

Judging the Habitability of Extraterrestrial Planet Based on Structure of the Earth: Is the Plate Tectonic Essential for Existing Life

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Abstract

The search for extraterrestrial life is one of the most significant areas of scientific investigation, with a focus on identifying habitable planets beyond Earth. This review critically demonstrates the role of plate tectonics in life formation, based on the theory foundation that humans had discovered on Earth. The Earth's structure and its geodynamic processes are used as a model for assessing the potential habitability of other planetary bodies. Plate tectonics on Earth plays an important role in regulating climate stability, maintaining the magnetic field, and reshaping the surface. They are all supporting the necessary conditions for life. As plate tectonics on Earth are deeply linked with habitability, several exoplanets, such as Mars, Venus, and the icy moons of Jupiter (Europa), have shown that planets without plate tectonics may have the potential of forming life. Mars, for instance, has shown limited evidence of plate tectonics happening, but scientists suggest that its subsurface could still offer conditions for life. Venus has a thick crust and a lack of tectonic activities, but with unique volcanic and tectonic features that suggest the possibility of internal dynamic processes without traditional plate subduction. Europa is covered by a thick icy crust, and it is suggested that the existing subsurface ocean can be maintained by tidal heating rather than tectonics. The article discusses how habitability is not only dependent on plate tectonics but relies on a combination of factors, including liquid water, energy sources, and chemical disequilibrium. As a result, plate tectonics may not be the restrictive feature for a planetary body to have life.

Keywords

Plate tectonics; Life formation; Geodynamic processes; Tectonic activities; Internal dynamic processes; Relationship between plate tectonics and existing life on Earth; Further discovery; Structure and plate tectonics of planets in Solar system.

1. INTRODUCTION

'Does life exist beyond Earth in the universe?'

This question has intrigued scientists and philosophers for centuries, and people have already started the extensive exploration of the universe to seek existing life.

Life formation requires strong habitability. A suitable environment can supply sufficient conditions for creatures. To define it, a planet with high habitability requires several conditions: liquid water, a sufficient timespan, carbon-based molecules, and a stable planetary environment [27]. *However, how can humans know that if a planet can form those conditions? Earth, the only known habitable planet, offers insights into the essential role of plate tectonics in maintaining life-*

supporting conditions. The history of life formation is based on the Earth's recycling of volatiles (CO_2 , H_2O), regulating greenhouse gases, and sustaining the geodynamo that generates Earth's magnetic field through mantle convection and core dynamics [27].

Earth developed through billions of years to create a suitable and habitable environment for life formation by including liquid water, an atmosphere and ozone sphere, recycling elements, and the existence of carbon-based molecules. This leads to an objective: if humans want to find another habitable planet, an Earth-like planet is necessarily considered. It means they must have similar points to Earth, for example, like a similar atmosphere, liquid water formation, a similar temperature range, and maybe the same plate tectonic activities happened. It is considerable for the existing plate tectonics on an Earth-like planet.

Lammer proposed that planets without tectonic activities, like Mars and Venus today, show a lack of a magnetic field and suffer environmental consequences [27]. However, Europa, as a satellite of Jupiter and also without geological tectonic activities, presents a possibility of existing life, according to the underground ocean assumption, after humans began several Europa investigations.

In this paper, we will examine tectonics on both Earth and exoplanets, discussing the progress humans have made in investigating the universe over decades and the vision for future exploration. The content will include tectonics on the Earth, extraterrestrial planets, and plate tectonics, a discussion of future observation and research outlook, and finally, our point of view on the relationship between plate tectonics and the habitability of a planet.

2. PLATE TECTONICS ON EARTH

The theory of plate tectonics revolutionized Earth sciences in the 20th century. Earth's lithosphere which composed of both the crust and the uppermost rigid portion of the mantle, is divided into rigid plates that move relative to one another over the asthenosphere [12]. Two types of lithosphere exist: oceanic lithosphere, composed of basaltic crust and ultramafic mantle, and continental lithosphere which is thicker and composed of silica-rich rocks. Oceanic plates are typically younger (<200 Ma) due to continuous recycling at subduction zones, whereas continental plates, being more buoyant, can persist for billions of years. The lithosphere overlies the asthenosphere, which is a ductile, partially molten layer that facilitates plate motion through viscous deformation. The contrast in mechanical strength between the rigid lithosphere and the flowing asthenosphere is significantly important for understanding the concept of movement of plates. The heat energy released from the core of the Earth causes the mantle to flow in slow, circular motions. The hot material rises, cools, and then sinks, drive lithospheric plate motion [13]. According to this theory, plate motions also ultimately result from the negative buoyancy of the lithosphere subsiding from ridges (ridge push) towards a trench and sinking in subduction zones.

2.1. Climate Regulation via the Carbon Cycle

Additionally, mantle dynamics and subduction processes modulate plate tectonics, impacting Earth's evolution. Carbon, primarily recycled into the mantle via subduction of carbonate-rich sediments and altered oceanic crust [25]. As demonstrated by Kelemen and Manning, carbon lowers the melting point of mantle peridotite, facilitating partial melting and the generation of carbon dioxide-rich fluids. The viscosity of the volatile-rich fluids in the asthenosphere promotes localized mantle convection and plate mobility. Actually, the carbon compounds that recycled between the crust and mantle are originate from weathering, the chemical weathering of silicate and carbonate rocks consumes atmospheric carbon dioxide through acid dissolution, converting it into dissolved inorganic carbon (DIC) that is transported via rivers to the oceans, where it is ultimately sequestered in marine carbonates [6]. Conversely, volcanic degassing at

mid-ocean ridges and arcs returns carbon to the surface, creating a feedback loop that stabilizes Earth's long-term climate—a critical factor in maintaining lithospheric buoyancy and continental emergence. Additionally, silicate weathering consumes atmospheric carbon dioxide, the dissolved products ultimately form carbonate sediments, this carbon dioxide sink is balanced by volcanic outgassing, which reintroduces carbon dioxide through metamorphism of subducted carbonates. This Berner cycle operates on 100,000-year timescales [6], maintaining habitable conditions despite external forcings. Those are the principles of how carbon cycles form, which sustain life on the Earth by regulating atmospheric composition and climate stability, they serve as the fundamental basis for the Earth being a habitable planet.

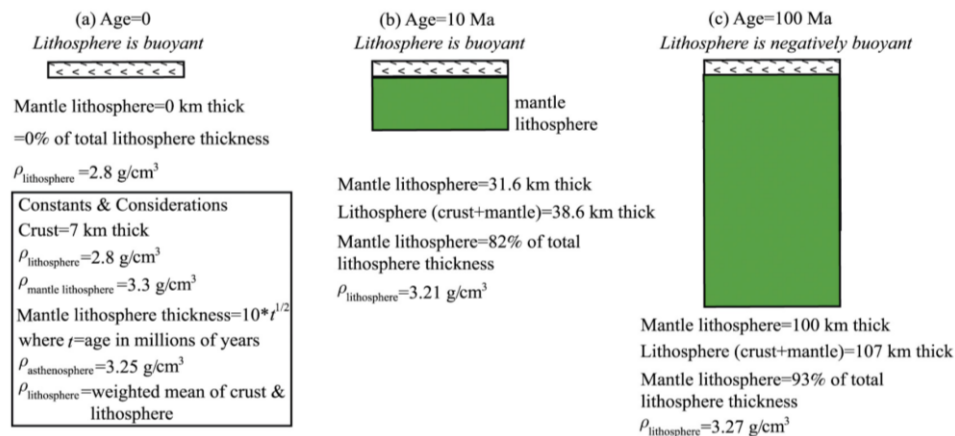


Figure 1.1. This figure shows the development of negative buoyancy with increasing age of modern oceanic lithosphere [45]

2.2. Recycling of Nutrients and Water

Subduction zones facilitate the transport of water and volatiles from the hydrosphere into the mantle. As oceanic plates descend, hydrated minerals (e.g., serpentine) and pore fluids are carried into the mantle, where dehydration reactions release water at depth [22]. This process not only allows the mantle to incorporate water but also leads to the formation of arc magmatism due to the partial melting [49]. The hydrothermal system at mid-ridges and subduction zones redistributes the nutrients (e.g., H_2 , CH_4) as energy sources. Vent fluids enriched in dissolved metals (e.g., Fe^{2+}) migrate upward and then mix with seawater, forming mineral deposits that sequester carbon [18]. The deep water cycle is significantly important in Earth's long-term water retention capacity through mantle-water interactions and maintaining the dynamic equilibrium of Earth's surface hydrosphere. Such processes support the seafloor biosphere, with biomass estimates exceeding 10^{29} cells [24]. Conclusively, subduction zones deliver water into the mantle, triggering magmatism and hydrothermal activity that redistributes nutrients, forms mineral deposits and supports deep-sea microbial life.

2.3. Generation of Magnetic Field

The primary mechanism linking plate tectonics to the geodynamo is the mantle's control over the Core-Mantle Boundary (CMB) heat flow. Subducting oceanic plates cool the lower mantle, increasing localized heat extraction from the core [13]. Conversely, mantle plumes reduce core cooling by insulating the CMB. Numerical models demonstrate that such variations in CMB heat flux can alter the morphology of core convection, leading to changes in magnetic field intensity and even triggering reversals [20]. Long-term tectonic cycles, such as supercontinent gathering and breakup, may induce large-scale variations in CMB heat flux. During supercontinent formation, enhanced subduction could increase core cooling, strengthening the dipole field [3]. Supercontinent breakdown, on the other hand, may decrease global heat input, which could

weaken the dynamo and increase the frequency of reversals [14]. This theory is supported by paleomagnetic evidence, which shows that significant tectonic reorganizations are correlated with times of high reversal rates. So we could find that the geodynamo and plate tectonics are co-dependent systems connected through mantle convection and CMB thermal coupling. Variations in plate motion alter core-mantle heat exchange, which in turn affects the geodynamo's stability and surface reshaping and ecological diversity. Such magnetic shielding protects the atmosphere from solar wind stripping, thereby preserving surface water and creating a stable environment for life.

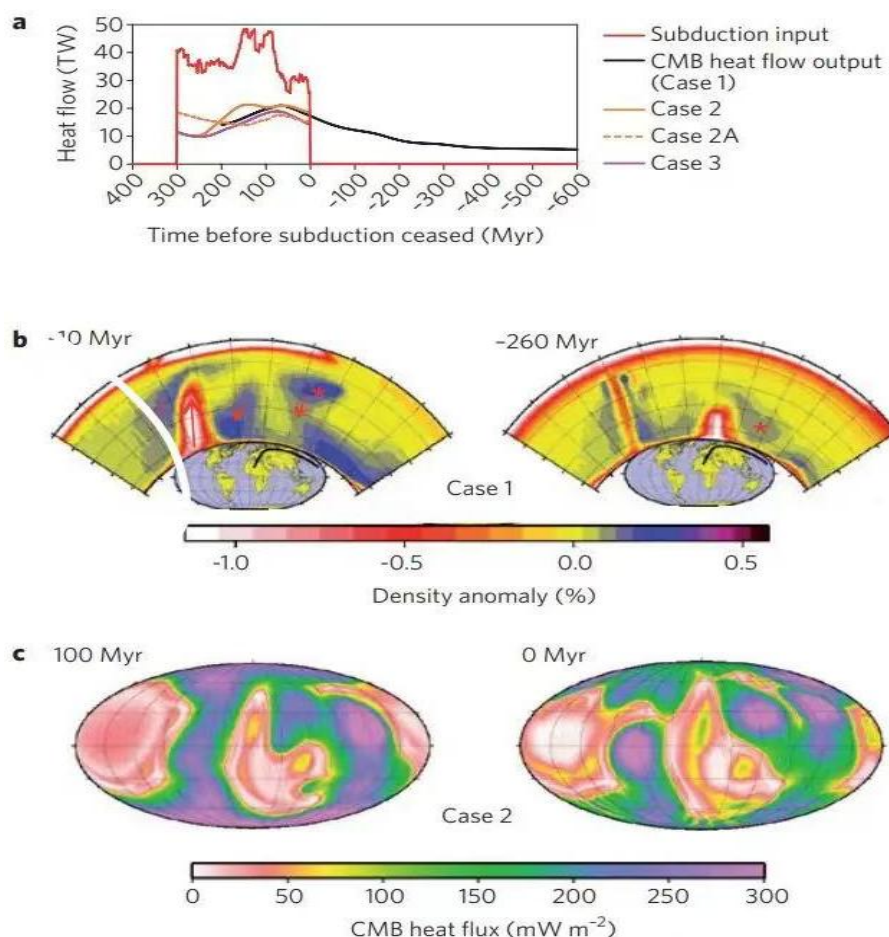


Figure 1.2. A representative case of the mantle flow model of the impact of subduction plates on the core-mantle boundary (CMB) heat flow [7]

2.4. Surface Reshaping and Ecological Diversity

The movement of continents driven by tectonics profoundly alters the global ocean circulation patterns and climate distribution, and at plate boundaries, hydrothermal fluids mix with surrounding cold seawater, creating unique chemical environments by providing energy and organic compounds, which meet the conditions of primordial soup, *and they potentially fulfill the prebiotic chemistry conditions*. The movements of tectonics are also reshaping the surface of the Earth with different landscapes, mountain buildings, ocean basins, mid-ocean ridges, etc.; they create diverse habitats for life. Earth's habitability over billions of years is maintained despite solar luminosity changes [42]. The dynamic exchange between the atmosphere, biosphere, and geosphere maintains the delicate balance required for the habitability of the Earth, leads to the existence of stable environment for life.

3. EXTRATERRESTRIAL PLANET AND PLATE TECTONICS

3.1. Introduction to Evaluating Tectonics on Exoplanets

Understanding tectonic activity on exoplanets presents significant challenges due to the vast distances involved and present observational limitations. Much of our knowledge must be inferred indirectly. This section explores approaches for evaluating tectonics beyond our planet, drawing on methods developed for studying planetary bodies apart from the Earth. Key strategies include analyzing bulk planetary properties and studying analogues within our solar system.

3.2. Mass-Radius Relationship as an Indirect Tectonic Indicator

Using the Mass-Radius relationship to understand the internal composition and layering of rocky exoplanets can help infer whether plate-like behavior is mechanically feasible. The relationship between mass and radius for a solid planet is a grounded tool for determining bulk planetary composition; It follows a universal functional form for solid planets up to 20 Earth masses [39]. This model is used to infer the planetary composition and the type of a planet by only having its mass and radius. The logarithmic equation ($\text{Log}^{10} R_s = k_1 + (1/3) \log_{10}(M_s) - k_2 M_s^{k_3}$), which is a key component of the M-R relationship, helps to connect the internal composition of a rocky planet and its M-R data.

All solid planets approximately follow this equation, where R_s and M_s are the scaled radius and mass, and the constants k_1 , k_2 , and k_3 depend on the planet's composition (like iron, rock, or water). The formula stems from the compression behavior of different materials under planetary conditions [39]. Establishing M-R relationships allows predictions of many exoplanets' masses and densities and helps distinguish rocky planets from those with volatile envelopes.

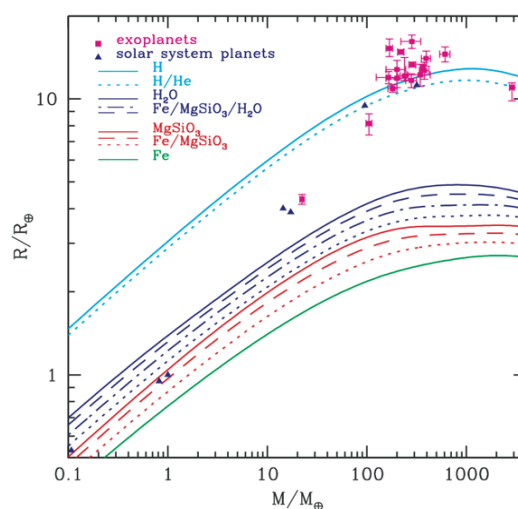


Figure 2.1. Mass-Radius relationships for solid planets

Solid lines represent homogeneous compositions: hydrogen (highest radius), H/He mixture (25% He), water ice, silicate (MgSiO_3 perovskite), and iron (lowest radius). Non-solid lines depict differentiated structures: silicate planets with iron cores (Earth-like: 32.5% Fe core; Mercury-like: 70% Fe core) and water-ice planets with silicate shells and iron cores (e.g., Ganymede-like: 45% ice, 48.5% silicate, 6.5% Fe). Solar system planets (blue triangles) and selected transiting exoplanets (magenta squares, e.g., GJ 436b, HD 149026b) are overlaid. At high masses, electron degeneracy pressure limits radius growth, causing radii to plateau or decrease [39].

3.3. Case Studies of Planetary Bodies in the Solar System

Studying tectonics on solar system bodies provides crucial insights and analogies for interpreting potential tectonic regimes on exoplanets, using indirect methods like those proposed for exoplanets

Mars: Mars, a terrestrial planet with maintained tectonic activity throughout its history, serves as a key analogue. Exploration since the 1960s has revealed significant findings about its internal structure and geological features. Discoveries such as liquid water-related features (surface, ancient lakes, subsurface) and auroras [50] have fueled discussions about its past and present habitability. After decades of investigations, humans discovered that the planet is not inherently sterile [10]. This leads to the possibility of an environment with survival conditions for Earth-based organisms, particularly in the subsurface. Although the environment on the surface is full of radiation and desiccation, high pressure, and a lack of liquid water, the subsurface is protected from harmful features for the formation of life. Nowadays, it is estimated that life could exist in the subsurface at depths up to 8 km [10].

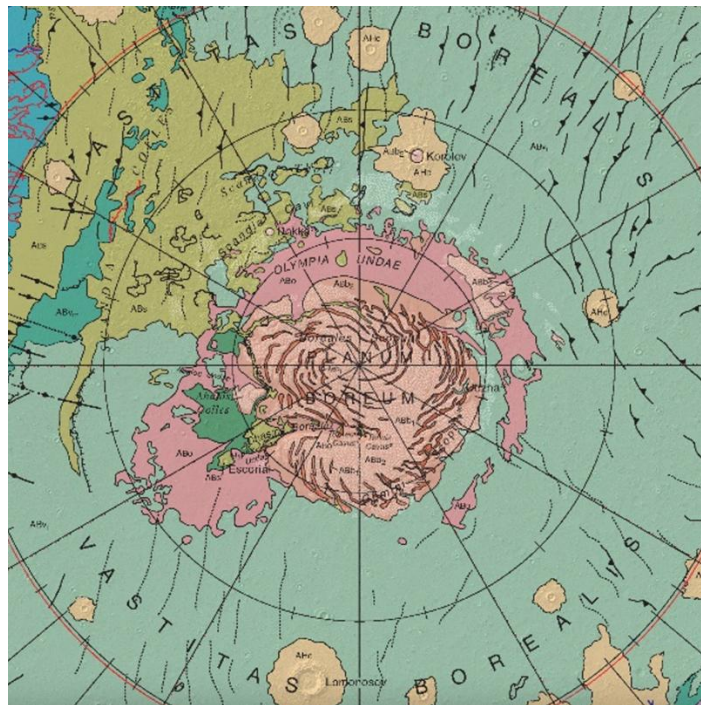


Figure 2.2. The northern plain on Mars nearly covers a third of the planet and constitutes the planet's broadest region of lowlands [46]

Plate Tectonics Debate: The geographic feature on Mars is lowland in the north and highland in the south, with the highland-lowland transition zones, for example, Cimmeria Terra and Arabia Terra. The northern lowlands of Mars were proposed to have formed through plate tectonics during the Late Noachian and Early Hesperian periods, with the hypothesis of subduction and seafloor spreading. The evidence that supports this hypothesis includes the smooth topography of the northern lowlands; the lack of roughness implies rapid seafloor spreading. And also because of the existing transition zones, which resemble passive and active margins [41].

However, the problem with the model of plate tectonics was shown to lack matched points with the observation of Mars [8]. Breuer [8] suggested considering the model of Stagnant Lid Convection [21] on the observation of Mars. In comparison, plate tectonics efficiently cools the mantle and core, while stagnant lid convection cools the outer layers more slowly and preserves heat in the deeper interior. The conclusion was given that the stagnant lid model displays more

advantages, including crust thickness matching and prolonged crust formation. D. Breuer gave a summary that Mars likely never experienced plate tectonics, while stagnant lid convection is able to explain Mars's thermal and crustal evolution, with a core superheating that drove an early dynamo.

Cerberus Fossae seismicity: the Cerberus Fossae region, as detected by the InSight mission. It reveals tectonic activity in the form of marsquakes, which indicate an ongoing extensional process in the graben system.

The seismic outcome data (both low-frequency and high-frequency marsquakes) suggests a warm and mechanically weak source region under Cerberus Fossae, which leads to volcanic activity. The volcanic and thermal processes occurring in the Cerberus Fossae region suggest that this area could have had or might still have subsurface water, heated by ongoing volcanic. This could create environments where life might exist, which is similar to hydrothermal vent ecosystems on Earth. The tectonic and volcanic activity observed in this region drives it to a significant point for future exploration in the search for signs of Martian habitability [44].

The absence of plate tectonics on Mars poses challenges for long-term climate regulation, which is essential for surface habitability.

Venus: Venus is another planet that has similar and contrasting points to the Earth, from decades of studying it. Due to the similarity of size, composition, and internal structure, the lack of plate tectonics is one of the most obvious contrasts to the Earth. Venus displays a wide range of volcanic and tectonic features, such as coronae, rift zones, tesserae, and novae. The existing features suggest processes like mantle plume activity and intraplate deformation may happen on Venus.

In comparison, Venus has a thicker crust than the Earth, which is about 70 km compared to Earth's average 35 km. This leads to greater rigidity and less dynamic resurfacing. Venus also has a 200 km lithosphere thickness, which is assumed, with most radioactive heating concentrated in the crust. Thermal conductivity of the mantle varies with depth and temperature; the heat flux from Venus's interior is modeled with values of 18.5–32.5 erg/s/cm², much lower than Earth's 61.5 erg/s/cm² [51].

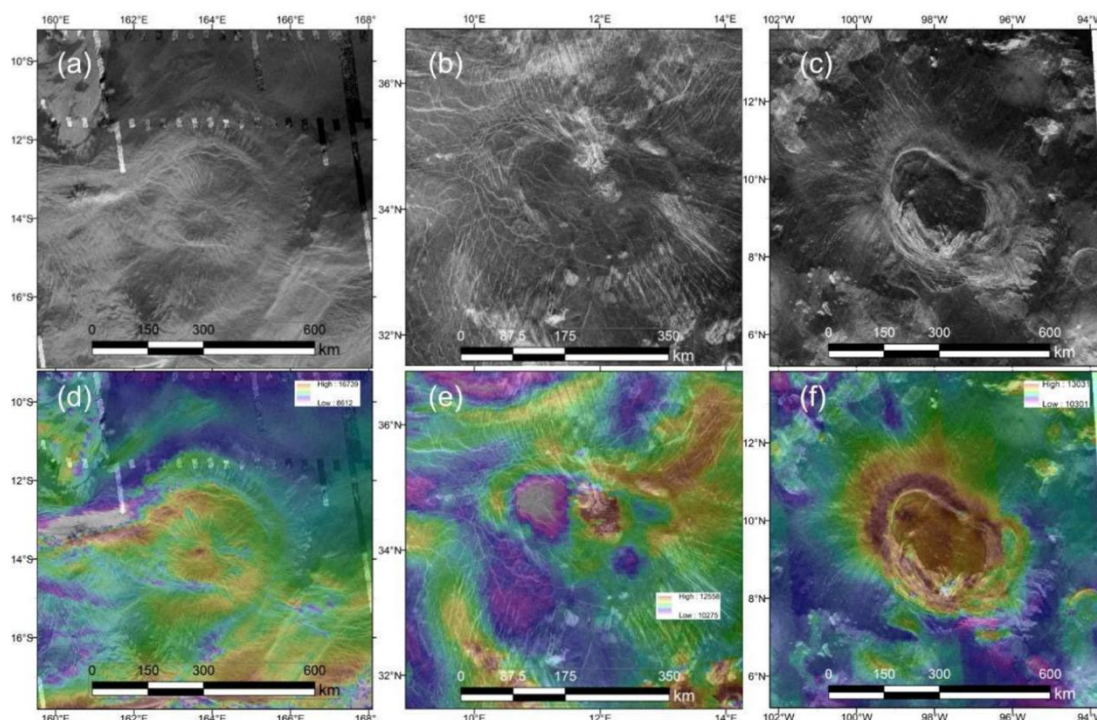


Figure 2.3. Magellan left-look SAR images of several coronaees on Venus [19]

Tectonics Style Discussion: Based on the similarity between Earth and Venus, it makes sense that if there is plate tectonics happening on it. In fact, unlike Earth, which maintains active plate tectonics that drive crustal recycling and volcanic activity, Venus lacks clear evidence of a global system of plate boundaries. However, the formation of coronae, rift zones, e.g., is still controversial. These features of tectonic and volcanic activity may structure the ongoing internal dynamics. In fact, the dynamic interior on Venus had been shown to be true through years of investigation. Venus presents tectonism results from internal thermal processes and lithospheric interactions rather than plate subduction. The record of tectonics seems to be long-lived and uniformly preserved [35]. As a key point of Venus's tectonics, subduction driven by mantle plumes may occur due to the internal dynamics of Venus. Coronae present circular structures with 200-800 km in diameter. They are within a system of concentric ridges and a central zone characterized by a complex, flat composition [35]. Fracture belts are another type that is often associated with faulting. They can be found globally and often represent lithospheric boundaries. Scientists threw out the ideas of suggested early stages of lithospheric rifting or internal stress fields. As a primary source of geological information, the data from radar investigation on Venus undertook missions including photographing, mapping, and so on. The Arecibo telescope was used in radar mapping on Venus, which played a long-term, significant role in this area since 1988. The telescope provided high-resolution images during the Magellan mission and also played a central role in life formation [9].

These unique features on Venus suggest a long-lived tectonic style but a dynamic non-plate-tectonic system.

Europa (Jupiter's Moon): The observation of Europa indicates a high possibility of the formation of a liquid ocean under the icy surface. The volume of this liquid ocean is estimated to be twice that of Earth's oceans [11]. Because of its position, the orbital resonance causes tidal flexing to occur in Europa's internal heating, which could maintain this liquid water environment by preventing the ocean from freezing. Based on the gravity measurements, it suggests that Europa is likely differentiated into a rocky mantle and a metallic core. They are under a thick ice shell, which acts as the crust of this planet.



Figure 2.4. the image of Europa captured by JunoCam, the public engagement camera aboard NASA's Juno spacecraft, during the mission's close flyby on Sept. 29, 2022 [32]

Potential life formation and environmental key features: According to the life formation process, energy, biogenic elements, and a comfortable environment are the essential features to produce life. The evidence for biochemical compounds existing, such as the detection of hydrated salts on Europa's surface and the possibility of the presence of organic molecules, for example, carbon dioxide and methane. Apart from those, comets could have impacts on it that caused the delivery of organic elements. These findings suggest a high potential for life

formation. The icy surface shell of Europa is constantly bombarded by Jupiter's magnetic field radiation. This leads to the breaking of water into oxidants and organics. Another noticeable point is the existence of energy on Europa, which relates to how Europa might have the potential to sustain life. Sources of energy include radiation, hydrothermal vents, and chemical disequilibrium [11]. The possibility of hydrothermal vents seems to become a main feature, as they could act as a source of energy.

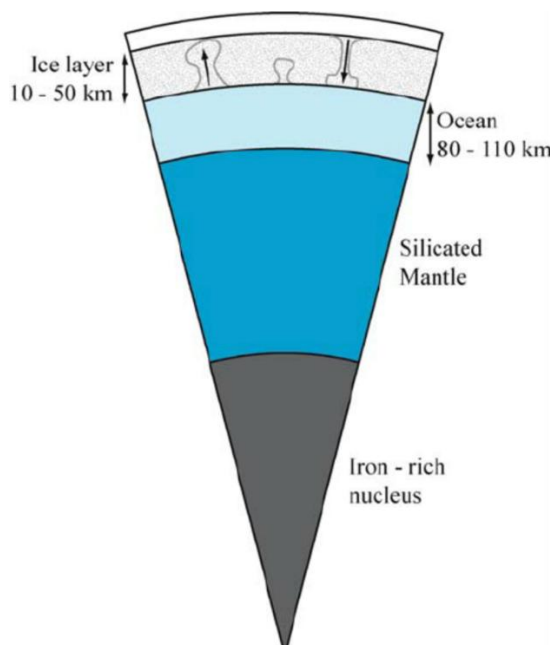


Figure 2.5. interior structure overview [5]

Due to high habitability, this causes the future exploration of Europa to be on schedule. The search for life on this planet is complicated due to the challenges of sampling and exposure, and the unknown internal dynamics. And because of the location of Europa, direct investigation can hardly be completed.

Chaos Terrain formation: Several recent studies suggested that there is chaos terrains formed above the shallow subsurface water lenses about 3km beneath its icy surface. Those terrains are driven by thermal plumes rising from below, leading to subsurface melting and ice disruption, and the formation of pressurized water lenses. The ongoing interaction between ice and water creates a similar condition with Earth's subglacial lakes. This suggests that Europa's icy shell may have large, stable liquid water environments, which could also provide the necessary conditions for life [37].

Despite lacking classical plate tectonics, Europa's subsurface dynamics may provide energy gradients necessary for life.

4. FUTURE OBSERVATIONS AND RESEARCH OUTLOOK

Future missions will provide critical new data to refine our understanding of planetary tectonics. Those help both within our solar system and by extension on exoplanets.

The data from the 'InSight' mission on Mars, which started collecting high-quality seismic data in 2019, help us reveal whether Mars's core is liquid or solid and estimate tectonic activities. This mission raised the prospect of using seismic missions in future studies on Europa or Titan [15].

Since radar mapping on Venus began in 1988, the imaging technology has improved, which will provide higher-resolution images of Venus surface, revealing deformation and geological tectonic features more clearly. The mission 'EnVision' planned by NASA following 'ESA' mission

in 2024, will include the Synthetic Aperture Radar and the VenSAR s-band radar. The mission aims to study the events that shaped Venus's surface and explore its thick atmosphere. The VenSAR S-band radar will capture high-quality images while the Subsurface Radar Sounder will provide data of the upper crust. These new technologies are expected to lead to significant improvement in understanding Venus and even other exoplanets [2].

NASA's Europa Clipper will hold a mission on assessing the habitability of Europa after entering Jupiter's orbit in 2030. The mission objectives are to investigate the interior of Europa, including its composition and geology. The technologies involved in the mission are remote sensing and in-situ instruments, which can cover investigating the ranges of the electromagnetic spectrum. Moreover, measurements of magnetic field, dust grains, neutral gas, and plasma surrounding Europa are included in the mission [36]. The mission could validate whether hydrothermal systems exist in icy moons.

5. IS PLATE TECTONICS ESSENTIAL FOR LIFE?

5.1. Arguments in Favor

Plate tectonics plays a critical role in sustaining planetary habitability because plate tectonics maintains climate stability and material cycling. It is fundamentally linked to the Earth's long-term habitability. In order to maintain a stable greenhouse effect, tectonic activity controls atmospheric CO₂ through the silicate weathering feedback mechanism, in which volcanic outgassing replaces atmospheric CO₂ and subduction recycles carbonates into the mantle. Extreme temperature swings that resemble either a frozen or runaway greenhouse state could occur on Earth if this balance is lost [28], *and also leads to serious problems*. Furthermore, the biosphere is supported by tectonically driven nutrient cycling, which enables the supply of essential bioavailable elements, such as phosphorus delivery through uplift and erosion [16]. Beyond surface climate regulation, tectonic processes also shape deep subsurface biospheres. In tectonically active areas, where fluid-rock interactions provide microbial life energy and nutrients, the deep biosphere is especially concentrated. Chemosynthetic ecosystems powered by serpentinization events that produce H₂ and CH₄ are found in hydrothermal vents at mid-ocean ridges and subduction zones [31]. Similarly, electron donors produced by the radioactive decay support microbial populations in continental fault zones through deep crustal splits [30]. These habitats not only show that tectonic processes produce subsurface habitats, but also stabilize surface conditions, indicating that sustained geodynamic activity is necessary for planetary habitability [4]. Without plate tectonics, Earth's climate would likely swing between extreme states, potentially precluding the persistence of complex life.

5.2. Counterarguments

But on the other hand, the appearance and persistence of life in stagnant, tectonically inactive environments, such as the subsurface oceans of Europa, challenge traditional Earth-based paradigms of habitability, which emphasize dynamic plate tectonics and global geochemical cycling. Unlike Earth, the moons lack plate tectonics, surface weathering, and solar-driven photosynthesis. For instance, Europa's ice shell dynamics play a crucial role in the potential for nutrient recycling, a key requirement for sustaining any long-term subsurface biosphere. However, recent studies suggest that alternative carbon and energy pathways, including serpentinization and impact-driven degassing, could sustain prebiotic chemistry and chemosynthetic ecosystems in such settings. Instead, subsurface oceans are maintained by tidal heating and radiogenic decay, creating long-term stable but chemically isolated environments [23]. For instance, Europa's Oxidant Transport means that the surface radiolysis generates oxidants (e.g., O₂, H₂O₂), which may be delivered to the ocean via ice convection, sustaining potential chemosynthetic life [47]. Additionally, serpentinization, provides sustained redox

gradients analogous to those found in tectonic hydrothermal systems, which is the aqueous alteration of olivine-rich rocks to produce hydrogen and simple hydrocarbons, provides both energy and carbon sources for microbial life. Also take Europa as a representative example; the thermodynamic models predict that active serpentinization in Europa's seafloor generates sufficient hydrogen to fuel methanogenesis [48]. These findings suggest that tectonic activity may not be universally necessary for life.

5.3. Middle-ground View

Although tectonics contributes significantly to sustaining habitable environments on Earth, it may not be a strict prerequisite for life elsewhere. Tectonic activity has long been considered a key driver of planetary habitability due to its role in regulating climate. However, while tectonics enhances habitability by maintaining geochemical cycles and stabilizing surface conditions over geological timescales, it is not an absolute requirement for life despite the fact that recycling nutrients and sustaining redox gradients through processes such as subduction and volcanism are extremely important. While plate tectonics may not be necessary for microbial life, it could be a critical factor in fostering surface complexity and the long-term evolution of multicellular organisms. But the research about Europa also indicates that alternative mechanisms can sustain habitable environments. Serpentinization provides redox gradients and carbon sources independent of plate tectonics. Therefore, we propose that while plate tectonics enhances planetary habitability, the fundamental requirements remain: liquid water, chemical disequilibrium, and energy availability

6. THE WAY OF FUTURE EXPLORATION AND THE RELATIONSHIP WITH TECTONIC STUDY

6.1. Technological Advances and Observational Signatures

The spaces for exploration of extraterrestrial life are still unlimited. Significant progress has been made in identifying potentially habitable targets, yet vast unknowns remain. To detect signs of life beyond Earth, future research must bridge the gap between planetary surface processes and atmospheric signals. Researchers must focus on the features for habitability, including geological features and internal dynamics. It should also aim to deepen our understanding of geologically familiar bodies such as Venus or Mars. People may discover more technical advancements and hence investigate the whole of Venus under the thick atmosphere. Progress in spectroscopy, thermal imaging, and radar is critical for the future.

When assessing the habitability of exoplanets, the focus should be on searching for observational features that reflect geological and biological activity. For Example, whether a planet has ongoing geological activity (such as volcanic eruptions) and observing surface renewal through intermittent changes in atmospheric composition and surface heterogeneity (such as the distribution of land and sea) [38]. Meanwhile, if significant thermodynamic disequilibrium (a state in which a system maintains energy or chemical gradients that are far from thermodynamic equilibrium, meaning the system has not settled into its most stable, lowest-energy state [26].) is detected in the planet's atmosphere, such as the presence of incompatible gases like oxygen and methane, it would be a strong indication of biological activity [38]. This unusual combination of oxygen and methane would be difficult to persist overtime because they react rapidly toward equilibrium. Its continuous presence suggests a biological source constantly supplying oxygen and methane, which is a typical biosignature criterion [38].

To capture those tiny but crucial signals, new generations of observation platforms are rising. The James Webb Space Telescope (JWST) has already detected some molecules, such as methane and carbon dioxide, in the atmosphere of certain exoplanets, which took an important

step forward in detecting potential life formation [33]. Extremely Large Telescopes (ELTs) with larger apertures and higher sensitivity, such as 39-metre optical telescopes, will provide high-resolution spectra to detect tiny features in the atmospheres of Earth-like planets, such as absorption lines of oxygen or seasonal variations. In the future, the large ultraviolet optical infrared radiation telescope (LUVOIR) from NASA's candidate missions, as well as Europe's proposed Large Interferometer for Exoplanet (LIFE), are expected to bring revolutionary breakthroughs. These next-generation space telescopes will have the capability to directly image and obtain spectra, in order to separate the signals of Earth-sized planets from the strong stellar background. With these technologies, we are able to detect biosignature gases such as O_2 , O_3 , and CH_4 , as well as to observe changes in the planetary atmosphere's composition over time. This enables the determination of whether the atmosphere is in a biologically-driven disequilibrium state [1]. Besides, seasonal variability in atmospheric composition, such as periodic methane spikes, may further strengthen biosignature interpretation.

6.2. Role of Analog Experiments and Models

In addition, experimental studies and analog simulations are also important in interpreting observational results. Researchers point out that the most feasible method for detecting exoplanets is to observe their atmospheres. However, to correctly interpret these observations, it is essential to understand how the surface and internal processes of a planet influence its atmospheric composition [40].

Therefore, studying the feedback mechanisms of lithosphere-atmosphere using Earth-analog experiments and numerical models is one of the key focuses of future work. As an example, thermal evolution and carbon cycle models can be used to predict trends in planetary climate evolution under different tectonic regimes. Existing models suggest that even in the absence of Earth-like plate tectonics, 'single-plate' planets with high radiogenic heating and ongoing volcanic activities may still have long-term carbon cycles and maintain a balanced, habitable climate [17, 29]. These models suggest that even in the absence of plate tectonics, geochemical cycles can still operate if internal heating and volcanic outgassing are sufficient.

To look ahead, multi-source integration methods driven by data (such as comprehensive analysis combining data from multiple telescopes, accompanied by technologies like machine learning) will further enhance our ability to interpret observational clues [17]. By integrating data from different platforms with Earth-analog experiments and theoretical models, researchers will be able to more effectively separate biological signals from abiotic processes, providing more reliable investigation of exoplanet observation and making substantial progress in searching for extraterrestrial life.

7. CONCLUSION

Plate tectonics has been essential for maintaining Earth's long-term stability and promoting biological prosperity. By regulating the carbon cycle through subduction and volcanic activity, it sustains atmospheric CO_2 levels and a temperate climate across geological intervals. By creating a range of ecosystems, tectonic activity also recycles essential nutrients, preserves geochemical gradients, and promotes biodiversity. The dynamism of seas and continents provides a strong foundation for evolution and also serves to minimize excessive environmental oscillations.

While plate tectonics provides a robust framework for sustaining surface life, emerging evidence suggests that it is not a universal prerequisite. Other planetary processes, such as stagnant-lid tectonics, severe weathering, or cryovolcanism, may potentially support habitable conditions. For instance, on icy worlds like Europa or Enceladus, chemical energy from subsurface hydrothermal systems may sustain life in the absence of solar radiation. Similarly, in

the absence of active tectonics, exoplanets with thick atmospheres or tidal heating might be able to keep liquid water. The discovery of Earth's extremophiles demonstrates how adaptable life is to a range of environments, suggesting that even worlds with peculiar geodynamics might harbor life provided specific conditions—such as liquid water, energy sources, and organic matter—are met. Future interdisciplinary approaches combining observation, theory, and analog experimentation will be key to refining our understanding of Planetary habitability.

As our knowledge of the cosmos expands, so too must our definitions of life and the planetary conditions that can support it. Thus, tectonics enhances habitability, but life may find other ways.

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