runa Antony, Gautami Samui, and Meloth Thamban. 2018. “Microbial Communities and Their Potential for Degradation of Dissolved Organic Carbon in Cryoconite Hole Environments of Himalaya and Antarctica.” *Microbiological Research* 208 (March): 32–42. https://doi.org/10.1016/j.micres.2018.01.004.

Sarkar, S., H. Moitra, S. Bhattacharya, et al. 2022. “Spectroscopic Studies on the Puga Hot Spring Deposits, Ladakh, an Astrobiological Martian Analog Site in India.” *Journal of Geophysical Research: Planets* 127 (11): e2022JE007299. https://doi.org/10.1029/2022JE007299.

Sarkar, Siddhartha, Mohammad Atif Khan, Niharika Sharma, et al. 2023. “Lake Desiccation Drives Carbon and Nitrogen Biogeochemistry of a Sub-Tropical Hypersaline Lake.” *Hydrobiologia* 850 (20): 4557–74. https://doi.org/10.1007/s10750-023-05193-8.

Sarkar, Sudipta, Akshansha Chauhan, Rajesh Kumar, and Ramesh P. Singh. 2019. “Impact of Deadly Dust Storms (May 2018) on Air Quality, Meteorological, and Atmospheric Parameters Over the Northern Parts of India.” *GeoHealth* 3 (3): 67–80. https://doi.org/10.1029/2018GH000170.

Sauro, Francesco, Riccardo Pozzobon, Matteo Massironi, Pierluigi De Berardinis, Tommaso Santagata, and Jo De Waele. 2020. “Lava Tubes on Earth, Moon and Mars: A Review on Their Size and Morphology Revealed by Comparative Planetology.” *Earth-Science Reviews* 209 (October): 103288. https://doi.org/10.1016/j.earscirev.2020.103288.

Schauberger, Clemens, Ronnie N. Glud, Bela Hausmann, et al. 2021. “Microbial Community Structure in Hadal Sediments: High Similarity along Trench Axes and Strong Changes along Redox Gradients.” *The ISME Journal* 15 (12): 3455–67. https://doi.org/10.1038/s41396-021-01021-w.

Schmieder, Robert, and Robert Edwards. 2011. “Fast Identification and Removal of Sequence Contamination from Genomic and Metagenomic Datasets.” *PLOS ONE* 6 (3): e17288. https://doi.org/10.1371/journal.pone.0017288.

Schopf, J. William, Vinod C. Tewari, and Anatoliy B. Kudryavtsev. 2008. “Discovery of a New Chert-Permineralized Microbiota in the Proterozoic Buxa Formation of the Ranjit Window, Sikkim, Northeast India, and Its Astrobiological Implications.” *Astrobiology* 8 (4): 735–46. https://doi.org/10.1089/ast.2007.0184.

Schulte, Mitch, David Blake, Tori Hoehler, and Thomas McCollom. 2006. “Serpentinization and Its Implications for Life on the Early Earth and Mars.” *Astrobiology* 6 (2): 364–76. https://doi.org/10.1089/ast.2006.6.364.

Schwander, Loraine, Max Brabender, Natalia Mrnjavac, Jessica L. E. Wimmer, Martina Preiner, and William F. Martin. 2023. “Serpentinization as the Source of Energy, Electrons, Organics, Catalysts, Nutrients and pH Gradients for the Origin of LUCA and Life." *Frontiers in Microbiology* 14 (October). https://doi.org/10.3389/fmicb.2023.1257597.

Seelos, Kimberly D., Raymond E. Arvidson, Bradley L. Jolliff, et al. 2010. "Silica in a Mars Analog Environment: Ka'u Desert, Kilauea Volcano, Hawaii." *Journal of Geophysical Research: Planets* 115 (E4). https://doi.org/10.1029/2009JE003347.

Sen, Gautam, Michael Bizimis, Reshmi Das, Dalim K. Paul, Arijit Ray, and Sanjib Biswas. 2009. "Deccan Plume, Lithosphere Rifting, and Volcanism in Kutch, India." *Earth and Planetary Science Letters* 277 (1): 101–11. https://doi.org/10.1016/j.epsl.2008.10.002.

Shroder, John Ford, Naim Eqrar, Hamidullah Waizy, Hemayatullah Ahmadi, and Brandon J. Weihs. 2022. "Review of the Geology of Afghanistan and Its Water Resources." *International Geology Review* 64 (7): 1009–31. https://doi.org/10.1080/00206814.2021.1904297.

Shukla, Akash, Karan Maniar, Aditya Pillai, et al. 2022. "Geothermal Water in Bakreshwar-Tantoli Region in West Bengal, India: Implications on Water Quality for Irrigation and Drinking Purposes." *Groundwater for Sustainable Development* 18 (August): 100773. https://doi.org/10.1016/j.gsd.2022.100773.

Shukla, Tanuj, Indra S. Sen, and Shipika Sundriyal. 2023. "Carbon Emissions from Emerging Glacier-Fed Himalayan Lakes." *Global and Planetary Change* 225 (June): 104134. https://doi.org/10.1016/j.gloplacha.2023.104134.

Siddaiah, N. Siva, and V. Rajamani. 1989. "The Geologic Setting, Mineralogy, Geochemistry, and Genesis of Gold Deposits of the Archean Kolar Schist Belt, India." *Economic Geology* 84 (8): 2155–72. https://doi.org/10.2113/gsecongeo.84.8.2155.

Sigoyer, Julia de, Stéphane Guillot, and Pierre Dick. 2004. "Exhumation of the Ultrahigh-Pressure Tso Morari Unit in Eastern Ladakh (NW Himalaya): A Case Study." *Tectonics* 23 (3). https://doi.org/10.1029/2002TC001492.

Sikka, Deshbandhu. 1989. "Malanjkhand: Proterozoic Porphyry Copper Deposit, M.P. India." *Journal of the Geological Society of India* 34 (5): 487–504. https://doi.org/10.17491/jgsi/1989/340505.

Singh, Prachi, Kunal R. Jain, Varun Shah, and Datta Madamwar. 2021. "White Rann of Kachchh Harbours Distinct Microbial Diversity Reflecting Its Unique Biogeography." *Science of The Total Environment* 783 (August): 147094. https://doi.org/10.1016/j.scitotenv.2021.147094.

Singh, Purnima, Shiv Mohan Singh, Takahiro Segawa, and Prashant Kumar Singh. 2024. "Bacterial Diversity and Biopotentials of Hamtah Glacier Cryoconites, Himalaya." *Frontiers in Microbiology* 15 (May). https://doi.org/10.3389/fmicb.2024.1362678.

Sinha, R., and B. C. Raymahashay. 2004a. "Evaporite Mineralogy and Geochemical Evolution of the Sambhar Salt Lake, Rajasthan, India." *Sedimentary Geology* 166 (1): 59–71. https://doi.org/10.1016/j.sedgeo.2003.11.021.

Sinha, R., and B. C. Raymahashay. 2004b. “Evaporite Mineralogy and Geochemical Evolution of the Sambhar Salt Lake, Rajasthan, India.” *Sedimentary Geology* 166 (1): 59–71. https://doi.org/10.1016/j.sedgeo.2003.11.021.

Skinner, James A., and Adriano Mazzini. 2009. “Martian Mud Volcanism: Terrestrial Analogs and Implications for Formational Scenarios.” *Marine and Petroleum Geology*, Mud Volcanism: Processes and Implications, vol. 26 (9): 1866–78. https://doi.org/10.1016/j.marpetgeo.2009.02.006.

Sogin, E. Maggie, Nikolaus Leisch, and Nicole Dubilier. 2020. “Chemosynthetic Symbioses.” *Current Biology* 30 (19): R1137–42. https://doi.org/10.1016/j.cub.2020.07.050.

Sorokin, Dimitry Y., Ben Abbas, Mitchell Geleijnse, Nikolai V. Pimenov, Marina V. Sukhacheva, and Mark C. M. van Loosdrecht. 2015. “Methanogenesis at Extremely Haloalkaline Conditions in the Soda Lakes of Kulunda Steppe (Altai, Russia).” *FEMS Microbiology Ecology* 91 (4): fiv016. https://doi.org/10.1093/femsec/fiv016.

Sorokin, Dimitry Y, Horia L Banciu, and Gerard Muyzer. 2015. “Functional Microbiology of Soda Lakes.” *Current Opinion in Microbiology*, Environmental microbiology • Extremophiles, vol. 25 (June): 88–96. https://doi.org/10.1016/j.mib.2015.05.004.

Sorokin, Dimitry Y., Tom Berben, Emily Denise Melton, Lex Overmars, Charlotte D. Vavourakis, and Gerard Muyzer. 2014. “Microbial Diversity and Biogeochemical Cycling in Soda Lakes.” *Extremophiles* 18 (5): 791–809. https://doi.org/10.1007/s00792-014-0670-9.

Sorokin, Dimitry Yu., and Johannes Gijs Kuenen. 2005. “Chemolithotrophic Haloalkaliphiles from Soda Lakes.” *FEMS Microbiology Ecology* 52 (3): 287–95. https://doi.org/10.1016/j.femsec.2005.02.012.

Sperling, Erik A., Michael J. Melchin, Tiffani Fraser, et al. 2021. “A Long-Term Record of Early to Mid-Paleozoic Marine Redox Change.” *Science Advances* 7 (28): eabf4382. https://doi.org/10.1126/sciadv.abf4382.

Spray, John G., Lucy M. Thompson, Marc B. Biren, and Catherine O’Connell-Cooper. 2010. “The Manicouagan Impact Structure as a Terrestrial Analogue Site for Lunar and Martian Planetary Science.” *Planetary and Space Science*, Exploring other worlds by exploring our own: The role of terrestrial analogue studies in planetary exploration, vol. 58 (4): 538–51. https://doi.org/10.1016/j.pss.2009.09.010.

Srikantia, S. V., and M. L. Razdan. 1980. “Geology of Part of Central Ladakh Himalaya with Particular Reference to Indus Tectonic Zone.” *Journal of the Geological Society of India* 21 (11): 523–45. https://doi.org/10.17491/jgsi/1980/211101.

Stres, Blaz, Woo Jun Sul, Bostjan Murovec, and James M. Tiedje. 2013. “Recently Deglaciated High-Altitude Soils of the Himalaya: Diverse Environments, Heterogenous Bacterial Communities and Long-Range Dust Inputs from the Upper Troposphere.” *PLOS ONE* 8 (9): e76440. https://doi.org/10.1371/journal.pone.0076440.

Streule, M.J., R.J. Phillips, M.P. Searle, D.J. Waters, and M.S.A. Horstwood. 2009. “Evolution and Chronology of the Pangong Metamorphic Complex Adjacent to the Karakoram Fault, Ladakh:

Constraints from Thermobarometry, Metamorphic Modelling and U–Pb Geochronology.” *Journal of the Geological Society* 166 (5): 919–32. https://doi.org/10.1144/0016-76492008-117.

Summons, Roger E., Jan P. Amend, David Bish, et al. 2011. “Preservation of Martian Organic and Environmental Records: Final Report of the Mars Biosignature Working Group.” *Astrobiology* 11 (2): 157–81. https://doi.org/10.1089/ast.2010.0506.

Sun, Ming, An Yin, Danping Yan, et al. 2018. “Role of Pre-Existing Structures in Controlling the Cenozoic Tectonic Evolution of the Eastern Tibetan Plateau: New Insights from Analogue Experiments.” *Earth and Planetary Science Letters* 491 (June): 207–15. https://doi.org/10.1016/j.epsl.2018.03.005.

Surya Prakash, L., P. John Kurian, K. Sen, et al. 2025. “Hydrothermal Methane Venting and Its Microbial Oxidation Along the Eastern Southwest Indian Ridge, 63.5°–68°E.” *Geophysical Research Letters* 52 (2): e2024GL110958. https://doi.org/10.1029/2024GL110958.

Suyal, Deep Chandra, Divya Joshi, Saurabh Kumar, et al. 2022. “Himalayan Microbiomes for Agro-Environmental Sustainability: Current Perspectives and Future Challenges.” *Microbial Ecology* 84 (3): 643–75. https://doi.org/10.1007/s00248-021-01849-x.

Ta, Kaiwen, Shun Chen, Mengran Du, et al. 2024. “Iron Oxides (Oxyhydroxides) Associated with Biogenic Iron-Organic Framework Structures in Deep-Sea Hydrothermal Vents of the Indian Ocean.” *Chemical Geology* 650 (April): 121980. https://doi.org/10.1016/j.chemgeo.2024.121980.

Takeuchi, Nozomu, Yoichiro Hori, Noboru Furukawa, Minoru Yoshida, and Yoshiyuki Fujii. 2020. “Glacio-Environmental Aspects Recorded in Two Shallow Ice Cores Drilled in 1980 at Accumulation Area of Khumbu Glacier of Mt. Everest in Nepal Himalayas.” *Arctic, Antarctic, and Alpine Research* 52 (1): 605–16. https://doi.org/10.1080/15230430.2020.1833681.

Tamburello, G., G. Chiodini, G. Ciotoli, et al. 2022. “Global Thermal Spring Distribution and Relationship to Endogenous and Exogenous Factors.” *Nature Communications* 13 (1): 6378. https://doi.org/10.1038/s41467-022-34115-w.

Tao, Chunhui, Jian Lin, Shiqin Guo, et al. 2012. “First Active Hydrothermal Vents on an Ultraslow-Spreading Center: Southwest Indian Ridge.” *Geology* 40 (1): 47–50. https://doi.org/10.1130/G32389.1.

Tarn, Jonathan, Logan M. Peoples, Kevin Hardy, James Cameron, and Douglas H. Bartlett. 2016. “Identification of Free-Living and Particle-Associated Microbial Communities Present in Hadal Regions of the Mariana Trench.” *Frontiers in Microbiology* 7 (May). https://doi.org/10.3389/fmicb.2016.00665.

Taubner, Ruth-Sophie, Patricia Pappenreiter, Jennifer Zwicker, et al. 2018. “Biological Methane Production under Putative Enceladus-like Conditions.” *Nature Communications* 9 (1): 748. https://doi.org/10.1038/s41467-018-02876-y.

Thakkar, M. G., Gaurav Chauhan, Aadil Hussain Padder, et al. 2023. “Geoheritage Merits of the Zanskar Range of the Kashmir Himalaya: A Field Geology Museum from Precambrian to Present.” *Geoheritage* 15 (2): 75. https://doi.org/10.1007/s12371-023-00842-9.

Thomas, Elin A., Todd Bond, Jess L. Kolbusz, Yakufu Niyazi, Denise J. B. Swanborn, and Alan J. Jamieson. 2024. “Deep-Sea Ecosystems of the Indian Ocean >1000 m.” *Science of The Total Environment* 957 (December): 176794. https://doi.org/10.1016/j.scitotenv.2024.176794.

Tu, Tzu-Hsuan, Li-Wei Wu, Yu-Shih Lin, Hiroyuki Imachi, Li-Hung Lin, and Pei-Ling Wang. 2017. “Microbial Community Composition and Functional Capacity in a Terrestrial Ferruginous, Sulfate-Depleted Mud Volcano.” *Frontiers in Microbiology* 8 (November). https://doi.org/10.3389/fmicb.2017.02137.

Turrini, Paolo, Alif Chebbi, Filippo Pasquale Riggio, and Paolo Visca. 2024. “The Geomicrobiology of Limestone, Sulfuric Acid Speleogenetic, and Volcanic Caves: Basic Concepts and Future Perspectives.” *Frontiers in Microbiology* 15 (March). https://doi.org/10.3389/fmicb.2024.1370520.

Twing, Katrina I., L. M. Ward, Zachary K. Kane, et al. 2022. “Microbial Ecology of a Shallow Alkaline Hydrothermal Vent: Strýtan Hydrothermal Field, Eyjafördur, Northern Iceland.” *Frontiers in Microbiology* 13 (November). https://doi.org/10.3389/fmicb.2022.960335.

Tyler, P. A. 2003. *Ecosystems of the Deep Oceans*. Elsevier.

Ullah, Zaheen, Huan Li, Asad Khan, et al. 2023. “Mineralogy and PGE Geochemistry of Chromitites and Peridotites of the Sapat Complex in the Indus Suture Zone, Northern Pakistan: Implications for Magmatic Processes in the Supra-Subduction Zone.” *International Geology Review* 65 (10): 1719–44. https://doi.org/10.1080/00206814.2022.2106519.

Ullah, Zaheen, Jian-Wei Li, Paul T. Robinson, et al. 2020. “Mineralogy and Geochemistry of Peridotites and Chromitites in the Jijal Complex Ophiolite along the Main Mantle Thrust (MMT or Indus Suture Zone) North Pakistan.” *Lithos* 366–367 (August): 105566. https://doi.org/10.1016/j.lithos.2020.105566.

Valdiya, K.S. 2016. *The Making of India*. Society of Earth Scientists Series. Springer International Publishing. https://doi.org/10.1007/978-3-319-25029-8.

Van Dover, C. L., S. E. Humphris, D. Fornari, et al. 2001. “Biogeography and Ecological Setting of Indian Ocean Hydrothermal Vents.” *Science* 294 (5543): 818–23. https://doi.org/10.1126/science.1064574.

Venkatachalam, Siddarthan, Vasudevan Gowdaman, and Solai Ramatchandirane Prabagaran. 2015. “Culturable and Culture-Independent Bacterial Diversity and the Prevalence of Cold-Adapted Enzymes from the Himalayan Mountain Ranges of India and Nepal.” *Microbial Ecology* 69 (3): 472–91. https://doi.org/10.1007/s00248-014-0476-4.

Ventosa, Antonio, ed. 2004. *Halophilic Microorganisms*. Springer. https://doi.org/10.1007/978-3-662-07656-9.

Verma, Jagdish, Anuradha Sourirajan, and Kamal Dev. 2022. “Bacterial Diversity in 110 Thermal Hot Springs of Indian Himalayan Region (IHR).” *3 Biotech* 12 (9): 238. https://doi.org/10.1007/s13205-022-03270-8.

Villalobos-Orchard, Javiera, Baptiste Debret, Pierre Bouilhol, et al. 2025. “Geochemical Signatures of Forearc Serpentinites from Oceanic to Continental Subduction.” *Geochimica et Cosmochimica Acta* 392 (March): 1–16. https://doi.org/10.1016/j.gca.2024.11.001.

Visscher, Pieter T., Kimberley L. Gallagher, Anthony Bouton, et al. 2020. “Modern Arsenotrophic Microbial Mats Provide an Analogue for Life in the Anoxic Archean.” *Communications Earth & Environment* 1 (1): 24. https://doi.org/10.1038/s43247-020-00025-2.

Voigt, J. R. C., C. W. Hamilton, L. P. Keszthelyi, M. Varnam, S. M. Hibbard, and K. M. Stack. 2025. “The 2014–2015 Holuhraun Lava Flow-Field in Iceland as a Planetary Analog for Young Volcanic Terrains in Elysium Planitia, Mars.” *The Planetary Science Journal* 6 (4): 81. https://doi.org/10.3847/PSJ/adb5f1.

Wadsworth, Jennifer, Charles S. Cockell, Alexander StJ Murphy, et al. 2020. “There’s Plenty of Room at the Bottom: Low Radiation as a Biological Extreme.” *Frontiers in Astronomy and Space Sciences* 7 (August). https://doi.org/10.3389/fspas.2020.00050.

Waele, Jo De, and Francisco Gutiérrez. 2022. *Karst Hydrogeology, Geomorphology and Caves*. John Wiley & Sons Ltd. 10.1002/9781119605379.

Wandrey, C.J., 1998, *Geologic map of South Asia (geo8ag)*: U.S. Geological Survey data release, https://doi.org/10.5066/P9YC1C8G.

Wang, Huiqun, and Mark I. Richardson. 2015. “The Origin, Evolution, and Trajectory of Large Dust Storms on Mars during Mars Years 24–30 (1999–2011).” *Icarus*, Dynamic Mars, vol. 251 (May): 112–27. https://doi.org/10.1016/j.icarus.2013.10.033.

Wee, Shu Ying, Virginia P. Edgcomb, David Beaudoin, Shari Yvon-Lewis, and Jason B. Sylvan. 2021. “Microbial Abundance and Diversity in Subsurface Lower Oceanic Crust at Atlantis Bank, Southwest Indian Ridge.” *Applied and Environmental Microbiology* 87 (22): e01519-21. https://doi.org/10.1128/AEM.01519-21.

Westall, F., K. Hickman-Lewis, N. Hinman, et al. 2018. “A Hydrothermal-Sedimentary Context for the Origin of Life.” *Astrobiology* 18 (3): 259–93. https://doi.org/10.1089/ast.2017.1680.

Whitaker, Rachel J., and Jillian F. Banfield. 2005. “Population Dynamics Through the Lens of Extreme Environments.” *Reviews in Mineralogy and Geochemistry* 59 (1): 259–77. https://doi.org/10.2138/rmg.2005.59.11.

Wieczorek, John, David Bloom, Robert Guralnick, et al. 2012. “Darwin Core: An Evolving Community-Developed Biodiversity Data Standard.” *PLOS ONE* 7 (1): e29715. https://doi.org/10.1371/journal.pone.0029715.

Wischer, Daniela, Deepak Kumaresan, Antonia Johnston, et al. 2015. “Bacterial Metabolism of Methylated Amines and Identification of Novel Methylotrophs in Movile Cave.” *The ISME Journal* 9 (1): 195–206. https://doi.org/10.1038/ismej.2014.102.

Wu, Xiaoyue, Jiashun Hu, Ling Chen, Liang Liu, and Lijun Liu. 2023. “Paleogene India-Eurasia Collision Constrained by Observed Plate Rotation.” *Nature Communications* 14 (1): 7272. https://doi.org/10.1038/s41467-023-42920-0.

Xiao, Xiang, Weishu Zhao, Zewei Song, et al. 2025. “Microbial Ecosystems and Ecological Driving Forces in the Deepest Ocean Sediments.” *Cell* 188 (5): 1363-1377.e9. https://doi.org/10.1016/j.cell.2024.12.036.

Yamaguchi, Nobuyasu, Tomoaki Ichijo, Akiko Sakotani, Takashi Baba, and Masao Nasu. 2012. “Global Dispersion of Bacterial Cells on Asian Dust.” *Scientific Reports* 2 (1): 525. https://doi.org/10.1038/srep00525.

Yang, Na, Yongxin Lv, Mukan Ji, Shiguo Wu, and Yu Zhang. 2024. “High Hydrostatic Pressure Stimulates Microbial Nitrate Reduction in Hadal Trench Sediments under Oxic Conditions.” *Nature Communications* 15 (1): 2473. https://doi.org/10.1038/s41467-024-46897-2.

Yang, Weifang, Chunhui Tao, Huaiming Li, et al. 2017. “230Th/238U Dating of Hydrothermal Sulfides from Duanqiao Hydrothermal Field, Southwest Indian Ridge.” *Marine Geophysical Research* 38 (1): 71–83. https://doi.org/10.1007/s11001-016-9279-y.

Zhang, Yue, Hongmei Jing, and Hao Liu. 2024. “Geographical Distribution and Driving Force of Microbial Communities in the Sediments of Diamantina and Kermadec Trenches.” *Frontiers in Microbiology* 15 (November). https://doi.org/10.3389/fmicb.2024.1474645.

Zhang, Zhihao, Yongqin Liu, Weishu Zhao, and Mukan Ji. 2023. “Radiation Impacts Gene Redundancy and Biofilm Regulation of Cryoconite Microbiomes in Northern Hemisphere Glaciers.” *Microbiome* 11 (1): 228. https://doi.org/10.1186/s40168-023-01621-y.

Zhong, Ying-Wen, Peng Zhou, Hong Cheng, et al. 2022. “Metagenomic Features Characterized with Microbial Iron Oxidoreduction and Mineral Interaction in Southwest Indian Ridge.” *Microbiology Spectrum* 10 (6): e00614-22. https://doi.org/10.1128/spectrum.00614-22.

Zhou, Yadong, Dongsheng Zhang, Ruiyan Zhang, et al. 2018. “Characterization of Vent Fauna at Three Hydrothermal Vent Fields on the Southwest Indian Ridge: Implications for Biogeography and Interannual Dynamics on Ultraslow-Spreading Ridges.” *Deep Sea Research Part I: Oceanographic Research Papers* 137 (July): 1–12. https://doi.org/10.1016/j.dsr.2018.05.001.

Zhu, Hai-Zhen, Cheng-Ying Jiang, and Shuang-Jiang Liu. 2022. “Microbial Roles in Cave Biogeochemical Cycling.” *Frontiers in Microbiology* 13 (September). https://doi.org/10.3389/fmicb.2022.950005.

Zimmer, Christophe, Krishan K. Khurana, and Margaret G. Kivelson. 2000. “Subsurface Oceans on Europa and Callisto: Constraints from Galileo Magnetometer Observations.” *Icarus* 147 (2): 329–47. https://doi.org/10.1006/icar.2000.6456.

Zorz, Jackie K., Christine Sharp, Manuel Kleiner, et al. 2019. “A Shared Core Microbiome in Soda Lakes Separated by Large Distances.” *Nature Communications* 10 (1): 4230. https://doi.org/10.1038/s41467-019-12195-5.

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Supplementary Material

Table 1: Astrobiology field sites around the globe that serve as planetary analogues.

Field site	Analog For	Key Features	Latitude	Longitude	Reference
Dallol Geothermal Area, Ethiopia	Early Earth, Mars	Acidic pools, high salinity, hydrothermal	14.20	40.30	Cavalazzi et al. 2019
Gakkel Ridge, Central Arctic Ocean	Europa and Enceladus	Hydrothermal Vent Fields	81.00	5.00	Ramirez-Llodra et al. 2023
Lost City, Mid-Atlantic Ridge, Atlantic Ocean	Europa and Enceladus	Hydrothermal Vent Fields	30.13	-42.12	Amador et al. 2017
Juan de Fuca, Pacific Ocean	Europa and Enceladus	Hydrothermal Vent Fields	48.26	-123.36	Kelley et al. 2012; Osinski et al. 2006
Mariana trench, Pacific Ocean	Europa and Enceladus	Hadal trench	11.35	142.20	Preston and Dartnell 2014
Lake Vostok, Antartica	Europa and Icy Moons	Subglacial lake, high pressure, darkness	-77.00	106.00	Cassaro et al. 2021
Kīlauea Volcano, Hawaii	Lunar and Mars	Volcanism, basaltic terrain	19.43	-155.29	Bergsten et al. 2021; D'Incecco et al. 2024; Seelos et al. 2010
Haughton Impact Crater, Canada	Lunar and Mars	Permafrost-preserved impact crater	75.00	-89.50	Spray et al. 2010; Cloutis et al. 2015
Atacama Desert, Chile	Mars	Hyperarid, high UV, Mars-like soil	-24.00	-69.25	Azua-Bustos et al. 2022; Lebre et al. 2017; Visscher et al. 2020
Death Valley, USA	Mars	Extreme heat, dryness, desiccation	36.50	-117.00	Farr 2004; Douglas et al. 2008
Icelandic Volcanic Fields	Mars	Basaltic geology, subglacial hydrothermalism	65.00	-17.00	Voigt et al. 2025; Fagents and Thordarson 2007
Rio Tinto, Spain	Mars	Acidic, iron-rich river, extremophiles	37.68	-6.57	Amils et al. 2014; 2007; Gómez et al. 2011
Tibetan Plateau, China	Mars	Cold, arid, high-UV, hypoxic	32.00	91.00	L. Liu et al. 2022; Sun et al. 2018
Strýtan Hydrothermal Field, Iceland	Mars and Europa	Alkaline Hydrothermal vent	65.82	-18.12	Twing et al. 2022
McMurdo Dry Valleys, Antarctica	Mars and Icy Moons	Cold, dry, permafrost, low nutrients	-77.50	161.50	Salvatore and Levy 2021
Svalbard Archipelago, Norway	Mars, icy moons	Glacial and permafrost environment	78.20	15.60	Kołodziejczyk et al. 2025; Hauber et al. 2011

Table 2: Compilation of putative planetary analogue sites across the Indian subcontinent classified by ecosystem type, geological context, mineralogy, and planetary analog relevance. Each site is characterized by its host lithology, geologic age, geochemical parameters (pH, temperature, salinity), and associated minerals. Salinity values are standardized as: Low (<1,000 mg/L TDS), Mid (1,000–10,000 mg/L TDS), and High (>10,000 mg/L TDS). The table highlights analog links to planetary bodies (Mars, Moon, Venus, and Icy Ocean worlds such as Europa and Enceladus) and to Early Earth. References provided for each field site correspond to published geological and geomicrobiological studies.

Environment	Field site	Lithology (hosted rocks)	Geological age of host rock (Ma)	Associated Minerals	Lat.	Long.	Altitude (m)	pH	Temp (°C)	Salinity	Planetary Analog	Rationale	References
Caves and mines	Borra Caves	Terrestrial subsurface karst cave hosted in proterozoic (Mesoproterozoic–Neoproterozoic) limestones of the Cuddapah Supergroup	5700	Calcite, aragonite, speleothems, oxides	18.33	83.05	705				Lunar/Mars	Lava tubes and fractured crust on Mars/Moon provide radiation-shielded habitats analogous to Earth's subsurface caves and mines.	Baskar and Baskar 2022; Baskar et al. 2009; 2011
	Kotumsar Cave	Terrestrial subsurface karst cave hosted in Proterozoic (Mesoproterozoic–Neoproterozoic) limestones of the Chhattisgarh Supergroup	1000	Calcite, aragonite, speleothems, oxides	18.85	81.95	560						
	Kolar Gold Fields	Terrestrial subsurface mine hosted in Archaean (Late Archaean, ~2.6 Ga) greenstone belt volcanics and granitoids	2500	Gold, quartz, sulfides (pyrite, arsenopyrite)	12.95	78.27	900						Siddaiah and Rajamani 1989; Reddy et al. 2017
	Jaduguda Uranium Mine	Terrestrial subsurface mine hosted in Proterozoic (Paleoproterozoic, ~1.6–1.4 Ga) metasediments and granites	1400	Uraninite, chalcopyrite, pyrite, chlorite, quartz	22.65	86.35	400						Pal et al. 2011
	Zawar Mines	Terrestrial subsurface mine hosted in Proterozoic (Paleoproterozoic, ~1.8–1.6 Ga) carbonates and volcanics of the Aravalli Supergroup	1600	Lead, zinc (sphalerite, galena), pyrite, carbonates	24.37	73.73	550						Pandey et al. 2007; Equeenuddin et al. 2017; Sikka 1989
	Malanjkhand Copper Mine	Terrestrial subsurface mine hosted in Proterozoic (Late Archaean–Early Proterozoic, ~2.5–2.0 Ga) granitoid-hosted copper deposit	2000	Chalcopyrite, bornite, quartz, magnetite, pyrite	22.00	80.70	600						
Desert ecosystems	Thar Desert	Proterozoic Marwar Supergroup, along with isolated outcrops of the Malani Igneous Suite, the Erinpura Granites, and the Sirohi Group. In the southwest (Jaisalmer and Barmer Basins), Mesozoic and Tertiary sedimentary deposits are found, bordered by the extensive Quaternary alluvium.	600	Dune sands chiefly quartz; playas dominated by halite with gypsum/anhydrite, calcite/dolomite and detrital quartz–feldspar–mica	27.02	71.72	200		-5 to 50		Mars	Hyperarid conditions and sandstorms serve as analogs for the Martian environment, where extreme aridity, dust storms, and limited water availability shape surface processes and habitability.	Khormali and Monger 2020; Sarkar et al. 2019

Environment	Field site	Lithology (hosted rocks)	Geological age of host rock (Ma)	Associated Minerals	Lat.	Long.	Altitude (m)	pH	Temp (°C)	Salinity	Planetary Analog	Rationale	References
Geothermal springs	Bakreswar	Springs emerge along fractures associated with Precambrian granitic rocks and sedimentary remnants of the Gondwana sequence (ranging from the Lower Permian to the Middle Jurassic)	100	Primarily granite within the Archean Chotanagpur Gneissic Complex	23.88	87.37	79	7-8	50 to 70	Low	Early Earth	Hydrothermal springs were likely sites for prebiotic chemistry and early life emergence.	Das et al. 2022; Majumdar et al, 2000; Shukla et al, 2022;
Mud volcanoes	Balochistan	Modern (Holocene) geothermal systems in Makran accretionary prism (mainly Oligocene–Miocene flysch	100	Silica sinter (opal-A), calcite/aragonite; sandstones/shales rich in quartz, feldspar, clay minerals.	26.01	65.51	200	6-7	30 to 90	Moderate	Mars	Observed mud volcano-like structures on Mars suggest cryovolcanic or sedimentary-fluid extrusion processes analogous to Earth mud volcanoes.	Delisle et al, 2002; Kassi et al., 2014; Yaseen et al, 2021
	Andaman Islands	MVs are hosted by the Eocene trench-slope deposits, called the Mithakhari Group, the clasts in the mud breccia are primarily from this lithology. Clasts of basalt belonging to the ~94 Ma old Ophiolite Group	94	illite, kaolinite, volcanic glass, brine and sulfide nodules	12.13	92.79				High			Chaudhuri et al. 2012; Achyuthan and Eastoe, 1999
Saline ecosystems	Rann of Kutch	Holocene supratidal salt flats (sabkhas) with annual flooding/evaporation	66	Surface halite crusts; gypsum grows within clays/sands; brines enriched in boron.	23.73	70.22	15	8-10	-2 to 48	High	Mars	Evaporitic basins mineral deposits record past aqueous activity and possible habitats for microbial life.	Biswas et al., 2021; Chavan et al, 2022; Singh et al.,2021
	Lonar Crater Lake	Pleistocene impact (~0.57 Ma) excavated into Deccan Traps basalts (~66 Ma)	66	Basalt dominated by plagioclase (labradorite) and pyroxene (augite/pigeonite); shocked glass and maskelynite reported	19.98	76.51	563	10.5	15 to 45	High			Fredriksson et al., 1973; Maloof et al., 2010; Antony et al., 2013
	Sambhar Lake	Holocene–Late Quaternary playa/lacustrine sediments surrounded by proterozoic Aravalli hills	200	Halite, gypsum/anhydrite, lacustrine carbonates; clastic quartz–feldspar–mica influx from catchment	26.92	75.20	360	9-10	7 to 37	High			Sinha et al., 2004; Singh et al., 2024; Sahay et al., 2012, Sarkar et al., 2023; Pal et al., 2020
Tectono-magmatic terrains	Deccan Traps	Late Cretaceous–Paleogene continental flood basalts (~66–64 Ma)	70	Tholeiitic basalts rich in plagioclase, clinopyroxene (augite), ± olivine; secondary zeolites common	20.50	75.00	600		-10 to 45		Early Earth/Venus	Volcanic provinces, oceanic crustal rocks, and ductile crustal processes were widespread on the early Earth and Venus	Sen et al. 2009; Beane et al. 1986; Dutta et al. 2019; 2018; Jungbluth et al. 2016
	Waziristan	Late Jurassic to Early Cretaceous ophiolites	150	braunite, cryptocrystalline quartz, minor hematite	28.63	70.59	100		-5 to 50				Jalil et al., 2023

Table 3: Compilation of putative planetary analogue sites across the Himalayan region classified by ecosystem type, geological context, mineralogy, and planetary analog relevance. Each site is characterized by its host lithology, geologic age, geochemical parameters (pH, temperature, salinity), and associated minerals. Salinity values are standardized as: Low (<1,000 mg/L TDS), Mid (1,000–10,000 mg/L TDS), and High (>10,000 mg/L TDS). The table highlights analog links to planetary bodies (Mars, Moon, Venus, and Icy Ocean worlds such as Europa and Enceladus) and to Early Earth. References provided for each field site correspond to published geological and geomicrobiological studies.

Environment	Field site	Lithology (hosted rocks)	Geological age of host rock (Ma)	Associated Minerals	Lat	Long	Altitude (m)	pH	Temp (°C)	Salinity	Planetary Analog	Rationale	References
Caves and mines	Krem Phyllut	Terrestrial subsurface karst cave hosted in Late Cretaceous–Paleogene limestones of the Shillong Plateau	66	Calcite, aragonite, speleothems	25.25	91.73	1300				Lunar/Mars	Lava tubes and fractured crust on Mars/Moon provide radiation-shielded habitats analogous to Earth's subsurface caves and mines.	Baskar and Baskar 2022; Baskar et al. 2009; 2011
	Mawsmai Caves	Terrestrial subsurface karst cave hosted in Late Cretaceous–Paleogene limestones of the Shillong Plateau	66	Calcite, aragonite, speleothems, silica	25.20	91.73	1200						
Desert ecosystems	Changthang	Quaternary alluvial–lacustrine cover over Ladakh Batholith (Cretaceous–Paleogene granitoids) and Tethyan sedimentary sequence (Paleozoic–Mesozoic carbonates/siliciclastics)	50	Batholith felsics (quartz–K-feldspar–plagioclase–biotite); Tethyan units dominated by calcite/dolomite, quartz arenites and shales (clays).	33.50	78.42	4500		-40 to 25			Hyperarid conditions, high UV, serve as terrestrial analogs for surface environments on Mars and the Lunar regolith, where desiccation, intense radiation, and limited shielding define habitability constraints	Ali et al, 2025
Geothermal springs	Puga	Active geothermal field depositing modern (Holocene) travertine/sinter on Trans-Himalayan basement; quartzo feldpathic geeiss of Late Proteozoic cambrian age at the deepest levels	100	Borates (borax/ulexite), thenardite (Na_2SO_4), halite, opaline silica, plus native sulfur and borax observed	33.22	78.36	4400	7.5-9	30 to 84	Low	Early Earth	Hydrothermal springs were likely sites for prebiotic chemistry and early life emergence.	Gopal et al, 2002, Sarkar et al, 2022; Harinarayana et al, 2006; Ansari et al., 2025; Kumari et al., 2024; Verma et al., 2022
	Chumathang	Holocene hot-spring precipitates (travertine) over Trans-Himalayan host rocks	100	Calcite/aragonite travertine; regional reports of borax/sulfur	33.36	78.33	3960	8-9	40 to 86	Mid			Ansari et al., 2023; Ansari et al., 2025; Verma et al., 2022
	Bamyan	Modern (Holocene) hot-spring activity associated with Quaternary tectonics; hosted in Paleozoic–Mesozoic carbonates and granites.	100	Travertine (calcite), opaline silica, and host-rock minerals (quartz–feldspars, calcite/dolomite from limestones).	35.35	68.00	2500	6-8	20 to 30	Mid			Jawadi et al., 2021
	Panamik	Ongoing Holocene hot-spring deposition in Nubra Valley	60	Spring precipitates include travertine (calcite/aragonite)	34.04	77.55	3200	7-8	60 to 70	Low			Ansari et al., 2023; Ansari et al., 2025; Verma et al., 2022
	Manikaran	Holocene hydrothermal deposits within Higher Himalayan metasedimentary/granitic rocks	0.01	Active travertine ($CaCO_3$) formation at vents	32.03	77.35	1760	6-7	35 to 94 (spring water)	Low			Husain et al., 2020

Environment	Field site	Lithology (hosted rocks)	Geological age of host rock (Ma)	Associated Minerals	Lat	Long	Altitude (m)	pH	Temp (°C)	Salinity	Planetary Analog	Rationale	References
Glacial ecosystem	Khardung La	Pass cuts Khardung Volcanics (Cenozoic rhyolitic to intermediate lavas) over Ladakh Batholith (Cretaceous–Paleogene)	100	Quartz–feldspar-rich rhyolites/ignimbrites; batholith granodiorite–granite with quartz–K-feldspar–plagioclase–biotite	34.28	77.60	5602		-30 to 15		Icy Ocean Worlds	Mimics outer ice shells of Europa, Enceladus, and other icy worlds	Lakhan et al, 2019; Srikantia and Razdan, 1980
	Siachen Glacier	Quaternary glacier on Karakoram bedrock (High-grade metamorphic complexes and granites)	1.5	Quartz–feldspar–mica gneisses/schists; granitoids with quartz–feldspars–biotite; local amphibolites	35.42	77.11	5400		-50 to 10				Saktura et al, 2023
	Taglang La	Metamorphosed sediments of the Tethyan/High Himalayan realm; nearby sections expose Permian carbonates below the pass	275	metasedimentary cover of alternating quartzite-schist carbonaceous schist and marble	33.51	77.77	5328		-30 to 10				Pandey et al. 2020
	Khumbu Glacier	Quaternary glacier over High Himalayan Crystalline (gneiss–schist) with abundant leucogranite intrusions	1.5	Quartz–feldspar–muscovite–biotite gneisses and leucogranites; garnet/sillimanite locally.	27.96	86.93	4900		-5 to 35				Takeuchi et al, 2020; Kirkbride et al, 2023
	Zanskar Basin	Quaternary glacier within Zanskar; bedrock includes Greater Himalayan Sequence and Tethyan units	1.5	Quartz–feldspar–mica assemblages in gneiss/schist; calcite in carbonates	33.49	76.98	4500		-20 to 10				Thakkar et al, 2023
	Spiti Valley	Tethyan Himalaya marine succession from Precambrian–Cretaceous, notably rich Triassic–Jurassic–Cretaceous carbonates/shales.	100	Limestone/dolomite (calcite), shales with clays; ferruginous horizons locally	32.25	78.02	3800		-30 to 30				Mandal et al, 2021; Salwan et al, 2010; Singla et al., 2021
	Hunder, Shyok valley	Cenozoic Khardung volcanic suite (intermediate–felsic lavas) and intrusives of the Ladakh Batholith (Cretaceous–Paleogene); SSZ also exposes Shyok ophiolites/flysch	100	Volcanics rich in plagioclase–pyroxene ± quartz; batholith granodiorite (quartz–feldspars–biotite); ophiolite serpentinized peridotite/gabbro assemblages.	34.59	77.42	3160		-20 to 35				Martin et al, 2025; Lone et al, 2023
	Nubra Valley	Quaternary aeolian dunes and glaciofluvial deposits over Ladakh Batholith / SSZ bedrock.	1.5	Dune/bar sands dominated by quartz with feldspar/mica; local carbonates in spring deposits	34.60	77.70	3048		-10 to 35				Chandra et al., 2023
	Pamir Plateau	Triassic–Cretaceous sedimentary sequences of South Pamir plus Early Cretaceous arc magmatism related to Neo-Tethys subduction	100	Arc volcanics (plagioclase–pyroxene–olivine ± amphibole) and sedimentary carbonates/siliciclastics (calcite, quartz–feldspar).	36.50	73.50	3000		-20 to 25				Liu et al., 2020;

Environment	Field site	Lithology (hosted rocks)	Geological age of host rock (Ma)	Associated Minerals	Lat	Long	Altitude (m)	pH	Temp (°C)	Salinity	Planetary Analog	Rationale	References
Saline ecosystems	Kyagar Tso Lake	Quaternary closed-basin lacustrine/playa deposits over Puga gneiss complex hosted in the Nidar Ophiolite	66	Evaporites incl. borax/ulexite (Na-borates), halite, gypsum/anhydrite, jarosite–alunite–copiapite–tamarugite, opaline silica, plus native sulfur reported in valley fill.	33.12	78.24	4700	9-10	-20 to 20	High	Icy Ocean Worlds	Subsurface brines under the ice, high salt concentrations, potential habitats in salt-rich oceans.	Pandey et al. 2020;
	Pangong Tso Lake	Quaternary–Holocene lacustrine system along India–Tibet suture, catchment on Ladakh Batholith and Karakoram	100	Carbonate muds, aragonite–calcite, with clastic quartz, feldspars; evaporite facies locally (halite, gypsum); hydrothermal carbonates along active faults.	33.72	78.90	4250	9	-35 to 20	Mid			Streule et al, 2009; Rathour et al, 2020; Sagwal et al 2023,
	Band-e-Amir Lakes	Lakes dammed by Holocene travertine; regionally underlain by Mesozoic (Jurassic–Cretaceous) carbonates in Bamyan	72	Travertine ($CaCO_3$) forms the natural dams; surrounding bedrock is limestone/dolostone	34.84	67.23	3000	8-9	-10 to 25	Mid			Shroder et al., 2021;
	Tso Kar Lake	Holocene closed-basin saline lake deposits within Ladakh's Quaternary lacustrine systems hosted in Changthang	50	Evaporites including halite, gypsum, and borates (e.g., ulexite/borax) documented regionally in Ladakh basins.	33.30	78.00	4530	9-10	-20 to 20	High			Dey et al, 2023; Gopal et al, 2002; Ali et al, 2025
	Tso Moriri Lake	Late-glacial to Holocene lacustrine carbonates/siliciclastics; catchment on Trans-Himalayan/Tethyan units	50	Carbonate muds (calcite/aragonite) with clastic quartz–feldspar from catchment.	32.90	78.32	4522	8.5-9.5	-20 to 20	Mid			Sigoyer et al, 2004; Gopal et al, 2002
Tectono-magmatic terrains	Ladakh	Mesozoic (Jurassic to Lower Cretaceous) ophiolites	130	Olivine, pyroxene, serpentine (pseudomorphs of olivine and pyroxene), and chromite.	32.75	78.00	4100		-25 to 10		Lunar/Mars	Hyperarid conditions, high UV, serve as terrestrial analogs for surface environments on Mars and the Lunar regolith, where desiccation, intense radiation, and limited shielding define habitability constraints	Villalobos-Orchard et al. 2025; Bhat et al. 2022; Ullah et al. 2020
	Rangit Window	Tectonic window exposing Lesser Himalayan units incl. Gondwana (Permo-Carboniferous) within the Rangit duplex (bounded by Ramgarh Thrust/MBT)	300	Predominantly siliciclastic (quartz–feldspar–mica) with coal-bearing horizons in the Gondwana sequence	27.29	88.29	400		-5 to 27		Early Earth/Venus	Volcanic provinces, oceanic crustal rocks, and ductile crustal processes were widespread on the early Earth and Venus	Schopf et al., 2008

Table 4: Compilation of putative planetary analogue sites across the Indian Ocean classified by ecosystem type, geological context, mineralogy, and planetary analog relevance. Each site is described in terms of its host lithology, geologic age, and key geochemical parameters (pH and temperature), along with associated minerals. Collectively, these sites serve as valuable parallels to Early Earth conditions and icy ocean worlds. References for each field site correspond to published geological and geomicrobiological studies.

Environment	Field site	Location	Lithology (hosted rocks)	Geological age of host rock (Ma)	Associated Minerals	Lat.	Long.	Altitude (m)	pH	Temp (°C)	Planetary Analog	Rationale	References
Deep-sea trenches	Makran Trench	Arabian Plate subducting beneath Eurasian Plate	Active trench/accretionary wedge — sediment pile from Quaternary to Neogene turbidites and hemipelagic muds.	65	Detrital quartz–feldspar–mica from hinterland; calcite from biogenic carbonate ooze; clay minerals (illite/smectite).	10.00	66.00	-3500		2 to 4	Early Earth	Early Earth's deep ocean subduction environments where high pressure + nutrient fluxes influenced early biospheres.	Mouchot et al., 2010; Fisher et al., 2012; Chen et al., 2024
	Java (Sunda) Trench	Indo-Australian Plate subducting beneath Eurasian Plate	Active trench with Quaternary trench-fill turbidites over oceanic crust (~Cretaceous age	45	Detrital quartz–feldspar–mica; volcanogenic glass; calcite/aragonite from biogenic sediment.	-10.32	109.97	-7290		1 to 2			Jamieson et al. 2022
	Diamantina Trench	Rift-related fracture zone	Cretaceous oceanic crust floored by basalt; trench-fill pelagic sediments (Neogene–Quaternary).	50	Basalt with plagioclase, pyroxene, olivine; pelagic carbonate ooze (calcite).	-35.00	104.00	-8047		1 to 2			Stewart and Jamieson, 2019; Zhang et al., 2024
Deep-sea vents	Wocan	Carlsberg Ridge	Active (modern) hydrothermal systems on slow- to intermediate-spreading ridges (Cretaceous–Jurassic oceanic crust).	100	Massive sulfide deposits — pyrite, chalcopyrite, sphalerite, barite, silica; basalts with plagioclase, clinopyroxene, olivine	6.37	60.52	-3105	n.d.	358	Icy Ocean Worlds	Hydrothermal activity at the ocean–rock interface inferred from plume chemistry; parallels Earth's vent-driven chemolithotrophy	Most et al., 2023
	Daxi	Carlsberg Ridge		100		6.80	60.30	-3450	n.d.	273			
	Tianxiu	Carlsberg Ridge		100		-3.65	63.75	-3500	n.d.	"high"			
	Onnuri	Central Indian Ridge		100		-11.42	66.42	-2170	n.d.	242			
	Kairei	Central Indian Ridge		100		-25.32	70.03	-2460	3.3	369			
	Solitaire	Central Indian Ridge		100		-19.55	65.83	-2606	4.4	307			
	Dodo	Central Indian Ridge		100		-18.33	65.47	-2745	3.3	356			
	Edmond	Central Indian Ridge		100		-23.88	69.60	-3320	3.1	382			
	Pelagia	South-East Indian Ridge		100		-26.15	71.43	-3690	3.2	368			
	Duanqiao	South-West Indian Ridge		100		-37.65	50.40	-1732	n.d.	277			
	Tiancheng	South-West Indian Ridge		100		-27.95	63.53	-2729	n.d.	"high"			
	Longqi	South-West Indian Ridge		100		-37.78	49.65	-2755	3.6	379			