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Earth's habitability in a planetary framework: The Archean rock record

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ABSTRACT

This study briefly synthesizes geochemical and isotopic evidence of co-evolution of Earth's surface, atmosphere, oceans and biosphere from Hadean to Archean geological records. Impact induced Hadean tectonics, emergence of oceans and the reducing atmosphere created conditions favourable for the initial biological processes. Intense Archean volcano-hydrothermal activity and tectonism were responsible for nutrient supply and circulation, supporting microbial life. Geochemical trends of bio-essential elements such as Fe, Mn, Mo, P, Ni, Co, and U indicate a strong relationship between elemental cycling and early life processes. Archean passive margin sedimentary rocks such as stromatolitic carbonates, banded iron formations (BIFs), manganese deposits, and carbonaceous shales present in the greenstone belts of Dharwar Craton preserve biosignatures indicating ancient microbial activity under varying redox conditions of early Earth. Higher thermal state of the Archean Earth led to intense volcano-exhalative activity, released Fe–Mn, gold as aqueous complexes, along with various sulphide minerals, creating alkaline to acidic, reduced and chemically enriched oceans favouring cyanobacterial growth. Oxygen released due to microbial activity deposited Fe and Mn as oxides at shallow shelves, which favoured the detoxification of the oceans, rendering the planet habitable for the growth and diversification of advanced life forms. Decayed organic matter contributed to the deposition of carbonaceous shales at the deeper ocean with $\delta^{13}C_{org}$ of −38.8‰ to −8‰ VPDB, coinciding with associated BIFs (−28.5‰) and Mn formations (−26.2 to −23.2‰ VPDB) reflecting on significant biological influence. Geological similarities of Mars, Venus with Earth suggest that life supporting conditions may have existed for a short time on these terrestrial planets.

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Research highlights

- Archean tectonics was the driving force for the Earth's habitability.
- Vigorous volcanism provided nutrients and paved way for the evolution of biosphere.
- BIF-Mn formations, stromatolitic carbonates, C-shales preserve biosignatures.
- Stable isotopic and geochemical proxies compliment coevolution of bio-geosphere.

1 Introduction

Recent developments in the expanding fields of geobiology and astrobiology have increasingly focused on the search for early life on Earth and other planetary bodies of our solar system involving multiple scientific disciplines including cosmology, biology, physics, chemistry and geology (Wang et al., 2023 and references therein). In this

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direction, understanding the Earth's earliest environments plays an important role, not only to trace the origin of life on our planet, but also to identify biosignatures on other planetary bodies, for which Earth's deep-time geochemical archives provide a valuable reference. There are some universal and basic conditions required for the origin and evolution of biosphere which can be inferred from specific lithounits on Earth, and may serve as important criteria for identifying extraterrestrial habitability (Korenaga, 2021; Wang et al., 2023). These include both internal and external factors including the presence of liquid water, a stable energy source, a protective atmosphere, temperature, availability of bio-essential elements such as C, H, N, O, P and S, as well as geological processes that recycle these nutrients (Schulze-Makuch and Irwin, 2018). Furthermore, Earth's tectonism through time has played an important role, which is dependent on planetary energy and material release, manifested through volcanism and orogeny in greenstone belts. These provided bio-essential trace elements to the oceans and thus creating conducive conditions for life processes (Robbins et al., 2016; Hickman-Lewis et al., 2020; Mukherjee and Large, 2020; Wang et al., 2023). This contribution presents a concise overview of environmental conditions during the Earth's incipient stages, from the Hadean through the Archean, within the broader context of its geological evolution. Considering the significance of the bio-geological environment for the origin and subsistence of life, the current understanding of the conditions that prevailed on early Earth such as the impact-driven Hadean landscape, atmosphere and ocean evolution, trace element availability, nutrient cycling, plate tectonics and the earliest evidences of life have been summarized, with special emphasis on the biosignatures from the Neoarchean passive margin sequences from the greenstone belts of Dharwar Craton. Furthermore, a comparison of these conditions with those on the other terrestrial planetary counterparts has been detailed to understand their habitability.

2 Impact environment

The impact environment of the Hadean Earth was defined by intense bombardment during the first billion years of the formation of the solar system, which significantly influenced the initial physical and chemical states of the inner planets and their potential to support biospheres. Current research suggests a prolonged phase of bombardment termed as the 'soft cataclysm' starting ∼4.1–4.2 Ga and continuing with significant impacts until ∼3.81 Ga, in contrast to the earlier idea of a short-lived spike in impacts at ∼3.9 Ga (hard cataclysm; Koeberl, 2006; Zellner, 2017). The most intense part of this solar-system-wide bombardment is known as the late heavy bombardment (LHB), as evidenced through the thermal events recorded in pre-4.0 Ga terrestrial zircons clustering at ∼3.9 Ga (Bell and Harrison, 2013).

From a biological perspective, the LHB was both catastrophic and possibly conducive to the emergence of life (Abramov et al., 2013). Large impacts may have sterilized the Earth's surface by raising global ocean temperatures above 100 ℃, making the environment inhospitable, while simultaneously creating widespread hydrothermal systems, which provided stable, energy-rich environments favourable for the origin of life (Sleep et al., 2001; Zahnle et al., 2007; Maruyama et al., 2018). The earliest tentative evidence for life may extend as far back as 4.1 Ga, based on C-isotope signatures preserved in graphite inclusions within zircons (Bell et al., 2015). While this finding requires further corroboration, it raises the possibility that life may have emerged relatively soon after Earth's formation. More robust signs of microbial life appear ∼3.8 Ga, coinciding with the declining stage of the LHB, suggesting that repeated global-scale impact events have influenced early biological evolution (Schidlowski, 1988; Papineau et al., 2010). Zircon with graphitic inclusions identified from the Jack Hills, Australia display δ^{13}C of -24 ± 5‰ reported to be consistent with biological fractionation indicative of a terrestrial biosphere (Bell et al., 2015). The 3.85 Ga Akilia sedimentary rock from Greenland reported to contain graphite inclusions within the apatite mineral, display the ^{13}C-depleted signatures (δ^{13}C ~ -13 to -17‰) suggested to be biogenic carbon (Dodd et al., 2019). Additionally, the extraterrestrial origin of prebiotic compounds before and during the LHB cannot be ruled out, as supported by several experimental and modelling studies demonstrating the formation of various organic molecules in chondritic material (e.g., Pasek and Lauretta, 2007; Furukawa et al., 2013; Takeuchi et al., 2020). Phylogenetic analyses based on 16S rRNA sequences as well as experimental studies suggest that all modern life descended from a common ancestral population, likely thermophilic or hyperthermophilic in nature (Shimizu et al., 2007; Akanuma et al., 2013). If early life originated in near-surface environments as proposed in the RNA hypothesis, then catastrophic impacts could have repeatedly eradicated surface organisms. In this scenario, deep hydrothermal ecosystems may have allowed thermophilic life to persist and recolonize after each cataclysm (Sasselov et al., 2020).

3 Atmosphere-ocean system

The formation of earliest atmosphere and oceans on the planet Earth is related to the Moon-forming impact, a collision between the proto-Earth and a Mars-sized body (Matsui and Abe, 1986), and this high energy impact melted a vast portion of Earth's interior forming a global magma ocean and a hot, silicate vapor atmosphere (Zahnle et al., 2007). With the planetary cooling, the silicate vapor gradually condensed, while the volatiles (H_2O and CO_2) were released through magma ocean degassing. This led to the formation of an atmosphere dominated by greenhouse gases, which enhanced the surface temperatures and delayed the solidification of magma ocean (Hamano et al., 2013; Lebrun et al., 2013). Continued planetary cooling led to the condensation of water vapor, which, by limiting radiative heat loss, delayed surface solidification. With the decrease of surface temperatures to ~500 K due to the solidification of magma ocean, thin basaltic crust began to form. Under high-pressure conditions associated with a dense CO_2-rich atmosphere, liquid water may potentially have remained thermodynamically stable at the surface or subsurface (Sleep et al., 2001; Lebrun et al., 2013). These conditions marked the emergence of the Earth's first oceans, which interacted with the mafic crust, contributed to the evolution of ocean chemistry and the stabilization of near-neutral pH conditions (Sleep et al., 2001).

Planetary evolution models and analogies to present-day volcanic gases suggest that the Hadean atmosphere was dominated by H_2O and CO_2, with minor CO, H_2, and halogen species such as HCl, consistent with both modern volcanic emissions and the NaCl content of present oceans (Liu, 2004; Zahnle et al., 2007; Sleep, 2010). Studies suggest that highly siderophile elements (HSEs) in the early mantle were in higher concentrations after core formation, indicating late accretion of reducing meteoritic material, which has also delivered C (as graphite) and N (as nitrides), suggesting a highly reducing early mantle and atmosphere favorable for prebiotic chemistry (e.g., formation of HCN and H_2CO; Dauphas, 2017). Experimental studies suggest that the Hadean surface environment was cold and alkaline, driven by weathering of impact ejecta, volcanic activity and wet-dry cycles, enabling the formation of key prebiotic molecules of amino acids and nucleosides through shock-induced reactions, thus setting the stage for the origin of life (e.g., Takeuchi et al., 2020; Ianeselli et al., 2022).

The Archean Eon marked a significant shift from an abiotic environment of the Hadean to a biologically modulated 'bio-geo' atmosphere (Goldblatt et al., 2024). Despite the reduced solar luminosity estimated at ~75–80% of present-day levels, geological evidences from fluvial sediments, limited glaciation and the presence of well-preserved volcano-sedimentary lithounits suggest a temperate global climate (Sagan and Chyba, 1997; Charnay et al., 2017). While atmospheric pressure as inferred from fossilized raindrop imprints was suggested to be comparable to or lower than modern levels, the surface temperatures were predominantly influenced by planetary albedo, atmospheric pressure, cloud dynamics, photochemical haze formation and water vapor feedbacks (Kasting et al., 1984). Despite the evidences of the advent of oxygenic photosynthesis deep in the Archean, the atmospheric O_2 levels remained extremely low (<0.2 ppmv). The delayed oxygenation of the atmosphere, culminating in the Great Oxidation Event (GOE) at ~2.4 Ga is thus accounted to the accumulation of O_2 beyond the critical threshold of ~0.1 ppmv, allowing the formation of a protective ozone layer (Goldblatt et al., 2006). The evolving Archean atmospheric changes were also reflected in the ocean chemistry, which remained largely anoxic (Catling and Zahnle, 2020), slightly acidic to neutral (pH 6.4–7.4), rich in ferrous iron (Fe^{2+}), low sulfate levels (<2.5 mM), with salinity ranging between 20–50 g/kg and dominated by ammonium (NH_4^+)-based nitrogen cycling (Blättler et al., 2016; Marty et al., 2018). Studies have also suggested that increased oxygen levels (GOE and NOE) in the atmosphere correlate with supercontinent break-up in the geological time scale as a consequence of increased surface weathering and subsequent burial of organic matter which led to atmospheric oxidation (Fig. 1; Brune et al., 2017; Duncan and Dasgupta, 2017). The chemolithoautotrophy, anoxygenic and oxygenic photosynthesis, nitrogen fixation, and microbially mediated carbonate precipitation of Archean era have not only enhanced the primary productivity, but also altered redox dynamics within the ocean-atmosphere system.

4 Trace element distribution and the evolution of geobiosphere

Bio-essential elements such as Fe, Mn, S, Ni, Cu, Cd, and Co dissolve to varying degrees under different oceanic conditions viz. ferruginous (anoxic, iron-rich), euxinic (anoxic, sulfide-rich), and oxic. Modelling studies suggest that their solubility could have supported cyanobacterial growth in Archean oceans (Saito et al., 2003). Phosphorus, initially suggested to be limited in the Archean due to iron scavenging was potentially retained by silica-rich oceans, but studies have demonstrated that Fe^{+2} solubilised P in the pre-oxygenated oceans even at diagenetic temperatures of ~200 °C, thus acting as a major nutrient for early life (Herschy et al., 2018). Enrichment of P in Archean black shales, contrasted with its lower concentrations during mass extinction events signifies its complex role in sustaining life and Earth's habitability (Fig. 1; Robbins et al., 2016). Molybdenum is another bio-essential and redox sensitive trace element essential for nitrogen fixation as part of the nitrogenase enzyme. In euxinic conditions, Mo is removed as thiomolybdates, limiting its availability and constraining primary productivity (Helz and Vorlicek, 2019). Nickel which is an essential element for methanogenesis and carbon cycling is suggested to have depleted during the Neoarchean due to mantle cooling and decreased weathering, a phenomenon termed as 'methanogen famine' (Konhauser et al., 2009). This depletion reduced methane emissions and contributed to GOE,

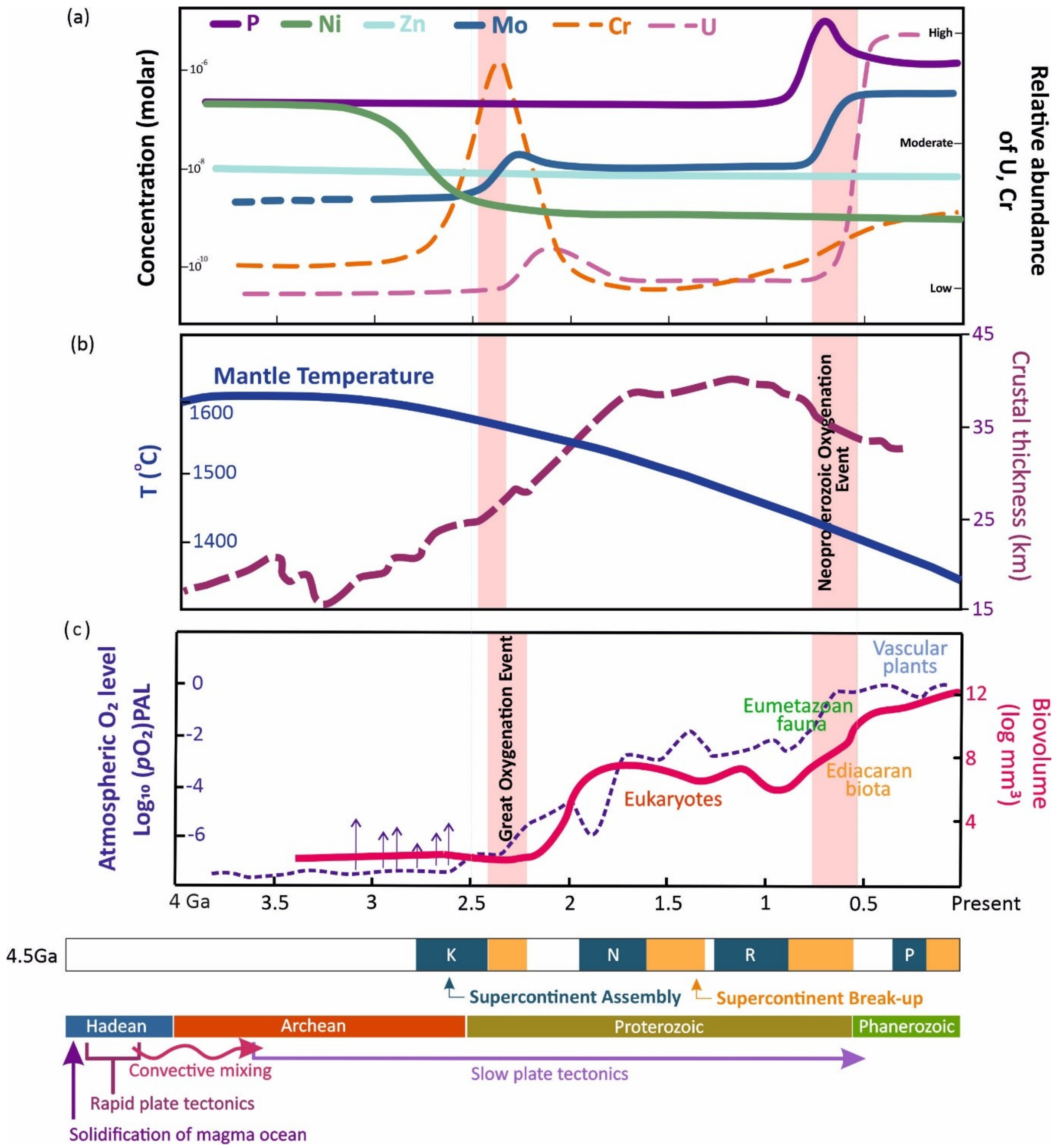

Fig. 1. (a) Trace element abundances in the early ocean (Robbins et al., 2016), (b) trends of continental crustal thickness through time (Hawkesworth et al., 2016), and secular cooling of mantle temperature, and (c) estimated atmospheric O_2 and biovolume variation through time (Payne et al., 2008; Chen et al., 2022). Timescales at the bottom indicate supercontinent assembly and fragmentation history; and tectonic evolution from Hadean to present (after Wang et al., 2023 and Korenaga, 2021 respectively).

thus playing a key role in atmosphere-biospheric transitions. Zinc has remained consistently available since the Archean, supporting biospheric stability and the rise of complex life (Scott et al., 2012). Cobalt was abundant in anoxic Archean oceans and was an important cofactor for life supporting processes, having peaked at ∼2.4 Ga due to hydrothermal activity and depleted with the rise of oxygen. Chromium isotopes reveal O_2 pulses before the GOE indicating intermittent photosynthetic activity that gradually influenced Earth's oxygenation, while uranium concentrations coincide with major oxygenation events of our planet (Crowe et al., 2013; Partin et al., 2013). Therefore, intense volcanic and hydrothermal activity enriched the anoxic Archean oceans with essential trace metals like Ni, Co, V, Zn, Mo, and Cd, which, together with dissolved Fe(II) led to microbial methanogenesis, acidification of oceans and reduced atmospheric CO_2. Furthermore, Fe-oxides/oxyhydroxides likely precipitated from ancient ocean water, selectively scavenging the trace metals such as Zn, V, Cu, Co, and Ni, thereby reducing their bioavailability, while Mn, Mo, and Cd remained bioavailable and were utilized by microbes to form metalloproteins, as shown in sedimentary records (BIFs, C-shales, pyrite; Saito et al., 2003; Robbins et al., 2016; Fig. 1). The gradual increase of O_2 levels along with the biomass volume reflects on co-evolution of environment and life indicating biogeochemical cycling of life essential elements and rise of atmospheric and ocean O_2 contents (Fig. 1; Chen et al., 2022). Based on the iron and nitrogen isotopes in BIFs, Hashizume et al. (2016), opine that the fluctuations in the photosynthetic activity controlled the organic matter levels at the ocean surface which influence the formation of silica and iron bands in the BIFs thereby reflecting on the ocean biosphere dynamics.

5 Plate tectonics

The early Earth began with stagnant-lid convection, followed by the onset of plate tectonics and formation of felsic crust by the Mesoarchean (O'Neill et al., 2007; Cawood et al., 2018). However, studies also suggest that plate tectonics and felsic crust have existed as early as the Hadean (Rosas and Korenaga, 2018; Keller and Harrison, 2020). Crustal growth models along with argon degassing records indicate rapid production of continental crust and its recycling during the Paleoarchean itself (Guo and Korenaga, 2020). Furthermore, magma ocean solidification models support the emergence of a chemically heterogeneous mantle, which may have facilitated the onset of vigorous tectonic activity with faster plate velocities than observed today, from the early to mid-Hadean (Korenaga, 2021 and references therein; Boukaré et al., 2025). Apart from this, the Hadean plate tectonics are also proposed to have been triggered by the ABEL (Advent of Bio-Elements) bombardment event ($\sim$4.37–4.20 Ga), which delivered volatiles viz. water, carbon, hydrogen, oxygen, and nitrogen to an initially dry and reductive Earth (Maruyama and Ebisuzaki, 2016; Maruyama et al., 2016, 2018; Santosh et al., 2017). Water played a key role in lithospheric subduction, triggering plate tectonics. This led to the formation of oceans and granitic continents, gradually establishing the "Habitable Trinity" between land, water and atmosphere (Dohm and Maruyama, 2015). Plate tectonics subsequently promoted nutrient cycling, generation of TTG magmas, and the mixing of primordial and oxidized materials, which together contributed to the emergence of metabolism and life (Maruyama et al., 2018).

Continued tectonic processes during the Archean regulated the Earth's climate by removing atmospheric CO_2 through the formation of marine carbonates and their subduction. Melting of heterogeneous mantle simultaneously produced ultramafic crust, which was subjected to serpentinization, releasing hydrogen, and thus creating reducing environments on the seafloor, favourable for the origin of life. Rapid plate movement also favoured the cooling of mantle (Fig. 1) and core, sustaining a geodynamo, and thus generating a magnetic field that shielded the planet from harmful solar radiation. It is also inferred that plate tectonic processes were initiated through rapid magnetite rich BIF accumulation under the influence of photoferrotrophic bacteria, which resulted in lithospheric rupture and subduction (Zhang et al., 2023).

6 Scope of extra-terrestrial life

The physical and chemical conditions such as sufficient mass, internal heat, magnetic field, and stable orbital dynamics play a major role in maintaining long-term climate stability and atmospheric retention, thereby rendering the planet in the habitable zone. Among the inner terrestrial rocky planets of the solar system (Mercury, Venus, Earth and Mars), Earth stands out as uniquely habitable, having maintained stable surface conditions and liquid water, plate tectonics, strong magnetic field shielding from harmful solar and cosmic radiation, and the presence of a large moon moderating axial tilt variations, which together have enabled the long-term climate regulation. Mars, though currently cold and arid, provides the most accessible and ancient geologic record, extending beyond 4 Ga. During its early history around 4.1–3.7 Ga (Noachian period), Mars has identified to have hosted large water bodies in impact and volcanic craters, particularly at its northern hemisphere (Takeuchi et al., 2020). These aqueous environments potentially required a denser, CO_2-rich atmosphere with low oxygen and greenhouse gases such as CH_4, sulfur compounds, and water vapor. Additionally, the Martian crust is found to be rich in volcanic sediments and early hydrothermal activity analogous to that of early Earth, which could have provided the necessary chemical energy for life through redox reactions and abundant bio-essential elements. Westall et al. (2011) suggested that primitive Mars and Earth shared similar life-supporting conditions, albeit limited in spatial extent and duration.

Venus, though currently inhospitable with surface temperatures $\sim$750 K and a dense, CO_2-rich atmosphere, also hosts traces of past habitability (Way and Del Genio, 2020; Warren and Kite, 2023; Westall et al., 2023). Its evolution is suggested to have been influenced by a combination of its slow retrograde rotation, persistent volcanic activity, thick cloud cover and lack of a magnetic field (Gillmann et al., 2022; Westall et al., 2023). The detection of phosphine gas in its cloud layers has led to the speculation about microbial life and ancient tectonic activity (Greaves et al., 2020). However, unlike Earth and Mars, its ancient crustal record is not preserved, thus limiting direct insights into its early history. Nevertheless, outgassing is suggested to have driven a runaway greenhouse effect, transforming it from a possibly Earth-like planet into an inhabitable planet today. Further, Mercury although often excluded from habitability discussions due to its small size, proximity to the Sun, and lack of atmosphere, provides important comparative data. Its magnetic field history and the stabilization of its rotation and obliquity through tidal interactions are similar to those of Venus, but contrast with Earth and Mars. Due to its small mass and extreme surface temperatures, Mercury retains only a very thin atmosphere primarily sustained by solar wind interactions, making it inhospitable for exploration. The harsh temperature fluctuations and intense solar radiation thus render the planet highly inhospitable, despite the presence of permanently shaded, ice-bearing regions.

7 Role of crustal growth and volcanism in Biogeochemical evolution

The concepts of origin and evolution of continental crust remain debated, with contrasting models of continuous versus episodic crustal growth (Armstrong, 1981; Taylor and McLennan, 1985; Hawkesworth et al., 2019). Except for the reports of detrital Hadean zircons, 4 Ga crust is unknown and 3 Ga crust is very limited (Arndt and Nisbet, 2012). The Archean mantle is estimated to have been 400–500 °C hotter than today, owing to higher levels of radioactive decay, core formation, and residual heat from Earth's accretion, as evidenced through the presence of high-temperature volcanic rocks, such as komatiites. This elevated geothermal gradients likely reduced mantle viscosity, promoting vigorous convection, widespread mantle plume activity, and rapid generation of oceanic crust, particularly during the Paleo- to Mesoarchean (Nisbet et al., 1993; Davies, 2007; Arndt et al., 2008; Fig. 2a). The subsequent fast recycling of the oceanic crust through subduction contributed to the production of early felsic crust. By the Neoarchean, this dynamic regime evolved into more organized tectonic processes, marked by increased arc magmatism, multiple subduction zones, and the development of evolved passive margins (Fig. 2b). These tectonomagmatic changes not only accelerated crustal growth but also created more stable oceanic and continental environments conducive to biogenic evolution. These processes are well preserved in different stable continental regions/cratons of the world, which are essentially composed of three significant lithounits i.e. tonalite trondhjemite granodiorite gneiss (TTG), ultramafic-mafic-felsic volcanic rocks and detrital-chemical sediments. Together, these units record the history of Earth's internal dynamics, tectonic activity, early continental crust formation, and surface processes including sedimentation and ocean-atmospheric evolution. In the early stages of crustal development, particularly during the Paleo- to Mesoarchean, high mantle heat flow and elevated geothermal gradients led to vigorous mantle plume magmatism or rapid plate motion. Hotter mantle temperatures produced greater volumes of melt, resulting in thick oceanic crust, estimated to be ∼20 km, two to three times thicker than modern equivalents (Sleep and Windley, 1982). This Mg-rich crust likely differentiated into layered sequences, contributing to subsequent crustal reworking through subduction and melting. Quantitative estimates by Kamber (2007) suggest that the Archean continental crust had three to four times higher heat production than today, rendering it thermally unstable and likely basaltic before ∼3.5 Ga. This process played a significant role in generating large volumes of TTG, which represent the oldest preserved crustal fragments (typically 3.6–3.4 Ga; Jayananda et al., 2018). Subsequent partial melting of TTGs during the tectonic activity contributed to the formation of potassic granites between 3.0–2.5 Ga. Simultaneously, greenstone belt volcanism, also largely plume-related provides evidences of progressive cooling of the Earth's mantle, marking the transition towards modern-style subduction and arc magmatism by the Neoarchean. It has been suggested that large mantle plumes have initiated subduction on planets with thick, buoyant oceanic crust by creating complex 3D structures (Van Kranendonk, 2010). Long lived mantle plumes on Mars created the Tharsis Rise, an enormous, elevated crustal region topped by Olympus Mons, which is the tallest volcano in the solar system. The weight of Tharsis caused a ∼5000 km wide system of radiating dikes and formed the 8 km deep Valles Marineris rift valley (Smith et al., 1999; Me‘ge, 2001). Plume magmatism built thick crustal welts and large features such as merged coronae on Venus, spanning thousands of kilometers, suggesting their impact on a stationary crust (Squyres et al., 1992). Van Kranendonk (2010) explained that during the Paleoarchean era, thick, buoyant oceanic crust may have undergone subduction in a manner analogous to the processes observed on Mars and Venus resulting in two distinct crusts i.e. high-grade gneiss terranes formed in primitive subduction zones and volcanic plateaus formed through upwelling mantle. Based on lunar and asteroid data, it has also been proposed that the primordial crust consists of anorthosite and K- and REE-rich basalt which was destroyed by tectonic activity (Maruyama and Ebisuzaki, 2016). During the Archean, the hotter mantle conditions favoured shallow angle subduction which gradually transitioned into the present-day steep subduction (Palin and Santosh, 2021). These tectonic

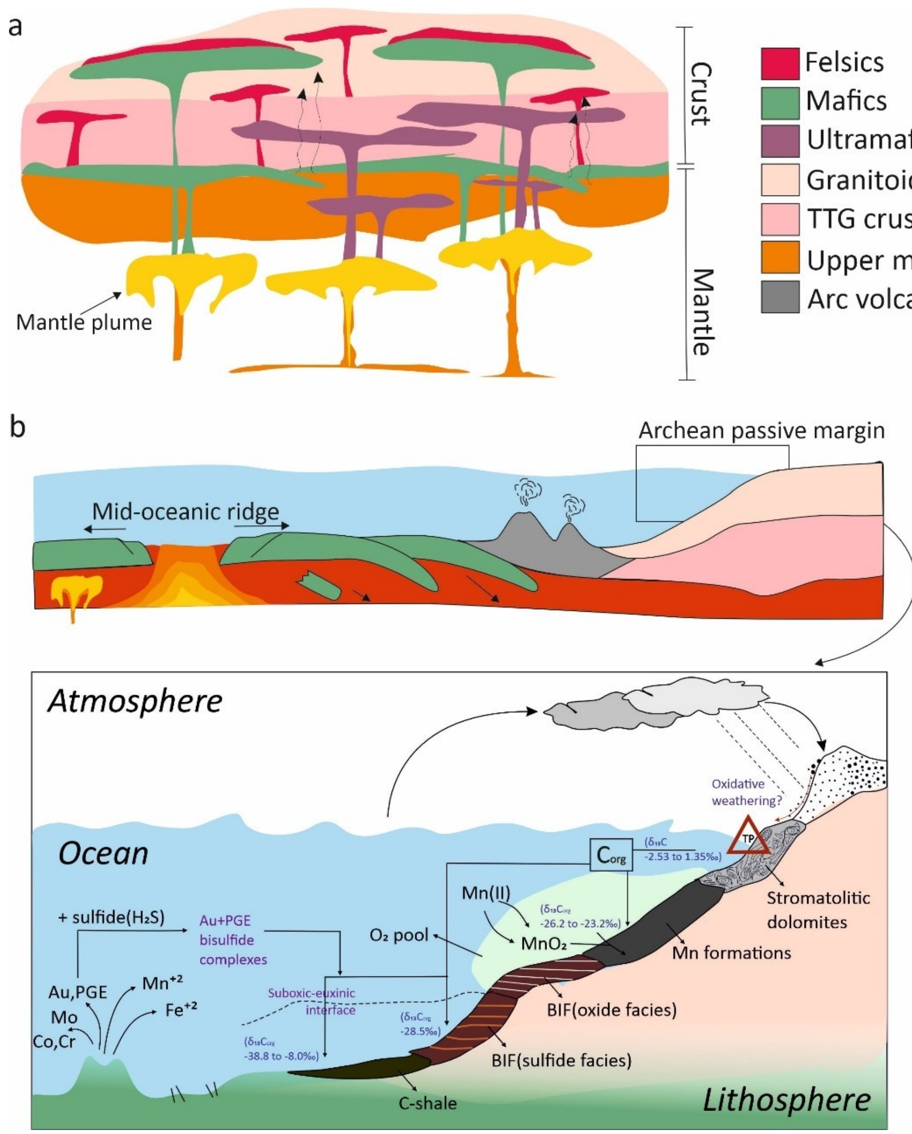

Fig. 2. Sketch showing (a) Paleo-Mesoarchean mantle plume activity forming ultramafic-mafic crust, and tonalite-trondhjemite-granodiorites (TTGs) through mafic crust subduction; granites and felsic volcanics form by partial melting and fractional crystallization; (b) Neoarchean ridge development with an increase in subduction zones generate island arc volcanics and felsic crust. Inset shows sedimentary processes and rock formation at a Neoarchean passive margin.

changes, along with major climatic and atmospheric fluctuations, including global glaciations and two GOEs are instrumental in transforming Earth's environment (Young, 2013; Mishima et al., 2017). The assembly of supercontinents enhanced nutrient transport to the oceans, driving biological evolution, while continued tectonic recycling of oceanic sediments and seawater played a vital role in sustaining Earth's habitability (Campbell and Allen, 2008; Santosh et al., 2024).

The intense mantle activity of the Hadean and early Archean, particularly widespread komatiitic and basaltic volcanism is not only responsible for crustal growth, but has also created dynamic hydrothermal plumbing systems that circulated seawater through hot oceanic crust. These systems provided diverse chemical environments including acidic, alkaline, and metal-rich fluids that concentrated bio-essential elements such as Ni, Cu, and Zn, laying the base for early biochemical reactions. Such environments, especially around mid-ocean ridges and volcanic islands, possibly served as habitats for prebiotic chemistry and the emergence of life. Serpentinization of ultramafic rocks like komatiites in early hydrothermal systems appears to have generated abundant molecular hydrogen, creating strong redox contrasts that could support the first chemoautotrophic life forms (Nisbet and Sleep, 2001). Combined with hydrogen loss to space and episodic

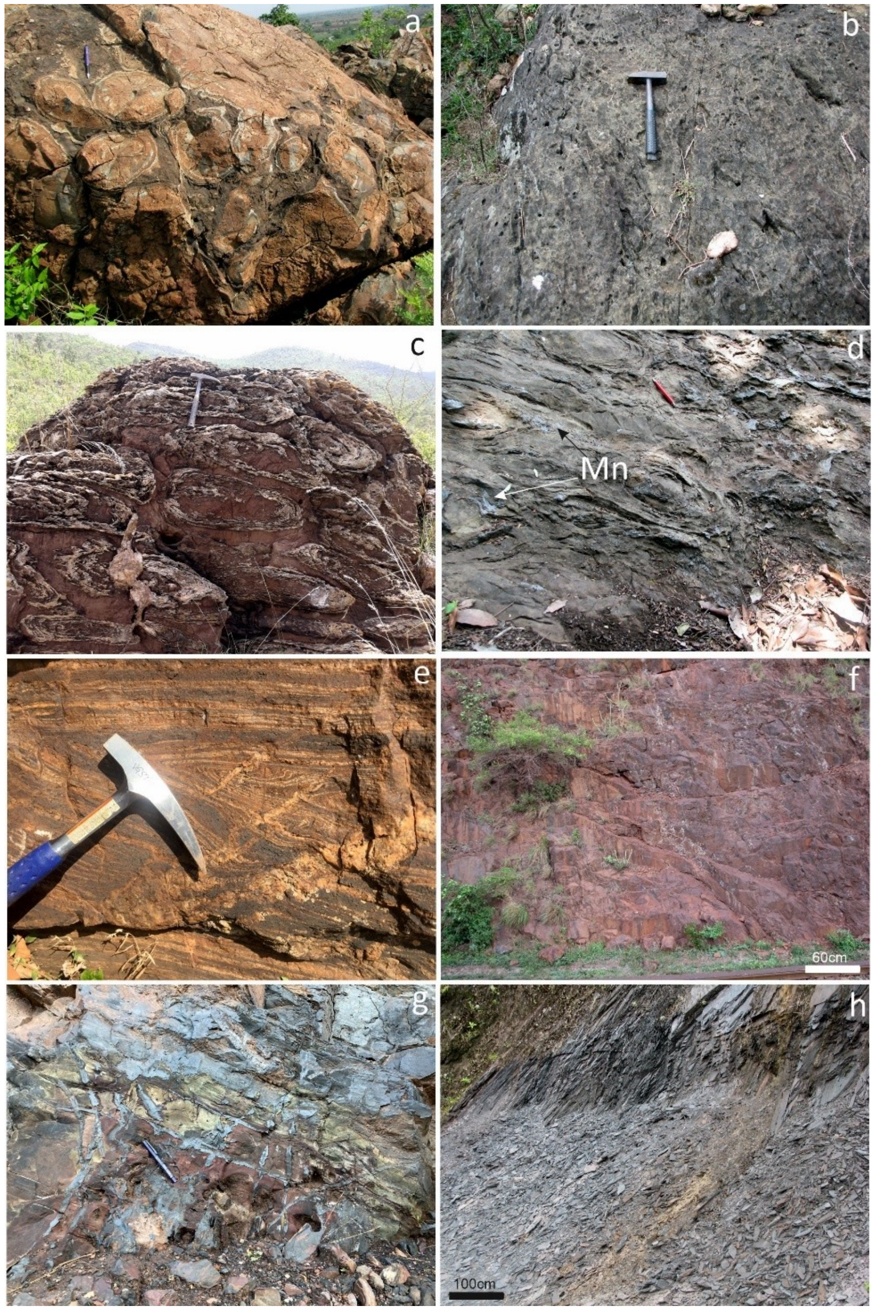

Fig. 3. Field photographs of (a, b) Pillow and vesicular basalts from the Chitradurga belt; (c) Ellipsoidal stromatolitic dolomites with Mn-mineralisation (d) from the Chitradurga and Shimoga belts; (e, f) oxic and sulphidic BIFs from Sandur Belt; (g) boxwork Mn-mineralisation and (h) carbonaceous shales from Sandur belt.

atmospheric oxidation (Sagan and Chyba, 1997), these deep Earth and surface interactions provided both the chemical energy and redox gradients essential for prebiotic evolution.

In the Dharwar Craton of southern peninsular India, well-preserved plume-related mafic-ultramafic rocks, arc-generated mafic-felsic sequences, and passive margin sedimentary rocks, including conglomerates, quartzites, Fe–Mn shales, stromatolitic carbonates, banded iron formations (BIFs), manganese formations, and carbonaceous shales, document the coupled evolution of greenstone and TTG terranes (Fig. 3). Simultaneous volcanism and sedimentation has also been evidenced through sediment-infill volcanic breccias and abundant pyroclastic flows, reflecting rapid growth of continental crust and the presence of sufficient continental freeboard (Fig. 4). Through TTGs and

Fig. 4. Field photographs showing outcrops of (a) basal oligomictic and (b) polymictic conglomerate with basalt, shale and BIF clasts from the Bababudan and Chitradurga belts; (c) sediment infill volcanic breccia with rhyolite flow from the Shimoga belt, and (d) current bedded quartzite from the Chitradurga belt.

granitoids, the episodic crustal growth in the Dharwar Craton from 3.6–2.5 Ga has been envisaged by Jayananda et al. (2018). These lithologies and volcanic-sedimentary associations record distinct tectonic stages characterized by (i) predominant plume-subordinate arc, (ii) subordinate plume-predominant arc, and (iii) dominant arc-related processes (Harshitha et al., 2025). Provenance studies on the Neoarchean passive margin sediments indicate a TTG-granitoid source, extensive sediment transport and recycling which appears to have released bio-essential trace elements in the depositional column (Harshitha et al., 2024), in turn contributing to the biogenic evolution.

8 Hadean-Archean geological Formations preserving early biosignatures

8.1 Hadean-Eoarchean (4.567–3.6 Ga)

Genetic analyses suggest that LUCA (the last universal common ancestor) likely emerged in hydrothermal environments, utilizing H_2, H_2S, CO_2, S and transition metals, with metabolic pathways resembling those of methanogens and clostridia (Weiss et al., 2016; Moody et al., 2024). Geological evidence supports this notion of the establishment of early life habitats near submarine hydrothermal vents before 3.77 Ga, and possibly as early as 4.28 Ga, as evidenced through chemical and mineralogical signatures of graphite coated apatite and delicate microfossils in BIFs of the Nuvvuagittuq Supracrustal Belt, northeastern Canada (Dodd et al., 2017; Papineau et al., 2022). Further evidences of Hadean biosignatures are found from a 4.1 Ga zircon from the Jack Hills, Western Australia, which contains encapsulated graphite with a δ^{13}C value of -24‰ consistent with biogenic carbon (Bell et al., 2015).

More robust evidence of early life has been retrieved from Eoarchean sedimentary rocks, specifically $\sim$3.7–3.8 Ga BIFs, turbiditic mica schists, and carbonates of the Isua Supracrustal Belt, southwest Greenland. Graphite globules with depleted δ^{13}C values ~ -19‰, along with stromatolite-like laminated structures in dolomitic layers (δ^{13}C ~ -19 to -25‰) provide both isotopic and morphological indications of microbial life (Rosing, 1999; Nutman et al., 2016). Similarly, apatite grains with graphite coatings along with the residual presence of N, S, and P in graphite of ∼3.83 Ga iron formations from the Akilia Supracrustal Belt are identified as metamorphosed remnants of biogenic material (Papineau et al., 2010).

8.2 Paleo-Mesoarchean (3.6–2.8 Ga)

Diverse metabolic pathways were already established by ∼3.6 Ga, as evidenced from multiple geochemical and microstructural evidences of both photo- and chemotrophic microbes from the Paleoarchean Pilbara and Barberton belts. The most important and direct evidences come from the identification of microbially induced sedimentary structures (MISS) from the 3.48 Ga Dresser Formation, 3.42 Ga Buck Reef Chert, 3.33 Ga Josefsdal Chert, 3.3 Ga Witkop and Fig Tree Formations etc (Westall and Xiao, 2024 and references therein). Their morphologies and chemical signatures indicate the activity of complex microbial communities capable of adapting to variable environmental stressors such as desiccation, UV radiation, salinity, and hydrothermal influence (Noffke and Awramik, 2013; Hofmann and Wilson, 2007). Insights into the microbial metabolisms have largely been inferred from BIFs, as Fe^{+2} acts as an electron donor during anoxygenic photosynthesis by photoferrotrophic microbes. While large BIF deposits are rare in the Paleoarchean, jaspilites from the 3.48 Ga Dresser Formation are linked to photoferroautotrophs based on Fe isotope variations (Johnson et al., 2022). Further evidence of microbial iron cycling comes from jaspilites in the Mendon Formation (3.33–3.26 Ga), where Fe-rich layers are interbedded with fine carbonaceous films morphologically similar to shallow water biofilms and phototrophic mats in the Josefsdal and Buck Reef Cherts, Barberton, South Africa (Trower and Lowe, 2016). Evidences of microbial colonization in hydrothermal and subsurface environments comprise carbonaceous filaments in hydrothermal chert veins from the Dresser Formation and Buck Reef Chert, indicating methanogenesis and sulphate reduction. Occurrence of chemotrophic microfossils and stellate carbonaceous clots further attest to diverse microbial life, suggesting that life was widespread across shallow marine, coastal, hydrothermal, and subsurface settings by the Paleoarchean. The Mesoarchean and subsequent periods are characterized by formation of stromatolitic carbonates reflecting on abundant biomass, likely supported by increased nutrient availability from continental erosion and the evolution of oxygenic photosynthesis (Peng et al., 2022). While the earliest structures were domical and stratiform, columnar stromatolites became more prominent in the Mesoarchean (Schopf et al., 2007). The Chobeni Formation stromatolites in South Africa (3.0 Ga) indicate local oxygenic conditions, while the 3.0 Ga Farrel Quartzite in the Pilbara Craton hosting carbonaceous acritarchs, and 3.22–3.21 Ga Moodies Group stromatolites showing similarities to modern cyanobacterial mats suggest adaptations to terrestrial environments (Homann, 2019).

8.3 Neoarchean (2.7–2.5 Ga)

A classic example preserving Neoarchean biogeochemical evidences is represented by the passive margin sequences from the greenstone belts of the Dharwar Craton from southern peninsular India, particularly the Chitradurga, Shimoga, and Sandur greenstone belts, which host stromatolitic carbonates, Mn formations, BIFs, and carbonaceous shales, suitable for understanding Archean geodynamics and biospheric evolution.

8.3.1 Stromatolitic carbonates

The dolomitic and manganiferous stromatolites from these three greenstone belts display varied morphological features such as convex up, stacking, columnar, domal etc. indicating different biological and environmental conditions of formation including water depth, wave action and energy levels, sedimentation rates and ocean chemistry (Khelen et al., 2019). These features display supra- to subtidal environments of stromatolitic growth suggesting that microbial communities were adapted to different ecological niches. The presence of stromatolitic carbonates across these environments points to active carbon and sulphur cycling, likely involving the trapping and binding of carbonate sediments by microbial mats, widespread photosynthesis and early localized oxygen production. The REE patterns of the Dharwar stromatolites indicate the ambient sea water chemistry, as reflected through variable La, Eu and Gd anomalies, La enrichment and no real positive Ce anomalies (Figs. 5, 6; Khelen et al., 2019; Govind et al., 2021). These stromatolites show a low degree of hydrothermal influence, resembling those of the Strelley Pool Formation of the Pilbara Craton, Western Australia (Fig. 5a), suggesting deposition under fluctuating oxygenic conditions. A significant terrigenous input appears to have suppressed the positive Eu anomaly, while the presence of variable positive Y anomalies, when compared with both high- and low-temperature hydrothermal fluids reflects temperature fluctuations in Archean ocean waters (Fig. 5a). The relationship between Eu/Eu* and Y/Ho further supports the combined influence of seawater and hydrothermal fluids during stromatolite formation (Fig. 6a). The positive La anomaly, as indicated by the relationship between Ce/Ce* and Pr/Pr* has further been interpreted as an apparent low-magnitude negative Ce anomaly (Bau and Dulski, 1996, 1999), thereby confirming the influence of hydrothermal activity and mildly oxidizing conditions (Fig. 6b). $\delta^{13}C$ (−2.53 to 1.35‰) and $\delta^{18}O$ (−20.95 to −7.72‰ VSMOW; Khelen et al., 2019) signatures indicate gradual increase of Archean sea water temperatures from 25 °C–75 °C during

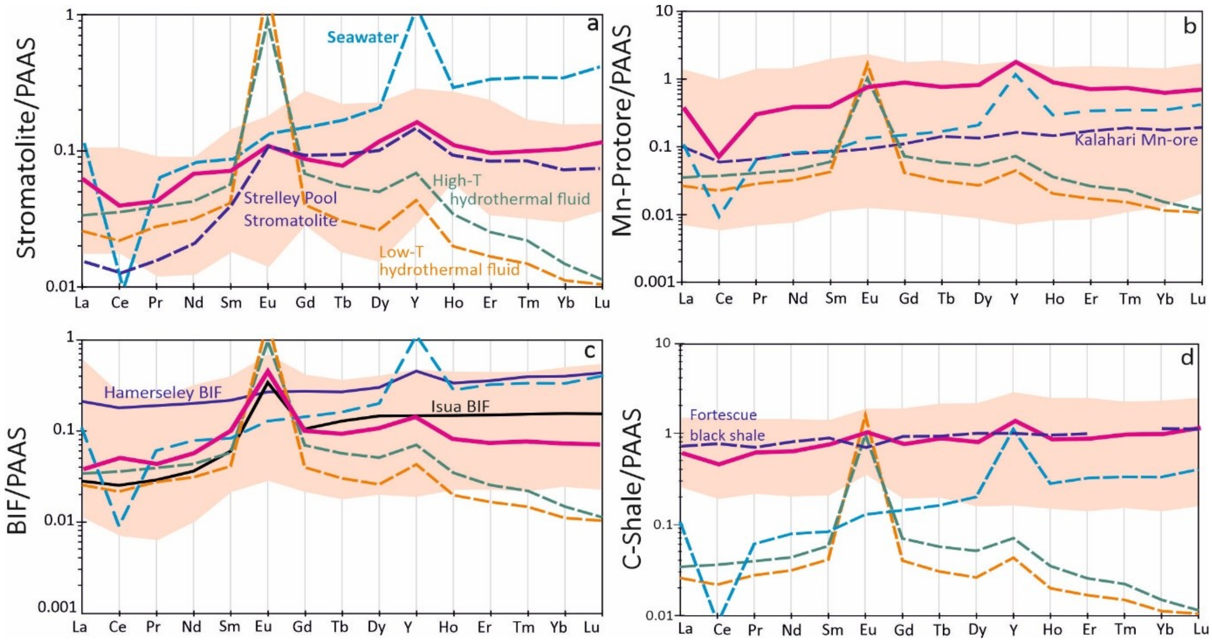

Fig. 5. Post Archean Australian Shale (PAAS) normalized REE patterns of Dharwar stromatolitic carbonates, BIFs, C-shales and Mn-protore sediments. Shaded area represents the range of REE patterns, while the thick pink line shows the respective representative pattern across all panels. Seawater, high-T and low-T hydrothermal patterns ($x10^{-3}$) are after Douville et al. (1999) and Bau and Dulski (1999). REE patterns of Strelley Pool stromatolite (Viehmann et al., 2020), Hamersley BIF (Haugaard et al., 2015), Isua BIF (Appel, 1983), Fortescue Formation black Shale (Wille et al., 2013) and Kalahari Mn-ore (Kuleshov et al., 2024) are also given for comparison. PAAS normalization values are after Pourmand et al. (2011).

their formation. The detrital zircon ages collectively reflect 800–900 Ma duration of their deposition in the passive margins of Dharwar greenstone belts. Oldest (∼3.5 Ga) zircons were sourced from both granitoid and mafic provenance. This has a direct relationship with the Paleoarchean mafic crust which is supposed to have formed during the initial stages of the crustal evolution (Manikyamba et al., 2022).

8.3.2 Manganese and iron formations

The Mn formations are characterized as Mn arenites, Mn–Fe arenites, Mn–Fe argillites, Fe–Mn arenite and argillites. The geochemical characteristics of the Mn protoore indicate mixing of Archean seawater, hydrothermal fluids and clastic sediment at varying proportions. The REE patterns of the Mn formations from the Dharwar Craton resemble those of seawater, characterized by negative Ce and positive Y anomalies. However, the low-magnitude Eu anomalies in these rocks suggest that the hydrothermal signature may have been masked by detrital input, as these formations were deposited on an Archean continental shelf (Fig. 5b, 6a). Although the REE patterns of the Kalahari Mn ores fall within the range of the Dharwar Mn formations, the absence of Ce, Eu, and Y anomalies likely reflects alteration due to later supergene enrichment processes (Fig. 5b). The real positive Ce anomalies displayed by these Mn formations are indicative of oxic conditions, which is a result of oxidation of Ce^{+3} to Ce^{+4} and its adsorption onto Fe–Mn oxides (Fig. 6b). Paleoredox proxies such as U/Th, Mo and U enrichment factors, authigenic uranium and trace element ratios measured from the Mn proto-ore suggest suboxic to oxic conditions of Mn precipitation accounting the existence of regionally oxygenated water columns in the shallow shelves of Neoarchean ocean basins of Dharwar Craton and their detrital zircons indicate Mn- depositional age bracket of 600 Ma (Harshitha et al., 2024). Organic Carbon isotope ratios reflect biogenic imprints for Mn-oxidation. The negative $\delta^{13}C_{org}$ values (−26.26 to −28.26‰; Author personal data; Fig. 2) are consistent with decrease in the isotope ratios from early to late Archean which is attributed to increased biological fractionation due to methanotrophic recycling and the evolution of oxygenic photosynthesis at 2.8 Ga or earlier.

The BIFs of Dharwar Craton are interlayered with clays and the associated chert bands consist of filamentous and coccoidal structures indicative of biogenic activity (Manikyamba et al., 1993). Negative Ce and Y anomalies, along with positive Eu anomalies, are well preserved in these BIFs, indicating deposition from seawater with

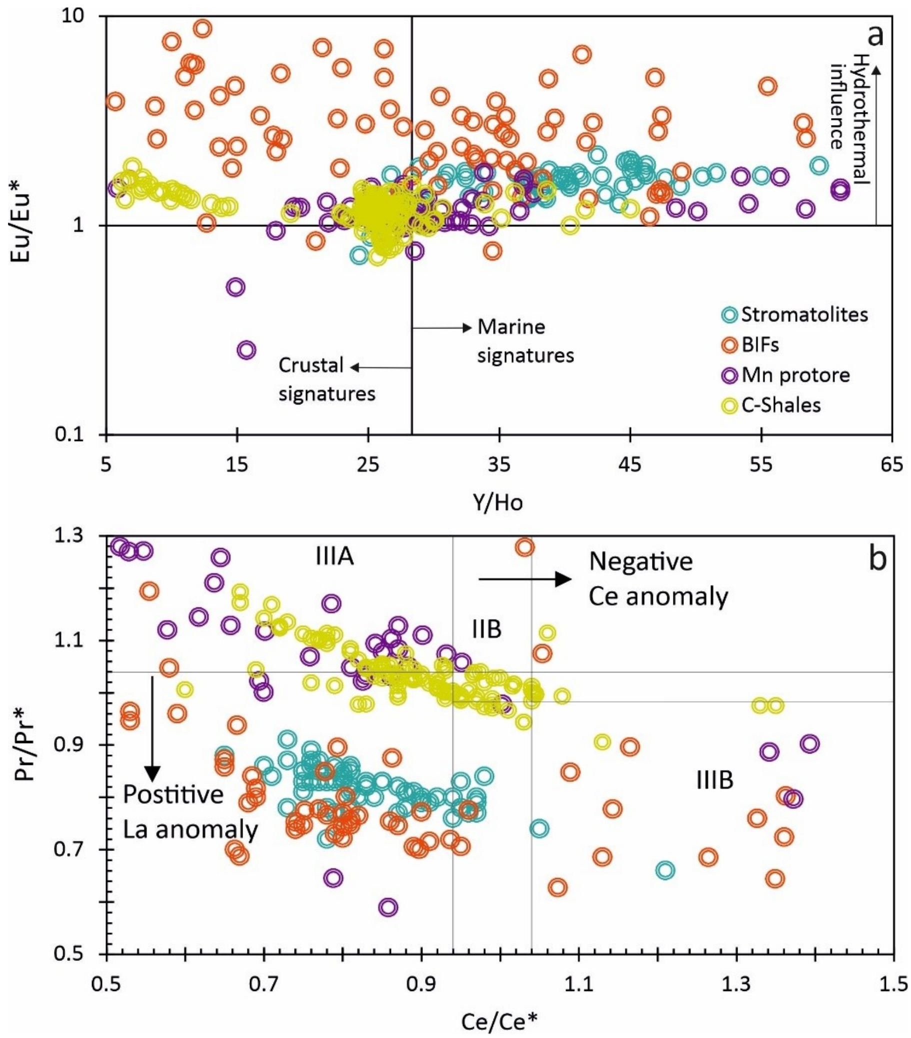

Fig. 6. (a) Eu/Eu* vs. Y/Ho and (b) Ce/Ce* vs. Pr/Pr* plots (after Bau and Dulski, 1999) of Dharwar stromatolitic carbonates, BIFs, Mn protore and carbonaceous shales.

significant hydrothermal input. Their REE patterns resemble those of both low- and high-temperature hydrothermal fluids (Fig. 5c, 6a). The Archean BIFs from the Dharwar and Isua greenstone belts exhibit a stronger hydrothermal signature (Manikyamba et al., 1993; Mukherjee et al., 2025) compared to the Paleoproterozoic BIFs of the Hamersley Basin in the Pilbara Craton, Western Australia, possibly reflecting more intense hydrothermal venting during the Archean (Dodd et al., 2017; Fig. 5c). The presence of positive La anomalies, combined with apparent negative Ce anomalies in some samples, further supports predominant hydrothermal influence and the preferential removal of Ce from the depositional water column (Fig. 6b). These BIFs preserve crystalline and poorly crystalline graphitic carbon within the apatite with δ^{13}C of -28.5‰ representing re-mineralization of syngenetic biomass (Dodd et al., 2019), providing evidences for the emergence of pre-biotic life on Earth, which could potentially be the remains of early life forms. Additionally, δ^{15}N signatures as high as $+12 \pm 0.8$‰ recovered from the organic matter within these BIFs support the emergence of modern-like nitrogen cycle, while comparative δ^{56}Fe systematics in Fe- and Si-rich bands further attest to fluctuating photosynthetic activity (Hashizume et al., 2016), consistent with BIF lamination models (Wu et al., 2012; Hinz et al., 2023).

8.3.3 Carbonaceous shales

Black shales or carbonaceous shales formed in anoxic, deep marine environments serve as rich sources of ancient organic matter. The black shales of the Dharwar greenstone belts are siliceous and have large disseminated sulphides and significant carbonaceous matter in clay mineral matrix. The low-magnitude positive Ce, Eu, and Y anomalies in these carbonaceous shales confirm their deposition in marine waters with minimal hydrothermal influence (Fig. 5d). Although these shales contain abundant hydrothermal sulphides and gold mineralization (Sindhuja et al., 2022), the lack of similarity in their REE patterns with those of both low- and high-temperature hydrothermal fluids may be attributed to the predominant terrigenous input in these rocks (Fig. 5d). The transport of terrigenous material to the deeper parts of the basin has overprinted the hydrothermal signatures, but preserved the Ce anomalies characteristic of the reducing water column in which these sediments were deposited (Fig. 6a, b). The δ^{34}S of these carbonaceous shales (1.3–2‰) suggest the hydrothermally sourced sulfur while the δ^{13}C values (-38.8 to -8‰; Fig. 2) are similar to those of the graphitic carbon of BIFs (Sindhuja et al., 2022).

Based on the stratigraphic associations in the field, trace element and isotopic characteristics of the BIFs, Mn formations, stromatolitic carbonates and carbonaceous phyllites, it is evident that Archean Dharwar ocean was characterised by anoxic to euxinic redox conditions with minor oxic pools at shelves (Fig. 2). Stromatolitic growth appears to have been initiated at the continental shelf generating oxygen. With the degradation of microbial mats at shallow shelves, the organic matter was carried to the deeper part of the basin combined with terrigenous and within basin volcanic material, which deposited as carbonaceous shales. Microbial mats have promoted the precipitation of Fe and Mn through photosynthesis and sulfate reduction, altering local redox conditions, promoting metal deposition and thereby detoxifying the primitive oceans which gradually molded the planet habitable for higher forms of life (Manikyamba et al., 1993, 2022; Harshitha et al., 2024).

9 Summary

This study presents a brief synthesis of the environmental, geological, and geochemical conditions including the role of Hadean impact-driven processes, Archean atmosphere-ocean evolution, tectonics, and microbial activity in transforming the Earth's habitability from an early hostile stage. Archean greenstone belts have well preserved Paleo-Neoarchean mafic-ultramafic sequences that are associated with detrital and chemical sediments. Volcanism provide insights on the tectonism and mantle processes which together document the evolution of plate tectonics, and release of bio-essential elements such as Fe, Mn, Mo, Ni, Co, U, and Zn. The associated sedimentary archives such as stromatolitic carbonates, banded iron formations (BIFs), manganese deposits, and carbonaceous shales throw light on Earth's surface conditions, interaction between lithosphere-hydrosphere-atmosphere and the initiation of biosphere. Trace element patterns and isotopic compositions (e.g., δ^{13}C, δ^{34}S, REEs) of these sedimentary rocks indicate the interaction between microbial life and ocean chemistry. The deposition of BIF and Mn formations from the ferruginous, toxic and reducing Archean oceans under the influence of stromatolitic activity helped detoxify the early oceans and atmosphere. Therefore, early geological, tectonic and biogeochemical processes played an important role in transforming the inhabitable Earth into a habitable planet through the formation of significant mineral deposits (Sindhuja et al., 2022; Manikyamba et al., 2022).

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Declaration of competing interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit Author Statement

C. Manikyamba: Conceptualisation, Visualization, Writing—original draft, Writing—review and editing.

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