The Habitability of Venus and a Comparison to Early Earth

Frances Westall[1], Dennis Höning[2], Guillaume Avice[3], Diana Gentry[4], Taras Gerya[5], Cedric Gillmann[6], Noam Izenberg[7], Michael Way[8], and Colin Wilson[9]

[1]CNRS-Centre de Biophysique Moleculaire, Orleans, France
[2]Potsdam-Institute for Climate Impact Research
[3]Centre National de la Recherche Scientifique
[4]NASA Ames Research Center
[5]ETH Zürich
[6]Rice University
[7]Johns Hopkins University
[8]NASA Goddard Institute for Space Studies
[9]University of Oxford

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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$ˆ\circ$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-Paleoarchean eons, we attempt to resume 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 to the global environment on 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.

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F. Westall[1], D. Höning[2,*], G. Avice[3], D. Gentry[4], T. Gerya[5], C. Gillmann[6], N. Izenberg[7], M.J. Way[8], and C. Wilson[9]

[1]CNRS-Centre de Biophysique Moléculaire, Orléans, France
[2]Potsdam Institute for Climate Impact Research, Potsdam, Germany
[3]Université Paris Cité, Institut de physique du globe de Paris, CNRS, 75005 Paris, France
[4]NASA Ames Research Center, Moffett Field, California, USA
[5]Dep. of Earth Sciences, ETH Zürich, Switzerland
[6]Rice University, Department of Earth, Environmental and Planetary Sciences, Houston, TX 77005, USA
[7]The Applied geophysics Laboratory, The Johns Hopkins University, 3400 North Charles Street, Malone 140, Baltimore, MD 21218, USA
[8]NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA and Theoretical Astrophysics, Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden
[9]Department of Physics, University of Oxford, Sherrington Road, Oxford OX1 3PU, UK
*Corresponding author: Dennis Höning, dennis.hoening@pik-potsdam.de

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Address(es) of author(s) should be given

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-Paleoarchean eons, we attempt to resume 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 to the global environment on 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 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 the star (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's tectonic activity, different models suggesting different scenarios. Venus's 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's 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., 2022b) 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 Section 2. The main challenge with this approach is the loss of the earliest records of Earth's ancient surface due to tectonic recycling and, perhaps, to a certain extent, to impact bombardment. 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 Section 3. Based on these constraints, the climate throughout Venus' history from general circulation models will be discussed in Section 4.

Speculation on present-day habitability is primarily focused on Venus's 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 Section 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 suggest the the admixture of a significant amount of interstellar water during the early evolution of the in 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., 2022, this issue).

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) – Eoarchean (4.0-3.6 Ga) period 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 Greenstone 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 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 hydrated 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) provinces, 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 issue). 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 (Sleep, 1994; Gillmann and Tackley, 2014; Smrekar et al., 2018, e.g.).

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,

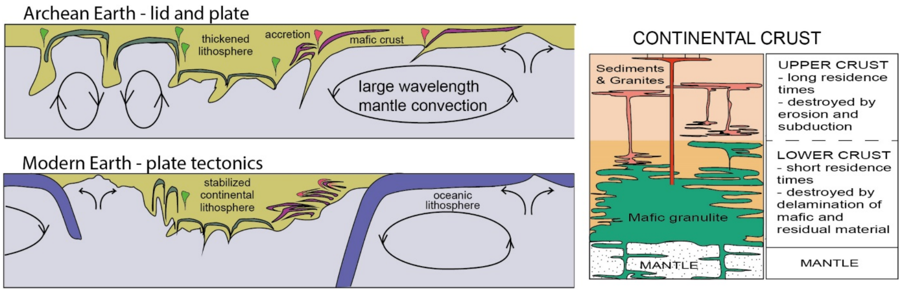

Fig. 1 Comparison of two styles of tectonics, lid and plate tectonics during the Archean epoch and modern-style Willson plate tectonics (after Hawkesworth et al. 2020)

represent only a part of the geological history of this period. 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). Indeed, a recent study of Paleoarchean zircons ages recording submantle δ18O 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 (see Lammer et al., 2018; Dehant et al., 2019; Korenaga, 2021, for example, as reviewed by). 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. Indeed, 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 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

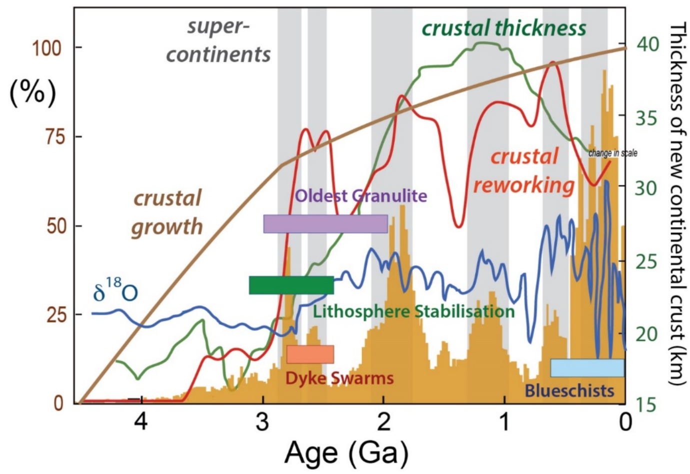

Fig. 2 Overview of changes in crustal growth, crustal thickness, crustal reworking, lithospheric stabilisation and the formation of supercontinents due to lateral accretion, the appearance of dykes swarms indicating rigid crust, changes in the oxygen isotope composition reflecting increasing continental 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).

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). Fig. 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^{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, 2016), 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 (c.f. discussions in Fischer and Gerya, 2016, and references therein). Thermal regimes of crustal reworking produced by this non-plate tectonic environment are also broadly consistent with metamorphic record (c.f. 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). 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 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, 2016). 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).

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 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 and barite 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 Section 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.

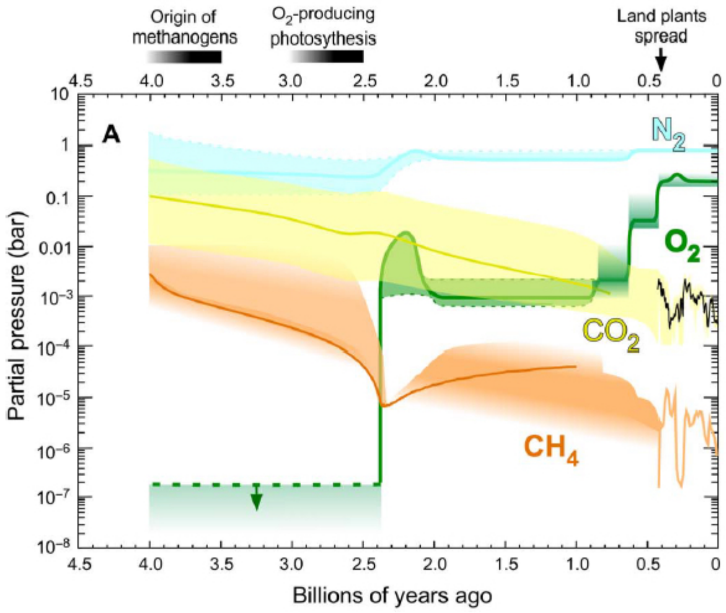

Fig. 3 Evolution of the composition of the Earth's atmosphere through geological time (Catling and Zahnle, 2020).

2.2.4 Early habitable environments

There are only a few exposed locations where Paleoarchean terranes are well-preserved (namely the ∼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 Hoggenoeg 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, 1989a; 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 ∼50°C and up to ∼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 born 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 VUV 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 chemototrophic 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 artefacts. 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). 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 (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 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 (Figure 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.

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

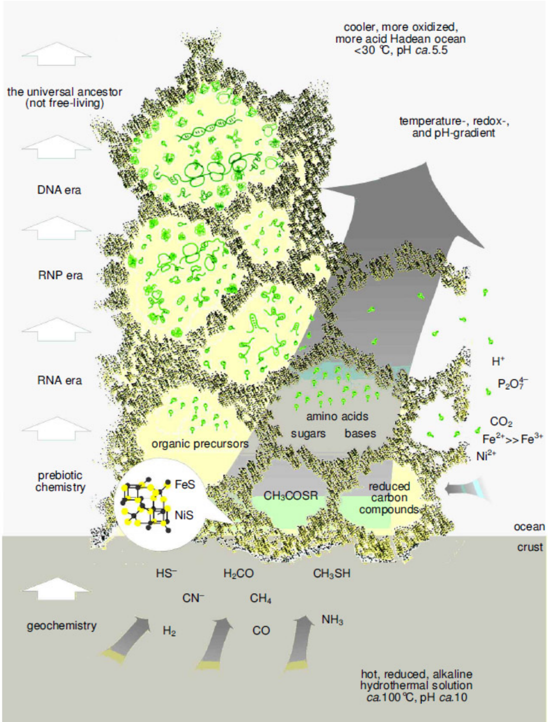

Fig. 4 Model for the emergence of cellular life in porous hydrothermal vent systems (after (Martin and Russell, 2003)).

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 (Figure 5) would

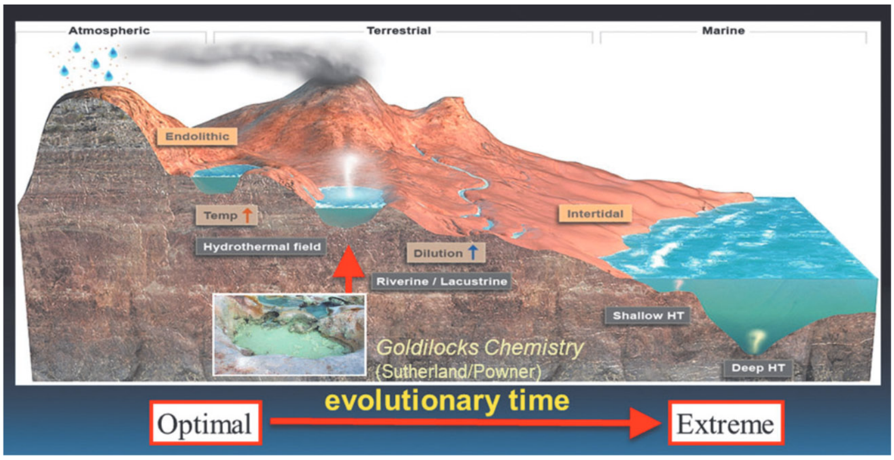

Fig. 5 Hypothetical emergence of life in subaerial hydrothermal springs. After Damer and Deamer (2020).

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 to 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 and heat 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 environment 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) 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 at 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 metamorphosed and altered rocks from the Eoarchean and, 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 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's important to understand why the LHB is currently out of favor. The hypothesised LHB was originally tied to a late giant planet instability in models of solar system planet formation (Gomes et al., 2005). 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 3.75 Ga Nuvvuagittuq Supracrustal terrane (Dodd et al., 2017; Papineau et al., 2022) that have since been reinterpreted as abiotic artefacts (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 artefacts (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 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

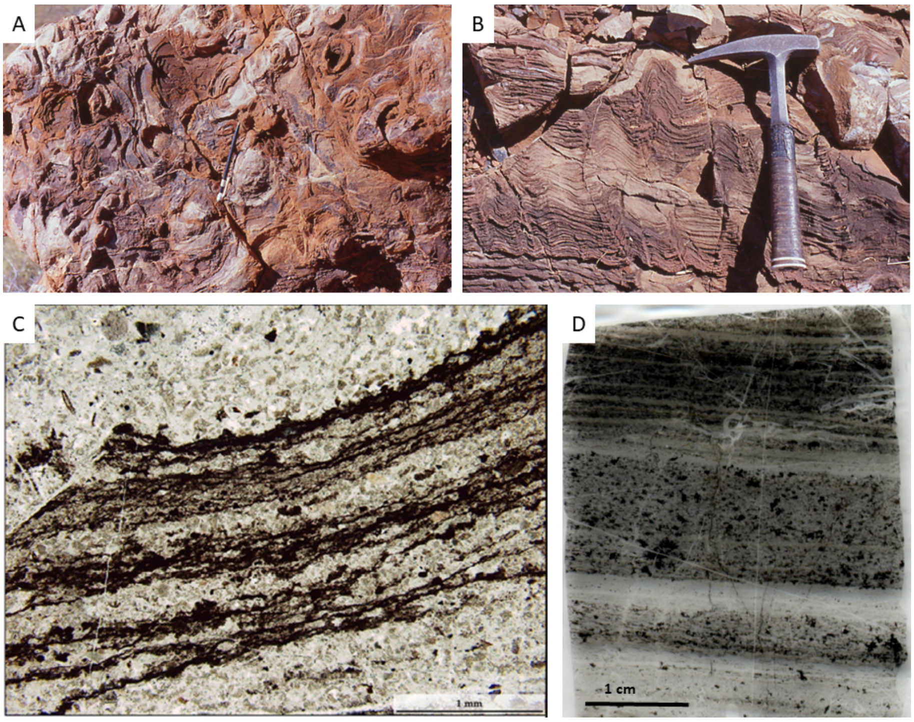

Fig. 6 Early terrestrial microorganisms. (A,B) 3.44 Ga old stromatolites from the Pilbara, Australia in plan view and cross section. (C) Tabular phototrophic mats from the 3.472 Ga old Middle Marker Formation, Barberton, South Africa. (D) Layers of carbonaceous clots representing chemotrophic colonies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

well as the rise of oxygenic phototrophs at about 3.0 Ga. Evidence for early terrestrial microorganisms is summarized in Fig. 6.

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 CO2, 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. Additionnally, 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, 2022). This topic is discussed further in (Gillmann et al., 2022; Rolf et al., 2022, this issue).

The exact style of resurfacing on Venus is still debated (Rolf et al., 2022, this issue). 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 through 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 and outgassing processes are proposed in Rolf et al. (2022) and Gillmann et al. (2022), respectively. It has been therefore 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 tessera terrains, observed on Venus to represent around 8% of the crust, 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, 2016, 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 those terrains can actually be considered felsic.

Volatile recycling would be efficient during the plate tectonics 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, 2016, 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 due to increasing the amount of heat producing elements in the mantle and due to recycling of volatiles that would decrease locally 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 affects directly surface conditions and the surface habitability of a planet. Broadly speaking, three processes can lead to significant outgassing and affect 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. (2022, this issue). After accretion and the capture of a possible primordial hydrogen atmosphere, it is the source of the early volatiles and 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, this issue). The velocity and mass of impactors means that large amounts of kinetic energy are transferred to the planet as thermal energy during a collision 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, possibly creating magma ponds/seas, and leading 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 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 issue). Its causes, partial melting of the mantle due to local pressure-temperature conditions exceeding the local solidus of the mantle material, are explained in Rolf et al. (2022, this issue), and its surface expressions are addressed in Smerkar et al. (2022, this issue) and Herrick et al. (2022, this issue). 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, <<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 ($\sim$1 km^3/yr) (Head et al., 1991; Phillips et al., 1992); or similar ($\sim$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 relatively 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 issue). Magmatic outgassing is a consequence of partial melting of hot, uprising mantle material. The lower 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 $\sim$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 a 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 (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, the atmospheric CO_2 on planets without plate tectonics is generally held to continuously increase. 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 issue). 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 (in 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 important cause of 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 Jr, 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 Jr, 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 Donahue et al. (1982) demonstrated a ratio $\sim$150 times that of Earth. 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 photo-dissociation 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 ratio much higher than all 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 proposed 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 Ga 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 issue).

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 $\sim$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), 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. (2022, this issue). One method of testing which hypothesis for Venus' evolution is correct is by examining data from the 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 issue). 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. (2022a, this issue) 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. 2022; Gillmann et al. 2022, this issue), 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 ∼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±10%; Holdaway and Yang 2016) - and in that scenario early Venus had temperatures (depending upon the atmosphere assumed) ranging from ∼320-500K. 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 300K. Pollack also demonstrated that, even at today's insolation (∼1.9 times Earth's), the surface temperature could have remained below 300K. 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 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 was mostly based on a simplified single mixed-layer/slab ocean. 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

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

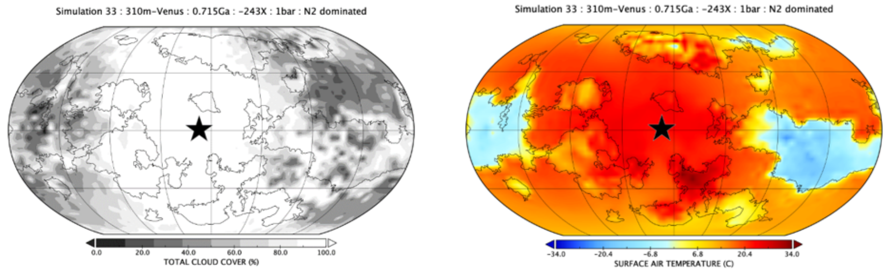

Fig. 7 Generated from General Circulation Model simulation 33 in Way and Del Genio (2020). This is a 1 bar N_2 Dominated atmosphere including 400 ppmv CO_2 and 1 ppmv CH_4. The rotation rate is the same as modern Venus (–243 x Earth). Insolation is set to the value that Venus received 715Ma (1.7 x Modern 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 keeps the oceans warm (red/orange colors) even in the anti-solar regions of the simulation.

is encouraging, but cannot be considered conclusive until these effects are observed in exoplanetary systems in the future. 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. 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 eons 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., 2022a, this issue), as it has done 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 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 issue).

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 conditions, 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 atmosphere pressures of about 0.5 bar on Earth, 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 plants, 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 the Venus' atmosphere compared to the 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 into 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 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 issue), 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 issue), 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 $\sim$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. 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., 2022b) 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 (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., 2022b).

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 issue) expands on this topic and surface-atmosphere interaction.

In short, most mechanisms that allow the surface conditions to evolve from the hypothetical temperate state of early Venus to the hot, dry present-day Venus, are more likely to have occurred over long periods of time rather than during a short extreme event. The more recently the transition takes place, the more extreme the scenario needs to be. Our knowledge of Venus is currently insufficient to rule out any but the most extreme scenarios, but further observation, through a better exploration of surface composition, should yield important evidence to constrain Venus' evolution.

Section 2 describes what to look for in the atmosphere today (D/H and Noble gases, see Avice et al. 2022 this issue, 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 diox-

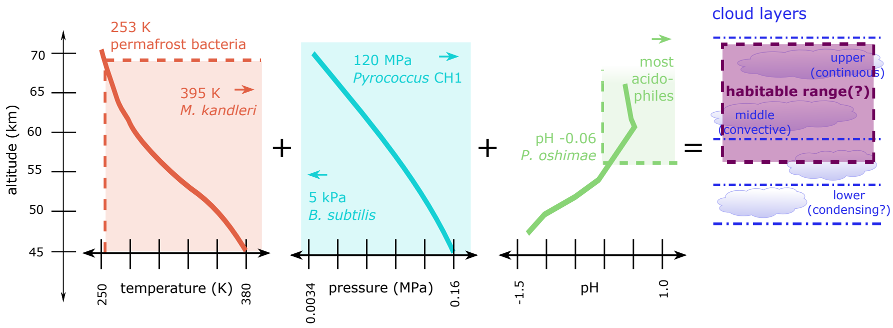

Fig. 8 The calculated temperature, pressure, and pH prevailing in Venus cloud aerosols in the height range 45–70 km from the surface (solid lines) and respective observed limits for terrestrial life (dashed lines and solid fill). The limits of terrestrial organisms may or may not reflect the possibilities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

ide as a polar solvent (Budisa and Schulze-Makuch, 2014); the possibility for water-based life to have retreated to underground high-pressure water refugia 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 ultraviolet radiation flux.

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 observed in the field, probably because microbes 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 Section 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); C, H, N, O, and S, with some evidence for P (Limaye et al., 2021a; Milojevic et al., 2021; Mogul et al., 2021); 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's 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 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 Figure 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 reproduction 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’s clouds is whether sufficient water exists in the cloud aerosols to allow occasional microbial growth. Both Seager et al. (2020) and Hallsworth et al. (2021b) estimate the water activity (a_w) as ≤ 0.004, far below the microbial activity limit of ~ 0.6. Limaye et al. (2021a) calculated a higher but still prohibitive estimate of 0.02; as with calculations of H_0 above,

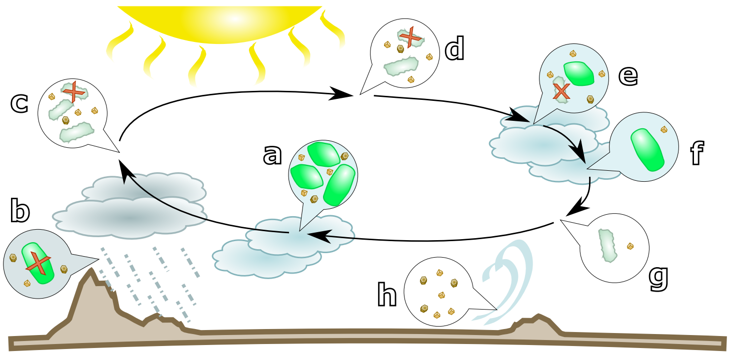

Fig. 9 Life cycle within a notional aerobiosphere. [a] Microbes (green) accumulate enough nutrients (brown) in a warm, wet cloud to divide. [b] Loss with precipitation. [c] Encounter with drier region; some transition to desiccated, inactive forms. [d] Dry forms accumulate damage, e.g., radiation. [e] 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 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's 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.

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. (2021) which may provide further evidence for phosphorus in the cloud layer. The latter two results have not yet been reconciled with other

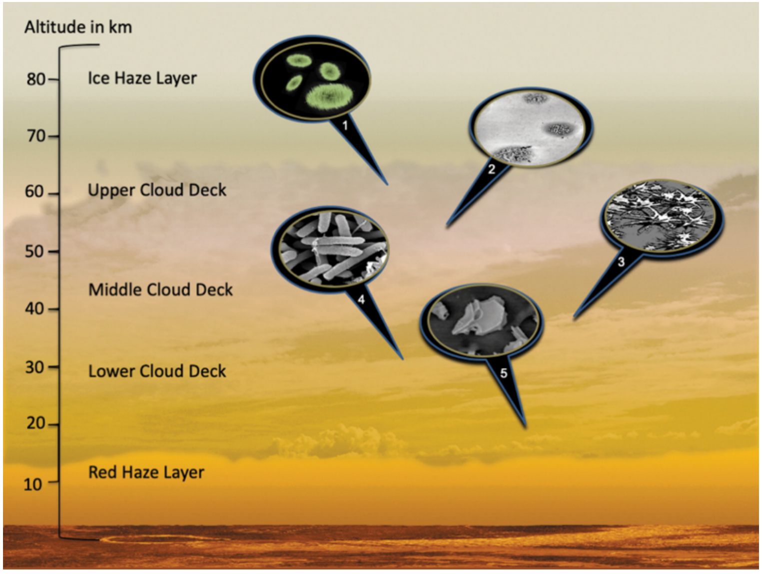

Fig. 10 Notional particles potentially to be encountered in the Venus cloud decks, inspired by terrestrial atmospheric sampling, to guide future instrument and analysis selection: (1) complex shapes with fluorescent properties, (2) particulate aggregates of sulfates and related compounds, (3) unidentified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

in situ measurements and therefore remain somewhat enigmatic (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's 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 lower 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. (2021) 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. (2021) 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,b,c) 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. (2021) ground based observations (Mogul et al., 2021) 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., 2021b) 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 1989b), 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., 2022, this issue). 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's 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 issue (chapters 2–4).

Another approach, isotope geochemistry, allows to constrain Venus's evolution in the even further past, right back to its formation and early evolution. The isotopic abundances of noble gases and light elements provides 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 issue). Although some noble gas isotope measurements were obtained already 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, allowing 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 issue).

Conducting these investigations will not only give us a better understanding of habitability of Venus 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., 2022a, this issue).

2. The search for biosignatures in Venusian clouds

If Venus was habitable in the past (meaning, did it have 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 a 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.

Conflict of interest

The authors declare that they have no conflict of interest.

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