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Hot climate inhibits volcanism on Venus: Constraints from rock deformation experiments and argon isotope geochemistry

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ABSTRACT

The disparate evolution of sibling planets Earth and Venus has left them markedly different. Venus' hot (460 °C) surface is dry and has a hypsometry with a very low standard deviation, whereas Earth's average temperature is 4 °C and the surface is wet and has a pronounced bimodal hypsometry. Counterintuitively, despite the hot Venusian climate, the rate of intraplate volcano formation is an order of magnitude lower than that of Earth. Here we compile and analyse rock deformation and atmospheric argon isotope data to offer an explanation for the relative contrast in volcanic flux between Earth and Venus. By collating high-temperature, high-pressure rock deformation data for basalt, we provide a failure mechanism map to assess the depth of the brittle–ductile transition (BDT). These data suggest that the Venusian BDT likely exists between 2 and 12 km depth (for a range of thermal gradients), in stark contrast to the BDT for Earth, which we find to be at a depth of ~25–27 km using the same method. The implications for planetary evolution are twofold. First, downflexing and sagging will result in the sinking of high-relief structures, due to the low flexural rigidity of the predominantly ductile Venusian crust, offering an explanation for the curious coronae features on the Venusian surface. Second, magma delivery to the surface—the most efficient mechanism for which is flow along fractures (dykes; i.e., brittle deformation)—will be inhibited on Venus. Instead, we infer that magmas must stall and pond in the ductile Venusian crust. If true, a greater proportion of magmatism on Venus should result in intrusion rather than extrusion, relative to Earth. This predicted lower volcanic flux on Venus, relative to Earth, is supported by atmospheric argon isotope data: we argue here that the anomalously unradiogenic present-day atmospheric $^{40}Ar/^{36}Ar$ ratio for Venus (compared with Earth) must reflect major differences in ^{40}Ar degassing, primarily driven by volcanism. Indeed, these argon data suggest that the volcanic flux on Venus has been three times lower than that on Earth over its 4.56 billion year history. We conclude that Venus' hot climate inhibits volcanism.

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1. Introduction

The present-day differences in the expression and intensity of volcanism on the telluric planets serves as a testament to the dynamic nature of planetary evolution (Wilson, 2009). For example, Earth and Venus are colloquially referred to as sibling planets because of their similar mass and bulk composition (i.e., bulk petrology). However, their contrasting atmospheric mass and chemistry (e.g., Gaillard and Scaillet, 2014; Mikhail and Sverjensky, 2014), climate (e.g., Pollack et al., 1980), geomorphology (e.g., Head and Solomon, 1981; Donahue and Russell, 1997; Basilevsky and Head, 2003; Ghail, 2015), and volcanic character (e.g., Fegley and Prinn, 1989; Head et al., 1992; Wilson, 2009) is striking: Earth is a crucible of life, whereas Venus is a barren wasteland. Suffice to say, then, Earth and Venus are not identical siblings. The major differences between Venus and Earth are discussed in detail below.

First, the average surface temperatures are 460 and 4 °C on Venus and Earth, respectively. The Earth also has an excess in surface water of about 1.2×10^{21} kg compared to Venus, a difference between five and six orders of magnitude (Donahue, 1999; Lécuyer et al., 2010). The high temperature and low water content of the Venusian surface are a combined consequence of the absence of a magnetic field (Donahue and Russell, 1997), the presence of a dense atmosphere dominated by CO_2 (at a pressure of 9 MPa), and its proximity to the Sun (with a solar irradiance of 2611 W/m^2, compared with 1366 W/m^2 on Earth).

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Second, hypsometric data show that >80% of the surface elevation of Venus ranges from −1.0 to +2.5 km; only ∼2% of the surface lies >2 km above the median radius (Fig. 1) (Head and Solomon, 1981; Basilevsky and Head, 2003; Taylor and McLennan, 2009). The surface of Earth, by contrast, has a pronounced bimodal hypsometry (i.e., it has continental rises and ocean basins; Fig. 1). The fact that Venus has a hypsometry with a very low standard deviation is not easily attributable to the absence of plate tectonics on Venus, because Mars—a planet that, like Venus, operates a stagnant-lid tectonic regime (Head and Solomon, 1981; Head et al., 1992; Donahue and Russell, 1997; Basilevsky and Head, 2003)—has a surface hypsometry with a very large standard deviation (Fig. 1).

Third, the way in which volcanism is manifest on Earth and Venus differs substantially (e.g., Wilson and Head, 1983; Wilson, 2009). For example, while the majority (*ca.* 90%) of Earth's volcanism occurs along curvilinear belts and rift-margins, which collectively define tectonic plate boundaries (Cottrell, 2015), Venus operates a stagnant-lid tectonic regime and is dominated by features interpreted to be related to mantle plumes (e.g., Head et al., 1992). Although Venus hosts volcanic features commonly observed on Earth, such as lava plains, discrete lava flows, shield volcanoes, and shield fields, it is also home to enigmatic, flat landforms such as coronae (Head et al., 1992; Stofan et al., 1992; Squyres et al., 1992; McKenzie et al., 1992; Grosfils and Head, 1994; Addington, 2001; Krassilnikov and Head, 2003; Grindrod and Hoogenboom, 2006; Robin et al., 2007; Wilson, 2009; Krassilnikov et al., 2012; Ivanov and Head, 2013).

An important difference between volcanism on Earth and Venus is that, by comparing intraplate volcanic fluxes on both Earth and Venus, it is clear that Earth is the most volcanically active of the two planets, possibly by at least an order of magnitude (Ivanov and Head, 2013). Indeed, while intraplate volcanic activity on Earth is evidently abundant, evidence for ongoing, present-day volcanism on Venus is comparatively sparse, although it is thought that the vast majority of the Venusian surface is volcanic in origin (Head et al., 1992; Basilevsky and Head, 2003; Wilson, 2009). However, a number of recent findings suggest that volcanic activity on Venus persists to the present: [1] infrared radiation from three volcanic regions showed some flows to be warmer than their surrounding rocks, implying that these lavas are younger than 2.5 Ma (Smrekar et al., 2010); [2] sporadic atmospheric SO_2 fluctuations have been observed at Venus (Esposito, 1984; Marcq et al., 2011); and [3] thermal spikes have been reported at Ganiki Chasma, a rift valley proximal to Ozza and Maat Montes (Shalygin et al., 2015). In addition, the sulfuric clouds that envelop the entire planet would not persist beyond 1–50 Ma without the replenishment of SO_2, the source of which is presumed to be magmatic (Fegley and Prinn, 1989; Bullock and Grinspoon, 2001).

To emphasise the difference between volcanic activity on Earth and Venus: while Earth's oceanic crust (that covers 60% of Earth's surface) has created >100,000 individual volcanoes (including seamounts) in <100 Ma (e.g., Wessel, 2001 and references therein), Venus' entire surface has produced roughly 70,000 individual volcanoes in <700 Ma (Head et al., 1992). The difference in the rate of volcano production is therefore at least an order of magnitude greater on Earth than on Venus. We further note that, because >70% of all extrusive volcanism on Earth occurs beneath ocean depths >1000 m under pressures >9 MPa, the presence of coronae, a landform unique to the surface of Venus, cannot simply be explained by the high Venusian atmospheric pressure (Smith,

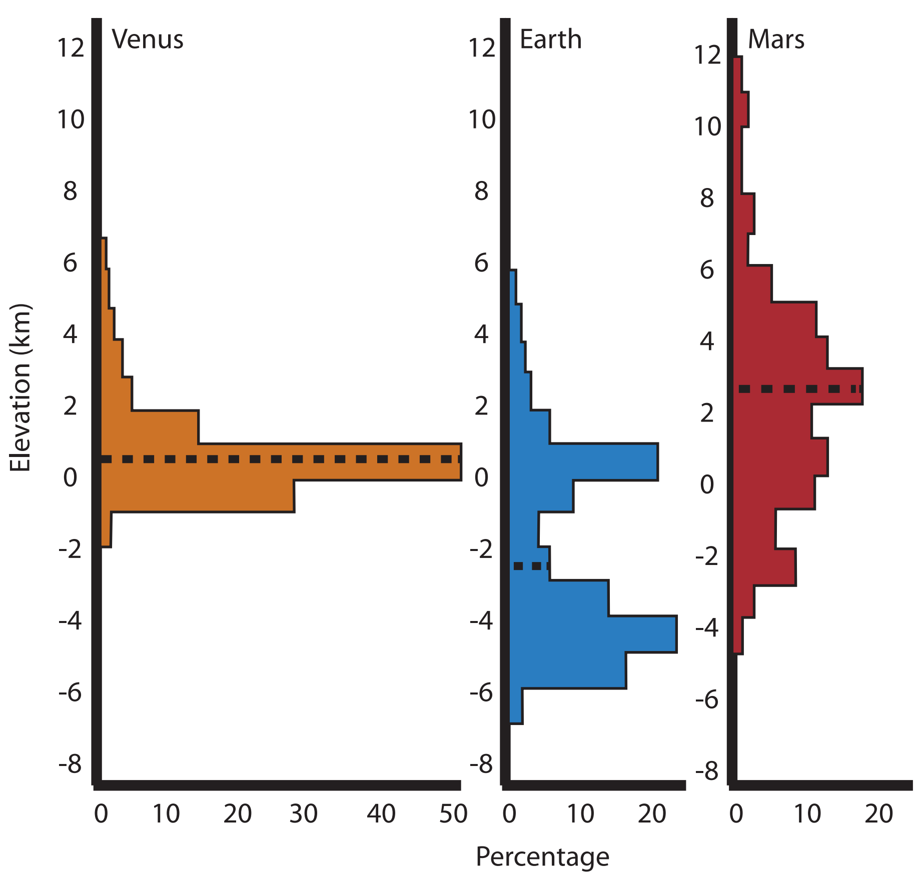

Fig. 1. Hypsography of Venus, Earth, and Mars (Head and Solomon, 1981; Basilevsky and Head, 2003; Taylor and McLennan, 2009). Dashed lines mark the mean surface relief for each planet.

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