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The Habitability of Venus

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Abstract
Venus today is inhospitable at the surface, its average temperature of 750 K being incompatible to the existence of life as we know it. However, the potential for past surface habitability and upper atmosphere (cloud) habitability at the present day is hotly debated, as the ongoing discussion regarding a possible phosphine signature coming from the clouds shows. We review current understanding about the evolution of Venus with special attention to scenarios where the planet may have been capable of hosting microbial life. We compare the possibility of past habitability on Venus to the case of Earth by reviewing the various hypotheses put forth concerning the origin of habitable conditions and the emergence and evolution of plate tectonics on both planets. Life emerged on Earth during the Hadean when the planet was dominated by higher mantle temperatures (by about 200 °C), an uncertain tectonic regime that likely included squishy lid/plume-lid and plate tectonics, and proto continents. Despite the lack of well-preserved crust dating from the Hadean and Paleoarchean, we attempt to review current understanding of the environmental conditions during this critical period based on zircon crystals and geochemical signatures from this period, as well as studies of younger, relatively well-preserved rocks from the Paleoarchean. For these early, primitive life forms, the tectonic regime was not critical but it became an important means of nutrient recycling, with possible consequences on the global environment in the long-term, that was essential to the continuation of habitability and the evolution of life. For early Venus, the question of stable surface water is closely related to tectonics. We discuss potential transitions between stagnant lid and (episodic) tectonics with crustal recycling, as well as consequences for volatile cycling between Venus' interior and atmosphere. In particular, we review insights into Venus' early climate and examine critical questions about early rotation speed, reflective clouds, and silicate weathering, and summarize implications for Venus' long-term habitability. Finally, the state of knowledge of the Venusian clouds and the proposed detection of phosphine is covered.

1 Introduction

With an average temperature of ~ 750 K, today the surface of Venus is far from environmental conditions suitable for life as we know it. However, billions of years ago, when the

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Sun was much fainter (Sagan and Mullen 1972; Hart 1979; Gough 1981; Claire et al. 2012), Venus was located in the middle of the classical habitable zone around our sun (Kasting 1993; Kopparapu et al. 2013), thus fueling speculations about the early habitability of the planet (Pollack 1971; Grinspoon and Bullock 2007; Way et al. 2016). Important preconditions for habitability at the surface of Venus include a temperature range allowing the existence of liquid water; surface geochemistry with available chemical energy and appropriate elemental and molecular constituents, such as active water/rock interfaces; and protection from lethal solar radiation. The latter could have been provided by liquid water, as well as by a large reflective cloud cover resulting from the presence of liquid water. Surface thermochemical conditions would have ultimately been controlled by Venus' tectonic activity, although different models suggest different scenarios. Venus' convection regime may have changed over the course of the planet's history and at least some models suggest that Venus could have maintained temperate surface conditions until as recently as 0.7 Ga (Way et al. 2016). Lastly, although the early Sun was fainter, Venus' more sunward position means that solar incident insolation during its early history was still 40% higher than for present-day Earth (Lammer et al. 2008). Even if the overall radiation environment at the surface (as determined by absorption in Venus' early atmosphere) was clement, it may have affected conditions for early life potentially inhabiting water on exposed landmasses or subsea environments, such as hydrothermal vents. Increasing solar luminosity, continuous degassing of CO_2 from Venus' mantle into the atmosphere, or large-scale volcanic eruptions (Way et al. 2022) may have brought an end to a potential early habitable period.

In order to gain insight into whether these preconditions existed in the early history of Venus, we address the mechanisms relevant to Earth's early planetary and biological evolution in Sect. 2. The main challenge with this approach is the loss of the earliest records of Earth's ancient surface due to tectonic recycling. Understanding of the early environmental conditions on Earth can be approached through a combination of modelling, inherited geochemical signatures in younger rocks, and comparison with well-preserved, younger crustal rocks formed about 1 billion years (Gyr) after solidification of the planet. We will also elaborate on tectonic processes and interior-atmosphere volatile exchange relevant to the evolution of Venus and a potential early habitable period in Sect. 3. Based on these constraints, the climate throughout Venus' history from general circulation models will be discussed in Sect. 4.

Speculation on present-day habitability is primarily focused on Venus' cloud aerosols. Although larger reservoirs of water are likely to be dissolved in the mantle and as atmospheric vapor, cloud droplets are the only known place where liquid water is found on Venus. This liquid water is dissolved in sulfuric acid, the aerosols' primary constituent. Section 5 discusses what is known about the requirements for Venus cloud habitability by comparison with Earth's aerobiosphere, as well as discussion of suggested Venusian biosignatures, such as UV absorption and the controversial report of phosphine detection. We conclude with an evaluation of mission requirements necessary to improve our constraints on Venus' past and present habitability in Sect. 6.

2 Early Earth History

2.1 Water on the Earth

The history of initial habitability on any planet is first and foremost the history of water, although long-lived habitability is also controlled by tectonics. Temperature and pressure, as well as the various gaseous species that comprise the atmosphere, determine the possibility of liquid water at the surface. A large part of the conditions that govern the onset (or lack thereof) of a habitable era is therefore set by the composition of the atmosphere and its interaction with factors, such as planetary characteristics, solar energy input, or material delivery.

Recent investigation of calcium-aluminium-rich inclusions (CAIs) in some of the most primitive meteorites suggests the admixture of a significant amount of interstellar water during the early evolution of the protosolar cloud. This, in turn, implies very early formation of planetary reservoirs of volatile elements (Aléon et al. 2022; cf. Grossman and Larimer 1974). Thus, early volatile-containing materials in the Solar System would have contributed to the building blocks (pebbles, e.g. Morbidelli et al. 2012; Raymond 2021; Johansen et al. 2021 and/or planetesimals, Chambers and Wetherill 1998; Levison et al. 2015; Burkhardt et al. 2021) of the inner rocky planets. Some of the early water (and other volatiles) would have been degassed and lost during the Moon forming impact (Benz et al. 1986; Canup 2004) with a Mars-sized planet (named Theia cf. Halliday 2000) that occurred approximately 4.51 Ga (Barboni et al. 2017). Although (Connelly and Bizzarro 2016), also using Pb isotope data, suggest slighter younger dates between 4.426–4.417 Ga. Recent calculations suggest that all of Earth's water and other volatiles may have been delivered by volatile-rich carbonaceous chondrites, initially formed outside the orbit of Jupiter but displaced inwards by the planet's growth and migration (Kleine et al. 2020). However, timing of the accretion of the volatiles to Earth is still an active area of research (Avice et al. 2022; Salvador et al. 2023, this journal). Note that Marty (2012) suggests that the isotope signatures of terrestrial H, N, Ne and Ar may be the result of mixing between two end-members of solar and chondritic compositions, with the N and H isotopic compositions suggesting a primitive meteoritic origin.

Liquid water is critical to magmatic processes on the Earth, including partial melting of the mantle and crustal recycling. Indeed, water is essential for the production of significant amounts of granitic melts formed by melting of pre-existing crustal rocks (Campbell and Taylor 1983; Jacob et al. 2021; Turcotte and Schubert 2002; Korenaga 2018). Although non-hydrous fractionation will form feldspathoids, as testified by the lunar anorthosites (Norman et al. 2003). These granitic melts, in turn, formed the early, buoyant, less dense granitoid rocks that were the cores of early continents. Thus, evidence of any of these phenomena can be used as proxies for the presence of liquid water.

Physical evidence for the existence of early granitoid crust, however, is restricted to: (1) zircon crystals formed by crustal fractionation during the Hadean (4.5–4.0 Ga) and Eoarchean (4.0–3.6 Ga) that were eroded from the initial crustal rocks and then sedimented. These ancient zircons have re-emerged in Palaeoarchean (3.5–3.3 Ga) rocks in Western Australia (Wilde et al. 2001; Mojzsis et al. 2001). (2) Small enclaves of granitoid rocks from this period still exist and are occasionally associated with metamorphosed sediments (metasediments), such as the 4.3 (O'Neil et al. 2008) to 3.8 (Cates and Mojzsis 2007) Nuvvuagittuq Supracrustal Belt and the 4.02 Ga Acasta Gneiss (Bowring and Williams 1999) in Canada, the 3.7–3.8 Ga Isua terrane in West Greenland (Moorbath et al. 1973), and the 3.5–3.2 Ga greenstone belts of the Pilbara in W. Australia (Nelson et al. 1999) and Barberton in South Africa (Lowe and Byerly 1999b). Finally, (3) inherited uranium-lead and hafnium isotope signatures in the reworked zircon crystals provide a certain amount of information pertaining to the pre-existing Hadean crust (Mulder et al. 2021).

Oxygen isotopic signatures preserved in zircon crystals, and dated at up to 4.4 Ga (Wilde et al. 2001; Mojzsis et al. 2001; Valley et al. 2014) (but possibly younger in age, Whitehouse et al. 2017) have been interpreted to suggest the exposure of the crust from which the crystals formed via hydrothermal processing, implying the presence of water recycled into the crust from the surface of the Earth by 4.4 Ga. Indeed, recent combined oxygen and silicon isotope measurements of zircons from the Hadean support the existence of significant quantities of siliceous sediments during the Hadean (Trail et al. 2018).

Another proxy for the presence of water is the existence of sediments; they imply erosion by and/or deposition in a body of water. Sediments are associated with the most ancient terranes preserved, the 4.3–3.8 Ga Nuvvuagittuq (Canada) and the 3.7–3.8 Ga Isua (West Greenland) supracrustal terranes, the latter of which includes also metamorphosed pillow basalts, undeniable structures produced under water. Further evidence of hydrosphere-crustal interactions comes from extremely high $\delta^{18}O$ values of up to $+9‰$ measured in metamorphic zircons formed about 3.5 Ga by reworking of metamorphic crust in the ca. 3.86 Ga, Eoarchean Saglek Block (North Atlantic Craton) (Vezinet et al. 2019).

2.2 Interior and Tectonic Processes on Earth

2.2.1 Brief Overview

The interior and tectonic processes on the early Earth had important implications for the building of a habitable planet (e.g. Schubert et al. 1989; Korenaga 2012; Höning et al. 2019a). Indeed, our present-day Solar System provides a perfect correlation between the occurrence of plate tectonics and planetary habitability, although with a sample size of one. A possible reason for this is the increased exchanges between the interior and the atmosphere of planets with plate tectonics, compared, for example with stagnant lid convection (Foley and Smye 2018; Höning et al. 2019b; Rolf et al. 2022; Gillmann et al. 2022, this journal). It has also long been suggested that plate tectonics and the presence of surface liquid water were entwined (Campbell and Taylor 1983, for example) and favoured volatile cycles, and possibly stabilizing feedback process for surface conditions. Moreover, while Venus (and Mars) appear to be operating under stagnant-lid-like convection today, it is possible that their convection regime changed over their past respective histories (e.g. Sleep 1994; Gillmann and Tackley 2014; Smrekar et al. 2018).

In a review of the evolution of continental crust and the onset of plate tectonics, Hawkesworth et al. (2020) note the paucity of early crustal preservation and reiterate the fact that inferences based on the few preserved remnants, represent only a part of the geological history of this early time. This fact is all the more important because it is apparent that tectonic signatures varied in time and place, and that a form of subduction may have been catalysed, at least temporarily, by impacts and mantle plumes, as well as by plate tectonics (Gillmann et al. 2016; O'Neill et al. 2017; Gerya et al. 2015a). A recent study of Paleoarchean zircons ages recording submantle $\delta^{18}O$ relates their production to impact induced crustal recycling (Johnson et al. 2022).

The timing of the onset of plate tectonics is still debated and ranges from ca. 4 Ga to 1 Ga (as reviewed by Lammer et al. 2018; Dehant et al. 2019; Korenaga 2021). Most estimates place the transition from an earlier convection regime (possibly from a more stagnant state, or already a plume-induced proto-plate tectonics, see also Fig. 1) between 3 and 4 Ga, with the process taking place gradually at different places and at different times. Prior to about 3.0 Ga, xenon isotopes suggest little recycling of volatiles in the crust (Péron and Moreira 2018). However, the recent review by Korenaga (2021) hypothesises an early start to plate tectonics during the Hadean, as soon as there was water at the surface of the planet. The existence of plate tectonics has numerous implications: firstly that the crust was sufficiently rigid as to allow crustal breakup under stress caused by vigorous mantle convection, as well

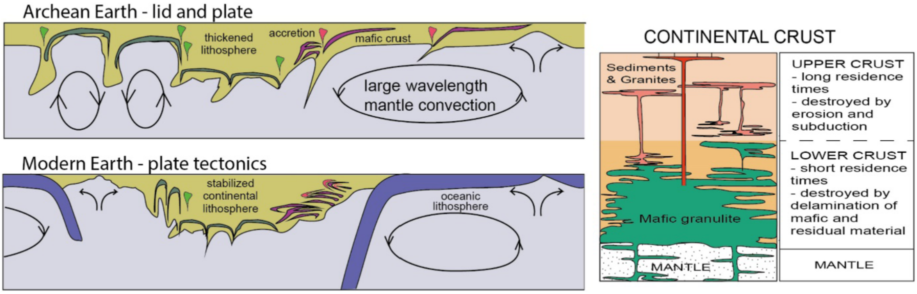

Fig. 1 Comparison of two styles of tectonics, lid and plate tectonics during the Archean epoch and modern-style Wilson plate tectonics (after Hawkesworth et al. 2020)

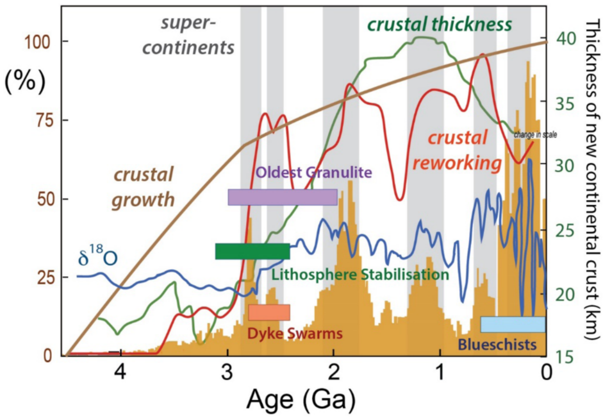

Fig. 2 Overview of changes in crustal growth, crustal thickness, crustal reworking, lithospheric stabilisation and the formation of supercontinents due to lateral accretion, the appearance of dykes swarms indicating rigid crust, changes in the oxygen isotope composition reflecting increasing continental sediment incorporated into the mantle/crust with time, and the appearance of blueschists indicating high temperature metamorphism, all signs of and influenced by the emergence of plate tectonics (after Hawkesworth et al. 2020)

as to allow the intrusion of dyke swarms (Cawood et al. 2018), and secondly, that it was dense enough (i.e. mafic in composition) to subduct (Van Kranendonk 2010; Hawkesworth et al. 2009; Cawood et al. 2013). The paired metamorphic zones so typical of convergent tectonics, and recognised by Th/Nb ratios, suggest that magmas, both related to subduction (suites of high Th/Nb magmas) and not related to subduction (low Th/Nb magmas), were concomitant in different locations of the planet (Hawkesworth et al. 2020).

In parallel to the initiation of plate tectonics, there was a change in the composition of juvenile continental crust from mafic to intermediate andesitic compositions (Dhuime et al. 2015), the latter characterising the upper continental crust (Chowdhury et al. 2017; Perchuk et al. 2018). Increasing crustal thickness and more acidic compositions of the granitic cores of the continents led to landmasses with higher relief, which influenced erosion and sedimentation, and hence the composition of the oceans and the atmospheres.

Major continental amalgamation to form super continents started at least by 2.8 Ga (Evans 2013). Rates of continental reworking (estimated from Hf isotope ratios, Belousova and Kostitsyn 2010; Dhuime et al. 2012) and destruction linked to tectonic processes started increasing from about 3.0 Ga, an indication of efficient recycling of the older, less buoyant, mafic continental crust. There was also a change in the global oxygen isotope ratios in zircons indicating incorporation of eroded sediments and, therefore, the presence of exposed landmasses (Valley et al. 2005; Spencer et al. 2014). Figure 2 compares the evolution of crustal growth and thickness with factors such as lithospheric stabilisation, change in style of metamorphism, as well as dyke swarm frequency. Korenaga (2018) has compiled a list of published models for continental growth through Earth's history which underlines the wide range of estimates for the initiation of plate tectonics from the Hadean to the Archean.

Continental landmass is an important source of phosphorus, one of the rate limiting nutrients for biomass development. On the early Earth, relatively low weathering rates of exposed land masses (because of their low relief) led to a relatively low influx of P in the form of apatite (Hao et al. 2020). New experimental and analytical work suggests that phosphate (HPO_4^{2-}) in the form of apatite (insoluble) can be reduced to phosphite (HPO_3^{2-}) by concurrent oxidation of Fe^{2+}. Phosphite is much more soluble and therefore would have been available for biomass development.

2.2.2 Evidence for Interior Processes and Tectonics, the Results of Modelling Studies

Recently, tectono-magmatic processes on pre-Phanerozoic Earth have been the subject of growing numerical geodynamic modelling efforts (e.g. Gerya 2022, and references therein). The resulting holistic modelling- and observation-based view of the global Precambrian tectono-magmatic evolution that has emerged (Gerya 2014; Rey et al. 2014; Bercovici and Ricard 2014; Rozel et al. 2017; Sobolev and Brown 2019; Gerya 2019; Hawkesworth et al. 2020; Gerya 2022) is briefly summarized below.

As envisaged in these models, Hadean-Archean plutonic squishy-lid/plume-lid/lid-and-plate tectonics before about 3 Ga were characterised by mantle potential temperatures 250–200 K higher than present day, which resulted in the widespread development of mantle-derived magmatism and rheologically-weak crust (Richter 1985; Gerya 2014; Rozel et al. 2017; Hawkesworth et al. 2020, see Figs. 1 and 2). Models suggest that the global tectono-magmatic style was dominated by plume- and drip-induced tectono-magmatic processes under conditions of an internally deformable (squishy, non-stagnant, non-rigid) lithospheric lid that is often compared to conditions on present-day Venus (e.g. Van Kranendonk 2010; Gerya et al. 2015b; Rozel et al. 2017; Harris and Bédard 2014; Hansen 2018). In this hypothesised pre-plate tectonics regime, both proto-oceanic and proto-continental lithospheres were formed by a combination of several tectono-magmatic differentiation processes (e.g. Sizova et al. 2015; Capitanio et al. 2020). Lid evolution was driven by episodic tectono-magmatic activity (e.g. Moore and Webb 2013; Johnson et al. 2014; Piccolo et al. 2019, 2020) controlling crustal and lithospheric growth and removal with a periodicity of $\sim$ 100 Myr (Sizova et al. 2015; Fischer and Gerya 2016a), which is comparable to the geological-geochemical record from some major Archean greenstone belts, e.g. East Pilbara in Western Australia and Kaapvaal in South Africa (cf. discussions in Fischer and Gerya 2016a, and references therein). Thermal regimes of crustal reworking produced by this non-plate tectonic environment are also broadly consistent with the metamorphic record (cf. discussions in Capitanio et al. 2019, and references therein). (Ultra)-slow rifting and oceanic spreading with intense decompression melting and thick mafic crust were capable of developing in the absence of subduction (e.g. Sizova et al. 2015; Capitanio et al. 2019, 2020). Due to the elevated mantle potential temperature (e.g., Herzberg et al. 2010), (ultra)slow spreading is associated with intense mantle decompression melting leading to thick mafic crust formation (e.g., Sizova et al. 2015) and thereby to high heat fluxes at ridges. In addition, heat fluxes were also higher in the continental crust, which was much hotter than present day due to widespread intrusions of mantle-derived magma (e.g., Sizova et al. 2015; Rozel et al. 2017; Piccolo et al. 2019). Importantly, the modern-style global mosaic of rigid plates separated by narrow, rheologically weak, plate boundaries did not exist in this pre-plate tectonics period (Bercovici and Ricard 2014). Voluminous melting of the upper mantle caused the formation of both cold lithospheric and hot sub-lithospheric, highly depleted, proto-cratonic mantles with lowered density and increased viscosity (e.g. Sizova et al. 2015; Capitanio et al. 2020; Perchuk et al. 2020, 2021). Note that this scenario is in direct contrast to the scenario proposed by Korenaga (2021), in which the Hadean was characterised by a vigorous plate tectonic regime and recycling of the earlier, thinner crust. This regime then slowed down during the Archean as a result of increasing mantle temperatures and therefore thicker crust that would have been more difficult to subduct.

Subsequently, during the period of protracted Archean-Proterozoic transitional tectonics between about 3 Ga and 0.75 Ga, notable secular cooling of the mantle potential temperature occurred (to 200–100 K above present day). As a result, squishy-lid/plume-lid/lid-and-plate tectonics may have gradually evolved towards the modern plate tectonics regime by combining elements of these two contrasting global styles in both space and time (e.g. Fischer and Gerya 2016b; Chowdhury et al. 2017, 2020; Sobolev and Brown 2019; Perchuk et al. 2018, 2019, 2020). The transitional tectonic regime was controlled by gradual stabilization of rheologically-strong continental and oceanic plate interiors (e.g. Sizova et al. 2010; Fischer and Gerya 2016a). Plume-induced subduction was likely common in the beginning, and triggered the onset of this transitional tectonic regime (Gerya et al. 2015a). Due to the hot mantle temperature and weak lithospheric plates subjected to bending-induced segmentation near trenches (Gerya et al. 2021), shallow slab break-off would have been very frequent, causing intermittent rather than continued subduction (e.g. van Hunen and van den Berg 2008; Perchuk et al. 2019, 2020; Gerya et al. 2021).

Elements of squishy-lid/plume-lid/lid-and-plate tectonics were also locally present and controlled continued development of granite-greenstone belts in (proto)continental domains (Fischer and Gerya 2016b). As noted above, different elements of modern plate tectonics likely emerged at different geological times and oceanic subduction likely became widespread earlier than modern-style (cold) continental collision (e.g. Sizova et al. 2010, 2014; Perchuk et al. 2018). Delamination of the mantle lithosphere in long-lived accretionary orogens controlled gradual changes of continental crust composition from mafic to more felsic components with related rising of the continents due to efficient recycling of lower continental, mafic crust and tectono-magmatic reworking and thickening of more felsic upper continental crust (Chowdhury et al. 2017; Perchuk et al. 2018). The intermittent subduction was likely initially inefficient in creating large volumes of silicic continental crust and, associated with massive decompression melting of the mantle, resulted in the formation of oceanic plateau-basalts (Perchuk et al. 2019). The presence of low-density, highly depleted, hot, ductile mantle under oceanic plates contributed to the formation of chemically layered cratonic keels through a viscous emplacement mechanism driven by oceanic subduction (Perchuk et al. 2020). This peculiar mechanism of cratonic growth deactivated after about 2 Ga due to a decrease in mantle temperature (Perchuk et al. 2020).

Finally, the establishment of modern plate tectonics after about 0.75 Ga followed cooling of mantle potential temperatures to less than 100 K above present day values. This process was attained gradually by a combination of four interrelated factors (Bercovici and Ricard 2014; Gerya 2014; Gerya et al. 2015b; Sobolev and Brown 2019; Gerya et al. 2021): (1) cooling and strengthening of the oceanic lithosphere that stabilized continued long-lived subduction, (2) emergence of a global mosaic of rigid plates divided by strongly localized, long-lived, rheologically-weak boundaries, (3) stabilisation and cooling of thick, rheologically strong continental lithospheres and the rise of the continents above the sea level, and (4) the growing intensity of surface erosion providing rheologically weak sediments deposited in the oceans that increasingly lubricated subduction in trenches. The transition to modern plate tectonics followed a long period of reduced tectono-magmatic activity – the boring billion, 1.7 to 0.75 Ga (Sobolev and Brown 2019).

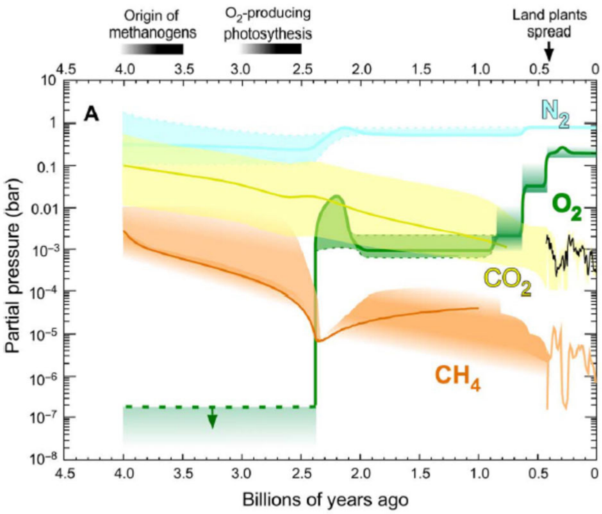

Fig. 3 Evolution of the composition of the Earth's atmosphere through geological time (Catling and Zahnle 2020)

2.2.3 Establishment of the Conditions for the Emergence of Life

Understanding the internal, dynamic processes of the early Earth is certainly essential for appreciating the building of habitable conditions on a global scale. However, the emergence of life and its early evolution were events that occurred on local scales, although perhaps combining the results of different prebiotic reactions occurring in different microenvironments (Stüeken et al. 2013). In this section we will review our present understanding of the environmental conditions reigning on early Earth that were of immediate importance for the emergence of life.

The primary requirement for establishing an environment conducive to the emergence of life is the presence of liquid water. We noted above various proxies indicating liquid water on the Hadean-Eoarchean Earth. One of the main constraints for liquid water at the surface is the composition and partial pressure of the atmosphere (Table 1 in Catling and Zahnle 2020, and references therein). After the Moon-forming impact about 4.5 Ga (e.g. Barboni et al. 2017) that effectively vaporised the surface of the Earth as well as the impactor, the Si-rich vapor recondensed and a thick CO_2 plus water greenhouse atmosphere formed (Zahnle et al. 2015; Sleep et al. 2014; Sossi et al. 2020). Removal of much of the CO_2 though crustal recycling during the Hadean would have resulted in an atmosphere containing approximately 1 bar CO_2 atmosphere and temperatures permitting oceans to form (at $\sim$ 500 K, Zahnle et al. 2015; Sleep et al. 2014).

In contrast to Sleep et al. (2014), Catling and Zahnle (2020) conclude that the early atmosphere could not have been very thick and that it was compensated by the presence of greenhouse gases (Fig. 3). These interpretations are based on geochemical investigations of nitrogen contained in fluid inclusions in quartz crystals of Paleoarchean age (Marty et al. 2013; Avice et al. 2018) and on physical phenomena, such as the sizes of gas bubbles in submarine lavas of similar age indicating hydrostatic pressures of not more than 0.5 bars (Som et al. 2012).

To date, we have no hard and fast evidence of when oceans formed but have listed the different proxies in Sect. 2.1, which suggest an early appearance of water (Catling and Zahnle 2020). Indeed, the Hadean Earth would have been more of an ocean planet and its primitive continents being characterised by submerged plateaus with emergent volcanic edifices and their surrounding land masses, similar to those characteristic of the Paleoarchean, as we will see below.

2.2.4 Early Habitable Environments

There are only a few exposed locations where Paleoarchean terranes are well-preserved (namely the $\sim$ 3.5–3.3 Ga Barberton, South Africa, and Pilbara, Australia, Greenstone Belts), most of which are subaqueous deposits. Indeed, until about 3.2 Ga, very little subaerial material from this time period exists. There are reports of quartzites and quartz-biotite schists from the Isua and Nuvvuagittuq terranes that are interpreted to be the metamorphosed remnants of sandstone and conglomerate protoliths (Bolhar et al. 2005; Cates and Mojzsis 2007; O'Neil et al. 2011), respectively, as well as some horizons of pebble conglomerates and sands attesting to deposition in a terrestrial setting in the 3.48 Ga Hooggenoeg Formation. Subaerial deposits are far more common in the younger, $<$ 3.2 Ga Moodies Group in the Barberton Greenstone Belt (Lowe and Byerly 1999b,a; Heubeck 2009; Hofmann et al. 1999), while subaerial spring deposits associated with a caldera have been described in the 3.48 Ga Dresser Formation in the Pilbara (Djokic et al. 2021). All the preserved subaqueous sedimentary deposits in the Barberton and Pilbara Greenstone Belts formed at relatively shallow water depths in depositional basins on top of the plateau-like protocontinents (i.e. at water depths ranging from littoral to below wave base, which could have been some tens to a few 100s m) (Lowe and Byerly 1999b). Nijman et al. (2017) compared the Paleoarchean depositional basins to collapse basins on Venus or Mars, forming on softened crust atop mantle plumes, although it has been argued that the early Earth's crust was not thick enough to support such a tectonic situation (comment by an anonymous reviewer). Nevertheless, the thickness of the Archean Earth's crust is modelled to have been greater than that of the present day owing to hotter mantle temperatures and magmas (Hawkesworth et al. 2020). The group of van Kranendonk (Djokic et al. 2021) proposes an alternative caldera-like scenario for at least some of the shallow basins. Although we have geochemical evidence for the existence of open ocean via a positive Eu anomaly reflecting a global, background hydrothermal signature (Jacobsen and Pimentel-Klose 1988; Hofmann and Wilson 2007; Hofmann and Harris 2008; Hickman-Lewis et al. 2020b), there is no morphological preservation of deep oceanic crust, which was probably removed (together with much of the early protocontinental crust) by a combination of tectonic overturn and possibly the high rate of impacts on the Hadean Earth (Melosh and Vickery 1989; Abramov et al. 2013; Kemp et al. 2010; Kamber 2015; Griffin et al. 2014; Maher and Stevenson 1988).

The early basins and emergent landmasses likely hosted a variety of habitable environments including subaqueous, littoral (i.e. tidal therefore partially subaerial), subaerial and hydrothermal settings (note, however, that hydrothermal settings were ubiquitous). These sedimentary environmental settings are attested by sedimentary structures, pillow lavas and geochemical signatures. Various proxies are used to infer the environmental conditions. Estimates of water temperatures on the early Earth from oxygen, silicon, and hydrogen isotopic signatures preserved in chert sediments are wide-ranging, from a cool 26 °C (Hren et al. 2009; Blake et al. 2010) to $\sim$ 50 °C and up to $\sim$ 70 °C (Robert and Chaussidon 2006; Van den Boorn et al. 2010; Marin-Carbonne et al. 2012; Tartèse et al. 2017). The latter studies especially noted the strong influence of the early Earth's abundant hydrothermal activity on the temperature signatures, as evidenced also by the aforementioned REE signatures (positive Eu and Y anomalies, and Y/Ho ratio Hofmann and Harris 2008; Hickman-Lewis et al. 2020b). It should be borne in mind that the sediments analysed were formed at the interface between the relatively shallow column of water and above warm or hot rock that could be easily heated; this may not have been the case in the "deep" ocean, and we do not know how deep the Earth's oceans were outside the shallow plateau areas. However, in the scenario where there was not much exposed continental landmass, the average ocean depths would have been about 2 km. The pH of the early oceans would have been variable, with alkaline conditions enhanced by aqueous alteration of the predominantly ultramafic and mafic crust (Kempe and Degens 1985; García-Ruiz et al. 2020), while more acidic conditions were the consequence of boiling and hydrogen-rich hydrothermal fluids as well as the CO_2-rich atmosphere (Morse and Mackenzie 1998; Catling and Zahnle 2020). Intermediate values were estimated by Friend et al. (2008), who interpreted circum-neutral pH from geochemical analyses of Eoarchean rocks from West Greenland. On a local scale, variations in pH could have been readily maintained around hydrothermal vents, where exiting fluids of a certain pH mix with seawater of different pH, or where the pH is changed by interaction with adjacent rock/sediment materials, e.g. acidic fluids flowing through mafic or ultramafic rocks and sediments becomes initially alkaline before returning to and slightly acidic pH if that is the ambient condition (Dass et al. 2018; Westall et al. 2018). Estimations of salinity for the early oceans vary, but fluid inclusion studies suggest that they range from present day values to about double these values (Marty et al. 2018; see also Knauth 2011; Catling and Zahnle 2020). These estimations will be relevant for the shallow water basins on top of the submerged protocontinents but environmental conditions in the open ocean may have differed.

While all environmental parameters indicate an anaerobic early Earth, extremely small amounts of oxygen would have formed locally by EUV photodissociation of water vapour in the atmosphere and at the surface of the seawater (Kasting et al. 1979). Oxygenated species could have resulted also from dissociation of boiling, pressurised hydrothermal fluids as they exited vents in shallow waters (pers. comm. C. Ramboz, 2009). Note also that the early oceans were more enriched in the transition metals essential for Earth-like life (Fe, V, Ni, As and Co) than today, owing to leaching of the early ultramafic and mafic rocks characteristic of the early volcanic crust (Hickman-Lewis et al. 2020a). Indeed, the early oceans could be considered iron-rich environments.

2.3 Early Life on Earth

2.3.1 Scenarios for the Emergence of Life

There is strong evidence for diversified life forms comprising chemotrophic and phototrophic microorganisms already in the Paleoarchean (3.6 to 3.2 Ga) based on morphological structures, as well as geochemical and organic biosignatures (Hofmann et al. 1999; Hassenkam et al. 2017; Djokic et al. 2017; Hickman-Lewis and Westall 2021). This suggests that life must have emerged during the Hadean. Or, if life appeared very rapidly (and we have no idea how long it took for life to emerge) at the latest, in the very early Eoarchean. Microbial fossils have been interpreted from the 4.28–3.8 Ga Nuvvuagittuq rocks of Canada (Dodd et al. 2017; Papineau et al. 2022), where jaspilite deposits probably represent hydrothermal chemical sediments. Relatively large filaments (about 16.5 µm in diameter and up to 1000s of µm in length) were hypothesised to be of microbial origin. Associated multiple sulfur isotopes are consistent with a microbial signature. However, Greer et al. (2020) and Lan et al. (2022) suggested that these and other Fe-rich microbial filaments in the highly metamorphosed, Nuvvuagittuq rocks are abiotic mineral features. Microbial life is strongly associated with hydrothermal deposits in later Paleoarchean sediments 3.33 Ga (Westall et al. 2015; Hickman-Lewis et al. 2020b), and confirmation of such traces in more ancient deposits is actively being sought.

There are many scenarios suggested for the emergence of life on Earth, including hydrothermal environments undersea (Baross and Hoffman 1985; Russell and Hall 1997; Martin and Russell 2003) and on land (Damer and Deamer 2020; Van Kranendonk et al. 2021); associated with impact craters (Sasselov et al. 2020); pumice rafts (Brasier et al. 2011); deep seated faults (Schreiber et al. 2012); and mixing of chemical precursors produced in combinations of these and other environments (Stüeken et al. 2013). Each of the scenarios has relative merits and some disadvantages, as reviewed by Westall et al. (2018). We will briefly summarise the different scenarios below.

An important point in addressing the scenarios for the origin of life is that the environmental requirements for this are not necessarily the same as those for flourishing, more evolved life forms. This will become evident also later in this chapter during the discussion of possible life forms in the clouds of Venus today. For life as we know it, based on organic carbon molecules and liquid water, the basic ingredients include the six essential elements, C, H, O, N, P, S, as well as transition metals (especially Fe), liquid water, an energy source (e.g., chemical, photonic, heat), and a suitable geological context. According to our current understanding of prebiotic chemistry processes, life as we know it could not emerge in an environment with free oxygen, thus anaerobic conditions are also important. According to some researchers (Pascal et al. 2013; Pross and Pascal 2013), the initial energy for pushing prebiotic reactions past the required activation level needs to be very high and can only be provided by UV radiation. Conversely, the complex compounds necessary for biological functions, such as peptides, information transferring molecules (RNA, DNA), or the lipids of cell membranes (Kminek and Bada 2006; Reisz et al. 2014), would rapidly break down under UV radiation. Others (Adam 2007; Adam et al. 2018) have hypothesized that beach sands enriched in uranium could have provided the radiation necessary for activating prebiotic processes. Although the existence of uranium placer deposits during the Hadean is highly unlikely owing to the small quantities of uranium in the early terrestrial rocks and the limited availability of oxygenated environments for leaching and concentrating it out of the rocks. If correct, the necessity of UV radiation for early prebiotic reactions would place serious constraints on where life could have emerged, i.e. life could only have emerged where there was exposed land and not, for example, on an ice covered ocean planet.

Another important condition for the emergence of life is the presence of natural gradients: in temperature, pH, ionic concentrations, water and osmotic potential, and energy (Westall et al. 2018). Gradients drive the diffusion of essential components for prebiotic chemistry and primitive metabolisms, via hydrothermal fluids, seawater, pore waters (in porous materials), river water, or (impact) lakes. As one commonly hypothesized requirement for life is compartmentalization, chemical constituents would have needed to be transferred into and out of the micro-scale compartments (e.g., pores in rocks and minerals, naturally-forming gels, vesicles, or micelles) in which prebiotic reactions would have taken place. In terms of the emergence of life, three key factors are critical: (1) the concentration of the various molecular building blocks of life, (2) their stabilisation and structural conformation, and (3) chemical evolution (as summarised from previous works by Westall et al. 2018).

In a manner that is *a priori* counter intuitive for non-prebiotic chemists, there are stages during prebiotic reactions when water is a hindrance. This is when it is necessary to concentrate the ingredients of life. Darwin's dilute, warm little pond will not work. Concentration allows basic prebiotic molecules to interact sufficiently with each other to create additional, more complex conformations. For example, Russell and Hall (1997), Russell (2021), Martin et al. (2008) view the reactive mineral-rich walls of pores in deep sea hydrothermal vents as a likely location for concentration and condensation of organic molecules. Porous silica gel was suggested by Westall et al. (2018) and Dass et al. (2018) because of its ubiquity

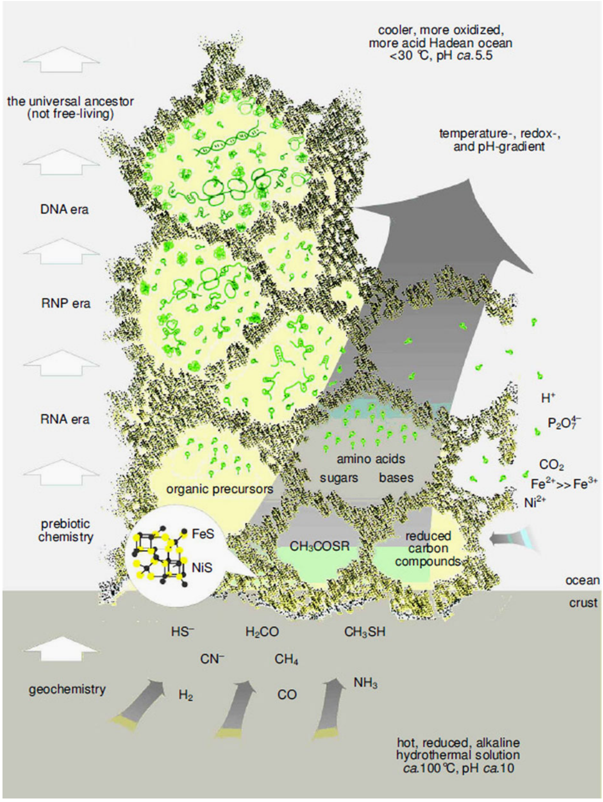

Fig. 4 Model for the emergence of cellular life in porous hydrothermal vent systems (after Martin and Russell 2003)

in the early terrestrial oceans, and its association with hydrothermal environments. Organic molecules chelate to the surface of the pores in the gel, which is permeable, letting through nutrients, molecules and enabling gradients. Other researchers prefer wetting-drying cycles that imply exposure of the organic molecules to the early atmosphere, either in a beach environment (Deamer 1997), or on land (Damer and Deamer 2020; Marshall 2020; Sasselov et al. 2020).

Deep sea hydrothermal vents were suggested as a suitable location for the origin of life by Baross and Hoffman (1985). This idea was further developed in great detail by Russell and various colleagues since the mid 1990s. Russell et al. (2010) noted the particular importance of alkaline vents for the emergence of life (Fig. 4). These were environments from which metal-rich fluids and small organic molecules formed during serpentinising reactions in the crust, including hydrogen, methane, minor formate, and ammonia, as well as calcium and traces of acetate, molybdenum and tungsten. Chemiosmotic energy would have been provided by proton and redox gradients across the porous vent walls. According to this hypothesis, prebiotic chemical reactions in the porous, reactive mineral constructs of the vents would concentrate molecules, helping them to form new structures and combinations. Eventually, all the constituents of life, except cell membranes, would be found within the pores, thus forming the first living entities (i.e. non membrane-bound cells). Finally membranes would form around the edges of the pores to enclose the proteins and RNA molecules, allowing the protocells to be expulsed into the ocean. In this scenario, UV radiation is not necessary to surmount the activation energy barrier.

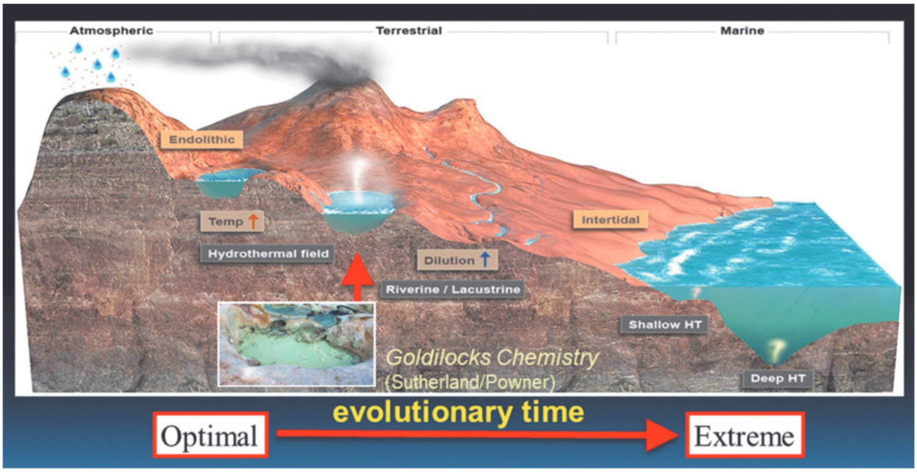

Fig. 5 Hypothetical emergence of life in subaerial hydrothermal springs. After Damer and Deamer (2020)

In support of the deep-sea hydrothermal vent scenario, Ménez et al. (2018) note that serpentinite-bearing hydrothermal environments requiring exhumation of mantle rocks to the surface are common for (ultra)slow spreading mid-ocean ridges and/or oceanic rifts. Such tectonic settings require lithospheric extension and were likely present since very early stages of lithospheric evolution and crustal differentiation (e.g. Sizova et al. 2015). Models show that their existence does not require global plate tectonics and/or subduction and can associate with several other styles of mantle convection and surface dynamics such as ridge-only convection or plutonic squishy lid that might be common styles for young Venus/Earth-sized terrestrial planets (Rozel et al. 2017; Sizova et al. 2015; Lourenço et al. 2018).

In a variant on the deep-sea hydrothermal scenario and based on their studies of well-preserved hydrothermal sediments from the Paleoarchean, Westall et al. (2018) suggested that volcanic sediments in the vicinity of hydrothermal vents may have hosted prebiotic reactions leading to the emergence of life. The scenario is very similar in principal to that of Russell (a porous medium comprised of reactive minerals), with the exception of the inclusion of porous silica gel, as noted above, a ubiquitous by-product of the early silica-rich seawater. The presence of these sediments around hydrothermal effluent extends the available environments for the emergence of life. Moreover, such environments existed at all water depths, from tidally-influenced littoral environments down to the deep sea. In this case, if UV radiation were an essential factor in prebiotic reactions, shallow water systems in the tidal zone would offer exposure to UV radiation, as well as protection of the more complex molecules under water and within the subaqueous sediments.

Another popular scenario suggests subaerial hydrothermal environments for the emergence of life. This is largely because of the findings that (1) UV radiation can contribute to the neoformation of prebiotic molecules (Pascal et al. 2013; Pross and Pascal 2013), (2) hydrophobic conditions are necessary at certain stages of prebiotic reactions to concentrate molecules (Damer and Deamer 2020; Deamer 1997; Marshall 2020; Sasselov et al. 2020), and (3) subaerial vents have been interpreted in ancient Paleoarchean terranes (Van Kranendonk et al. 2021). Hydrothermal vents on land (Fig. 5) would have provided a suitable environment for prebiotic processes as they are exposed to UV radiation, when necessary, as well as protected by water. The porous sediments and vent walls would have served the same function as hypothesized in the deep-sea vent scenario, mini-reactors localizing and supporting the prebiotic chemical reactions. Fully-formed microbial cells would have been transported to the oceans by rivers (UV avoidance being a necessity in this scenario). One could also envisage the transport of microbes attached to each other or to dust particles in small clumps that can travel significant distances through the air. In this scenario, despite exposure to UV and desiccation, cells in the interior of the clump will remain shielded and wet for a certain time even though cells on the surface of the clump die (Madronich et al. 2018). This scenario works on the Earth today but the higher UV flux on the early Earth may have been a considerable constraint.

The common denominator in the most popular of the above origin-of-life scenarios is hydrothermal environments, either undersea or on land. Here, the contact of hot water with reactive mineral surfaces would have provided the chemical energy for prebiotic reactions. The early volcanic rocks were more ultramafic than today, comprising predominantly iron and magnesium-rich basalts and komatiites. There would have been the possibility of exposure to UV radiation in beach environments, shallow water vents, or subaerial vents, at significant moments (if it was indeed essential). The mineral surfaces, perhaps assisted by the presence of ubiquitous silica gel, would have facilitated increasing molecular concentration, conformation and complexity in mineral and silica pores. The necessary gradients would have been provided by the through flow of fluids and nutrients from the vent effluent to the immediately surrounding environment (including sediments) and protocells would have formed.

We have only considered here in detail a few of the wide variety of environments suggested for the emergence of life, but we noted above some of the other hypotheses. However, we may never know exactly where life originated. It is clear that there were numerous possibilities for prebiotic chemistry in different scenarios. It is possible that important components of living cells were formed in different types of environments and eventually concentrated together in one location. Although certain prebiotic chemists do not endorse this idea, considering that the processes leading to life needed to have occurred in one location (N. Lane, pers. comm,, 2022). It is also possible that life emerged in more than one place during the course of the Hadean, possibly even under different scenarios in different times and places. Large impacts or other more localized environmental changes could have wiped out life in some regions while in others it continued to flourish. Given the biochemical, genetic, and other evidence we have today that all modern life shares a common ancestor (Weiss et al. 2018, and references therein), eventually, the early world ocean must have been dominated by one form of life, presumably the metabolically most effective, using the molecular machinery that we know today.

2.3.2 Scenarios for the Emergence of Life and the Problem of Prebiotic Chemistry in the Laboratory

The origin of life has traditionally been addressed through experiments in prebiotic chemistry in carefully controlled laboratory conditions. This has led to a significant amount of confusion in the origins of life community because the realities of the early terrestrial environment were, and are still, rarely taken into account. A prime example of this situation is the stabilisation of ribose (sugar), one of the essential ingredients of RNA. The element boron has been suggested to have been critical to the stabilisation of the sugar (Benner et al. 2010; Scorei 2012). Boron is a constituent of tourmaline, a mineral present in the sediments of Eoarchean terranes and was certainly present on the Hadean Earth (Grew et al. 2011) but some researchers have suggested its presence as boron salts on exposed landmasses, thereby inferring that life could have emerged in subaerial rivers (Benner et al. 2010). Another solution for the stabilisation of ribose hypothesises is exposure to ice. Szostak (2016) invokes seasonal changes in a subaerial hydrothermal setting (similar to Yellowstone), whereby temperature changes could have induced a temporally icy setting. Trinks et al. (2005) suggest sea ice as an important setting for prebiotic chemistry in terms of concentration of organic molecules and for providing optimal conditions for the early replication of nucleic acids. Support for this scenario was based on models suggesting that the early Earth had a cold start (Catling and Zahnle 2020). They are predicated on the lower luminosity of the Sun and the necessity of either high partial pressure for a CO_2 atmosphere or a large amount of greenhouse gases, such as CH_4 (Sagan and Mullen 1972).

Is such a scenario realistic? While there is no evidence during the Archean of glacial conditions (beaches were bathed by tidal waves and hosted evaporite mineral precipitation), heat flow from the mantle during the Hadean is modelled to have been lower than during the Archean (Ruiz 2017; Korenaga 2018). Radiogenic heating of the mantle continued up to about 3.0–2.5 Ga when it reached a maximum (1500–1600 °C compared with 1350 °C today) and then decreased thereafter (Herzberg et al. 2010). Although Foley et al. (2014) propose mantle temperatures more than 2000 °C for post magma ocean times.

The aforementioned examples underlines two important points regarding the origin of life on Earth. In the first place, the difficulties in interpreting early habitable environmental conditions are based on the relatively distorted prism of the relatively rare occurrences of metamorphosed and altered rocks from the Eoarchean. Secondly, the fact that experiments in prebiotic chemistry often do not take into account realistic early Earth scenarios. There is also the point that, while life on Earth may have emerged in one particular environment (or several), this does not mean that life on another terrestrial planet, such as Venus, could not have originated in an alternative scenario.

2.3.3 Evidence for Early Life

After life on Earth became established, the variety of environments on the early Earth seem to have provided a plethora of habitats, each characterised by different and, likely, time-variable characteristics. Given the anaerobic conditions prevailing on the early Earth and the negative effects of oxygen on modelled prebiotic chemistry, early terrestrial organisms had to have inhabited anaerobic environments. The earliest ecosystems would have supported chemoautotrophs, *i.e.* microorganisms obtaining their energy from oxidation of organic substances, such as methyl compounds (chemoorganotrophs), or inorganic substances, such as ferrous iron, hydrogen sulfide, elemental sulfur, thiosulfate, or ammonia (*i.e.* chemolithotrophs). These were the key substrates or electron donors that were immediately available to support life on the early Earth. Heterotrophs, or organisms that depend on carbon for their nutrient supply (by consuming them, their debris, or their waste products), may have emerged as early as the first autotrophs.

Organisms that developed the ability to use sunlight as a more powerful and effective source of energy, *i.e.* phototrophs, emerged after the chemotrophs. Initially (3.8 to 3.5 Ga), phototrophs may have used hydrogen and/or sulfur as a reductant. A decrease in the availability of these compounds in Earth's atmosphere, possibly related to the global production of methane by the early biosphere (methanogenesis), may have led to the development of ferrous iron-based phototrophy at or before 3.0 Ga (Olson 2006). The efficiency of even these early forms of photosynthesis, combined with the abundant availability of sunlight, appears to have conferred an immense metabolic advantage to the phototrophs; they were already relatively widespread by about 3.5 Ga (Noffke et al. 2013; Hickman-Lewis et al. 2018a), which indicates their relatively rapid evolution and spread (*i.e.* biomass) in environments with sufficient insolation. Liu et al. (2020) considers this an additional point in favour of an origin of life during the Hadean and not after the (now) controversial Late Heavy Bombardment (LHB) of 3.9 Ga. Given the implication for the timing of the origin of life it is important to understand why the LHB is currently out of favor. The hypothesised LHB was originally tied to dating of the returned lunar samples by Turner and Cadogan (1975) and Tera et al. (1973) that showed a preponderance of ca. 3.96 Ga ages that they hypothesised could have been produced by a "lunar cataclysm". Modelling has shown that such an event could have been created by instability in the orbits of the giant planets, particularly Jupiter (Walsh et al. 2011; Deienno et al. 2016). Recent analysis of lunar impact glass ages (Zellner 2017) demonstrates the unlikeliness of a late bombardment peak. Observations of a binary Jupiter Trojan (Nesvorný 2018), coupled with studies based on cratering statistics, geochronological databases tied to closure temperature, and resolved ages using orbital dynamics and thermal modeling (Mojzsis et al. 2019; Clement et al. 2019), show that any giant planet instability would have occurred before about 4.45 Ga.

We noted above purported microbial fossils associated with hydrothermal activity from the 3.8 Ga Nuvvuagittuq Supracrustal terrane (Dodd et al. 2017; Papineau et al. 2022) that have since been reinterpreted as of abiotic origin (McMahon 2019; Greer et al. 2020; Lan et al. 2022). Furthermore, while organic molecules in garnets from the 3.7 Ga Isua Greenstone Belt may be remnants of microbial life (Hassenkam et al. 2017), purported microbial stromatolites described from the same rocks (Nutman et al. 2016, 2019) are apparently of abiotic origin (Allwood et al. 2018; Zawaski et al. 2020). Nevertheless, by 3.5 Ga, the Barberton and Pilbara Greenstone Belts, the two main locations with well-preserved crustal rocks, document abundant evidence of microbial life. Most readily visible are small, domical stromatolites ∼several cm in height occurring in shallow water environments in the Pilbara (Hofmann et al. 1999; Allwood et al. 2006), that represent the macroscopic evidence of phototrophic microbial mat formation. However, most phototrophic biofilms and mats from the Paleoarchean in Barberton and the Pilbara are represented by tabular mats (Byerly et al. 1986; Westall et al. 2011a, 2006a; Noffke et al. 2013; Hickman-Lewis et al. 2018b). Evidently, these phototrophic biosignatures occur in very shallow water environments, the organisms relying on access to sunlight to obtain their energy.

The shallow water environment, together with warm seawater, would have led to relatively high salt concentrations. Westall et al. (2006a) describe microcrystalline, silica-pseudomorphed evaporate mineral sequences in 3.33 Ga coastal sediments in the Barberton Greenstone Belt, South Africa, while (Lowe and Byerly 1999a) document an horizon of nacholite crystals in 3.42 Ga sediments from Barberton (Knauth 2011). Thus, given the abundant evidence for microbial life in these shallow water environments, it must have been at least partially halophilic (Westall et al. 2015; Hickman-Lewis and Westall 2021). Moreover, the volcanic sedimentary environment with its associated hydrothermal activity, hosted chemotrophic life, including chemolithotrophs, as well as chemoorganotrophs, the latter in the direct vicinity of hydrothermal vents (Westall et al. 2006b, 2011b; Hickman-Lewis et al. 2020a). Colonies inhabiting hydrothermal environments would have comprised thermophiles and probably hyperthermophiles.

(Hickman-Lewis and Westall 2021) review the widespread distribution of early life in the Barberton Greenstone Belt through the Archean (3.5–2.6 Ga), showing how its nature and distribution throughout this early period of Earth's history were controlled by both the gradual evolution of the environment, as well as the rise of oxygenic phototrophs at about 3.0 Ga. Figure 6 illustrates a variety of early biogenic remains from the Paleoarchean Barberton Greenstone Belt (South Africa) and Strelley Pool Chert (Pilbara Greenstone Belt, Australia) sediments, including macroscopic stromatolites from the 3.43 Ga Strelley Pool (Fig. 6A, B) (e.g. Hofmann et al. 1999; Allwood et al. 2006), tufted tabular stromatolites

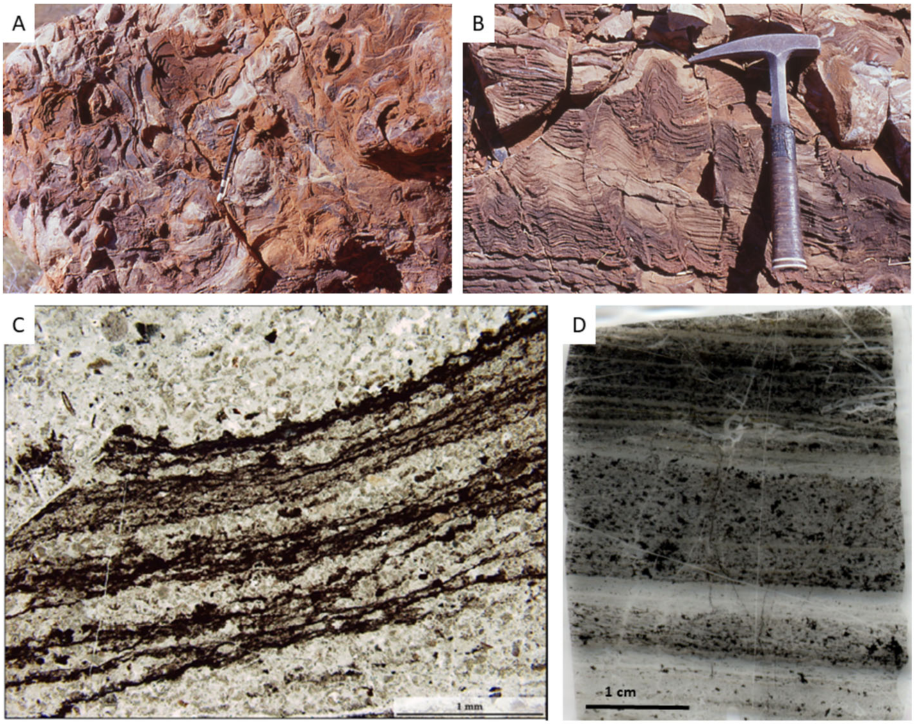

Fig. 6 Early terrestrial microorganisms. (**A**, **B**) 3.44 Ga old stromatolites from the Pilbara, Australia in plan view and cross section. (**C**) Tabular phototrophic mats from the 3.472 Ga old Middle Marker Formation, Barberton, South Africa. (**D**) Layers of carbonaceous clots representing chemotrophic colonies in the vicinity of hydrothermal vents

from the 3.72 Ga Middle Marker Horizon, Barberton (Hickman-Lewis et al. 2018a), and clotted probable chemolithic microbial colonies from the 3.33 Ga Josefsdal Chert, Barberton (Hickman-Lewis et al. 2020a).

3 Tectono-Magmatic Processes on Venus vs. Hadean-Archean Earth

3.1 Tectonics

High surface temperatures that prevail on present-day Venus may strongly affect the interior and the surface (Phillips et al. 2001; Noack et al. 2012; Gillmann and Tackley 2014). Extensive outgassing and a greenhouse effect such as the one observed on Venus directly affect surface mobilization (horizontal velocity and inclusion of the lithosphere in the convective cell). Several studies that coupled 1D, 2D and 3D interior dynamics models with atmospheric evolution models have investigated the effects of an evolving atmosphere formed through mantle degassing of H_2O and CO_2 (Noack et al. 2012; Gillmann and Tackley 2014). However, the feedback between the atmosphere and the mantle can be quite complex. Some models, in which digitized atmospheric temperature values from a non-grey (wavelength-dependent) radiative-convective atmospheric model by Bullock and Grinspoon (2001) were used, suggest that high surface temperatures lead to surface mobilization (Noack et al. 2012).

Higher surface temperatures translate into lower surface viscosity, reducing the viscosity contrast between the surface and the mantle, and allowing the surface layer to be mobilized by mantle convection.

On the other hand, models that consider plastic yielding of the lithosphere and couple the interior evolution to a grey atmosphere (thermal opacity uses a single value, independent of wavelength), find that a high surface temperature stops surface recycling and promotes a stagnant-lid regime (Gillmann and Tackley 2014). Instead, a lower surface temperature will lead to higher viscosities and higher convective stresses that, in turn, may promote plastic yielding and surface mobilization (Lenardic et al. 2008). Venus may have experienced lower surface temperatures during its early thermal history, due to the efficient removal of water by escape processes (Gillmann and Tackley 2014). During this time more moderate conditions may have existed at its surface and allowed the sequestration of atmospheric CO_2, preventing its accumulation in the atmosphere. Global circulation models even suggest that a temperate Venus could have been maintained under habitable surface conditions until as recently as 0.7 Ga (Way et al. 2016). The difference between the results from numerical models is mostly due to the various rheologies and mechanisms considered, and may indicate possible competition between multiple processes on real planets. As such, there may be a sweet spot when rheology remains stiff enough for the lid to break and convective stress to be transmitted to the lid, but soft enough to allow vigorous convection and prevent the lid from growing too static. Additionally, the specifics of the regime may depend on the history of the planet (for instance Weller et al. 2015; Weller and Kiefer 2020) and in particular the transition between the magma ocean solidification and the solid mantle convection (see Salvador et al. 2017, 2023). This topic is discussed further in (Gillmann et al. 2022; Rolf et al. 2022, this journal).

The exact style of resurfacing on Venus is still debated (Rolf et al. 2022, this journal). Different scenarios that have been discussed in various studies (Armann and Tackley 2012; Gillmann and Tackley 2014; Karlsson et al. 2020; Lourenço et al. 2020) could have operated at various times throughout Venus' history: (1) stagnant lid: the surface was continuously renewed by volcanic activity without any kind of surface mobilization (Armann and Tackley 2012; Gillmann and Tackley 2014; Karlsson et al. 2020); (2) episodic lid: at periods plate tectonic like surface mobilization takes place with more quiescent periods in between (Armann and Tackley 2012; Gillmann and Tackley 2014; Uppalapati et al. 2020); (3) plutonic squishy lid (Lourenço et al. 2020): recycling of the lithosphere by eclogitic dripping and delamination, with strong plates separated by hot magmatic intrusions. These scenarios are different in terms of the efficiency of volatile recycling, which, in turn, has important implications for mantle dynamics and thermochemical history. In addition to this, the exact convection regime is probably not static and could have changed throughout the history of Venus (Gillmann and Tackley 2014; Weller et al. 2015; Weller and Kiefer 2020).

Understanding the tectonic regime throughout Venus' history is important as it is closely linked to its volatile history. First, outgassing, and thus the atmosphere thickness and bulk composition, are directly governed by the mantle dynamics and volatile release by volcanism. More detailed overviews of the mantle based outgassing processes are proposed in Rolf et al. (2022) and Gillmann et al. (2022), respectively. It has therefore been postulated that one could infer the tectonic style of a planet based on its volatile history and atmosphere characteristics. In particular, Venus' ^{40}Ar measurements have been used to suggest that the planet only outgassed 10 to 34% of its total ^{40}Ar inventory (Kaula 1999; O'Rourke and Korenaga 2015; Namiki and Solomon 1998; Volkov and Frenkel 1993), compared to Earth's 50%. That would imply Venus outgassing was limited during most of its evolution or was only important during its early history (when ^{40}Ar had not formed yet). Therefore such measurements argue against an Earth-like tectonic regime for all but primitive Venus at least. One should note that the thick CO_2 atmosphere and large N_2 inventory could point toward strong outgassing at some point in the history of Venus; this question is not yet solved. It has been suggested that such a period may have been very ancient, possibly dating back to the magma ocean phase (Gaillard et al. 2022) or the Late Accretion (Gillmann et al. 2020). CO_2 could also have been released by different processes depending on surface conditions (Höning et al. 2021).

Planetary tectonics also ties into the possibility of a carbonate-silicate cycle and thereby on the potential of long-term habitability. On Earth, the climate is stabilized as CO_2, outgassed at mid-ocean ridges and other volcanic units, is consumed by silicate weathering processes, precipitated as carbonates on the seafloor, and recycled back into the mantle at subduction zones (Walker et al. 1981; Kasting and Catling 2003). The land fraction is an important parameter in this cycle, since silicate weathering is particularly efficient on land that is emerged over sea-level. Higher rates of seafloor weathering at mid-ocean ridges can partly compensate for a smaller land fraction (e.g., Foley 2015), but the global mean surface temperature would nevertheless be expected to be higher if most of the planet's surface is covered by oceans.

In the stagnant lid scenario, recycling of volatiles is the least efficient because the thick static lid is not part of the convection. Water, carbonates (if formed during moderate atmospheric conditions), and sulfates may have never been recycled into the mantle. The observed tessera terrains, that represent around 8% of the crust on Venus, have been suggested to resemble continental crust on the Earth (Gilmore et al. 2015). If so, they may be difficult to form in this scenario, as their formation would require some kind of crustal recycling in the presence of water. However, models (Karlsson et al. 2020) have not yet been able to simulate their behaviour satisfactorily. While delamination of the lower crust may take place in this scenario, if the crust grows thicker than the basalt to eclogite transition depth (Sizova et al. 2015; Fischer and Gerya 2016a, e.g.,), water recycling remains unlikely. On Earth, felsic material can form without water. However, such a mechanism would struggle to produce enough felsic material to account for the total volume of present-day Venus tesserae (Smrekar et al. 2018, and references therein). Future missions may place a constraint on how much of the tessera terrains can actually be considered felsic.

Volatile recycling would be efficient during plate tectonic periods in the episodic lid scenario, while in the plutonic squishy lid case, the efficiency would presumably be lower than in the episodic case but still notably higher (Sizova et al. 2015; Fischer and Gerya 2016a, e.g.,) than in the stagnant lid scenario. Volatiles that are introduced back into the mantle would have major consequences for mantle dynamics and subsequent magmatic evolution. Recycled crust will become negatively buoyant when undergoing the phase transition from basalt to eclogite. The recycled crust is rich in incompatible elements, such as heat producing elements and volatiles, which can significantly affect subsequent melting of the mantle. The subducted crustal material will refertilize the mantle and promote partial melting, both by increasing the amount of heat producing elements in the mantle and recycling of volatiles that would locally decrease the melting temperature. In addition to decreasing the local solidus, recycled volatiles will also decrease the viscosity of the mantle material, thus affecting the interior dynamics and the cooling behavior of the mantle, and consequently the subsequent outgassing.

Constraints on the style of recycling on Venus may be derived from the inferred crustal thickness, and variations in the crustal age and geoid (Kiefer and Hager 1991; Armann and Tackley 2012; King 2018). The episodic lid models and the plutonic squishy lid, with a low reference mantle viscosity and a low eruption rate, seem to produce a crustal thickness that is closer to the inferred crustal thickness of Venus compared to stagnant lid cases (Rolf et al. 2018; Lourenço et al. 2020). Surface age variations indicated by Venus' cratering record may be easier to reconcile with the episodic lid scenario (Uppalapati et al. 2020) and the long wavelength of the gravity spectrum can be matched well if the last resurfacing event ended a few hundred Myr ago (Rolf et al. 2018). Whether these observations are consistent with the plutonic squishy lid regime remains to be tested in future models. It should be noted again, however, that the stagnant lid, episodic lid, and plutonic squishy lid scenarios are not mutually exclusive, but may have been active at different times during Venus' history, as seems to have been the case on early Earth. Additionally, they constitute a continuum of behaviours rather than distinct, clear-cut end-members. Finally, local variations are to be expected, and different crust deformation processes could occur at different locations of the surface of Venus at a given time (see Rolf et al. 2022). Thus, recycling of volatiles may have significantly changed during the thermal evolution of Venus, and its present-day state is the result of complex feedback mechanisms between the interior, surface and atmosphere (Gillmann et al. 2022). Future work assessing volatile exchange associated with changes in the tectonic regime throughout Venus' history is necessary in order to advance our knowledge of stable surface water in the past.

3.2 Outgassing

Outgassing is an important source of secondary volatiles for the atmosphere of a terrestrial-type planet. It therefore directly affects surface conditions and the surface habitability of a planet. Broadly speaking, three processes can lead to significant outgassing and affects on the atmosphere (including the fluid envelope) in the long term: (i) magma ocean solidification, (ii) collision with impactors, especially large ones at an early stage, and (iii) volcanism.

Magma ocean evolution, solidification, outgassing and its consequences on the atmosphere and surface conditions on rocky planets, in particular on Venus, are discussed in detail in Salvador et al. (2023, this journal). After accretion and the capture of a possible primordial hydrogen atmosphere, it is the source of the early volatiles and a secondary atmosphere. It is generally understood that CO_2 outgasses early and in large quantities, while water should be released near the end of the magma ocean phase, if at all (Salvador et al. 2017). It has been proposed that a freezing magma ocean could retain a large portion of its water (Solomatova and Caracas 2021). Outgassing from magma oceans is an active research topic, and it has been highlighted that the actual species outgassed to form this early secondary atmosphere could heavily depend on the magma ocean's redox state (e.g. Lichtenberg et al. 2021; Gaillard et al. 2022) It has been suggested that this phase could already set the planet on an habitable or uninhabitable evolutionary path, depending on the duration of the magma ocean, and ability of the planet to cool down fast enough to allow liquid water to condense on its surface (Gillmann et al. 2009; Lebrun et al. 2013; Hamano et al. 2013; Salvador et al. 2017; Turbet et al. 2021) before it is lost to space.

Large impacts and their consequences are discussed in Gillmann et al. (2022), Salvador et al. (2023, this journal). The velocity and mass of impactors means that large amounts of kinetic energy are transferred to the planet as thermal energy during a collisional event. For bodies that are large enough (or fast enough), that is, above a few tens of kilometers in radius, impacts can cause large-scale melting of the crust and the mantle of the planet. They may create magma ponds/seas, and lead to the release of volatiles into the atmosphere (e.g. for Venus, Gillmann et al. 2016). Such events are more frequent and important during early evolution, especially during the accretion phase and are accompanied by the additional release of volatiles contained in the impactors (Sakuraba et al. 2019; Gillmann et al. 2020;

Sakuraba et al. 2021). Volatile release by impactors can substantially modify the composition of the atmosphere and the state of the surface. If the impactor is large enough there could be implications for habitability ranging from the short term (earthquakes, tsunamis, storms, lava ponds/oceans) to the long term (increased greenhouse effect, increase in CO_2 concentrations).

Volcanic outgassing is discussed in Gillmann et al. (2022, this journal). Its causes are explained in Rolf et al. (2022, this journal) and include partial melting of the mantle due to local pressure-temperature conditions exceeding the local solidus of the mantle material. Its surface expressions are addressed in Smerkar et al. (2022, this journal) and Herrick et al. (2022, this journal). For Venus, recent volcanic production can be roughly estimated, but with large uncertainties. Observation of the surface and atmosphere can provide some constraints for modelling efforts, but recent volcanic production rates are debated. They could be very low, $\ll 1$ km^3, in agreement with the minimal effect of volcanism on randomly distributed impact craters (Basilevsky and Head 1997; Schaber et al. 1992); moderately lower than on Earth (~ 1 km^3/yr) (Head et al. 1991; Phillips et al. 1992); or similar (~ 10 km^3/yr; Fegley and Prinn 1989; Bullock and Grinspoon 2001) to Earth's production rates (e.g. Byrne and Krishnamoorthy 2021). Long-term numerical modelling of mantle dynamics offers a reasonable solution for estimating a range of possible outgassing rates from volcanic production, keeping in mind the lack of hard constraints on values before 1 Ga, or on the state of Venus' mantle. However, little evidence exists for volatile concentration in Venus' lava, leading to further uncertainties, as volatile output strongly depends on the redox state (oxygen fugacity) of the mantle. In addition, it has been suggested that the high surface pressure in the Venusian atmosphere could suppress water outgassing compared to CO_2 (Gaillard and Scaillet 2014). It is currently debated if the present-day atmosphere is geologically ($<$1Ga) recent (as suggested by Way and Del Genio 2020) or a fossil atmosphere (Head et al. 2021).

Extrapolating Venus' outgassing rates back in time is subject to even greater uncertainties since the tectonic regime may have changed (discussed in Rolf et al. 2022, this journal). Magmatic outgassing is a consequence of partial melting of hot, uprising mantle material. The shallower the depth to which the mantle material rises, the smaller the lithostatic pressure and therefore the lower the solidus temperature. A thick, insulating lid on top of the mantle would usually create a barrier to hot, uprising plumes and therefore a relatively small melting region (O'Neill et al. 2014). In contrast, on planets with plate tectonics, the melting region beneath mid-ocean ridges is extended close to the surface. On Earth, this mechanism causes a basaltic crust production rate of at least ~ 19 km^3/yr (Cogné and Humler 2006). An additional effect associated with plate tectonics is the subduction of water. In subduction zones at depths of 100–200 km, subducted hydrous minerals become unstable and release their water (Rüpke et al. 2004; Stern 2011). Since water reduces the solidus temperature of the surrounding rock, partial melt is produced that rises to the surface, which is also accompanied by outgassing. Altogether, the tectonic regime has a tremendous effect on the outgassing rate. If early Venus possessed plate tectonics, its outgassing rate would likely have been much higher than it is today. The nature of outgassed species is also important for surface conditions. It has been highlighted that the mantle redox state (the mantle oxygen fugacity) could greatly affect the speciation in the atmosphere, with oxidised mantles (such as the Earth's) leading to the outgassing of CO_2 and water. On the other hand, a reduced mantle could rather favor CO or H_2 (e.g. Kasting et al. 1993a; Gaillard et al. 2021; Frost and McCammon 2008; Hirschmann 2012).

On Venus, not only is CO_2 the major current component of the atmosphere, but it is also responsible in large part for the high surface temperatures. Large rates of CO_2 outgassing can inhibit global glaciation due to this species' role as a greenhouse gas. This is particularly important if a carbonate-silicate cycle is active on the planet, where silicate weathering serves as a sink to atmospheric CO_2 (e.g., Kadoya and Tajika 2014). On the other hand, high rates of CO_2 degassing can enhance the greenhouse effect and ultimately lead to the evaporation of water. Whereas an active carbonate silicate cycle would balance high rates of outgassing to some extent, recycling of CO_2 into the mantle on planets without plate tectonics is rare (e.g., Foley and Smye 2018; Höning et al. 2019b). The solar flux that Venus receives today, and has received in its history, is substantially higher than that the present-day Earth receives, and the threshold towards surface water evaporation is the most relevant bottleneck to Venus' habitability (see also Gillmann et al. 2022, this journal). Small outgassing rates during Venus' early evolution, in combination with an active carbonate-silicate cycle, would increase the likelihood of an early, habitable Venus, while significant early outgassing would go against habitable conditions.

On Earth, water is a major component of volcanic outgassing (on the order of 1%). It is possible that Venus is much drier, due to loss during the magma ocean phase and the inability to condense water early on (Gillmann et al. 2009; Hamano et al. 2013), or that high surface pressure stifles water outgassing (Gaillard and Scaillet 2014), but the planet's current state and modelling seem consistent with marginal water outgassing during recent history at least (Gillmann and Tackley 2014). Beyond its availability for a possible liquid layer, water also affects surface conditions by being a strong greenhouse gas and, despite its low abundance in Venus' current atmosphere, is the second highest contributor to high surface temperatures on the planet.

Initial analysis by the Pioneer Venus Large Probe Neutral Mass Spectrometer (PV-LNMS) indicated the possible presence of CH_4 (Donahue and Hodges 1992). It was speculated that CH_4 was likely not well mixed in the atmosphere, given the measured variations in abundance. Later analysis of the same data by the same team indicated that the detection was unlikely (Donahue and Hodges 1993) and was due to contamination from terrestrial CH_4 brought along in the instrument and hence "was generated by a reaction between an unidentified highly deuterated atmospheric constituent and a poorly deuterated instrumental contaminant." However, the instrumental contaminant has never been identified and hence the detection of CH_4 in the Venusian atmosphere remains an open question.

3.3 D/H Ratio

Venus' atmosphere today contains only about 30 ppm H_2O (Fegley 2014, and refs. therein). The first in-situ D/H measurement by the PV-LNMS demonstrated a ratio ~ 150 times that of Earth (Donahue et al. 1982). Upper atmosphere measurements of D/H by Venus Express (Fedorova et al. 2008) documented much higher values, which are inconsistent with those of Donahue et al. (1982). Fedorova et al. (2008) attributed these differences to "a lower photodissociation of HDO and/or a lower escape rate of D atoms versus H atoms." Ground based measurements do not always concord with both space and in-situ measurement, although in some cases they are consistent (Matsui et al. 2012). Various measurements have been suggested to imply a vertical variation of HDO/H_2O (see Marcq et al. 2018, and references therein) at odds with current chemical models. Despite these discrepancies, the general view is that hydrogen in Venus' atmosphere has a D/H much higher than any other reservoirs of hydrogen in the solar system, which implies that Venus lost hydrogen to space. This may indicate that after an early wet, possibly habitable, time (Donahue et al. 1982; Way and Del Genio 2020), water dissociated and the hydrogen was removed from the atmosphere to space. Dissociation of water molecules and the escape of hydrogen probably had a strong influence on the entire geodynamical history of the planet (Baines et al. 2013)

However, while recent studies propose scenarios for the evolution of the D/H of Earth's water (Pahlevan et al. 2019; Kurokawa et al. 2018), estimating the amount of water lost from

Venus over the last 4.5 Gyr remains extremely challenging for several reasons. Firstly, the history of hydrogen escape cannot be easily re-constructed since it depends on numerous factors (solar irradiation history, atmospheric composition and vertical structure, regime of escape etc.). Secondly, the starting D/H ratio for hydrogen in the Venus atmosphere remains unknown. An important contribution from solar gases would imply a low starting D/H ratio, while contributions from comets could have increased this ratio up to 4–5 times that of Earth (Altwegg et al. 2015). New investigations of the elemental and isotopic composition of noble gases in the Venus atmosphere, especially of xenon, would help shed further light on the history of hydrogen (and water) escape from Venus (see Avice and Marty 2020 and Avice et al. 2022, this journal).

4 The Origin and Persistence of Habitability on Venus

4.1 Climate History

The initial stages of Venus' habitable state are more shrouded in mystery than those of Earth's. We begin our analysis of Venusian habitability with the longevity of the post-accretion magma ocean. Early work by Hamano et al. (2013) and Lebrun et al. (2013) showed that, if the time needed for the crystallization of Venus' magma ocean is ~ 100 million years or longer, there is the risk of dissociation and loss of its primordial H_2O steam atmosphere: the hydrogen, as well as some of the oxygen, escapes during this time while any leftover oxygen is absorbed into the magma ocean. After the cooling and crystallization of the magma ocean, the planet (denoted by Hamano as a Type II world) may inherit a thick CO_2 dominated atmosphere not that different from what we observe today on Venus. In this scenario, the D/H ratio measured by Donahue et al. (1982) is a possible remnant of the primordial CO_2+Steam(H_2O) dominated atmosphere. In an alternative scenario for Venus (which Hamano et al. termed a Type I world), the magma ocean crystallization takes place over ~ 1 million years (similar to that of Earth: Katyal et al. 2020; Nikolaou et al. 2019). This scenario avoids the loss of the steam atmosphere, which may then condense out onto the surface, possibly allowing for a period of habitability of undetermined length.

More recent work by Turbet et al. (2021) has expanded the 1-D models of Hamano et al. (2013), Lebrun et al. (2013) to a 3-D GCM where cloud effects can be modeled and their importance quantified. The Turbet et al. (2021) models of steam+CO_2 and steam+N_2 atmospheres demonstrate that there are little to no day side clouds at the substellar point to shield the planet from high solar insolation (as will be seen in the cold-start cases below). Their model also demonstrates the presence of high clouds at the polar and night side, which are effective at trapping outgoing infrared radiation preventing the cooling of the planet. The Turbet study supports the Type-II outcome modeled in Hamano et al. (2013), where the magma ocean steam atmosphere is never able to condense out on the surface, and once again the H_2 escapes and most of the oxygen is absorbed by the magma ocean. One major shortcoming in all of the models above is the inability to provide better constraints on exactly what the constituents were of the outgassed magma ocean atmosphere, which presently is an active area of research (e.g. Bower et al. 2022; Gaillard et al. 2022). Alongside these unknowns can be added the inability to constrain the albedo (Salvador et al. 2017, 2023), which would again influence whether Venus becomes a Type I or Type II world. The lack of definitive evidence for one scenario or the other implies that the question of the existence of Venus' past habitability remains open. More details on magma ocean and atmospheric evolution is provided in Salvador et al. (2023, this journal). One method of testing which hypothesis for Venus' evolution is correct is by examining data from the upcoming DAVINCI mission (Garvin et al. 2022), which should provide better constraints on when Venus lost its water and the timescale over which it happened by examining a number of noble gas isotopes (see Avice et al. 2022, this journal). Another more indirect method would be possible by looking at exoplanet demographics – if we observe planets in the Venus Zone (Kane et al. 2014) that have temperate conditions then at least we know it is possible. See Way et al. (2023, this journal) for how exoplanet research may inform Venus' history.

To date, very little work has been done to examine how Venus (or the Earth for that matter) moves from a post-magma ocean state to a period of habitability with moderate surface temperatures and oceans, despite this transition being a cornerstone of the onset of habitability. As mentioned above, the first step would be to provide better constraints on exactly what the constituents were of the magma ocean atmosphere (e.g. Bower et al. 2022; Gaillard et al. 2022). One also needs to account for large impacts occurring in the first few hundred million years of the planet's evolution (see Salvador et al. 2023; Gillmann et al. 2022, this journal), which could have major consequences on the atmospheric mass and composition, as large amounts of water, CO_2, N_2, and other species could be delivered or removed (e.g. Schlichting and Mukhopadhyay 2018; Gillmann et al. 2020). Thus, it is unlikely that surface conditions would remain consistent throughout that early time. Some works have attempted to examine the first 100s of million years (e.g. Harrison 2020), as described above, but many unknowns still remain.

There is another problem for those interested in Venus' habitability: How could Venus ever have been habitable like early (or modern) Earth when Venus at 4.5 Ga received ~ 1.5 times the incident solar flux that Earth receives today? Most studies resulting in temperate conditions have been made assuming a cold start in the post-magma ocean phase, which hypothesizes that the early magma ocean cooled quickly (a few million years) and that water was able to condense out on the surface (Hamano Type I discussed above). The first to successfully model such temperate conditions in the Pre-Fortunian (Hiesinger and Tanaka 2020) was Pollack (1971), who used a 1-D radiative convective non-grey model. He presented two options at 4.5 Ga when the solar luminosity was $\sim 30\%$ lower than today. The first was an early Venus with a 50% cloud cover – the motivation for 50% was that he believed modern Earth has roughly this amount (modern measurements indicate $70 \pm 10\%$; Holdaway and Yang 2016) – and in that scenario early Venus had temperatures (depending upon the atmosphere assumed) ranging from ~ 320–500 K. The second choice was a 100% cloud cover model, yet the motivation for such a model was not disclosed. In this scenario Pollack discovered that the planet could host moderate surface temperatures below 300 K. Pollack also demonstrated that, even at today's insolation (~ 1.9 times Earth's), the surface temperature could have remained below 300 K. This 100% cloud cover assumption was the basis for all subsequent Venus habitability studies (e.g. Grinspoon and Bullock 2007) yet no mechanism for producing 100% cloud cover mechanism was ever provided. It would not be until the exoplanet work of Yang et al. (2014) that such a mechanism was discovered. Yang et al. (2014) used the NCAR CAM General Circulation Model (GCM)[1] and discovered that, for slowly rotating planetary atmospheres, an expanded Hadley cell would provide the 100% cloud cover at the subsolar point. Modern Earth actually contains three Hadley cells in the north and three in the south. The reason Earth does not have a single Hadley cell in each hemisphere is because its 'fast' rotation generates a strong Coriolis force deflecting the north-south overturning cells. In a slowly rotating world, the Coriolis force is very weak and hence a single north and south Hadley cell is present. Subsequent Venus-focused work

[1] https://www.cesm.ucar.edu/models/atm-cam/.

by Way et al. (2016), using the ROCKE-3D (Way et al. 2017) GCM with a fully coupled dynamic ocean, confirmed Yang's work which utilzied a simplified single mixed-layer/slab ocean without any horizontal heat transport. Later ROCKE-3D GCM work by Way et al. (2018) utilized both fully coupled dynamic oceans and mixed-layer/slab oceans to confirm Yang's general conclusions over a large range of rotation rates and insolation. The fact that two independent GCMs observe the same behavior is encouraging, but cannot be considered conclusive until these effects are observed in exoplanetary systems in the future. However, these models require at least some surface water. Some tens of cm in soil would be sufficient according to more recent work in Way and Del Genio 2020. Whether or not water was able to condense on the surface at all after the magma ocean phase depends on the atmosphere at this time whose composition is a matter of on-going debate as mentioned above (e.g. Bower et al. 2022). It should be noted that we have no constraints on what early Venus' rotation rate was, but an early slow rotation rate can be achieved via a number of mechanisms including solid body tidal dissipation (e.g. MacDonald 1964; Goldreich and Peale 1966; Way and Del Genio 2020), Core-Mantle friction (Goldreich and Peale 1970; Correia and Laskar 2001; Correia et al. 2003; Correia and Laskar 2003), and oceanic tidal dissipation (Green et al. 2019). The possible role of impactors in Venus' rotational evolution goes back at least to the work of McCord (1968), although no detailed hydrodynamical simulations have ever been performed to examine the impactor parameters and lack of an observable moon as we have for Earth. Our moon is likely the remnant of an impactor (e.g. Benz et al. 1986; Canup 2004; Lock and Stewart 2017), see section on Archean Earth above. Moreover, given the youthful age (200–750 Myr) of the surface of Venus (e.g. McKinnon et al. 1997; Bottke et al. 2016), there is little chance of observing cratered remains of any such ancient impactors. If such an impactor did collide with the planet in Venus' past, it may be possible to detect it isotopically if it was sufficiently different from the bulk composition of Venus, but measuring this would be challenging. To paraphrase Way and Del Genio (2020) "it is clear that Brasser et al. (2016) and Mojzsis et al. (2019) prefer the hypothesis that the Earth's late veneer was mainly delivered by a single Charon- or Ceres-sized impactor. For that reason, if a larger object was involved in the late evolution of Venus' spin or obliquity, it may be possible to detect its geochemical fingerprints in a future in situ mission." Thus, all discussions of the habitability of Venus over any time scale discussed herein assumes that the planet was rotating slowly enough to generate $\sim 100\%$ cloud cover at the subsolar point and extending across most of the sunlit hemisphere of the planet (see Fig. 7).

It should be noted that the persistence of Venus' habitability was originally predicated upon the notion that the faint young Sun's increase in brightness through time (e.g. Gough 1981; Claire et al. 2012) would take some hundreds of million years to subsequently increase surface temperatures, driving the planet into a runaway greenhouse. Regardless, some form of volatile cycling would be required to keep the planet's climate stable over geological time (Höning et al. 2021; Krissansen-Totton et al. 2021; Gillmann et al. 2022; Way et al. 2023, this journal), as for Earth, normally through some form of weathering (e.g. Walker et al. 1981; Kasting and Catling 2003; Krissansen-Totton et al. 2018; Höning 2020; Graham and Pierrehumbert 2020). At the same time, the work of Yang et al. (2014), Way and Del Genio (2020) has definitively shown that, if the cloud albedo feedback for slowly rotating worlds is correct, then increases in solar insolation through time cannot be the deciding factor in the evolution of Venus from a temperate planet to a hothouse as long as volatile cycling takes place.

From this broad overview of the possible conditions at the onset, persistence, and loss of habitability, it appears that the question of transitioning from one state or era to another is a major challenge that will need to be addressed by future models. The period toward the

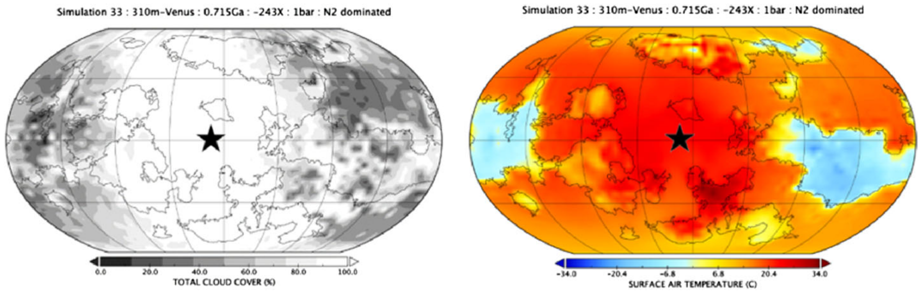

Fig. 7 Generated from General Circulation Model simulation 33 in Way and Del Genio (2020). This is a 1 bar N_2 Dominated atmosphere including 400 ppmv CO_2 and 1 ppmv CH_4. The sidereal rotation rate is the same as modern Venus ($-243 \times$ Earth). Insolation is set to the value that Venus received 715 Ma ($1.7 \times$ Modern Earth or 2358.9 W/m^2). This is a snapshot of 1/12 of a Venusian solar year. Left: percentage total cloud cover. The black star represents the location of the subsolar point. Right: surface temperature map. Note that the highest temperature regions (dark red) are located near the subsolar point and on the southern landmass, while the coldest regions are on the anti-solar continental landmasses (blue). The fully coupled dynamic ocean, which includes horizontal heat transport, keeps the oceans warm (red/orange colors) even in the anti-solar regions of the simulation

end of the magma ocean phase has been highlighted as an important criterion for subsequent evolution and needs to be studied more intensely before any definitive conclusions can be drawn. In the same way, much more work needs to be done to explore how a planet may go from a temperate to a moist and then a runaway greenhouse state (e.g. Kasting 1988), and 3D GCMs will be needed (e.g. Boukrouche et al. 2021).

4.2 Linking Possible Past Habitable States to Present-Day Observations

Present-day Venus looks nothing like what habitable models suggest Venus could have been like in the past. Therefore, we should first attempt to understand how the planet could have radically changed from an hypothesized temperate climate with a relatively thin atmosphere to the dense hothouse we observe today. Then, we take a look at what signs of a previous habitable time interval or of the stages required to bring Venus to its present state could be observable today.

The evolution of Venus from an hypothetical habitable time interval to the present-day must bring its atmosphere to the current inventory of major species ($11 \cdot 10^{18}$ kg of N_2, 10^{16} kg of H_2O and $4.69 \cdot 10^{20}$ kg of CO_2). It must also remove any molecular oxygen. Ideally, it would also bring the D/H ratio to its present value (Donahue et al. 1982), but due to uncertainties in the loss mechanisms, and varying isotopic ratios for the volcanic and meteoritic sources, this is challenging (Grinspoon 1987, 1992; Gurwell 1995). Likewise, the stable isotope ratios of noble gases have been suggested to derive from early hydrodynamic escape but cannot be modelled by a unique self-consistent scenario due to the lack of constraints on early atmospheric conditions, structure and composition, as well as solar energy input (see Avice et al. 2022, this journal).

Nitrogen evolution has long been assumed to be relatively straightforward once the magma ocean crystallized, since, in the absence of fixation by living organisms, it was not expected to be part of complex cycles (e.g. Stüeken et al. 2016). However, the understanding of the nitrogen cycle, even on Earth, is much less advanced than that of CO_2 (Stüeken et al. 2020). On Earth (Marty and Dauphas 2003), it is thought to be approximately in balance between sources (half volcanic outgassing and half oxidative weathering) and the sink (burial with a touch of subducted flux). In the past, though, nitrogen fluxes are likely to have significantly changed (Goldblatt 2018). This possibly affected surface pressure, despite variations that are much lower than those expected on Venus for CO_2, for instance. Some reasons behind these variations include possible volcanic production changes with time (from mantle conditions and composition evolution), and changes in the composition of the atmosphere (e.g. presence/absence of oxygen) (e.g. Som et al. 2016; Catling and Zahnle 2020), leading to changes in the chemical reactions between the atmosphere and the surface (i.e. weathering). For example, some results suggest maximum atmosphere pressures of about 0.5 bar on Earth (probably much less), 2.7 Gyr ago, using barometric calculations from fossilized raindrops and gas bubbles in basaltic lava (Som et al. 2012, 2016). However, the past N_2 abundance in the atmosphere is still poorly constrained and generally thought to have possibly varied by a factor 2–3 relative to present-day (Goldblatt et al. 2009; Johnson and Goldblatt 2015; Goldblatt 2018). In such a scenario, considerable build-up of nitrogen in the atmosphere of Earth over its history may be expected. What this could mean for Venus is still uncertain, given the differences between the two planets, the lack of data relative to Venus' past and the dependence of the nitrogen fluxes on surface conditions. Comparing the nitrogen abundances on the two planets, one should also consider that some nitrogen is stored in Earth's continental crust. Still, a better understanding of the nitrogen exchanges applied to Venus will provide valuable insight on the planet's evolution.

The greater abundance of nitrogen in Venus' atmosphere compared to Earth's ($4 \cdot 10^{18}$ kg) could imply it has escaped even less than on Earth and was thus protected from losses (Lammer et al. 2018), despite the fact that the ^{40}Ar value suggests that Venus' mantle is less degassed than Earth's. Some early temperate Venus models use an atmospheric nitrogen content similar to Earth's (e.g. Way et al. 2016). While it is likely that, by the end of the magma ocean phase, the primordial nitrogen-based species would have been trapped by the hot surface and removed from the atmosphere, collisions with large impactors would have delivered additional nitrogen over the first few hundred million years. Gillmann et al. (2020) proposed that about $5 \cdot 10^{18}$ kg N_2 could have been brought to the atmosphere this way, despite this number being highly dependent on impactor vaporization and composition. The rest (about half) of the present-day inventory of N_2 could realistically be released into the atmosphere over the following 4 Gyr by volcanic activity, but actual fluxes depend on volcanic production rates, mantle composition and surface conditions (Gillmann et al. 2020; Gaillard and Scaillet 2014), as well as burial fluxes, which are all poorly constrained. Confirmation of the volatile composition of the lava and the volcanic plumes could help refine these estimates and better assess the feasibility of long term outgassing of the current nitrogen content of Venus' atmosphere.

CO_2 evolution is a more complex issue, since it can interact more easily with the surface. The main question is how it was possible to evolve from very low CO_2 abundances, in a temperate atmosphere, to a full-fledged atmosphere with 88 bar CO_2. Volcanic outgassing has been proposed to be responsible for Venus' atmospheric CO_2 inventory (see Gillmann et al. 2022, this journal), despite the possible high surface pressure (Gaillard and Scaillet 2014). This implies that, if CO_2 is available for outgassing (i.e. present in the mantle and transferred into the melt; see Gillmann et al. 2022 this journal), it will be released into the atmosphere. However, it has been shown that, with Earth-like outgassing (Earth-like composition of the gases released into the atmosphere during a volcanic eruption, indicating probable Earth-like oxidation of the Venusian mantle), at least the equivalent of ~ 10 global resurfacing events is needed to build up Venus' CO_2 atmosphere (Lopez et al. 1998). More recent work (Head et al. 2021), estimates that the number of equivalent global resurfacing events needed to obtain the amount of CO_2 in the present atmosphere of Venus is about 100. This would indicate that most of the present-day atmosphere would have originated from the period before the present geological record, which is in line with the interpretation of ^{40}Ar in the atmosphere of Venus that suggests that the bulk of the outgassing occurred rather early during its evolution. Numerical modeling of the mantle of Venus (e.g. Armann and Tackley 2012; Gillmann and Tackley 2014) also implies that global volcanic events are unlikely to occur with such a high frequency due to the massive internal heat dissipation they cause. The mantle requires time for heat to accumulate again before a new event is triggered. Therefore, volcanism is unlikely to have been the cause for the full atmosphere build up, or even for more than a fraction of the build-up. It does not preclude volcanism from triggering a transition, though (e.g. Way et al. 2022). Instead, whatever outgassing was due to volcanism took place on the long term, but without allowing us to be more specific about a precise age for a possible transition.

Weller and Kiefer (2021) present an alternative picture of how Venus' atmosphere could go from a very low CO_2 abundance to 20–60 bar. Weller and Kiefer (2021) demonstrate that a significant fraction of the present-day atmosphere can be produced with a single overturn (early hot planet, about 5 bar CO_2 per overturn), no overturns, or multiple overturns (later cold planet). Interestingly, these overturns do not need to be global and can occur on geologically short timescales. Weller et al. (2022) also suggests that a significant portion of Venus' atmosphere present-day N_2 and CO_2 inventory could be best produced under an early plate tectonics regime and may be reached without initial magma ocean contribution.

An alternative solution that has been suggested is that a global volcanic event, possibly akin to Earth-like Large Igneous Provinces (LIPs), could have both outgassed CO_2 from mantle reservoirs and destabilized carbon crustal reservoirs (such as carbonates and other carbon rich sediments, see Retallack et al. 2006; Svensen et al. 2009; Ganino and Arndt 2009; Nabelek et al. 2014), leading to the accumulation of CO_2 in the atmosphere on a short timescale (Way and Del Genio 2020; Krissansen-Totton et al. 2021; Höning et al. 2021; Way et al. 2022) at an undefined date. Such a mechanism and its feasibility are rather difficult to assess in the absence of observation. While Earth has experienced several LIPs during its evolution, no trace of CO_2 partial pressure increase on the order of tens of bars has been recorded (Schaller et al. 2011, for an example of estimate in the order of tens of thousands ppm CO_2). However, such events have been associated with dramatic climate change and global extinction events (e.g. Wignall 2001), making them important enough to affect life on a global scale and planetary habitability. They could possibly trigger a climate transition by overwhelming any volatile cycling in effect hence driving the planet into a moist and then runaway greenhouse (Way and Del Genio 2020; Way et al. 2022).

The remaining issue with this habitable scenario can simply be stated as "where is the oxygen?" If there were once substantial surface reservoirs of water on the surface of Venus and they were driven into the atmosphere as the planet warmed up, then why does the atmosphere not contain many bars of oxygen? In essence, as a planet enters the moist greenhouse state, water is transported into the stratosphere. Over time this water is photodissociated, the hydrogen can escape via diffusion and the oxygen should be left over (Kasting 1988). Studies have shown that it is difficult for oxygen to escape in substantial quantities in the present day Venusian atmosphere (e.g. Persson et al. 2020) where the H^+:O^+ ratio is $\sim$ 2:1 over the solar cycle (e.g. Barabash et al. 2007; Persson et al. 2018). Assuming Venus' atmosphere has not changed over geological time, Persson et al. (2020) demonstrated that it would have lost between 0.02–0.6 meters of a global equivalent layer of water over the past 3.9 billion years via atmospheric escape. Additionally, non-thermal escape is a slow, ongoing process that declines with time, as the solar extreme UV input decreases. This implies that it takes a long time to remove any significant amount of oxygen from Venus' atmosphere. In turn, if atmospheric escape alone is considered, progressive loss after an early habitable time billions of years ago would be favored. In fact, it has been speculated that exoplanetary worlds with multiple bars of oxygen may indicate a former temperate period with oceans (Luger and Barnes 2015; Wordsworth and Pierrehumbert 2013). It has been suggested that surface interaction and oxidation could have been a major sink of oxygen during the magma ocean phase (Kasting et al. 1993b; Gillmann et al. 2009), but this can be an efficient way to suppress oxygen accumulation only until the magma ocean solidifies.

Way and Del Genio (2020) speculated that the resurfacing we see on Venus today could have been the means to sequester the leftover oxygen. Gillmann et al. (2020) have simulated ongoing oxidation of the fresh, solid, basaltic crust and found it able to extract oxygen from the atmosphere at a maximum rate slightly higher than atmospheric escape, at most. Pieters et al. (1986), Lécuyer et al. (2000) have calculated that a hypothetical equivalent layer of approximately 50 km of hematite would be necessary to account for the oxidation of the content of an Earth ocean on Venus. More recent work by Warren and Kite (2021) has suggested that, for this hypothesis to be valid volcanic ash produced by explosive volcanism needs to be oxidized. In their model oxidation efficiency was increased by the larger free surface of the material (they therefore assume a 100% oxidation efficiency). However, such a mechanism still requires layers of kilometers to tens of kilometers of oxidized material to be emplaced onto the surface of the planet. This hypothesis also needs to consider that only very limited pyroclastic activity has been identified on Venus today (Campbell and Clark 2006; Ghail and Wilson 2015; Grosfils et al. 2000, 2011; Keddie and Head 1995; McGill 2000), as explosive volcanism requires volatile contents $>$ 3–5 wt%, several wt% higher than typical Earth magmas ($<$ 1 wt%) (Head et al. 2021). As a result, it is possible that such a mechanism might have actually played a role in the more distant past of Venus, rather than relatively recently. Again, better understanding of the nature and composition of the surface layers of Venus would be a tremendous help to understanding its history. Gillmann et al. (2022, this journal) expands on this topic and surface-atmosphere interaction.

Section 2 describes what to look for in the atmosphere today (D/H and noble gases, see Avice et al. 2022 this journal, for more details on noble gases) and what to look for on the surface in terms of felsic materials (similar to material from Earth's continents, formed at subduction factories) that may have a connection to surface water-rock interactions. On the other hand, if tesserae prove to be mainly basaltic, they formed without the need for liquid water, which would support a dryer evolution at least at the time they were formed.

5 Present-Day Habitability

5.1 The Clouds of Venus

The question of Venus' present-day habitability has been discussed for decades (Morowitz and Sagan 1967; Cockell 1999; Grinspoon and Bullock 2007). As covered in prior sections, it is often reasoned that if conditions on early Venus were similar to conditions on early Earth during the period in which Earth life arose – carbon molecules, surface water and rock-water interactions, and N, P, S, and transition metals, as well as suitable surface geology, volcanism and hydrothermal activity – this indicates the potential for an Earth-like biochemistry to have arisen on early Venus. However, modern-day Venus' surface is too hot for liquid water to be present, which rules out such biochemical reactions. Speculative alternative biochemistries compatible with the modern Venus surface have been proposed, such as the use of supercritical carbon dioxide as a polar solvent (Budisa and Schulze-Makuch 2014); the possibility for water-based life to have retreated to underground high-pressure water refugia

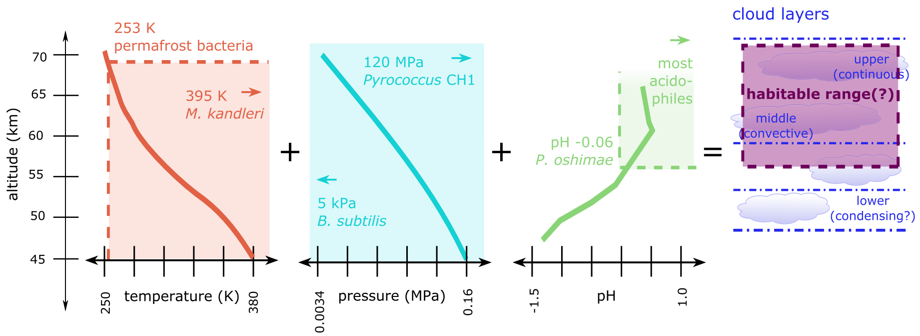

Fig. 8 The calculated temperature, pressure, and pH prevailing in Venus cloud aerosols in the height range 45–70 km from the surface (solid lines) and respective observed limits for terrestrial life (dashed lines and solid fill). The limits of terrestrial organisms may or may not reflect the possibilities for Venus

has also been discussed (Schulze-Makuch and Irwin 2002). However, the only liquid water known to exist today on Venus is that dissolved within its sulphuric acid clouds. There has therefore been a great deal of interest in the potential for present-day habitability of the Venus cloud aerosols, and whether such a habitat could have existed contemporaneously with surface water for long enough for life to have made the transition.

Figure 8 shows the calculated temperature, pressure, and pH in the middle Venus atmosphere (Grinspoon and Bullock 2007; Dartnell et al. 2015), juxtaposed with the respective observed limits for terrestrial life. The resulting discussion of a potential 'habitable range', and its relation to the limits of terrestrial cloud- and airborne microorganisms, is the subject of the following section. Future missions may help to constrain additional major variables affecting habitability in this altitude range, such as water availability and better constraining ultraviolet radiation flux (e.g. Mogul et al. 2021b).

5.2 Life in the Clouds

Earth's biosphere is a dynamic system of organisms and their interactions with the physical environment, including both transient and enduring habitats as well as short-term transport pathways (wind, rain) and long-term dormant refugia (polar ice, the deep subsurface). It includes a significant atmospheric component, the aerobiosphere. Tropospheric cloud water – the warmest and wettest airborne habitat – carries between 10^3 and 10^5 viable cells per mL (Amato et al. 2007), some of which is metabolically active (Amato et al. 2017). In addition to liquid cloud water, viable microbes are transported both regionally and globally as dust (Schuerger et al. 2018), ranging from 10^1 to 10^6 cells per cubic meter of air (Bowers et al. 2011; Burrows et al. 2009). These viable, dry bioaerosols extend throughout the troposphere and into the stratosphere (Bryan et al. 2019). However, most and possibly all of these desiccated microbes are inactive. Airborne microbial reproduction has not yet been directly observed in the field, although there have been indirect laboratory demonstrations (e.g. Sattler et al. 2001); this is likely in part because microbes in the field do not stay airborne for very long compared to typical generation times (Gentry et al. 2021).

At its most abstract, the requirements needed to support life (as we know it) were summarized by Hoehler (2007) as: a solvent (water); nutrients (C, H, N, O, P, S, and trace elements like Fe); energy for primary producers (autotrophs, chemical or photonic); and a stable environment (temperature, pH, radiation, etc.). The limits of habitability are often reasoned by analogy to therefore be the limits of life with respect to these requirements; the limits for the emergence of life are not fully understood, but may be different from or more constrained than established life which has had time to adapt and diversify, as noted above in Sect. 2.3.

By these metrics, hypothetical life in Venusian aerosols may be within the bounds of temperature, pressure, and pH (Grinspoon and Bullock 2007; Nicholson et al. 2010); radiation (Schulze-Makuch and Irwin 2002; Dartnell et al. 2015; Mogul et al. 2021b); C, H, N, O, and S, with some evidence for P (Limaye et al. 2021; Milojevic et al. 2021; Mogul et al. 2021a); and energy sources (photonic and/or oxidation-reduction potential, Limaye et al. 2018; Mogul et al. 2021b). Seager et al. (2020) argue that because the pH scale becomes highly compressed at extreme acid (or base) concentrations, the Hammett acidity function (H_0) is a more representative metric for the Venus aerosols' acid activity. H_0 for Venus' aerosols is poorly constrained. It has been estimated from as low as -11 (Seager et al. 2020) based on the current understanding of bulk aerosol composition, to ≥ -1.5 by Mogul et al. (2021b) with favorable assumptions regarding trace aerosol composition, the latter of which has some support in recent modeling by Rimmer et al. (2021) speculating the presence of ammonium or other hydroxide salts; however, even under the most favorable conditions, the results are at or below the acidity of any known Earth habitat, a substantial challenge for the hypothesis of an Earth-like biochemistry. The previously discussed alternative biochemistry hypotheses, such as a theoretical biochemistry based on sulphuric acid as a polar solvent instead of water, are not sufficiently detailed to be constrained in the same way.

An airborne ecosystem faces the additional unique requirement that its organisms must be able to stay aloft long enough to reproduce in a suitable, microbial-scale environment. Otherwise, the aerobiosphere will eventually settle out to extinction (if the planetary surface is uninhabitable, as with Venus), or be limited to transportation of a continual flux of organisms from the surface (as appears to be the case on Earth). A stable microbial aerobiosphere – using the term 'microbe' generally, without implied similarity to terrestrial microbiology – therefore has much stricter constraints than initially apparent. Microbes in a long-lived aerobiosphere (i.e., an atmospheric habitat) cannot rely on the common survival strategy of dormancy, i.e., 'waiting it out' to grow and reproduce during brief influxes of water, light, heat, etc. as is observed in microbes from Earth's deserts, poles, and other extreme environments. In effect, the 'soft' constraints of surviving versus thriving (activity, growth, and reproduction) become converted to hard habitability constraints when assessing potential atmospheric habitability, and are further related to the typical particle residence time determined by the large- and small-scale atmospheric dynamics.

On Earth, residence time for liquid water cloud particles, the most clement airborne microenvironment, ranges from hours to days; this is roughly on order with typical microbial generation times for common surface soil- or water-dwelling microbes. Smaller and lighter particles in drier and colder parts of Earth's atmosphere, such stratospheric aerosols, may be resident for as much as a few years; however, extremophilic microbes observed capable of withstanding similar conditions in other terrestrial habitats reproduce far more slowly, with an example of a 60-day mean generation time reported for Siberian permafrost at -10 °C (Bakermans et al. 2003). Another survival strategy often found in extremophilic environments with highly dynamic conditions – for example, a desert which might receive all of its rainfall on one or two days a year – is adaptation to long periods of dormancy followed by brief periods of repair and growth (e.g., Friedmann et al. 1993). Microbes have been observed to survive decades and perhaps far longer of complete desiccation, freezing, or other extreme conditions in the field (see Schulze-Makuch et al. 2018; Lowenstein et al. 2011; Knowlton et al. 2013 and references therein), but it should be emphasized that they do not reproduce during these periods and thus this phenomenon does not necessarily extend

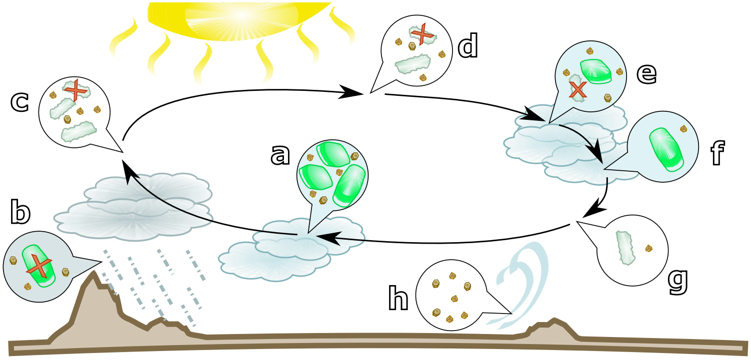

Fig. 9 Life cycle within a notional aerobiosphere. [**a**] Microbes (green) accumulate enough nutrients (brown) in a warm, wet cloud to divide. [**b**] Loss with precipitation. [**c**] Encounter with drier region; some transition to desiccated, inactive forms. [**d**] Dry forms accumulate damage, e.g., radiation. [**e**] Encounter with high-humidity region; some rehydrate and repair. [**f**] Survivors grow, potentially exhausting available nutrients. [**g**] Wet/dry cycles may repeat, depending on cloud dynamics. [**h**] Nutrients (e.g., surface minerals), energy, and wet periods become sufficient to allow division, beginning the cycle anew

the criteria for long-term aerobiosphere habitability. This is an important point: on Earth, airborne life has so far been observed to originate within at most a few generations from surface habitats.

Our knowledge of the microenvironments and typical residence times of Venus cloud droplets is limited, though they are likely longer-lasting than Earth's clouds. Seager et al. (2020) implemented a model that suggests coagulation rates constrain 3 μm-diameter cloud aerosols to 6 months aloft; Grinspoon and Bullock (2007) note that Hadley circulation may impose an overall 70–90 day upper bound.

Conditions favorable to metabolic activity and reproduction must also have sufficient continuity. A generalization of the constraints that shape Earth's aerobiosphere is shown in Fig. 9: cloud formation, precipitation, particle trajectories, cycles of dehydration and rehydration, and nutrient and radiation flux, among others. The hydrated periods of metabolic activity must align with the availability of nutrients and energy to allow growth to reproduce before the particle containing the microbe(s) rains or settles below the surface, or habitable altitude range.

Given the above, the most significant question for the potential present-day habitability of Venus' clouds is whether sufficient water exists in the cloud aerosols to allow occasional microbial growth. Both Seager et al. (2020) and Hallsworth et al. (2021a) estimate the water activity (a_w) as ≤ 0.004, far below the microbial activity limit of ~ 0.6. Limaye et al. (2021) calculated a higher but still prohibitive estimate of 0.02; as with calculations of H_0 above, the speculative models of Mogul et al. (2021b) and Rimmer et al. (2021) could allow currently unmeasured trace aerosol constituents to raise this to within known limits.

Understanding the habitability of Venus' clouds will require both future missions and modeling, with close coordination between experts in atmospheric dynamics, aerosol properties, cloud microphysics, and aerobiology. Key parameters to constrain include detailed measurements of Venus' aerosol composition, including trace constituents that could be nutrients or provide acid neutralization; typical residence times for particles with microbe-like properties in the Venusian atmosphere; and typical generation times for potential Earth analogue microorganisms, especially primary producers able to survive repeated desiccation and high acidity.

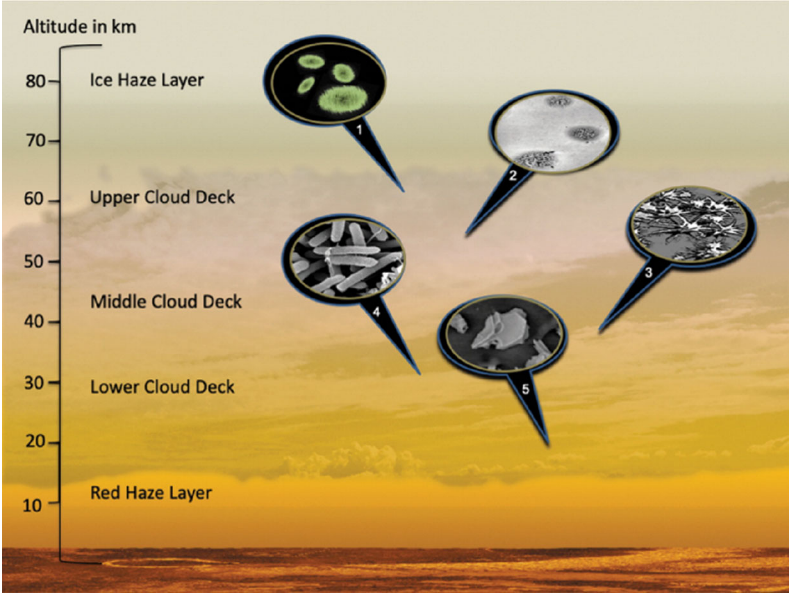

Fig. 10 Notional particles potentially to be encountered in the Venus cloud decks, inspired by terrestrial atmospheric sampling, to guide future instrument and analysis selection: (1) complex shapes with fluorescent properties, (2) particulate aggregates of sulfates and related compounds, (3) unidentified group of complex shapes adhered to an aerosol particle, (4) objects that resemble Earth bacteria or archaea, and (5) volcanic ash particles

Given the importance of microenvironments within cloud droplets to habitability, it is relevant to note several lines of evidence pointing to the existence of multiple cloud aerosol constituents beyond sulphuric acid and water: (1) UV absorption in the upper clouds of Venus is caused by an as-yet-unidentified "unknown UV absorber"; (2) VEx/VMC imager's analysis of the phase functions of light reflected from the upper clouds show more variation in refractive index than can be explained by H_2SO_4:H_2O mixtures alone; (3) particulates are observed to exist at altitudes below the main cloud base, where temperatures are too high for H_2SO_4:H_2O droplets to persist in liquid form; (4) X-ray Fluorescence analysis of collected droplets conducted from Venera and Vega descent probes found evidence of iron, chlorine and phosphorus in cloud droplets; and (5) the recent reanalysis of the Pioneer Venus LNMS data by Mogul et al. (2021a) which may provide further evidence for phosphorus in the cloud layer. The latter two results have not yet been reconciled with other in situ measurements and therefore remain something of an enigma (see review in Titov et al. 2018). The identification of cloud particle composition, down to the trace level, is clearly of great importance for assessing the present day habitability of the cloud deck (Fig. 10). In this respect, new investigations including measurement of the abundance and isotope ratios of volatile elements would likely shed light on the past and present dynamics of the cloud region of the Venus atmosphere (Avice et al. 2022).

5.3 Suggested Venusian Biosignatures

Interest in the habitability of Venus' clouds is furthered by several currently unexplained observations of the Venusian atmosphere that bear some similarities to known terrestrial biosignatures; if the clouds can be shown to bear equivalent similarities to the corresponding terrestrial habitats, the case for dedicated life detection investigation strengthens, and vice versa.

The Venus cloud layers have significant spectral absorption features not currently explained by what is known about the bulk aerosol composition, most notably in the UV but also at some longer wavelengths. Limaye et al. (2018) and Mogul et al. (2021b) suggested that this could be caused by phototrophy and/or 'sunscreen' pigments similar to carotenoids – in other words, analogous to the green 'color' of Earth resulting from the global presence of chlorophyll.

There are also discontinuities or unexplained variances in atmospheric sulfur and other chemical cycling (Bierson and Zhang 2020; Shao et al. 2020). Spacek and Benner (2021) suggested that these result from the presence of organic carbon, while Limaye et al. (2018) suggested that redox-based metabolic processes could play a role.

Recently, there have been controversial claims for the presence of a biosignature, the molecule phosphine (PH_3), in Venusian clouds. We summarize the controversy below. In September of 2020, Greaves et al. (2021b) published an analysis of JCMT (James Clerk Maxwell Telescope) and ALMA (Atacama Large Millimeter Array) spectra of the Venusian atmosphere that demonstrated that phosphine (PH_3) may have been detected. At the same time another paper by Bains et al. (2021), with many of the same authors as in the Greaves et al. (2021b) work, was submitted to arXiv with the title "Phosphine on Venus Cannot be Explained by Conventional Processes."

Subsequently a series of papers were submitted (posted to arXiv) and eventually published that put into question the veracity of the original JCMT and ALMA observations (e.g. Snellen et al. 2020; Thompson 2021; Villanueva et al. 2021; Akins et al. 2021; Lincowski et al. 2021). Additional papers placed upper limits via other space and ground based measurements that further questioned the PH_3 detection (Encrenaz et al. 2020; Trompet et al. 2021). Greaves et al. (2021a,c,d) offered a response to such criticisms, and more back-and-forth rebuttals continue in the literature today. At the same time another paper may have offered support to the Greaves et al. (2021b) ground based observations (Mogul et al. 2021a) by looking at in-situ archival data from the Pioneer Venus Large Probe Neutral Mass Spectrometer (PV-LNMS). Subsequently, a few papers have been published that look into the possible origins of PH_3 in planetary atmospheres in addition to the Bains 2020 paper (e.g. Bains et al. 2019a,b, 2021; Sousa-Silva et al. 2020; Omran et al. 2021; Cockell et al. 2021; Truong and Lunine 2021; Limaye et al. 2021) and whether factors, such as water activity, pH, etc. play a role in PH_3 production (e.g. Hallsworth et al. 2021a; Rimmer et al. 2021). Other work has considered the effects of Cosmic Rays on PH_3 production, but found it difficult to produce as much as 20 ppb (McTaggart 2022). While there is yet no consensus on the detection of phosphine in the atmosphere of Venus, its potential discovery has initiated many efforts including a mission to search for life in the clouds of Venus (Seager et al. 2021). This demonstrates that detection of potential biosignatures in planetary atmospheres is a high priority goal for investigations targeting Venus and its exoplanet cousins.

5.4 The Venus Life Equation

Izenberg et al. (2021) proposed a general framework for assessing the probability of extant life on modern-day Venus. This 'Venus Life Equation' breaks down the qualitative factors affecting the probability of the *origination* of life (O), the *robustness* (size and diversity) of the supportable biosphere (R), and whether habitable conditions could have persisted *continuously* between the origin of life and the current day (C). The factors supporting a high value for O by analogy between early Venus and Earth are discussed above. R, by contrast, is very low for the atmospheric habitat hypothesis, as a result of both limited substrate (the total liquid volume of Venus' aerosols is at least five orders of magnitude less than, say, Earth's surface and ground water) and the typical low biodiversity of ecosystems highly constrained by water availability. The value C is affected by both the potential for global extinction events, such as asteroid strikes and coronal mass ejections, and overall planetary climate history, as affected by volcanism, stellar evolution, and many other factors. The former is relatively similar for Venus and Earth; the latter depends primarily on the water history of Venus as discussed above. The Venus Life Equation thus suggests a non-zero value for the probability of extant Venusian life. It also confirms that continuity (spatial and temporal) of conditions amenable to life is one of the most important unknowns that can be quantitatively constrained by direct in situ observation, through robust improvement of understanding of atmospheric zones and geologic/hydrologic history.

This latter point is of particular importance where the Venusian aerosols are concerned. Unlike on Earth, where localized extinction-level events occurred but conditions for life persisted in other habitats (and cf. the subsurface punctuated habitability suggested for Mars by Melosh and Vickery 1989), this may not have been a possibility on Venus.

6 Investigation Priorities

There are two investigation priorities concerning the habitability of Venus:

1. To study past habitability. This can be addressed both through orbital observations of the surface and crust, in order to understand the geodynamic regime through time, and through noble gas and light element isotope measurements, to obtain insights into the history of volatiles through formation and evolution.
2. To characterize the present cloud-level environment including searching for molecular biosignatures of past or present-day life. This can be partially addressed by descent probes, but a more comprehensive investigation would require sustained presence in the clouds as from a balloon platform.

1. Studying the past habitability of Venus

It is very difficult to access Venus' history. Modelling and comparative planetology with other planets of our Solar system alongside exoplanets (for example, their age in conjunction with their rotation rate) will provide insight into the past conditions on Venus but models are only as good as the data initially used. Both the onset of, and exit from, a potential habitable phase need to be modelled. The period toward the end of the magma ocean phase has been highlighted as an important criterion for subsequent evolution and needs to be studied more intensely before any definitive conclusions can be drawn as to whether Venus ever hosted liquid water at its surface (e.g. Salvador et al. 2023, this journal). Similarly, much more work needs to be done to explore how a planet may go from a temperate to a moist and then a runaway greenhouse state (e.g. Kasting 1988), and coupled interior-atmosphere models as well as 3D GCMs will be needed (e.g. Boukrouche et al. 2021). Future Venus missions will address habitability in a range of different investigations. One approach to reconstructing Venus' history is to study its geologic record, as preserved in its surface and crust; this provides a record of the last billion years or so of surface evolution.

Of particular interest is the possibility that the tessera highlands show emissivity signatures consistent with widespread (continental-scale) granitic composition, like that found in Earth's continental crust; such a detection would suggest that large volumes of liquid water were present during their formation (Gilmore et al. 2017). However, non-detection of this felsic signature would not be conclusive, as such continental crust might have been covered by aeolian or other deposits, or otherwise not detectable from orbit. Determining Venus' current geodynamic regime – through gravity mapping and through searches for recent or ongoing geological activity – will help to constrain estimates of current heat and volatile loss from the interior, important factors in modelling the evolution of Venus' climate and habitability. The EnVision and VERITAS orbiters both will provide extensive datasets to address these investigations, as will DAVINCI descent imaging of tesserae, as will discussed in far more detail in companion publications in this journal (Chaps. 2–4).

Another approach, isotope geochemistry, allows one to constrain Venus' evolution in the distant past, right back to its formation and early evolution. The isotopic abundances of noble gases and light elements provide constraints on acquisition and loss processes of volatiles, and about their exchanges between mantle and atmosphere, so are particularly important for reconstructing the history of water. For example, measuring the magnitude of radiogenic/fissiogenic excesses of ^{4}He and $^{129,\,131-136}Xe$ produced at different times over Venus' history, will help to distinguish between scenarios for the geological evolution of Venus (stagnant lid, episodic plate tectonics episodes etc. see Gillmann et al. 2022, this journal). Although some noble gas isotope measurements were already obtained from Pioneer Venus and Venera in the 1970s and early 1980s, the upcoming DAVINCI entry probe mission will measure a greater variety of these isotopes with much greater precision, including the first measurements of krypton and xenon isotopes, permitting much better constraints on formation and evolution scenarios than are currently possible. Venus atmospheric sample return missions, though technically demanding, would allow isotopic ratio measurement to even higher precision and thus would offer correspondingly greater constraints on evolution scenarios. These investigations, and their implications for determining the history of water, are reviewed in detail in (Avice et al. 2022, this journal).

Conducting these investigations will not only give us a better understanding of Venus' evolution and potential habitability through time, but also will help us to assess habitability in terrestrial worlds in other planetary systems; these parallels are explored in much more detail in (Way et al. 2023, this journal).

2. The search for biosignatures in Venusian clouds

If Venus was habitable in the past (meaning, it had liquid water on its surface, the other ingredients of life being a given on a rocky planet such as Venus, and similar to early Earth), and life emerged, could it have survived to the present day in atmospheric aerosols? With regard to the habitability of the Venusian cloud deck, high priority in situ investigations include the structure of the atmosphere and variables, such as temperature, pressure, pH, UV radiation flux (cf. Grinspoon and Bullock 2007; Dartnell et al. 2015), and above all, detailed composition of the cloud aerosols, including water activity, acid activity, and trace constituents such as organics and ammonia. Comparison of these variables with those on Earth would substantially improve our ability to provide a 'habitable range'. Moreover, analysis of the aerosols will permit detailed study of the micro-environmental conditions within them. Could they be conducive to hosting an airborne biosphere, permitting life to thrive (not just survive), even if they are "extreme" by terrestrial standards? Future descent probes, like the upcoming DAVINCI (Garvin et al. 2022) probe, or the descent phase of lander missions such as Venera-D (Zasova et al. 2019) will be essential for this investigation by providing vertical profiles of atmospheric composition with far greater sensitivity and vertical resolution than is available from past missions. Far more spatially and temporally extensive investigations will require cloud-level aerial platforms (e.g. Cutts et al. 2018; Baines et al. 2018; Arredondo et al. 2021) offering sustained presence in the clouds. Instrumentation on such platforms should, in particular, seek to measure the composition, size, and lifetime of cloud and aerosol particles, as these are the most habitable environmental niches of astrobiological interest.

In situ investigations should also look for signs of extant life (biomolecules, metabolites). A staged approach to detection of biosignatures was developed by the Venus Life Finder Missions team (Seager et al. 2022), consisting of missions increasing in size and complexity. In a first mission, a small entry probe would descend through the clouds carrying an autofluorescence backscatter nephelometer, which would characterize the shape and composition of cloud particles and search for the fluorescence in UV light as a biomarker (Baumgardner et al. 2022). Such a mission is in development, at the time of writing, and may launch as soon as 2023 (French et al. 2022). A second proposed mission would put more capable chemical and environmental detection instrumentation on a long-lived balloon floating in Venus' clouds; such instrumentation could eventually include an aerosol mass spectrometer (Baines et al. 2021) and/or a fluorescent microscope which provides particular sensitivity to biomolecules (Sasaki et al. 2022). These could eventually lead to a third mission which would bring back a sample of Venus cloud material to Earth, so that it could be examined with the highly sensitive instrumentation available in terrestrial laboratories. Even if no metabolically active life forms are detected, information from these investigations will inform the models used to determine the history of the planet and its potential for having been habitable and seen the independent emergence of life.

One final note is that any information from Venus *in situ* and any possible, future sample return mission would be extremely valuable for studying the habitability of exoplanets.

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Declarations

Competing Interests The authors declare that they have no conflict of interest.

References

Abramov O, Kring DA, Mojzsis SJ (2013) The impact environment of the Hadean earth. Geochemistry 73(3):227–248

Adam Z (2007) Actinides and life's origins. Astrobiology 7:852–872

Adam ZR, Hongo Y, Cleaves HJ, Yi R, Fahrenbach AC, Yoda I, Aono M (2018) Estimating the capacity for production of formamide by radioactive minerals on the prebiotic Earth. Sci Rep 8(1):1–8

Akins AB, Lincowski AP, Meadows VS, Steffes PG (2021) Complications in the ALMA detection of phosphine at Venus. Astrophys J Lett 907(2):L27

Aléon J, Lévy D, Aléon-Toppani A, Bureau H, Khodja H, Brisset F (2022) Determination of the initial hydrogen isotopic composition of the solar system. Nat Astron 6(4):458–463

Allwood AC, Walter MR, Kamber BS, Marshall CP, Burch IW (2006) Stromatolite reef from the early Archaean era of Australia. Nature 441(7094):714–718

Allwood AC, Rosing MT, Flannery DT, Hurowitz JA, Heirwegh CM (2018) Reassessing evidence of life in 3,700-million-year-old rocks of Greenland. Nature 563(7730):241–244

Altwegg K, Balsiger H, Bar-Nun A, Berthelier JJ, Bieler A, Bochsler P, Briois C, Calmonte U, Combi M, De Keyser J, Eberhardt P, Fiethe B, Fuselier S, Gasc S, Gombosi TI, Hansen KC, Hässig M, Jackel A, Kopp E, Korth A, LeRoy L, Mall U, Marty B, Mousis O, Neefs E, Owen T, Reme H, Rubin M, Semon T, Tzou CY, Waite H, Wurz P (2015) 67P/Churyumov-Gerasimenko, a Jupiter family comet with a high D/H ratio. Science 347(6220):3. https://doi.org/10.1126/science.1261952

Amato P, Parazols M, Sancelme M, Laj P, Mailhot G, Delort AM (2007) Microorganisms isolated from the water phase of tropospheric clouds at the Puy de Dôme: major groups and growth abilities at low temperatures: microorganisms from the water phase of tropospheric clouds. FEMS Microbiol Ecol 59(2):242–254. https://doi.org/10.1111/j.1574-6941.2006.00199.x

Amato P, Joly M, Besaury L, Oudart A, Taib N, Moné AI, Deguillaume L, Delort AM, Debroas D (2017) Active microorganisms thrive among extremely diverse communities in cloud water. PLoS ONE 12(8):e0182–869. https://doi.org/10.1371/journal.pone.0182869

Armann M, Tackley PJ (2012) Simulating the thermochemical magmatic and tectonic evolution of Venus's mantle and lithosphere: two-dimensional models. J Geophys Res, Planets 117(E12):E12003

Arredondo A, Hodges A, Abrahams JNH, Bedford CC, Boatwright BD, Buz J, Cantrall C, Clark J, Erwin A, Krishnamoorthy S, Magana L, McCabe RM, McIntosh EC, Noviello JL, Pellegrino M, Ray C, Styczinski M, Weigel P (2021) VALENTiNE: a concept for a new frontiers class long duration in-situ balloon mission to Venus. In: 52nd lunar and planetary science conference, Lunar and Planetary Institute, Virtual, p 1526. https://ui.adsabs.harvard.edu/abs/2021LPI....52.1526A

Avice G, Marty B (2020) Perspectives on atmospheric evolution from noble gas and nitrogen isotopes on Earth, Mars & Venus. Space Sci Rev 216(3):36. https://doi.org/10.1007/s11214-020-00655-0

Avice G, Marty B, Burgess R, Hofmann A, Philippot P, Zahnle K, Zakharov D (2018) Evolution of atmospheric xenon and other noble gases inferred from Archean to Paleoproterozoic rocks. Geochim Cosmochim Acta 232:82–100. https://doi.org/10.1016/j.gca.2018.04.018

Avice G, Parai R, Jacobson S, Labidi J, Trainer M, Mikhail PP (2022) Noble gases and stable isotopes track the originand early evolution of the Venus atmosphere. Space Sci Rev 218:60. https://doi.org/10.1007/s11214-022-00929-9

Baines KH, Atreya SK, Bullock MA, Grinspoon DH, Mahaffy P, Russell CT, Schubert G, Zahnle K (2013) The atmospheres of the terrestrial planets: clues to the origins and early evolution of Venus, Earth, and Mars. In: Comparative climatology of terrestrial planets. University of Arizona Press, Tucson, pp 1–28. https://doi.org/10.2458/azu_uapress_9780816530595-ch006

Baines KH, Cutts JA, Nikolić D, Madzunkov SM, Renard J, Mousis O, Barge LM, Limaye SS (2018) An aerosol instrument package for characterizing the Venus cloud habitability zone. Astrobiology 18(9):1181–1198. https://www.liebertpub.com/doi/10.1089/ast.2017.1783

Baines KH, Nikolić D, Cutts JA, Delitsky ML, Renard JB, Madzunkov SM, Barge LM, Mousis O, Wilson C, Limaye SS et al (2021) Investigation of Venus cloud aerosol and gas composition including potential biogenic materials via an aerosol-sampling instrument package. Astrobiology 21(10):1316–1323

Bains W, Petkowski JJ, Sousa-Silva C, Seager S (2019a) Trivalent phosphorus and phosphines as components of biochemistry in anoxic environments. Astrobiology 19(7):885–902

Bains W, Petkowski JJ, Sousa-Silva C, Seager S (2019b) New environmental model for thermodynamic ecology of biological phosphine production. Sci Total Environ 658:521–536

Bains W, Petkowski JJ, Seager S, Ranjan S, Sousa-Silva C, Rimmer PB, Zhan Z, Greaves JS, Richards AM (2021) Phosphine on Venus cannot be explained by conventional processes. Astrobiology 21(10):1277–1304. https://doi.org/10.1089/ast.2020.2352

Bakermans C, Tsapin AI, Souza-Egipsy V, Gilichinsky DA, Nealson KH (2003) Reproduction and metabolism at −10 °C of bacteria isolated from Siberian permafrost. Environ Microbiol 5:321–326. https://doi.org/10.1046/j.1462-2920.2003.00419.x

Barabash S, Fedorov A, Sauvaud J, Lundin R, Russell C, Futaana Y, Zhang T, Andersson H, Brinkfeldt K, Grigoriev A et al (2007) The loss of ions from Venus through the plasma wake. Nature 450(7170):650–653

Barboni M, Boehnke P, Keller B, Kohl IE, Schoene B, Young ED, McKeegan KD (2017) Early formation of the Moon 4.51 billion years ago. Sci Adv 3(1):e1602,365

Baross JA, Hoffman SE (1985) Submarine hydrothermal vents and associated gradient environments as sites for the origin and evolution of life. Orig Life Evol Biosph 15(4):327–345
Basilevsky A, Head J (1997) Onset time and duration of corona activity on Venus: stratigraphy and history from photogeologic study of stereo images. Earth Moon Planets 76(1):67–115
Baumgardner D, Fisher T, Newton R, Roden C, Zmarzly P, Seager S, Petkowski JJ, Carr CE, Špaček J, Benner SA et al (2022) Deducing the composition of Venus cloud particles with the autofluorescence nephelometer (AFN). Aerospace 9(9):492
Belousova E, Kostitsyn Y (2010). Griffi n, wl, begg, gc
Benner SA, Kim HJ, Kim MJ, Ricardo A (2010) Planetary organic chemistry and the origins of biomolecules. Cold Spring Harb Perspect Biol 2(7):a003467
Benz W, Slattery WL, Cameron AGW (1986) The origin of the Moon and the single-impact hypothesis I. Icarus 66(3):515–535. https://doi.org/10.1016/0019-1035(86)90088-6
Bercovici D, Ricard Y (2014) Plate tectonics, damage and inheritance. Nature 508(7497):513–516
Bierson CJ, Zhang X (2020) Chemical cycling in the Venusian atmosphere: a full photochemical model from the surface to 110 km. J Geophys Res, Planets 125(7):e2019JE006,159. https://doi.org/10.1029/2019JE006159
Blake RE, Chang SJ, Lepland A (2010) Phosphate oxygen isotopic evidence for a temperate and biologically active Archaean ocean. Nature 464(7291):1029–1032
Bolhar R, Kamber BS, Moorbath S, Whitehouse MJ, Collerson KD (2005) Chemical characterization of Earth's most ancient clastic metasediments from the Isua Greenstone Belt, southern West Greenland. Geochim Cosmochim Acta 69(6):1555–1573
Bottke WF, Vokrouhlicky D, Ghent B, Mazrouei S, Robbins S, Marchi S (2016) On asteroid impacts, crater scaling laws, and a proposed younger surface age for Venus. In: Lunar and planetary science conference, p 2036
Boukrouche R, Lichtenberg T, Pierrehumbert RT (2021) Beyond runaway: initiation of the post-runaway greenhouse state on rocky exoplanets. Astrophys J 919(2):130. https://doi.org/10.3847/1538-4357/ac1345. arXiv:2107.14150
Bower D, Hakim K, Sossi P, Sanan P (2022) Retention of water in terrestrial magma oceans and carbon-rich early atmospheres. Planet Sci J 3(93):1–28
Bowers RM, McLetchie S, Knight R, Fierer N (2011) Spatial variability in airborne bacterial communities across land-use types and their relationship to the bacterial communities of potential source environments. ISME J 5(4):601–612. https://doi.org/10.1038/ismej.2010.167
Bowring SA, Williams IS (1999) Priscoan (4.00–4.03 Ga) orthogneisses from northwestern Canada. Contrib Mineral Petrol 134(1):3–16
Brasier MD, Matthewman R, McMahon S, Wacey D (2011) Pumice as a remarkable substrate for the origin of life. Astrobiology 11(7):725–735
Brasser R, Mojzsis S, Werner S, Matsumura S, Ida S (2016) Late veneer and late accretion to the terrestrial planets. Earth Planet Sci Lett 455:85–93. https://doi.org/10.1016/j.epsl.2016.09.013
Bryan NC, Christner BC, Guzik TG, Granger DJ, Stewart MF (2019) Abundance and survival of microbial aerosols in the troposphere and stratosphere. ISME J 13(1111):2789–2799. https://doi.org/10.1038/s41396-019-0474-0
Budisa N, Schulze-Makuch D (2014) Supercritical carbon dioxide and its potential as a life-sustaining solvent in a planetary environment. Life 4(33):331–340. https://doi.org/10.3390/life4030331
Bullock MA, Grinspoon DH (2001) The recent evolution of climate on Venus. Icarus 150(1):19–37
Burkhardt C, Spitzer F, Morbidelli A, Budde G, Render JH, Kruijer TS, Kleine T (2021) Terrestrial planet formation from lost inner solar system material. Sci Adv 7(52):eabj7601
Burrows SM, Elbert W, Lawrence MG, Pöschl U (2009) Bacteria in the global atmosphere – part 1: review and synthesis of literature data for different ecosystems. Atmos Chem Phys 9(23):9263–9280. https://doi.org/10.5194/acp-9-9263-2009
Byerly GR, Lower DR, Walsh MM (1986) Stromatolites from the 3,300–3,500-Myr Swaziland Supergroup, Barberton mountain land, South Africa. Nature 319(6053):489–491
Byrne PK, Krishnamoorthy S (2021) Estimates on the frequency of volcanic eruptions on Venus. J Geophys Res, Planets 127(1):e2021JE007040
Campbell BA, Clark DA (2006) Geologic map of the Mead quadrangle (V-21), Venus, vol 2897. US Geological Survey, Denver
Campbell IH, Taylor SR (1983) No water, no granites-no oceans, no continents. Geophys Res Lett 10(11):1061–1064
Canup RM (2004) Simulations of a late lunar-forming impact. Icarus 168(2):433–456. https://doi.org/10.1016/j.icarus.2003.09.028
Capitanio F, Nebel O, Cawood P, Weinberg R, Chowdhury P (2019) Reconciling thermal regimes and tectonics of the early Earth. Geology 47(10):923–927

Capitanio FA, Nebel O, Cawood PA (2020) Thermochemical lithosphere differentiation and the origin of cratonic mantle. Nature 588(7836):89–94
Cates N, Mojzsis S (2007) Pre-3750 Ma supracrustal rocks from the Nuvvuagittuq supracrustal belt, northern Quebec. Earth Planet Sci Lett 255(1–2):9–21
Catling DC, Zahnle KJ (2020) The Archean atmosphere. Sci Adv 6(9):eaax1420
Cawood PA, Hawkesworth C, Dhuime B (2013) The continental record and the generation of continental crust. Geol Soc Am Bull 125(1–2):14–32
Cawood PA, Hawkesworth CJ, Pisarevsky SA, Dhuime B, Capitanio FA, Nebel O (2018) Geological archive of the onset of plate tectonics. Philos Trans R Soc A, Math Phys Eng Sci 376(2132):20170,405
Chambers J, Wetherill G (1998) Making the terrestrial planets: N-body integrations of planetary embryos in three dimensions. Icarus 136(2):304–327
Chowdhury P, Gerya T, Chakraborty S (2017) Emergence of silicic continents as the lower crust peels off on a hot plate-tectonic Earth. Nat Geosci 10(9):698–703
Chowdhury P, Chakraborty S, Gerya TV, Cawood PA, Capitanio FA (2020) Peel-back controlled lithospheric convergence explains the secular transitions in Archean metamorphism and magmatism. Earth Planet Sci Lett 538:116,224
Claire MW, Sheets J, Cohen M, Ribas I, Meadows VS, Catling DC (2012) The evolution of solar flux from 0.1 nm to 160 μm: quantitative estimates for planetary studies. Astrophys J 757:95. https://doi.org/10.1088/0004-637X/757/1/95
Clement MS, Morbidelli A, Raymond SN, Kaib NA (2019) A record of the final phase of giant planet migration fossilized in the asteroid belt's orbital structure. Mon Not R Astron Soc Lett 492(1):L56–L60. https://doi.org/10.1093/mnrasl/slz184
Cockell CS (1999) Life on Venus. Planet Space Sci 47(12):1487–1501. https://doi.org/10.1016/S0032-0633(99)00036-7
Cockell CS, McMahon S, Biddle JF (2021) When is life a viable hypothesis? The case of Venusian phosphine. Astrobiology 21(3):261–264
Cogné JP, Humler E (2006) Trends and rhythms in global seafloor generation rate. Geochem Geophys Geosyst 7(3):Q03011
Connelly J, Bizzarro M (2016) Lead isotope evidence for a young formation age of the Earth–Moon system. Earth Planet Sci Lett 452:36–43
Correia ACM, Laskar J (2001) The four final rotation states of Venus. Nature 411:767–770. https://doi.org/10.1038/35081000
Correia ACM, Laskar J (2003) Long-term evolution of the spin of Venus. II. Numerical simulations. Icarus 163:24–45. https://doi.org/10.1016/S0019-1035(03)00043-5
Correia ACM, Laskar J, de Surgy ON (2003) Long-term evolution of the spin of Venus. I. Theory. Icarus 163:1–23. https://doi.org/10.1016/S0019-1035(03)00042-3
Cutts JA, Baines K, Grimm R, Matthies L, Hall JL, Limaye S, Thompson TW (2018) Aerial platforms for scientific investigation of Venus. https://trs.jpl.nasa.gov/bitstream/handle/2014/49516/CL%2318-7416.pdf?sequence=1
Damer B, Deamer D (2020) The hot spring hypothesis for an origin of life. Astrobiology 20(4):429–452
Dartnell LR, Nordheim TA, Patel MR, Mason JP, Coates AJ, Jones GH (2015) Constraints on a potential aerial biosphere on Venus: I. Cosmic rays. Icarus 257:396–405. https://doi.org/10.1016/j.icarus.2015.05.006
Dass AV, Jaber M, Brack A, Foucher F, Kee TP, Georgelin T, Westall F (2018) Potential role of inorganic confined environments in prebiotic phosphorylation. Life 8(1):7
Deamer DW (1997) The first living systems: a bioenergetic perspective. Microbiol Mol Biol Rev 61(2):239–261
Dehant V, Debaille V, Dobos V, Gaillard F, Gillmann C, Goderis S, Grenfell JL, Höning D, Javaux EJ, Karatekin Ö et al (2019) Geoscience for understanding habitability in the solar system and beyond. Space Sci Rev 215(6):1–48
Deienno R, Gomes RS, Walsh KJ, Morbidelli A, Nesvorný D (2016) Is the grand tack model compatible with the orbital distribution of main belt asteroids? Icarus 272:114–124
Dhuime B, Hawkesworth CJ, Cawood PA, Storey CD (2012) A change in the geodynamics of continental growth 3 billion years ago. Science 335(6074):1334–1336
Dhuime B, Wuestefeld A, Hawkesworth CJ (2015) Emergence of modern continental crust about 3 billion years ago. Nat Geosci 8(7):552–555
Djokic T, Van Kranendonk MJ, Campbell KA, Walter MR, Ward CR (2017) Earliest signs of life on land preserved in ca. 3.5 Ga hot spring deposits. Nat Commun 8(1):1–9
Djokic T, Van Kranendonk MJ, Campbell KA, Havig JR, Walter MR, Guido DM (2021) A reconstructed subaerial hot spring field in the 3.5 billion-year-old Dresser Formation, North Pole Dome, Pilbara Craton, Western Australia. Astrobiology 21(1):1–38

Dodd MS, Papineau D, Grenne T, Slack JF, Rittner M, Pirajno F, O'Neil J, Little CT (2017) Evidence for early life in Earth's oldest hydrothermal vent precipitates. Nature 543(7643):60–64
Donahue T, Hodges R Jr (1992) Past and present water budget of Venus. J Geophys Res, Planets 97(E4):6083–6091
Donahue TM, Hodges RR Jr (1993) Venus methane and water. Geophys Res Lett 20(7):591–594
Donahue T, Hoffman J, Hodges R, Watson A (1982) Venus was wet: a measurement of the ratio of deuterium to hydrogen. Science 216(4546):630–633
Encrenaz T, Greathouse TK, Marcq E, Widemann T, Bézard B, Fouchet T, Giles R, Sagawa H, Greaves J, Sousa-Silva C (2020) A stringent upper limit of the PH_3 abundance at the cloud top of Venus. Astron Astrophys 643:L5
Evans DA (2013) Reconstructing pre-Pangean supercontinents. Geol Soc Am Bull 125(11–12):1735–1751
Fedorova A, Korablev O, Vandaele AC, Bertaux JL, Belyaev D, Mahieux A, Neefs E, Wilquet W, Drummond R, Montmessin F et al (2008) HDO and H_2O vertical distributions and isotopic ratio in the Venus mesosphere by Solar Occultation at Infrared spectrometer on board Venus Express. J Geophys Res, Planets 113(E5):E00B22
Fegley B (2014) Venus. In: Treatise on geochemistry. Elsevier, Amsterdam, pp 127–148. https://doi.org/10.1016/B978-0-08-095975-7.00122-4
Fegley B, Prinn RG (1989) Estimation of the rate of volcanism on Venus from reaction rate measurements. Nature 337(6202):55–58
Fischer R, Gerya T (2016a) Early Earth plume-lid tectonics: a high-resolution 3D numerical modelling approach. J Geodyn 100:198–214
Fischer R, Gerya T (2016b) Regimes of subduction and lithospheric dynamics in the Precambrian: 3D thermomechanical modelling. Gondwana Res 37:53–70
Foley BJ (2015) The role of plate tectonic–climate coupling and exposed land area in the development of habitable climates on rocky planets. Astrophys J 812(1):36
Foley BJ, Smye AJ (2018) Carbon cycling and habitability of Earth-sized stagnant lid planets. Astrobiology 18(7):873–896
Foley BJ, Bercovici D, Elkins-Tanton LT (2014) Initiation of plate tectonics from post-magma ocean thermochemical convection. J Geophys Res, Solid Earth 119(11):8538–8561. https://doi.org/10.1002/2014JB011121
French R, Mandy C, Hunter R, Mosleh E, Sinclair D, Beck P, Seager S, Petkowski JJ, Carr CE, Grinspoon DH et al (2022) Rocket lab mission to Venus. Aerospace 9(8):445
Friedmann EI, Kappen L, Meyer MA, Nienow JA (1993) Long-term productivity in the cryptoendolithic microbial community of the Ross Desert, Antarctica. Microb Ecol 25(1):51–69
Friend CR, Nutman AP, Bennett VC, Norman M (2008) Seawater-like trace element signatures (REE + Y) of Eoarchaean chemical sedimentary rocks from southern West Greenland, and their corruption during high-grade metamorphism. Contrib Mineral Petrol 155(2):229–246
Frost DJ, McCammon CA (2008) The redox state of Earth's mantle. Annu Rev Earth Planet Sci 36:389–420
Gaillard F, Scaillet B (2014) A theoretical framework for volcanic degassing chemistry in a comparative planetology perspective and implications for planetary atmospheres. Earth Planet Sci Lett 403:307–316
Gaillard F, Bouhifd MA, Füri E, Malavergne V, Marrocchi Y, Noack L, Ortenzi G, Roskosz M, Vulpius S (2021) The diverse planetary ingassing/outgassing paths produced over billions of years of magmatic activity. Space Sci Rev 217(1):1–54
Gaillard F, Bernadou F, Roskosz M, Bouhifd MA, Marrocchi Y, Iacono-Marziano G, Moreira M, Scaillet B, Rogerie G (2022) Redox controls during magma ocean degassing. Earth Planet Sci Lett 577:117,255
Ganino C, Arndt NT (2009) Climate changes caused by degassing of sediments during the emplacement of large igneous provinces. Geology 37(4):323–326
García-Ruiz JM, Van Zuilen MA, Bach W (2020) Mineral self-organization on a lifeless planet. Phys Life Rev 34:62–82
Garvin JB, Getty SA, Arney GN, Johnson NM, Kohler E, Schwer KO, Sekerak M, Bartels A, Saylor RS, Elliott VE et al (2022) Revealing the mysteries of Venus: the DAVINCI mission. Planet Sci J 3(5):117
Gentry DM, Iraci LT, Barth E, McGouldrick K, Jessup KL (2021) Habitability of cloudy worlds: intersecting constraints and unknowns. In: Proceedings of LPSC LII. Lunar and Planetary Institute, vol 52, p 2691. https://www.hou.usra.edu/meetings/lpsc2021/pdf/2691.pdf. Abstract #2691
Gerya T (2014) Precambrian geodynamics: concepts and models. Gondwana Res 25(2):442–463
Gerya T (2019) Geodynamics of the early Earth: quest for the missing paradigm. Geology 47(10):1006–1007
Gerya T (2022) Numerical modeling of subduction: state of the art and future directions. Geosphere 18(2):503–561
Gerya T, Stern R, Baes M, Sobolev S, Whattam S (2015a) Plume-induced subduction initiation triggered plate tectonics on Earth. Nature 527(7577):221–225

Gerya TV, Stern RJ, Baes M, Sobolev SV, Whattam SA (2015b) Plate tectonics on the Earth triggered by plume-induced subduction initiation. Nature 527(7577):221–225

Gerya TV, Bercovici D, Becker TW (2021) Dynamic slab segmentation due to brittle–ductile damage in the outer rise. Nature 599(7884):245–250

Ghail RC, Wilson L (2015) A pyroclastic flow deposit on Venus. Geol Soc (Lond) Spec Publ 401(1):97–106

Gillmann C, Tackley P (2014) Atmosphere/mantle coupling and feedbacks on Venus. J Geophys Res, Planets 119(6):1189–1217

Gillmann C, Chassefière E, Lognonné P (2009) A consistent picture of early hydrodynamic escape of Venus atmosphere explaining present Ne and Ar isotopic ratios and low oxygen atmospheric content. Earth Planet Sci Lett 286(3–4):503–513. https://doi.org/10.1016/j.epsl.2009.07.016

Gillmann C, Golabek GJ, Tackley PJ (2016) Effect of a single large impact on the coupled atmosphere-interior evolution of Venus. Icarus 268:295–312

Gillmann C, Golabek GJ, Raymond SN, Schönbächler M, Tackley P, Dehant V, Debaille V (2020) Dry late accretion inferred from Venus's coupled atmosphere and internal evolution. Nat Geosci 13(4):265–269

Gillmann C, Way MJ, Avice G, Breuer D, Golabek GJ, Höning D, Krissansen-Totton J, Lammer H, Plesa AC, Persson M, O'Rourke JG, Salvador A, Scherf M, Zolotov MY (2022) The long-term evolution of the atmosphere of Venus: processes and feedback mechanisms. Space Sci Rev 218:56. https://doi.org/10.1007/s11214-022-00924-0

Gilmore MS, Mueller N, Helbert J (2015) VIRTIS emissivity of Alpha Regio, Venus, with implications for tessera composition. Icarus 254:350–361. https://doi.org/10.1016/j.icarus.2015.04.008

Gilmore M, Treiman A, Helbert J, Smrekar S (2017) Venus surface composition constrained by observation and experiment. Space Sci Rev 212(3):1511–1540

Goldblatt C (2018) Atmospheric evolution Springer, Cham, pp 62–76. https://doi.org/10.1007/978-3-319-39312-4_107

Goldblatt C, Claire MW, Lenton TM, Matthews AJ, Watson AJ, Zahnle KJ (2009) Nitrogen-enhanced greenhouse warming on early Earth. Nat Geosci 2(12):891–896. https://doi.org/10.1038/ngeo692

Goldreich P, Peale SJ (1966) Resonant rotation for Venus? Nature 209:1117–1118. https://doi.org/10.1038/2091117a0

Goldreich P, Peale SJ (1970) The obliquity of Venus. Astron J 75:273. https://doi.org/10.1086/110975

Gough DO (1981) Solar interior structure and luminosity variations. Sol Phys 74(1):21–34. https://doi.org/10.1007/BF00151270

Graham RJ, Pierrehumbert R (2020) Thermodynamic and energetic limits on continental silicate weathering strongly impact the climate and habitability of wet, rocky worlds. Astrophys J 896(2):115. https://doi.org/10.3847/1538-4357/ab9362. arXiv:2004.14058

Greaves JS, Richards A, Bains W, Rimmer PB, Clements DL, Seager S, Petkowski JJ, Sousa-Silva C, Ranjan S, Fraser HJ (2021a) Reply to: no evidence of phosphine in the atmosphere of Venus from independent analyses. Nat Astron 5(7):636–639

Greaves JS, Richards AM, Bains W, Rimmer PB, Sagawa H, Clements DL, Seager S, Petkowski JJ, Sousa-Silva C, Ranjan S et al (2021b) Phosphine gas in the cloud decks of Venus. Nat Astron 5(7):655–664

Greaves JS, Richards A, Bains W, Rimmer PB, Sagawa H, Clements DL, Seager S, Petkowski JJ, Sousa-Silva C, Ranjan S et al (2021c) Addendum: phosphine gas in the cloud deck of Venus. Nat Astron 5(7):726–728

Greaves JS, Rimmer PB, Richards A, Petkowski JJ, Bains W, Ranjan S, Seager S, Clements DL, Silva CS, Fraser HJ (2021d) Low levels of sulphur dioxide contamination of phosphine spectra from Venus' atmosphere. ArXiv preprint. arXiv:2108.08393

Green JAM, Way MJ, Barnes R (2019) Consequences of tidal dissipation in a putative Venusian ocean. Astrophys J Lett 876(2):L22. https://doi.org/10.3847/2041-8213/ab133b. arXiv:1903.07517

Greer J, Caro G, Cates NL, Tropper P, Bleeker W, Kelly NM, Mojzsis SJ (2020) Widespread poly-metamorphosed Archean granitoid gneisses and supracrustal enclaves of the southern Inukjuak Domain, Québec (Canada). Lithos 364:105,520

Grew ES, Bada JL, Hazen RM (2011) Borate minerals and origin of the RNA world. Orig Life Evol Biosph 41(4):307–316

Griffin W, Belousova E, O'Neill C, O'Reilly SY, Malkovets V, Pearson N, Spetsius S, Wilde S (2014) The world turns over: Hadean–Archean crust–mantle evolution. Lithos 189:2–15

Grinspoon DH (1987) Was Venus wet? Deuterium reconsidered. Science 238(4834):1702–1704. https://doi.org/10.1126/science.238.4834.1702

Grinspoon DH (1992) Venusian hydrology: steady state reconsidered. In: International colloquium on Venus. LPI contributions, vol 789, p 36

Grinspoon DH, Bullock MA (2007) Astrobiology and Venus exploration Am. Geophys Union, Washington, pp 191–206. https://doi.org/10.1029/176GM12

Grosfils EB, Aubele J, Crumpler L, Gregg TK, Sakimoto S (2000) Volcanism on Earth's seafloor and Venus. In: Environmental effects on volcanic eruptions. Springer, Berlin, pp 113–142
Grosfils EB, Long SM, Venechuk EM, Hurwitz DM, Richards JW, Kastl B, Drury DE, Hardin JS (2011) Geologic map of the Ganiki Planitia quadrangle (V-14), Venus. Venus: US Geological Survey Scientific Investigations Map 3121
Grossman L, Larimer JW (1974) Early chemical history of the solar system. Rev Geophys 12(1):71–101
Gurwell MA (1995) Evolution of deuterium on Venus. Nature 378(6552):22–23. https://doi.org/10.1038/378022b0
Halliday AN (2000) Terrestrial accretion rates and the origin of the Moon. Earth Planet Sci Lett 176(1):17–30
Hallsworth JE, Koop T, Dallas TD, Zorzano MP, Burkhardt J, Golyshina OV, Martín-Torres J, Dymond MK, Ball P, McKay CP (2021a) Water activity in Venus's uninhabitable clouds and other planetary atmospheres. Nat Astron 5(7):665–675
Hamano K, Abe Y, Genda H (2013) Emergence of two types of terrestrial planet on solidification of magma ocean. Nature 497:607–610. https://doi.org/10.1038/nature12163
Hansen VL (2018) Global tectonic evolution of Venus, from exogenic to endogenic over time, and implications for early Earth processes. Philos Trans R Soc A, Math Phys Eng Sci 376(2132):20170,412
Hao J, Knoll AH, Huang F, Hazen RM, Daniel I (2020) Cycling phosphorus on the Archean Earth: Part I. Continental weathering and riverine transport of phosphorus. Geochim Cosmochim Acta 273:70–84
Harris LB, Bédard JH (2014) Crustal evolution and deformation in a non-plate-tectonic Archaean Earth: comparisons with Venus. In: Evolution of Archean crust and early life. Springer, Berlin, pp 215–291
Harrison T (2020) Hadean Earth. Springer, Berlin. https://books.google.se/books?id=LFfsDwAAQBAJ
Hart MH (1979) Habitable zones about main sequence stars. Icarus 37(1):351–357
Hassenkam T, Andersson M, Dalby K, Mackenzie D, Rosing M (2017) Elements of Eoarchean life trapped in mineral inclusions. Nature 548(7665):78–81
Hawkesworth C, Cawood P, Kemp T, Storey C, Dhuime B (2009) A matter of preservation. Science 323(5910):49–50
Hawkesworth CJ, Cawood PA, Dhuime B (2020) The evolution of the continental crust and the onset of plate tectonics. Front Earth Sci 8:326
Head JW, Campbell DB, Elachi C, Guest JE, McKenzie DP, Saunders RS, Schaber GG, Schubert G (1991) Venus volcanism: initial analysis from Magellan data. Science 252(5003):276–288
Head J, Wilson L, Ivanov M, Wordsworth R (2021) Contributions of volatiles to the Venus atmosphere from the observed extrusive volcanic record: implications for the history of the Venus atmosphere. In: EGU general assembly conference abstracts. EGU general assembly conference abstracts, EGU21, p 13,030
Herrick R, Izenberg N, Ghail R (2022) Resurfacing history and volcanic activity of Venus. Space Sci Rev
Herzberg C, Condie K, Korenaga J (2010) Thermal history of the Earth and its petrological expression. Earth Planet Sci Lett 292(1–2):79–88. https://doi.org/10.1016/j.epsl.2010.01.022
Heubeck C (2009) An early ecosystem of Archean tidal microbial mats (Moodies Group, South Africa, ca. 3.2 Ga). Geology 37(10):931–934
Hickman-Lewis K, Westall F (2021) A southern African perspective on the co-evolution of early life and environments. S Afr J Geol 124(1):225–252
Hickman-Lewis K, Cavalazzi B, Foucher F, Westall F (2018a) Most ancient evidence for life in the Barberton greenstone belt: microbial mats and biofabrics of the 3.47 Ga Middle Marker horizon. Precambrian Res 312:45–67
Hickman-Lewis K, Westall F, Cavalazzi B (2018b). Trace of early life in the Barberton greenstone belt
Hickman-Lewis K, Cavalazzi B, Sorieul S, Gautret P, Foucher F, Whitehouse MJ, Jeon H, Georgelin T, Cockell CS, Westall F (2020a) Metallomics in deep time and the influence of ocean chemistry on the metabolic landscapes of Earth's earliest ecosystems. Sci Rep 10(1):1–16
Hickman-Lewis K, Gourcerol B, Westall F, Manzini D, Cavalazzi B (2020b) Reconstructing Palaeoarchaean microbial biomes flourishing in the presence of emergent landmasses using trace and rare earth element systematics. Precambrian Res 342:105,689
Hiesinger H, Tanaka K (2020) Chap. 15 – The planetary time scale. In: Gradstein FM, Ogg JG, Schmitz MD, Ogg GM (eds) Geologic time scale 2020. Elsevier, Amsterdam, pp 443–480. https://doi.org/10.1016/B978-0-12-824360-2.00015-2
Hirschmann MM (2012) Magma ocean influence on early atmosphere mass and composition. Earth Planet Sci Lett 341:48–57
Hoehler TM (2007) An energy balance concept for habitability. Astrobiology 7(6):824–838. https://doi.org/10.1089/ast.2006.0095
Hofmann A, Harris C (2008) Silica alteration zones in the Barberton greenstone belt: a window into subseafloor processes 3.5–3.3 Ga ago. Chem Geol 257(3–4):221–239
Hofmann A, Wilson AH (2007) Silicified basalts, bedded cherts and other sea floor alteration phenomena of the 3.4 Ga Nondweni greenstone belt, South Africa. Dev Precambrian Geol 15:571–605

Hofmann H, Grey K, Hickman A, Thorpe R (1999) Origin of 3.45 Ga coniform stromatolites in Warrawoona Group, Western Australia. Geol Soc Am Bull 111(8):1256–1262
Holdaway D, Yang Y (2016) Study of the effect of temporal sampling frequency on DSCOVR observations using the GEOS-5 nature run results (part II): cloud coverage. Remote Sens 8(5):431. https://doi.org/10.3390/rs8050431
Höning D (2020) The impact of life on climate stabilization over different timescales. Geochem Geophys Geosyst 21(9):e2020GC009,105
Höning D, Tosi N, Hansen-Goos H, Spohn T (2019a) Bifurcation in the growth of continental crust. Phys Earth Planet Inter 287:37–50
Höning D, Tosi N, Spohn T (2019b) Carbon cycling and interior evolution of water-covered plate tectonics and stagnant-lid planets. Astron Astrophys 627:A48
Höning D, Baumeister P, Grenfell JL, Tosi N, Way MJ (2021) Early habitability and crustal decarbonation of a stagnant-lid Venus. J Geophys Res, Planets 126(10):e2021JE006,895
Hren M, Tice M, Chamberlain C (2009) Oxygen and hydrogen isotope evidence for a temperate climate 3.42 billion years ago. Nature 462(7270):205–208
Izenberg NR, Gentry DM, Smith DJ, Gilmore MS, Grinspoon DH, Bullock MA, Boston PJ, Słowik GP (2021) The Venus life equation. Astrobiology 21(10):1305–1315. https://doi.org/10.1089/ast.2020.2326
Jacob JB, Moyen JF, Fiannacca P, Laurent O, Bachmann O, Janoušek V, Farina F, Villaros A (2021) Crustal melting vs. fractionation of basaltic magmas: part 2, attempting to quantify mantle and crustal contributions in granitoids. Lithos 402:106,292
Jacobsen SB, Pimentel-Klose MR (1988) Nd isotopic variations in Precambrian banded iron formations. Geophys Res Lett 15(4):393–396
Johansen A, Ronnet T, Bizzarro M, Schiller M, Lambrechts M, Nordlund Å, Lammer H (2021) A pebble accretion model for the formation of the terrestrial planets in the Solar System. Sci Adv 7(8):eabc0444. https://doi.org/10.1126/sciadv.abc0444. arXiv:2102.08611
Johnson B, Goldblatt C (2015) The nitrogen budget of Earth. Earth-Sci Rev 148:150–173
Johnson TE, Brown M, Kaus BJ, VanTongeren JA (2014) Delamination and recycling of Archaean crust caused by gravitational instabilities. Nat Geosci 7(1):47–52
Johnson TE, Kirkland CL, Lu Y, Smithies RH, Brown M, Hartnady MI (2022) Giant impacts and the origin and evolution of continents. Nature 608(7922):330–335
Kadoya S, Tajika E (2014) Conditions for oceans on Earth-like planets orbiting within the habitable zone: importance of volcanic CO_2 degassing. Astrophys J 790(2):107
Kamber BS (2015) The evolving nature of terrestrial crust from the Hadean, through the Archaean, into the Proterozoic. Precambrian Res 258:48–82. https://doi.org/10.1016/j.precamres.2014.12.007
Kane SR, Kopparapu RK, Domagal-Goldman SD (2014) On the frequency of potential Venus analogs from Kepler data. Astrophys J 794(1):L5. https://doi.org/10.1088/2041-8205/794/1/l5
Karlsson R, Cheng KW, Crameri F, Rolf T, Uppalapati S, Werner SC (2020) Implications of anomalous crustal provinces for Venus' resurfacing history. J Geophys Res, Planets 125(10):e2019JE006,340
Kasting JF (1988) Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. Icarus 74:472–494. https://doi.org/10.1016/0019-1035(88)90116-9
Kasting J (1993) Earth's early atmosphere. Science 259(5097):920–926. https://doi.org/10.1126/science.11536547
Kasting JF, Catling D (2003) Evolution of a habitable planet. Annu Rev Astron Astrophys 41(1):429–463. https://doi.org/10.1146/annurev.astro.41.071601.170049
Kasting JF, Liu S, Donahue T (1979) Oxygen levels in the prebiological atmosphere. J Geophys Res, Oceans 84(C6):3097–3107
Kasting JF, Eggler DH, Raeburn SP (1993a) Mantle redox evolution and the oxidation state of the Archean atmosphere. J Geol 101(2):245–257
Kasting JF, Whitmire DP, Reynolds RT (1993b) Habitable zones around main sequence stars. Icarus 101(1):108–128. https://doi.org/10.1006/icar.1993.1010
Katyal N, Ortenzi G, Lee Grenfell J, Noack L, Sohl F, Godolt M, García Muñoz A, Schreier F, Wunderlich F, Rauer H (2020) Effect of mantle oxidation state and escape upon the evolution of Earth's magma ocean atmosphere. Astron Astrophys 643:A81. https://doi.org/10.1051/0004-6361/202038779. arXiv:2009.14599
Kaula WM (1999) Constraints on Venus evolution from radiogenic argon. Icarus 139(1):32–39
Keddie ST, Head JW (1995) Formation and evolution of volcanic edifices on the Dione Regio rise, Venus. J Geophys Res, Planets 100(E6):11,729–11,754
Kemp A, Wilde S, Hawkesworth C, Coath C, Nemchin A, Pidgeon R, Vervoort J, DuFrane S (2010) Hadean crustal evolution revisited: new constraints from Pb–Hf isotope systematics of the Jack Hills zircons. Earth Planet Sci Lett 296(1–2):45–56
Kempe S, Degens ET (1985) An early soda ocean? Chem Geol 53(1–2):95–108

Kiefer WS, Hager BH (1991) A mantle plume model for the equatorial highlands of Venus. J Geophys Res, Planets 96(E4):20,947–20,966

King SD (2018) Venus resurfacing constrained by geoid and topography. J Geophys Res, Planets 123(5):1041–1060

Kleine T, Budde G, Burkhardt C, Kruijer T, Worsham E, Morbidelli A, Nimmo F (2020) The non-carbonaceous–carbonaceous meteorite dichotomy. Space Sci Rev 216(4):1–27

Kminek G, Bada JL (2006) The effect of ionizing radiation on the preservation of amino acids on Mars. Earth Planet Sci Lett 245(1–2):1–5

Knauth LP (2011) Salinity history of the Earth's ocean. In: Encyclopedia of geobiology. Springer, Netherlands

Knowlton C, Veerapaneni R, D'Elia T, Rogers SO (2013) Microbial analyses of ancient ice core sections from Greenland and Antarctica. Biology 2(11):206–232. https://doi.org/10.3390/biology2010206

Kopparapu RK, Ramirez R, Kasting JF, Eymet V, Robinson TD, Mahadevan S, Terrien RC, Domagal-Goldman S, Meadows V, Deshpande R (2013) Habitable zones around main-sequence stars: new estimates. Astrophys J 765:131. https://doi.org/10.1088/0004-637X/765/2/131. arXiv:1301.6674

Korenaga J (2012) Plate tectonics and planetary habitability: current status and future challenges. Ann NY Acad Sci 1260(1):87–94

Korenaga J (2018) Crustal evolution and mantle dynamics through Earth history. Philos Trans R Soc A, Math Phys Eng Sci 376(2132):20170,408

Korenaga J (2021) Hadean geodynamics and the nature of early continental crust. Precambrian Res 359:106,178

Krissansen-Totton J, Arney GN, Catling DC (2018) Constraining the climate and ocean pH of the early Earth with a geological carbon cycle model. Proc Natl Acad Sci 115:4105–4110. https://doi.org/10.1073/pnas.1721296115. arXiv:1804.00763

Krissansen-Totton J, Fortney JJ, Nimmo F (2021) Was Venus ever habitable? Constraints from a coupled interior-atmosphere-redox evolution model. Planet Sci J 2(5):216. https://doi.org/10.3847/PSJ/ac2580. arXiv:2111.00033

Kurokawa H, Foriel J, Laneuville M, Houser C, Usui T (2018) Subduction and atmospheric escape of Earth's seawater constrained by hydrogen isotopes. Earth Planet Sci Lett 497:149–160. https://doi.org/10.1016/j.epsl.2018.06.016

Lammer H, Kasting JF, Chassefière E, Johnson RE, Kulikov YN, Tian F (2008) Atmospheric escape and evolution of terrestrial planets and satellites. Space Sci Rev 139(1):399–436

Lammer H, Zerkle AL, Gebauer S, Tosi N, Noack L, Scherf M, Pilat-Lohinger E, Güdel M, Grenfell JL, Godolt M et al (2018) Origin and evolution of the atmospheres of early Venus, Earth and Mars. Astron Astrophys Rev 26(1):1–72

Lan Z, Kamo SL, Roberts NM, Sano Y, Li XH (2022) A Neoarchean (ca. 2500 Ma) age for jaspilite-carbonate BIF hosting purported micro-fossils from the Eoarchean ($\geq$ 3750 Ma) Nuvvuagittuq supracrustal belt (Québec, Canada). Precambrian Res 377:106,728

Lebrun T, Massol H, Chassefière E, Davaille A, Marcq E, Sarda P, Leblanc F, Brandeis G (2013) Thermal evolution of an early magma ocean in interaction with the atmosphere. J Geophys Res, Planets 118:1155–1176. https://doi.org/10.1002/jgre.20068

Lécuyer C, Simon L, Guyot F (2000) Comparison of carbon, nitrogen and water budgets on Venus and the Earth. Earth Planet Sci Lett 181(1–2):33–40

Lenardic A, Jellinek A, Moresi LN (2008) A climate induced transition in the tectonic style of a terrestrial planet. Earth Planet Sci Lett 271(1–4):34–42

Levison HF, Kretke KA, Duncan MJ (2015) Growing the gas-giant planets by the gradual accumulation of pebbles. Nature 524(7565):322–324

Lichtenberg T, Bower DJ, Hammond M, Boukrouche R, Sanan P, Tsai SM, Pierrehumbert RT (2021) Vertically resolved magma ocean–protoatmosphere evolution: H_2, H_2O, CO_2, CH_4, CO, O_2, and N_2 as primary absorbers. J Geophys Res, Planets 126(2):e2020JE006,711

Limaye SS, Mogul R, Smith DJ, Ansari AH, Słowik GP, Vaishampayan P (2018) Venus' spectral signatures and the potential for life in the clouds. Astrobiology 18(9):1181–1198. https://doi.org/10.1089/ast.2017.1783

Limaye SS, Mogul R, Baines KH, Bullock MA, Cockell C, Cutts JA, Gentry DM, Grinspoon DH, Head JW, Jessup KL, Kompanichenko V, Lee YJ, Mathies R, Milojevic T, Pertzborn RA, Rothschild L, Sasaki S, Schulze-Makuch D, Smith DJ, Way MJ (2021) Venus, an astrobiology target. Astrobiology 21(10):1163–1185. https://doi.org/10.1089/ast.2020.2268

Lincowski AP, Meadows VS, Crisp D, Akins AB, Schwieterman EW, Arney GN, Wong ML, Steffes PG, Parenteau MN, Domagal-Goldman S (2021) Claimed detection of PH_3 in the clouds of Venus is consistent with mesospheric SO_2. Astrophys J Lett 908(2):L44

Liu B, Raymond SN, Jacobson SA (2020) Early solar system instability triggered by dispersal of the gaseous disk. Nature 604(7907):643–646. https://doi.org/10.1038/s41586-022-04535-1

Lock SJ, Stewart ST (2017) The structure of terrestrial bodies: impact heating, corotation limits, and synestias. J Geophys Res, Planets 122(5):950–982. https://doi.org/10.1002/2016JE005239

Lopez I, Oyarzun R, Marquez A, Doblas-Reyes F, Laurrieta A (1998) Progressive build up of CO_2 in the atmosphere of Venus through multiple volcanic resurfacing events. Earth Moon Planets 81(3):187–192. https://doi.org/10.1023/A:1006369831384

Lourenço DL, Rozel AB, Gerya T, Tackley PJ (2018) Efficient cooling of rocky planets by intrusive magmatism. Nat Geosci 11(5):322–327

Lourenço DL, Rozel AB, Ballmer MD, Tackley PJ (2020) Plutonic-squishy lid: a new global tectonic regime generated by intrusive magmatism on Earth-like planets. Geochem Geophys Geosyst C008:756

Lowe DR, Byerly G (1999a) Petrology and sedimentology of cherts and related silicified sedimentary rocks in the Swaziland Supergroup. In: Geologic evolution of the Barberton greenstone belt, South Africa. Geological Society of America Special Paper, vol 329, pp 83–114

Lowe DR, Byerly GR (1999b) Geologic evolution of the Barberton greenstone belt, South Africa, vol 329. Geol. Soc. Am., Boulder

Lowenstein TK, Schubert BA, Timofeeff MN (2011) Microbial communities in fluid inclusions and long-term survival in halite. GSA Today 21(1):4–9. https://doi.org/10.1130/GSATG81A.1

Luger R, Barnes R (2015) Extreme water loss and abiotic O_2 buildup on planets throughout the habitable zones of M dwarfs. Astrobiology 15(2):119–143. https://doi.org/10.1089/ast.2014.1231. arXiv:1411.7412

MacDonald GJF (1964) Tidal friction. Rev Geophys Space Phys 2:467–541. https://doi.org/10.1029/RG002i003p00467

Madronich S, Björn LO, McKenzie RL (2018) Solar UV radiation and microbial life in the atmosphere. Photochem Photobiol Sci 17(12):1918–1931

Maher KA, Stevenson DJ (1988) Impact frustration of the origin of life. Nature 331(6157):612–614

Marcq E, Mills FP, Parkinson CD, Vandaele AC (2018) Composition and chemistry of the neutral atmosphere of Venus. Space Sci Rev 214(1):1–55

Marin-Carbonne J, Chaussidon M, Robert F (2012) Micrometer-scale chemical and isotopic criteria (O and Si) on the origin and history of Precambrian cherts: implications for paleo-temperature reconstructions. Geochim Cosmochim Acta 92:129–147

Marshall M (2020) The water paradox and the origins of life. Nature 588(7837):210–213

Martin W, Russell MJ (2003) On the origins of cells: a hypothesis for the evolutionary transitions from abiotic geochemistry to chemoautotrophic prokaryotes, and from prokaryotes to nucleated cells. Philos Trans R Soc Lond B, Biol Sci 358(1429):59–85

Martin W, Baross J, Kelley D, Russell MJ (2008) Hydrothermal vents and the origin of life. Nat Rev Microbiol 6(11):805–814

Marty B (2012) The origins and concentrations of water, carbon, nitrogen and noble gases on Earth. Earth Planet Sci Lett 313:56–66

Marty B, Dauphas N (2003) The nitrogen record of crust–mantle interaction and mantle convection from Archean to present. Earth Planet Sci Lett 206(3–4):397–410

Marty B, Zimmermann L, Pujol M, Burgess R, Philippot P (2013) Nitrogen isotopic composition and density of the Archean atmosphere. Science 342(6154):101–104. https://doi.org/10.1126/science.1240971

Marty B, Avice G, Bekaert DV, Broadley MW (2018) Salinity of the Archaean oceans from analysis of fluid inclusions in quartz. C R Géosci 350(4):154–163

Matsui H, Iwagami N, Hosouchi M, Ohtsuki S, Hashimoto G (2012) Latitudinal distribution of HDO abundance above Venus' clouds by ground-based 2.3 μm spectroscopy. Icarus 217(2):610–614

McCord TB (1968) The loss of retrograde satellites in the solar system (1896–1977). J Geophys Res 73(4):1497–1500. https://doi.org/10.1029/JB073i004p01497

McGill GE (2000) Geologic map of the Sappho Patera quadrangle (V-20), Venus. The Survey

McKinnon WB, Zahnle KJ, Ivanov BA, Melosh HJ (1997) Cratering on Venus: models and observations. In: Bougher SW, Hunten DM, Phillips RJ (eds) Venus II: geology, geophysics, atmosphere, and solar wind environment, p 969

McMahon S (2019) Earth's earliest and deepest purported fossils may be iron-mineralized chemical gardens. Proc R Soc B 286(1916):20192,410

McTaggart R (2022) The cosmogenic production of phosphorus in the atmosphere of Venus. Icarus 374:114,791

Melosh H, Vickery A (1989) Impact erosion of the primordial atmosphere of Mars. Nature 338(6215):487–489

Ménez B, Pisapia C, Andreani M, Jamme F, Vanbellingen QP, Brunelle A, Richard L, Dumas P, Réfrégiers M (2018) Abiotic synthesis of amino acids in the recesses of the oceanic lithosphere. Nature 564(7734):59–63

Milojevic T, Treiman AH, Limaye S (2021) Phosphorus in the clouds of Venus: potential for bioavailability. Astrobiology 21(10):1250–1263. https://doi.org/10.1089/ast.2020.2267
Mogul R, Limaye SS, Way MJ, Cordova JA (2021a) Venus' mass spectra show signs of disequilibria in the middle clouds. Geophys Res Lett 48(7):e2020GL091,327. https://doi.org/10.1029/2020GL091327
Mogul R, Limaye SS, Lee YJ, Pasillas M (2021b) Potential for phototrophy in Venus' clouds. Astrobiology 21(10):1237–1249
Mojzsis SJ, Harrison TM, Pidgeon RT (2001) Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago. Nature 409(6817):178–181
Mojzsis SJ, Brasser R, Kelly NM, Abramov O, Werner SC (2019) Onset of giant planet migration before 4480 million years ago. Astrophys J 881(1):44
Moorbath S, O'nions R, Pankhurst R (1973) Early Archaean age for the Isua iron formation, West Greenland. Nature 245(5421):138–139
Moore WB, Webb AAG (2013) Heat-pipe Earth. Nature 501(7468):501–505
Morbidelli A, Lunine JI, O'Brien DP, Raymond SN, Walsh KJ (2012) Building terrestrial planets. Annu Rev Earth Planet Sci 40:251–275. https://doi.org/10.1146/annurev-earth-042711-105319
Morowitz H, Sagan C (1967) Life in the clouds of Venus? Nature 215(5107):1259–1260. https://doi.org/10.1038/2151259a0
Morse JW, Mackenzie FT (1998) Hadean ocean carbonate geochemistry. Aquat Geochem 4(3):301–319
Mulder JA, Nebel O, Gardiner NJ, Cawood PA, Wainwright AN, Ivanic TJ (2021) Crustal rejuvenation stabilised Earth's first cratons. Nat Commun 12(1):1–7
Nabelek PI, Bédard JH, Rainbird RH (2014) Numerical constraints on degassing of metamorphic CO_2 during the Neoproterozoic Franklin large igneous event, Arctic Canada. Geol Soc Am Bull 126(5–6):759–772
Namiki N, Solomon SC (1998) Volcanic degassing of argon and helium and the history of crustal production on Venus. J Geophys Res, Planets 103(E2):3655–3677
Nelson D, Trendall A, Altermann W (1999) Chronological correlations between the Pilbara and Kaapvaal cratons. Precambrian Res 97(3–4):165–189
Nesvorný D (2018) Dynamical evolution of the early solar system. Annu Rev Astron Astrophys 56(1):137–174. https://doi.org/10.1146/annurev-astro-081817-052028
Nicholson WL, Fajardo-Cavazos P, Fedenko J, Ortíz-Lugo JL, Rivas-Castillo A, Waters SM, Schuerger AC (2010) Exploring the low-pressure growth limit: evolution of Bacillus subtilis in the laboratory to enhanced growth at 5 kilopascals. Appl Environ Microbiol 76(22):7559–7565. https://doi.org/10.1128/AEM.01126-10
Nijman W, Kloppenburg A, de Vries ST (2017) Archaean basin margin geology and crustal evolution: an East Pilbara traverse. J Geol Soc 174(6):1090–1112
Nikolaou A, Katyal N, Tosi N, Godolt M, Grenfell JL, Rauer H (2019) What factors affect the duration and outgassing of the terrestrial magma ocean? Astrophys J 875(1):11. https://doi.org/10.3847/1538-4357/ab08ed
Noack L, Breuer D, Spohn T (2012) Coupling the atmosphere with interior dynamics: implications for the resurfacing of Venus. Icarus 217(2):484–498
Noffke N, Christian D, Wacey D, Hazen RM (2013) Microbially induced sedimentary structures recording an ancient ecosystem in the ca. 3.48 billion-year-old Dresser Formation, Pilbara, Western Australia. Astrobiology 13(12):1103–1124
Norman MD, Borg LE, Nyquist LE, Bogard DD (2003) Chronology, geochemistry, and petrology of a ferroan noritic anorthosite clast from Descartes breccia 67215: clues to the age, origin, structure, and impact history of the lunar crust. Meteorit Planet Sci 38(4):645–661
Nutman AP, Bennett VC, Friend CR, Van Kranendonk MJ, Chivas AR (2016) Rapid emergence of life shown by discovery of 3,700-million-year-old microbial structures. Nature 537(7621):535–538
Nutman AP, Bennett VC, Friend CR, Van Kranendonk MJ, Rothacker L, Chivas AR (2019) Cross-examining Earth's oldest stromatolites: seeing through the effects of heterogeneous deformation, metamorphism and metasomatism affecting Isua (Greenland) 3700 Ma sedimentary rocks. Precambrian Res 331:105,347
Olson JM (2006) Photosynthesis in the Archean era. Photosynth Res 88(2):109–117. https://doi.org/10.1007/s11120-006-9040-5
Omran A, Oze C, Jackson B, Mehta C, Barge LM, Bada J, Pasek MA (2021) Phosphine generation pathways on rocky planets. Astrobiology 21(10):1264–1276
O'Neil J, Carlson RW, Francis D, Stevenson RK (2008) Neodymium-142 evidence for Hadean mafic crust. Science 321(5897):1828–1831
O'Neil J, Francis D, Carlson RW (2011) Implications of the Nuvvuagittuq greenstone belt for the formation of Earth's early crust. J Petrol 52(5):985–1009
O'Neill C, Lenardic A, Höink T, Coltice N (2014) Mantle convection and outgassing on terrestrial planets. In: Comparative climatology of terrestrial planets, pp 473–486

O'Neill C, Marchi S, Zhang S, Bottke W (2017) Impact-driven subduction on the Hadean Earth. Nat Geosci 10(10):793–797

O'Rourke JG, Korenaga J (2015) Thermal evolution of Venus with argon degassing. Icarus 260:128–140

Pahlevan K, Schaefer L, Hirschmann MM (2019) Hydrogen isotopic evidence for early oxidation of silicate Earth. Earth Planet Sci Lett 526:115,770. https://doi.org/10.1016/j.epsl.2019.115770

Papineau D, She Z, Dodd MS, Iacoviello F, Slack JF, Hauri E, Shearing P, Little CT (2022) Metabolically diverse primordial microbial communities in Earth's oldest seafloor-hydrothermal jasper. Sci Adv 8(15):eabm2296

Pascal R, Pross A, Sutherland JD (2013) Towards an evolutionary theory of the origin of life based on kinetics and thermodynamics. Open Biol 130:156

Perchuk AL, Safonov OG, Smit CA, van Reenen DD, Zakharov VS, Gerya T (2018) Precambrian ultra-hot orogenic factory: making and reworking of continental crust. Tectonophysics 746:572–586

Perchuk AL, Zakharov VS, Gerya T, Brown M (2019) Hotter mantle but colder subduction in the Precambrian: what are the implications? Precambrian Res 330:20–34

Perchuk AL, Gerya TV, Zakharov VS, Griffin WL (2020) Building cratonic keels in Precambrian plate tectonics. Nature 586(7829):395–401

Perchuk AL, Gerya TV, Zakharov VS, Griffin WL (2021) Depletion of the upper mantle by convergent tectonics in the early Earth. Sci Rep 11(1):1–12

Péron S, Moreira M (2018) Onset of volatile recycling into the mantle determined by xenon anomalies. Geochem Perspect Lett 9:21–25

Persson M, Futaana Y, Fedorov A, Nilsson H, Hamrin M, Barabash S (2018) H^+/O^+ escape rate ratio in the Venus magnetotail and its dependence on the solar cycle. Geophys Res Lett 45(20):10,805–10,811. https://doi.org/10.1029/2018GL079454

Persson M, Futaana Y, Ramstad R, Masunaga K, Nilsson H, Hamrin M, Fedorov A, Barabash S (2020) The Venusian atmospheric oxygen ion escape: extrapolation to the early solar system. J Geophys Res, Planets 125(3):e06336. https://doi.org/10.1029/2019JE006336

Phillips RJ, Raubertas RF, Arvidson RE, Sarkar IC, Herrick RR, Izenberg N, Grimm RE (1992) Impact craters and Venus resurfacing history. J Geophys Res, Planets 97(E10):15,923–15,948

Phillips RJ, Bullock MA, Hauck SA (2001) Climate and interior coupled evolution on Venus. Geophys Res Lett 28(9):1779–1782

Piccolo A, Palin RM, Kaus BJ, White RW (2019) Generation of Earth's early continents from a relatively cool Archean mantle. Geochem Geophys Geosyst 20(4):1679–1697

Piccolo A, Kaus BJ, White RW, Palin RM, Reuber GS (2020) Plume – lid interactions during the Archean and implications for the generation of early continental terranes. Gondwana Res 88:150–168

Pieters CM, Head JW, Pratt S, Patterson W, Garvin J, Barsukov VL, Basilevksy AT, Khodakovsky IL, Selivanov AS, Panfilov AS, Gektin YM, Narayeva YM (1986) The color of the surface of Venus. Science 234(4782):1379–1383. https://doi.org/10.1126/science.234.4782.1379

Pollack JB (1971) A nongrey calculation of the runaway greenhouse: implications for Venus' past and present. Icarus 14(3):295–306

Pross A, Pascal R (2013) The origin of life: what we know, what we can know and what we will never know. Open Biol 120:190

Raymond SN (2021) A terrestrial convergence. Nat Astron 5:875–876. https://doi.org/10.1038/s41550-021-01488-9

Reisz JA, Bansal N, Qian J, Zhao W, Furdui CM (2014) Effects of ionizing radiation on biological molecules—mechanisms of damage and emerging methods of detection. Antioxid Redox Signal 21(2):260–292

Retallack GJ, Metzger CA, Greaver T, Jahren AH, Smith RM, Sheldon ND (2006) Middle-late Permian mass extinction on land. Geol Soc Am Bull 118(11–12):1398–1411

Rey PF, Coltice N, Flament N (2014) Spreading continents kick-started plate tectonics. Nature 513(7518):405–408

Richter FM (1985) Models for the Archean thermal regime. Earth Planet Sci Lett 73(2–4):350–360

Rimmer PB, Jordan S, Constantinou T, Woitke P, Shorttle O, Hobbs R, Paschodimas A (2021) Hydroxide salts in the clouds of Venus: their effect on the sulfur cycle and cloud droplet pH. Planet Sci J 2(4):133. https://doi.org/10.3847/psj/ac0156

Robert F, Chaussidon M (2006) A palaeotemperature curve for the Precambrian oceans based on silicon isotopes in cherts. Nature 443(7114):969–972

Rolf T, Capitanio FA, Tackley PJ (2018) Constraints on mantle viscosity structure from continental drift histories in spherical mantle convection models. Tectonophysics 746:339–351

Rolf T, Weller M, Gülcher A, Byrne P, O'Rourke JG, Herrick R, Bjonnes E, Davaille A, Ghail R, Gillmann C, Plesa AC (2022) Dynamics and evolution of Venus' mantle through time. Space Sci Rev 218:70. https://doi.org/10.1007/s11214-022-00937-9

Rozel A, Golabek GJ, Jain C, Tackley PJ, Gerya T (2017) Continental crust formation on early Earth controlled by intrusive magmatism. Nature 545(7654):332–335

Ruiz J (2017) Heat flow evolution of the Earth from paleomantle temperatures: evidence for increasing heat loss since 2.5 Ga. Phys Earth Planet Inter 269:165–171

Rüpke LH, Morgan JP, Hort M, Connolly JA (2004) Serpentine and the subduction zone water cycle. Earth Planet Sci Lett 223(1–2):17–34

Russell MJ (2021) The "water problem"(sic), the illusory pond and life's submarine emergence—a review. Life 11(5):429

Russell MJ, Hall A (1997) The emergence of life from iron monosulphide bubbles at a submarine hydrothermal redox and pH front. J Geol Soc 154(3):377–402

Russell M, Hall A, Martin W (2010) Serpentinization as a source of energy at the origin of life. Geobiology 8(5):355–371

Sagan C, Mullen G (1972) Earth and Mars: evolution of atmospheres and surface temperatures. Science 177(4043):52–56

Sakuraba H, Kurokawa H, Genda H (2019) Impact degassing and atmospheric erosion on Venus, Earth, and Mars during the late accretion. Icarus 317:48–58

Sakuraba H, Kurokawa H, Genda H, Ohta K (2021) Numerous chondritic impactors and oxidized magma ocean set Earth's volatile depletion. Sci Rep 11(1):1–14

Salvador A, Massol H, Davaille A, Marcq E, Sarda P, Chassefière E (2017) The relative influence of H_2O and CO_2 on the primitive surface conditions and evolution of rocky planets. J Geophys Res, Planets 122(7):1458–1486

Salvador A, Avice G, Breuer D, Gillmann C, Lammer H, Marcq E, Raymond SN, Sakuraba H, Scherf M, Way MJ (2023) Magma ocean, water, and the early atmosphere of Venus. Space Sci Rev

Sasaki S, Yamagishi A, Yoshimura Y, Enya K, Miyakawa A, Ohno S, Fujita K, Usui T, Limaye SS (2022) In situ biochemical characterization of Venus cloud particles using a life-signature detection microscope. Can J Microbiol 68(6):413–425

Sasselov DD, Grotzinger JP, Sutherland JD (2020) The origin of life as a planetary phenomenon. Sci Adv 6(6):eaax3419

Sattler B, Puxbaum H, Psenner R (2001) Bacterial growth in supercooled cloud droplets. Geophys Res Lett 28(2):239–242. https://doi.org/10.1029/2000GL011684

Schaber G, Strom R, Moore H, Soderblom LA, Kirk RL, Chadwick D, Dawson D, Gaddis L, Boyce J, Russell J (1992) Geology and distribution of impact craters on Venus: what are they telling us? J Geophys Res, Planets 97(E8):13,257–13,301

Schaller MF, Wright JD, Kent DV (2011) Atmospheric P_{CO_2} perturbations associated with the Central Atlantic Magmatic Province. Science 331(6023):1404–1409

Schlichting HE, Mukhopadhyay S (2018) Atmosphere impact losses. Space Sci Rev 214(1):1–31

Schreiber U, Locker-Grütjen O, Mayer C (2012) Hypothesis: origin of life in deep-reaching tectonic faults. Orig Life Evol Biosph 42(1):47–54

Schubert G, Turcotte D, Solomon S, Sleep N (1989) Coupled evolution of the atmospheres and interiors of planets and satellites. In: Origin and evolution of planetary and satellite atmospheres, pp 450–483

Schuerger AC, Smith DJ, Griffin DW, Jaffe DA, Wawrik B, Burrows SM, Christner BC, Gonzalez-Martin C, Lipp EK, Schmale DG III, Yu H (2018) Science questions and knowledge gaps to study microbial transport and survival in Asian and African dust plumes reaching North America. Aerobiologia 34(4):425–435. https://doi.org/10.1007/s10453-018-9541-7

Schulze-Makuch D, Irwin LN (2002) Reassessing the possibility of life on Venus: proposal for an astrobiology mission. Astrobiology 2(2):197–202. https://doi.org/10.1089/15311070260192264

Schulze-Makuch D, Wagner D, Kounaves SP, Mangelsdorf K, Devine KG, de Vera JP, Schmitt-Kopplin P, Grossart HP, Parro V, Kaupenjohann M, Galy A, Schneider B, Airo A, Frösler J, Davila AF, Arens FL, Cáceres L, Cornejo FS, Carrizo D, Dartnell L, DiRuggiero J, Flury M, Ganzert L, Gessner MO, Grathwohl P, Guan L, Heinz J, Hess M, Keppler F, Maus D, McKay CP, Meckenstock RU, Montgomery W, Oberlin EA, Probst AJ, Sáenz JS, Sattler T, Schirmack J, Sephton MA, Schloter M, Uhl J, Valenzuela B, Vestergaard G, Wörmer L, Zamorano P (2018) Transitory microbial habitat in the hyperarid Atacama desert. Proc Natl Acad Sci 115(11):2670–2675. https://doi.org/10.1073/pnas.1714341115

Scorei R (2012) Is boron a prebiotic element? A mini-review of the essentiality of boron for the appearance of life on Earth. Orig Life Evol Biosph 42(1):3–17

Seager S, Petkowski JJ, Gao P, Bains W, Bryan NC, Ranjan S, Greaves J (2020) The Venusian lower atmosphere haze as a depot for desiccated microbial life: a proposed life cycle for persistence of the Venusian aerial biosphere. Astrobiology. https://doi.org/10.1089/ast.2020.2244

Seager S, Petkowski JJ, Carr CE, Grinspoon D, Ehlmann B, Saikia SJ, Agrawal R, Buchanan W, Weber MU, French R, Klupar P, Worden SP (2021) Venus life finder mission study. ArXiv e-prints. arXiv:2112.05153

Seager S, Petkowski JJ, Carr CE, Grinspoon DH, Ehlmann BL, Saikia SJ, Agrawal R, Buchanan WP, Weber MU, French R et al (2022) Venus life finder missions motivation and summary. Aerospace 9(7):385
Shao WD, Zhang X, Bierson CJ, Encrenaz T (2020) Revisiting the sulfur-water chemical system in the middle atmosphere of Venus. J Geophys Res, Planets 125(8):e2019JE006,195. https://doi.org/10.1029/2019JE006195
Sizova E, Gerya T, Brown M, Perchuk L (2010) Subduction styles in the Precambrian: insight from numerical experiments. Lithos 116(3–4):209–229
Sizova E, Gerya T, Brown M (2014) Contrasting styles of Phanerozoic and Precambrian continental collision. Gondwana Res 25(2):522–545
Sizova E, Gerya T, Stüwe K, Brown M (2015) Generation of felsic crust in the Archean: a geodynamic modeling perspective. Precambrian Res 271:198–224
Sleep NH (1994) Martian plate tectonics. J Geophys Res, Planets 99(E3):5639–5655
Sleep NH, Zahnle KJ, Lupu RE (2014) Terrestrial aftermath of the Moon-forming impact. Philos Trans R Soc A, Math Phys Eng Sci 372(2024):20130,172. https://doi.org/10.1098/rsta.2013.0172
Smerkar S, Ghail R, Byrne P (2022) Volcano-tectonic processes on Venus. Space Sci Rev
Smrekar SE, Davaille A, Sotin C (2018) Venus interior structure and dynamics. Space Sci Rev 214(5):88. https://doi.org/10.1007/s11214-018-0518-1
Snellen I, Guzman-Ramirez L, Hogerheijde M, Hygate A, Van der Tak F (2020) Re-analysis of the 267 GHz ALMA observations of Venus – no statistically significant detection of phosphine. Astron Astrophys 644:L2
Sobolev SV, Brown M (2019) Surface erosion events controlled the evolution of plate tectonics on Earth. Nature 570(7759):52–57
Solomatova NV, Caracas R (2021) Genesis of a CO_2-rich and H_2O-depleted atmosphere from Earth's early global magma ocean. Sci Adv 7(41):eabj0406
Som D, Catling S, Harnmeijer J, Polivka P, Buick R (2012) Air density 2.7 billion years ago limited to less than twice modern levels by fossil raindrop imprints. Nature 484:359. https://doi.org/10.1038/nature10890
Som S, Buick R, Hagadorn J, Blake T, Perreault J, Harnmeijer J, Catling D (2016) Earth's air pressure 2.7 billion years ago constrained to less than half of modern levels. NatGeo 9:448. https://doi.org/10.1038/ngeo2713
Sossi PA, Burnham AD, Badro J, Lanzirotti A, Newville M, O'Neill HS (2020) Redox state of Earth's magma ocean and its Venus-like early atmosphere. Sci Adv 6(48):eabd1387. https://doi.org/10.1126/sciadv.abd1387
Sousa-Silva C, Seager S, Ranjan S, Petkowski JJ, Zhan Z, Hu R, Bains W (2020) Phosphine as a biosignature gas in exoplanet atmospheres. Astrobiology 20(2):235–268
Spacek J, Benner SA (2021) The organic carbon cycle in the atmosphere of Venus and evolving red oil. In: LPI contributions, Lunar and Planetary Institute. https://ui.adsabs.harvard.edu/abs/2021LPICo2629.4052S. Abstract #4052
Spencer CJ, Cawood PA, Hawkesworth CJ, Raub TD, Prave AR, Roberts NM (2014) Proterozoic onset of crustal reworking and collisional tectonics: reappraisal of the zircon oxygen isotope record. Geology 42(5):451–454
Stern CR (2011) Subduction erosion: rates, mechanisms, and its role in arc magmatism and the evolution of the continental crust and mantle. Gondwana Res 20(2–3):284–308
Stüeken EE, Anderson RE, Bowman JS, Brazelton WJ, Colangelo-Lillis J, Goldman AD, Som SM, Baross JA (2013) Did life originate from a global chemical reactor? Geobiology 11(2):101–126. https://doi.org/10.1111/gbi.12025
Stüeken E, Kipp M, Koehler M, Schwieterman E, Johnson B, Buick R (2016) Modeling pN_2 through geological time: implications for planetary climates and atmospheric biosignatures. Astrobiology 16(12):949–963. https://doi.org/10.1089/ast.2016.1537
Stüeken EE, Som SM, Claire M, Rugheimer S, Scherf M, Sproß L, Tosi N, Ueno Y, Lammer H (2020) Mission to planet Earth: the first two billion years. Space Sci Rev 216(2):31. https://doi.org/10.1007/s11214-020-00652-3
Svensen H, Planke S, Polozov AG, Schmidbauer N, Corfu F, Podladchikov YY, Jamtveit B (2009) Siberian gas venting and the end-Permian environmental crisis. Earth Planet Sci Lett 277(3–4):490–500
Szostak JW (2016) On the origin of life. Medicina 76(4):199–203
Tartèse R, Chaussidon M, Gurenko A, Delarue F, Robert F (2017) Warm Archean oceans reconstructed from oxygen isotope composition of early-life remnants. Geochem Perspect Lett 3:55–65
Tera F, Papanastassiou D, Wasserburg G (1973) A lunar cataclysm at ~ 3.95 AE and the structure of the lunar crust. In: Lunar and planetary science conference, vol 4
Thompson MA (2021) The statistical reliability of 267-GHz JCMT observations of Venus: no significant evidence for phosphine absorption. Mon Not R Astron Soc Lett 501(1):L18–L22

Titov DV, Ignatiev NI, McGouldrick K, Wilquet V, Wilson CF (2018) Clouds and hazes of Venus. Space Sci Rev 214(8):126. https://doi.org/10.1007/s11214-018-0552-z
Trail D, Boehnke P, Savage PS, Liu MC, Miller ML, Bindeman I (2018) Origin and significance of Si and O isotope heterogeneities in Phanerozoic, Archean, and Hadean zircon. Proc Natl Acad Sci 115(41):10,287–10,292
Trinks H, Schröder W, Bierbricher C (2005) Sea ice as a promoter of the emergence of first life. Orig Life Evol Biosph 35:429–445
Trompet L, Robert S, Mahieux A, Schmidt F, Erwin J, Vandaele A (2021) Phosphine in Venus' atmosphere: detection attempts and upper limits above the cloud top assessed from the SOIR/VEx spectra. Astron Astrophys 645:L4
Truong N, Lunine J (2021) Volcanically extruded phosphides as an abiotic source of Venusian phosphine. Proc Natl Acad Sci 118(29):e2021689118
Turbet M, Bolmont E, Chaverot G, Ehrenreich D, Leconte J, Marcq E (2021) Day–night cloud asymmetry prevents early oceans on Venus but not on Earth. Nature 598(7880):276–280
Turcotte DL, Schubert G (2002) Geodynamics. Cambridge University Press, Cambridge
Turner G, Cadogan P (1975) The history of lunar bombardment inferred from ^{40}Ar-^{39}Ar dating of highland rocks. In: Lunar and planetary science conference proceedings, vol 6, pp 1509–1538
Uppalapati S, Rolf T, Crameri F, Werner S (2020) Dynamics of lithospheric overturns and implications for Venus's surface. J Geophys Res, Planets 125(11):e2019JE006,258
Valley J, Lackey J, Cavosie A, Clechenko C, Spicuzza M, Basei M, Bindeman I, Ferreira V, Sial A, King E et al (2005) 4.4 billion years of crustal maturation: oxygen isotope ratios of magmatic zircon. Contrib Mineral Petrol 150(6):561–580
Valley JW, Cavosie AJ, Ushikubo T, Reinhard DA, Lawrence DF, Larson DJ, Clifton PH, Kelly TF, Wilde SA, Moser DE et al (2014) Hadean age for a post-magma-ocean zircon confirmed by atom-probe tomography. Nat Geosci 7(3):219–223
Van den Boorn S, Van Bergen M, Vroon P, De Vries S, Nijman W (2010) Silicon isotope and trace element constraints on the origin of 3.5 Ga cherts: implications for early Archaean marine environments. Geochim Cosmochim Acta 74(3):1077–1103
van Hunen J, van den Berg AP (2008) Plate tectonics on the early Earth: limitations imposed by strength and buoyancy of subducted lithosphere. Lithos 103(1–2):217–235
Van Kranendonk MJ (2010) Two types of Archean continental crust: plume and plate tectonics on early Earth. Am J Sci 310(10):1187–1209
Van Kranendonk MJ, Baumgartner R, Djokic T, Ota T, Steller L, Garbe U, Nakamura E (2021) Elements for the origin of life on land: a deep-time perspective from the Pilbara Craton of Western Australia. Astrobiology 21(1):39–59
Vezinet A, Thomassot E, Pearson DG, Stern RA, Luo Y, Sarkar C (2019) Extreme δ^{18}O signatures in zircon from the Saglek Block (North Atlantic Craton) document reworking of mature supracrustal rocks as early as 3.5 Ga. Geology 47(7):605–608
Villanueva G, Cordiner M, Irwin P, de Pater I, Butler B, Gurwell M, Milam S, Nixon C, Luszcz-Cook S, Wilson C et al (2021) No evidence of phosphine in the atmosphere of Venus from independent analyses. Nat Astron 5(7):631–635
Volkov V, Frenkel MY (1993) The modeling of Venus' degassing in terms of K-Ar system. Earth Moon Planets 62(2):117–129
Walker JCG, Hays PB, Kasting JF (1981) A negative feedback mechanism for the long-term stabilization of the Earth's surface temperature. J Geophys Res 86:9776–9782. https://doi.org/10.1029/JC086iC10p09776
Walsh KJ, Morbidelli A, Raymond SN, O'Brien DP, Mandell AM (2011) A low mass for Mars from Jupiter's early gas-driven migration. Nature 475(7355):206–209
Warren AO, Kite ES (2021) Degassing, decarbonation, and dehydration: investigating the likelihood of a habitable era on Venus. In: 52nd lunar and planetary science conference. Lunar and planetary science conference, p 1253
Way MJ, Del Genio AD (2020) Venusian habitable climate scenarios: modeling Venus through time and applications to slowly rotating Venus-like exoplanets. J Geophys Res, Planets 125(5):e2019JE006,276
Way MJ, Del Genio AD, Kiang NY, Sohl LE, Grinspoon DH, Aleinov I, Kelley M, Clune T (2016) Was Venus the first habitable world of our solar system? Geophys Res Lett 43(16):8376–8383
Way MJ, Aleinov I, Amundsen DS, Chandler MA, Clune TL, Del Genio AD, Fujii Y, Kelley M, Kiang NY, Sohl L, Tsigaridis K (2017) Resolving orbital and climate keys of Earth and extraterrestrial environments with dynamics (ROCKE-3D) 1.0: a general circulation model for simulating the climates of rocky planets. Astrophys J Suppl Ser 231:12. https://doi.org/10.3847/1538-4365/aa7a06. arXiv:1701.02360

Way MJ, Del Genio AD, Aleinov I, Clune TL, Kelley M, Kiang NY (2018) Climates of warm Earth-like planets I: 3-D model simulations. ArXiv e-prints. arXiv:1808.06480

Way MJ, Ernst RE, Scargle JD (2022) Large-scale volcanism and the heat death of terrestrial worlds. Planet Sci J 3(4):92. https://doi.org/10.3847/psj/ac6033

Way MJ, Ostberg C, Foley BJ, Gillmann C, Höning D, Lammer H, O'Rourke J, Persson M, Plesa I, Salvador A, Scherf M, Weller M (2023) Synergies between Venus & exoplanetary observations. Space Sci Rev. 219:13. https://doi.org/10.1007/s11214-023-00953-3

Weiss MC, Preiner M, Xavier JC, Zimorski V, Martin WF (2018) The last universal common ancestor between ancient Earth chemistry and the onset of genetics. PLoS Genet 14(8):e1007,518. https://doi.org/10.1371/journal.pgen.1007518

Weller MB, Kiefer WS (2020) The physics of changing tectonic regimes: implications for the temporal evolution of mantle convection and the thermal history of Venus. J Geophys Res, Planets 125(1):e05960. https://doi.org/10.1029/2019JE005960

Weller MB, Kiefer WS (2021) Punctuated evolution of the Venusian atmosphere from mantle outgassing. In: 52nd lunar and planetary science conference. Lunar and planetary science conference, p 1555

Weller M, Lenardic A, O'Neill C (2015) The effects of internal heating and large scale climate variations on tectonic bi-stability in terrestrial planets. Earth Planet Sci Lett 420:85–94

Weller M, Evans A, Ibarra D, Johnson A, Kukla T (2022) Atmospheric evidence of early plate tectonics on Venus. LPI Contrib 2678:2328

Westall F, De Ronde CE, Southam G, Grassineau N, Colas M, Cockell C, Lammer H (2006a) Implications of a 3.472–3.333 Gyr-old subaerial microbial mat from the Barberton greenstone belt, South Africa for the UV environmental conditions on the early Earth. Philos Trans R Soc B, Biol Sci 361(1474):1857–1876

Westall F, de Vries ST, Nijman W, Rouchon V, Orberger B, Pearson V, Watson J, Verchovsky A, Wright I, Rouzaud JN, Marchesini D, Severine A (2006b) The 3.466 Ga "Kitty's Gap Chert," an early Archean microbial ecosystem. In: Processes on the early Earth. Geol. Soc. Am., Boulder. https://doi.org/10.1130/2006.2405(07)

Westall F, Cavalazzi B, Lemelle L, Marrocchi Y, Rouzaud JN, Simionovici A, Salomé M, Mostefaoui S, Andreazza C, Foucher F et al (2011a) Implications of in situ calcification for photosynthesis in a ∼ 3.3 Ga-old microbial biofilm from the Barberton greenstone belt, South Africa. Earth Planet Sci Lett 310(3–4):468–479

Westall F, Foucher F, Cavalazzi B, de Vries ST, Nijman W, Pearson V, Watson J, Verchovsky A, Wright I, Rouzaud JN et al (2011b) Volcaniclastic habitats for early life on Earth and Mars: a case study from 3.5 Ga-old rocks from the Pilbara, Australia. Planet Space Sci 59(10):1093–1106

Westall F, Campbell KA, Bréhéret JG, Foucher F, Gautret P, Hubert A, Sorieul S, Grassineau N, Guido DM (2015) Archean (3.33 Ga) microbe-sediment systems were diverse and flourished in a hydrothermal context. Geology 43(7):615–618

Westall F, Hickman-Lewis K, Hinman N, Gautret P, Campbell K, Bréhéret JG, Foucher F, Hubert A, Sorieul S, Dass AV et al (2018) A hydrothermal-sedimentary context for the origin of life. Astrobiology 18(3):259–293

Whitehouse MJ, Nemchin AA, Pidgeon RT (2017) What can Hadean detrital zircon really tell us? A critical evaluation of their geochronology with implications for the interpretation of oxygen and hafnium isotopes. Gondwana Res 51:78–91

Wignall P (2001) Large igneous provinces and mass extinctions. Earth-Sci Rev 53(1–2):1–33. https://doi.org/10.1016/S0012-8252(00)00037-4

Wilde SA, Valley JW, Peck WH, Graham CM (2001) Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. Nature 409(6817):175–178

Wordsworth R, Pierrehumbert R (2013) Water loss from terrestrial planets with CO_2-rich atmospheres. Astrophys J 778(2):154

Yang J, Boué G, Fabrycky DC, Abbot DS (2014) Strong dependence of the inner edge of the habitable zone on planetary rotation rate. Astrophys J 787:L2. https://doi.org/10.1088/2041-8205/787/1/L2. arXiv:1404.4992

Zahnle KJ, Lupu R, Dobrovolskis A, Sleep NH (2015) The tethered Moon. Earth Planet Sci Lett 427:74–82

Zasova L, Gorinov D, Eismont N, Kovalenko I, Abbakumov A, Bober S (2019) Venera-d: a design of an automatic space station for Venus exploration. Sol Syst Res 53(7):506–510

Zawaski MJ, Kelly NM, Orlandini OF, Nichols CI, Allwood AC, Mojzsis SJ (2020) Reappraisal of purported ca. 3.7 Ga stromatolites from the Isua supracrustal belt (West Greenland) from detailed chemical and structural analysis. Earth Planet Sci Lett 545:116,409

Zellner NEB (2017) Cataclysm no more: new views on the timing and delivery of lunar impactors. Orig Life Evol Biosph 47(3):261–280. https://doi.org/10.1007/s11084-017-9536-3

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