



Subsurface life can modify volatile cycling on a planetary scale

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Abstract. The past decade of environmental microbiology has revealed that subsurface environments, both marine and continental, harbor one of the largest ecosystems of our planet, with diversity and biomass rivaling those of the surface. In addition, subsurface life has been recently shown to contribute significantly to the planet’s biogeochemistry, with microbial activity potentially playing an important role in controlling the flux and composition of volatiles recycled between the Earth’s surface and interior, which has broad implications for the search for life beyond our planet. Current efforts to discover extraterrestrial life are focused on planetary bodies with largely inhospitable surfaces, such as Mars, Venus, Europa, Titan, and Enceladus. In these locations, subsurface environments might provide niches of habitability, making the study of deep microbial life a priority for future astrobiological missions. Understanding how volatile elements are exchanged between planetary surfaces and interiors and the role of a subsurface biosphere in altering their composition and flux might provide a tractable target for defining planetary habitability and the detection of subsurface life forms.

1. Introduction

The circumstellar habitable zone has traditionally been defined as the range of orbits around a star where a planetary surface can support liquid water, given sufficient atmospheric pressure and clement temperature conditions (Kasting et al. 1993). However, in the last three decades it has become clear that planetary surfaces may not offer the only opportunity for life to thrive. Microbial life has been found to be abundant and diverse in the Earth's crust, at depths of several kilometers (Magnabosco et al. 2018) and temperatures approaching 150°C, the isotherm currently considered to be the upper limit of life (Merino et al. 2019; Heuer et al. 2020), see Fig. 1.

Subsurface environments are of particular relevance in considering life on extraterrestrial planets given the shelter they provide to extreme temperature fluctuations, solar and interstellar radiation, and violent weather events (McMahon & Parnell 2014). Considering the range of current temperatures under which Earth life has been shown to thrive (i.e., -18 °C to 122 °C by culture-dependent approaches, see Merino et al. (2019)), the distance for a "subsurface habitable zone" around any given star can be extended to tens and hundreds of astronomical units, depending on the mass of the planet considered (McMahon & Parnell 2014).

The recent discovery of underground water on Mars (Orosei et al. 2018) and the Moon (Benna et al. 2019) has made it plausible to consider extraterrestrial life to exist in the subsurface of rocky planets and moons. The prevalence of subsurface life on Earth suggests that the narrow definition of circumstellar habitability (as conditions where liquid water is present on a planetary surface) might grossly underestimate the number of planets and moons capable of hosting life.

2. Subsurface life and habitable zones

As the number of confirmed exoplanets keeps growing, our best chance of finding signs of life is linked to our ability to detect biosignatures in planetary atmospheres (Schwieterman

et al. 2018) using a range of techniques, generally involving remote spectroscopic observations (Seager 2014). Therefore, for subsurface life to be detectable, it would need to leave an atmospheric biosignature detectable through spectroscopic observations.

It is generally assumed that the current redox imbalance in the atmosphere of modern Earth is the result of oxygenic photosynthetic activity over the course of the last 2.5 billion years (Fischer et al. 2016). This is, however, only partially correct, as a number of other biotic and abiotic processes have contributed to the net accumulation of oxidants (i.e., molecular oxygen) in Earth's atmosphere. Plate tectonics plays a key role in the redox balance of Earth's surface and interior (Stagno & Fei 2020). Earth is characterized by a special form of tectonics dominated by subduction processes as the primary means of recycling lithospheric crust (Stern & Gerya 2018).

Subduction is responsible for linking Earth's surface with its interior, recycling surface oxidants and other volatile elements into the mantle, and contributing to the long-term removal of reduced organic carbon from Earth's more oxidized surface. Carbon and other elements (e.g., water, nitrogen) that are subducted along with the altered oceanic crust and overlying sediments can be either delivered to the deep mantle or recycled back to the surface through arc volcanism and secondary geothermal activity. Understanding the quantitative mass balance between surface recycling and deep mantle delivery of volatiles is a key aspect of modeling Earth's oxidation state as well as understanding climate stability, atmospheric composition and habitability (Bekaert et al. 2021).

During subduction, volatile-rich fluids are released from the upper mantle, as well as the crustal and sedimentary portions of the downgoing slab. These fluids then migrate through the overlying mantle wedge and continental crust, and are ultimately released across the forearc, volcanic arc front and backarc. Whereas volatile fluxes emitted at the arc front can be constrained from direct geochemical measurements at active volcanoes, little is known about what effect volatile fluxes

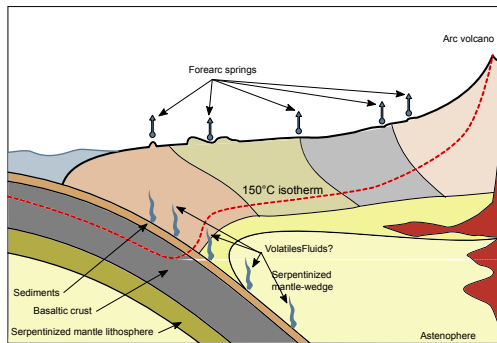


Fig. 1. Schematic representation of a subduction zone showing the depth of the theoretical upper temperature limit for Earth's life (150°C isotherm).

through the forearc and backarc may have on the global budget of volatile recycling (Bekaert et al. 2021). Importantly, much of the forearc subsurface is at low temperatures (<150 °C) that are conducive to microbial life and shallow low-temperature water–rock interactions (Barry et al. 2019; Fullerton et al. 2021), potentially altering the speciation and isotopic composition of volatiles in subduction zones.

Recent studies highlighting the importance of the extensive global subsurface microbial biosphere have demonstrated the significant roles of the deep biosphere in altering Earth's biogeochemical cycles (Magnabosco et al. 2018) and driving a wide range of key biogeochemical transformations. Relative to oceanic and continental lithosphere, the cold geothermal gradients of subduction zones may provide suitable conditions for microbial life to extend down to great depths. However, the presence, magnitude, and extent of deep microbial biosphere in subduction zones is largely unconstrained, especially at depth.

For example, hydrothermal vents and rocks exhumed at the Mariana forearc have provided clues into the presence of microbial life in subduction zones, potentially down to ~15 km depth (Ohara et al. 2012; Plümper et al. 2017; Fryer et al. 2020). Indirect indication of much deeper life was provided by organic compounds included in clasts of serpentinite exhumed from about 10 km depth in mud volcanoes and interpreted as biomarkers (Plümper

et al. 2017). Fluids released by geological processes in subduction zones appear to be key factor controlling the distribution and magnitude of deep microbial activity at convergent margins (Plümper et al. 2017), and may include highly energetic fluids sourced from several tens of kilometers depth (Vitale Brovarone et al. 2020). Other indirect evidence of deep microbial activity in subduction zones is provided by the analysis of hydrothermal vents in the Costa Rica forearc (Barry et al. 2019; Fullerton et al. 2021). Importantly, the latter study quantified the role of deep microbial life in modulating the fluxes of carbon between shallow and deep Earth reservoirs, suggesting that deep subsurface life might impact the long term volatile budget of our planet.

3. Conclusion

Taken together, available research suggests that a global impact of a biosphere on atmospheric composition is possible beyond the need for extensive surface ecosystems (D'Hondt et al. 2004; Knittel & Boetius 2009; Giovannelli et al. 2020). This is probably true as long as planetary volatile cycling is present between the planetary interior and its surface. Besides Earth plate tectonics, other forms of tectonic activity are possible. Examples are subsidence, drips and plumes, and delamination and upwellings tectonic (Stern et al. 2018). Regardless of the setting, the key element linking long term stability and habitability of a planet is a mechanism of volatile cycling (Foley & Smye 2018; Rushby et al. 2018).

A planet not able to recycle elements and oxidants is likely to lose its redox disequilibria early during planetary evolution, potentially hampering the emergence of life or bringing it to rapid extinction (Chopra & Lineweaver 2016). Whatever the specific mechanisms of volatile cycling, the presence of a redox imbalance between the planetary interior and its surface on geologically active planets is highly probable. Given the ability (and necessity!) of life to exploit redox gradients (Jelen et al. 2016; Kleidon 2010; Moore et al. 2017), it is plausible to hypothesize the presence of vast subsurface biospheres around the uni-

verse (Chopra & Lineweaver 2016; Parnell & McMahon 2016). Taking this into account will open up the selection of targets of astrobiological interest in the next decade, while simultaneously requiring more detailed studies of the role of Earth subsurface biosphere in altering the long term volatile cycling on our planet.

Acknowledgements. The authors wish to acknowledge the Agenzia Spaziale Italiana (ASI) and the Italian Society of Astrobiology for organizing the 1st Italian Space Agency workshop on Astrobiology in October 2020, that lead to fruitful discussions captured in this contribution. The authors wish also to acknowledge conversations on the topic with numerous collaborators and colleagues involved in current subsurface biosphere research. This work was partially supported by grant G-2016-7206 from the Alfred P. Sloan Foundation and the Deep Carbon Observatory to PHB, JMdM, DG, and KGL. GLJ was supported by FONDECYT Grant 11191138 (ANID Chile). DG and SMM acknowledge the support of the project ENIGMA (NASA Astrobiology Institute cycle 8) Grant Number 80NSSC18M0093. All authors contributed equally to this paper.

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