Assessing the evidence for active volcanism on Venus: current limitations and prospects for future investigations

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Abstract

One of the biggest unknowns about Venus is how volcanically active it is today. Venus has a similar size and density to Earth, suggesting it may have a comparable composition, and therefore it is expected to be volcanically active; however, exploring Venus and confirming current volcanic activity is difficult because of the thick omnipresent optically opaque clouds that hamper traditional observations of the lower atmosphere and surface. Further, surface conditions make long-lived missions challenging. Despite the difficulty, there have been tantalizing hints of currently active or very recent volcanism. Here, we review what is known about active volcanism, point out gaps in knowledge to be addressed, and highlight techniques and approaches that need to be developed before the new decade of Venus exploration. It is crucial to constrain the activity and rate of volcanism today and through time to begin to understand the geodynamic state of the planet.

We find that the combination of all evidence strongly indicates that Venus is volcanically active today. The best evidence for active volcanism comes from combining data sets and approaches – specifically at Idunn Mons, Maat Mons, and Aramaiti Corona – in contrast to those from a single study or data set alone. Considering the evidence for activity, observations do not favor so-called "catastrophic" models of resurfacing, instead they are better represented by ongoing regional scale events. To reliably detect and characterize active or recent effusive basaltic volcanism new missions must collect high-resolution imaging, repeat observations, radar polarimetry, evidence of outgassing, and high-resolution topographical data that provide insights into surface changes over time. The ability to capture and interpret these data is vital for understanding Venus's geological activity, particularly in regions where volcanic processes are suspected to be ongoing.

Keywords

Venus, Volcanism, Weathering, Radar, Emissivity, Atmosphere, Geodynamics

1) Introduction:

Venus is often considered Earth's sister planet, being of similar size and density, and therefore, inferred bulk composition (Fegley, 2014; Stofan, 2004). Yet, it took a very different evolutionary path, resulting in a hot caustic surface environment inhospitable to life as we know it (e.g., O'Rourke et al., 2023; Prinn and Fegley, 1987; Widemann et al., 2023). Although volcanic geomorphological features and materials present the majority of Venus' surface (Ghail et al., 2024; Head et al., 1992), sedimentary processes may occur more than is often assumed (Carter et al., 2023). Studying the surface of Venus directly is difficult as we do not have samples of the surface, as we do for the Earth, Moon, Mars, and asteroids, and the surface is cloaked from direct view to most remote sensing instruments by thick, omnipresent aerosol-rich clouds (**Fig. 1**) (e.g., Cloutis, 2021; Crisp et al., 1991; Fegley, 2014; Glaze et al., 2018; Meadows and Crisp, 1996). The only way to image the surface remotely from orbit is with imaging synthetic aperture radar (SAR), such as the near-global mosaic provided by Magellan, along with limited surface optical observations from the Venera landers and near-infrared emissivity measurements from flyby and orbital spacecraft (Galileo, Venus Express, Parker Solar Probe) (e.g., Basilevsky et al., 1986; Garvin et al., 1984; Gilmore et al., 2023; Grimm and Hess, 1997; Saunders et al., 1990). Radar imaging, going back to Pioneer Venus Orbiter (1978-81), has shown Venus to be a volcanic wonderland with some of the most extensive volcanic plains and structures in the Solar System (e.g., Barsukov et al., 1986c; Ghail et al., 2024; Head et al., 1992; Stofan, 2004).

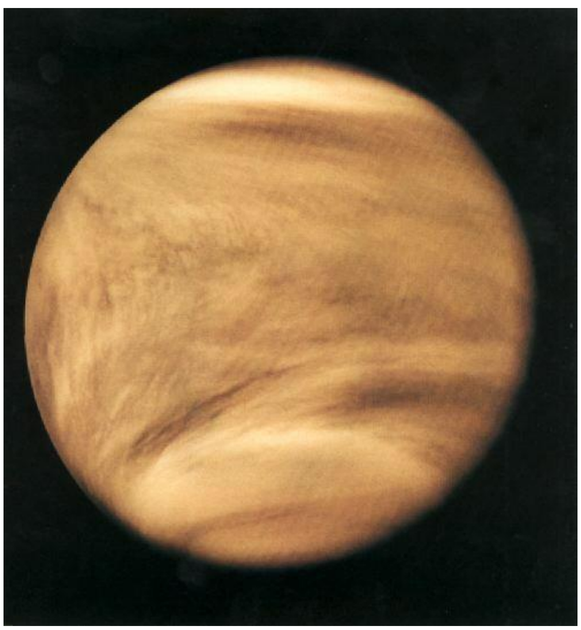

Fig. 1. Ultraviolet image of Venus showing the omnipresent clouds as seen by the Pioneer Venus Orbiter on February 5, 1979. Image from NASA GSFC.

https://nssdc.gsfc.nasa.gov/photo_gallery/photogallery-venus.html

While Venus has not received the exploration focus that the Moon and Mars have over the past 30+ years, we are entering a new decade of Venus exploration (Hall, 2019; Limaye and Garvin, 2024; Widemann et al., 2023). Spacecraft exploration of Venus largely started in the 1960s with NASA's Mariner and the Soviet Union's Venera and Vega mission programs (Taylor, 2014).

The Soviet Venera and Vega programs continued through the 1980s and consisted of atmospheric probes and balloons, orbiters, and landers (Fegley, 2014; Krasnopolsky, 2001; Lorenz, 2019; Taylor, 2014). Venera and Vega landers provided the only surface composition measurements to date (Surkov et al., 1986; Surkov et al., 1984). The Soviet program included with Venera 15 and 16 orbiters that provided radar mapping of the northern hemisphere (Barsukov et al., 1986c), as well as microwave brightness temperature mapping in 3 wavelengths. NASA sent Pioneer Venus 1 and 2 in 1978, an orbiter (PVO) and atmospheric probes (Oyama et al., 1980; Pettengill et al., 1980), respectively, and later implemented the Magellan Venus radar mapping mission via its Shuttle-based launch in 1989 (Pettengill et al., 1992; Saunders et al., 1990). Results from these missions revealed an inhospitably hot surface covered in large volcanoes with a thick CO_2-dominant atmosphere (e.g., Taylor, 2014). Venus-focused missions took an approximately 15-year hiatus until ESA's Venus Express orbiter in 2005, the first ESA mission to Venus (Svedhem et al., 2007a), and JAXA's Venus Climate Orbiter Akatsuki in 2010 (Nakamura et al., 2011).

In the coming decade (2028-2038), we will have extensive new data for the surface from the upcoming accepted and potential missions– NASA's DAVINCI (Garvin et al., 2022) and VERITAS (Smrekar et al., 2022) missions, ESA's EnVision mission (Ghail et al., 2021), ISRO's Venus Orbiter Mission (VOM) (Sundararajan, 2021), Roscosmos' Venera-D mission (Eismont et al., 2019; Zasova et al., 2019), China's VOICE and aerosol sample return missions (Wang et al., 2022), and the privately funded Morning Star mission (Seager et al., 2022) – see overall summary of mission concepts in Widemann et al. (2023) and Limaye and Garvin (2023). Some of the most significant scientific questions for these missions to investigate include whether Venus is still volcanically active, how active it is, and the volcanic resurfacing rate over time. It is crucial to constrain the rate of any volcanic activity to understand the geodynamic state of Venus, its volatile budget, and its current tectonic regime. Here, we review what is known about recent volcanism, identify important gaps in knowledge that need to be addressed, and highlight techniques and approaches that need to be developed before the new decade of Venus exploration.

2) Morphologic constraints on lava types

Dual-polarimetric S-band radar images from Arecibo Telescope (~ 1 km resolution), Venera 15/16 (C-band orbital SAR at 0.5 km resolution), and the S-band radar images (at ~75 m resolution) from orbital Magellan spacecraft have revealed a volcanic wonderland with a wide range of different volcanic landforms on Venus that are largely consistent with effusive basaltic volcanism based on the morphology of these features (**Fig. 2**) (Barsukov et al., 1986c; Crumpler, 1997; D'Incecco et al., Submitted; Ghail et al., 2024; Hahn and Byrne, 2023; Head et al., 1992; Ivanov and Head, 2013). Over 100 large-scale shield volcanoes greater than 100 km in diameter, which resemble terrestrial shield volcanoes and, therefore, have been interpreted as basaltic in composition (Crumpler, 1997; Hahn and Byrne, 2023; Ivanov and Head, 2025). In addition, over 80,000 small lava shield volcanoes similar to those in Iceland (Hahn and Byrne, 2023). This is likely an underestimate of their actual numbers due to resolution (Hahn and Byrne, 2023). There are extensive lava flow fields with individual flows reaching lengths up to ~1000 km with a variety of flow textures and morphologies (Byrnes and Crown, 2002; Ivanov and Head, 2013; Roberts et al., 1992). Comparative analyses using terrestrial analogs have been increasingly employed to refine these interpretations (e.g., D'Incecco et al., 2024b). Lava channels associated with such lava fields are found globally (e.g., Komatsu et al., 1993). Similarly, channels resembling lunar sinuous rilles are also found globally (e.g., Baker et al., 1992). Further in the plains regions, there are up to one hundred canali-type channels ranging from tens to thousands of kilometers in length that maintain a nearly constant width (up to a few km) (Baker et al., 1992; Bledsoe and Klimczak, 2025; Bray et al., 2007; Komatsu and Baker, 1994; Komatsu et al., 1993; Oshigami et al., 2009). Based on both the morphology and size of these features, the lava that produced them has been interpreted as basaltic, komatiitic, ultramafic, carbonatitic, or exotic material (such as sulfates or sulfur) in composition (Baker et al., 1992; Gregg and Greeley, 1993; Kargel et al., 1994; Williams-Jones et al., 1998). Non-volcanic origins of canali have also been proposed (Jones and Pickering, 2003; Waltham et al., 2008).

The common occurrence of small shield volcanoes (< ~500 m in height, 2 to 20 km in diameter) with gentle (<5 °) slopes (i.e., typical of many shield volcanoes in Iceland) suggests effusive eruptions of volatile-poor basaltic magmas (Aubele and Slyuta, 1990; Head et al., 1992). There are an estimated ~84,000 of these features spread across the surface (Garvin and Williams Jr, 1990; Hahn and Byrne, 2023; Ivanov and Head, 2004). These are likely basaltic in composition; however, due to their small size, which is at the edge of the radar resolution, constraining their precise lava-type and formation mechanism remains highly uncertain (D'Incecco et al., 2023; D'Incecco et al., 2024a; D'Incecco et al., Submitted).

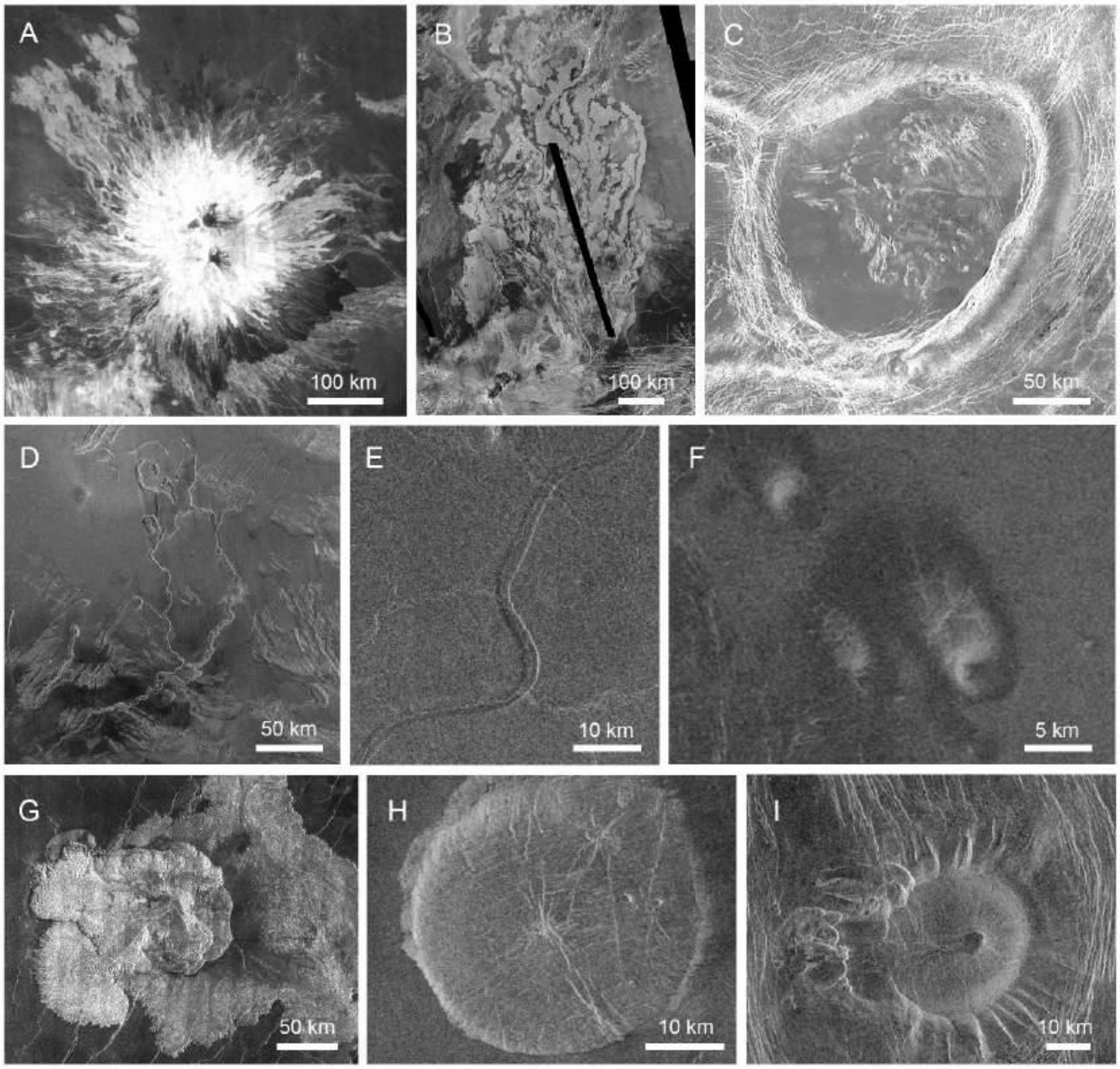

Figure 2. Representative Magellan radar images of Venusian volcanic landforms. A) large-scale shield volcano *Sapas Mons*, B) large lava field *Mylitta Fluctus*, C) *Neyterkob* corona, D) sinuous rilles *Lo Shen Valles*, E) canali-type channel *Baltis Vallis*, F) small volcanic edifices with wind streaks, G) festoon flow, H) steep-sided dome, I) scalloped margin dome. North is up. Images from NASA GSFC/JPL/USGS. Figure from D'Incecco et al. (Submitted).

Finally, there are also enigmatic steep-sided volcanic features, such as festoon flows, pancake-like domes, and scalloped margin domes, which have radar features suggestive of either different compositions or unique formation mechanisms (e.g., D'Incecco et al., 2023; D'Incecco et al., 2024a; D'Incecco et al., Submitted; Pavri et al., 1992). These flow types have similarly steep sides and radar-bright features and have been interpreted as either high-viscosity silicic lavas or crystal-rich high-viscosity basaltic lavas (e.g., Borrelli et al., 2025; Bridges, 1995; Cao et al., 2025; Fink et al., 1993; Glaze et al., 2008; Pavri et al., 1992; Stofan et al., 2000).

Beyond effusive style eruptions, there is limited evidence for explosive pyroclastic eruptions, however counter-indicated (Wilson and Head, 1986). The thick, dense atmosphere, with surface pressure equivalent to ~ 1 km ocean depth on the Earth, is thought to restrict explosive volcanic activity (e.g., Airey et al., 2015; Garvin et al., 1982; Head and Wilson, 1986); however, there has been extensive direct and indirect (deep hyaloclastite) evidence for basaltic explosive volcanism at terrestrial ocean depths greater than 1 km (Clague et al., 2009; Helo et al., 2011; Newland et al., 2022; Resing et al., 2011). Limited apparent pyroclastic deposits in radar images suggest evidence for partially explosive basaltic eruptions (e.g., Campbell et al., 2017; Garvin et al., 1982; Ghail and Wilson, 2015; Head et al., 1991). They have been interpreted to be analogous to welded basaltic ignimbrites with high surface roughness or thin, low-density, mantling pyroclastic deposits (e.g., Ganesh et al. 2022). These deposits are characterized by a diffuse appearance with high radar backscatter returns, typically found adjacent to large volcanic centers (e.g., Campbell and Clark, 2006; Campbell et al., 2017; Ganesh et al., 2022; Head et al., 1991; Keddie and Head, 1995). Many such deposits are difficult to classify since they have radar characteristics similar to much of the surrounding surface and therefore pyroclastic activity may be more common on Venus than expected (Ghail and Wilson, 2015). Future missions with higher radar resolution and polarimetric capabilities may be able to better distinguish pyroclastic deposits from surrounding terrains (Section 9.3).

3) In situ constraints on the composition of lava

Our best information about the composition of Venusian lava comes from the hugely successful Venera and Vega landers (1975 to 1985), which directly measured the composition of surface materials, including the first optical images of the surface (**Fig. 3**); however, the longest survived for only 127 minutes (Venera 13). Each lander carried a different suite of instruments, and not all of the successful landers measured the full bulk major element composition, and no mission directly measured the mineralogy of the rocks (Krasnopolsky, 2001; Marov, 1978; Surkov et al., 1986; Surkov et al., 1984; Treiman, 2007). Further, the studied landing regions were chosen based on operational landing criteria, which resulted in all being within volcanic plains with similar geologic terrain type (Basilevsky et al., 2007; Weitz and Basilevsky, 1993). Despite these limitations, the Venera and Vega landers provide our most detailed chemical analyses of Venus' crustal materials (Surkov et al., 1986; Surkov et al., 1984; Treiman, 2007), with major element distribution analyses from Venera 13, 14, and Vega 2. Importantly, these measurements also provide very small-area ground truth for orbital NIR emissivity and radar measurements (Dyar et al., 2020; Gilmore et al., 2017; Gilmore et al., 2023; Helbert et al., 2021).

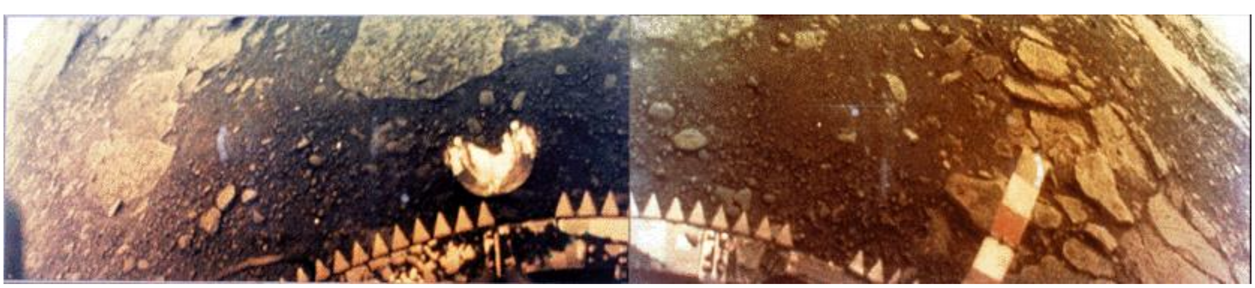

Fig. 3. Fragments of Venus surface panorama from Venera 13 camera. Image from NASA GSFC; Original image from ROSCOSMOS; https://nssdc.gsfc.nasa.gov/imgcat/html/object_page/v13_vg261_262.html

Bulk major element abundances were measured by X-ray fluorescence at three landing sites by Venera 13 and 14 and Vega 2; Venera 8, 9, and 10 and Vega 1 and 2 measured K, Th, and U by gamma-ray spectroscopy (Table 1; Barsukov, 1992; Barsukov et al., 1986b; Kargel et al., 1993; Surkov et al., 1986; Surkov et al., 1984; Surkov et al., 1987; Treiman, 2007). Venera 13 and 14 measurements and Vega 2 include most major elements, except for Na and some others, such as Mg, which are at the 2-sigma detection limit; thus inhibiting measurements of the Mg#. Previous work has used these measurements with terrestrial analogs and terrestrial discrimination diagrams (including classical normative analysis), such as a TAS (total alkalis vs. silica) diagram (Irvine and Baragar, 1971; Le Maitre, 2002) to constrain the rock type, assuming they are igneous or isochemically altered (except sulfur) igneous rocks (e.g., Barsukov, 1992; Filiberto, 2014; Garvin and Bryan, 1987; Ivanov, 2016; Kargel et al., 1993; Semprich, 2024; Shellnutt, 2013; Surkov et al., 1986; Surkov et al., 1984; Treiman, 2007). Based on these comparisons, Venera 14 and Vega 2 measurements are consistent with tholeiitic basalts, as interpreted by Garvin et al. (1984), with varying degrees of alteration – primarily based on sulfur contents and wt% totals (Filiberto, 2014; Kargel, et al. 1993; Treiman, 2007; Surkov et al. 1986; Surkov et al. 1984; Semprich 2024). Venera 13 is consistent with an alkalic, high-K, basalt with potentially a CO_2-bearing source region like those found at Tristan da Cunha (Filiberto, 2014; Garvin and Bryan, 1987; Semprich, 2024). Assuming these represent igneous rocks with varying amounts of alteration, we can use terrestrial analogs from Filiberto (2014) to calculate the missing Na. Based on these terrestrial analogs, we estimate 4 +/- 2 wt% Na_2O for Venera 13 and 3 +/- 2 wt% Na_2O for Venera 14 and Vega 2 compared to previous estimations of 2 +/- 1, 2.4 +/- 0.8, and 2 wt% for Venera 13 and 14 and Vega 2 respectively (Surkov et al., 1986; Surkov et al., 1984) (**Table 1**).

Table 1. Compositional analyses from Venera and Vega Missions from Barsukov et al. 1986b; Barsukov 1992; Surkov et al., 1986; Surkov et al., 1984; as summarized in Treiman, 2007

Table 1a. Major Element Composition (wt%)

	Venera 13	+/- 2 σ	Venera 14	+/- 2 σ	Vega 2	+/- 2 σ
SiO_2	45.1	6.0	48.7	7.2	45.6	6.4
TiO_2	1.6	0.9	1.3	0.8	0.2	0.2
Al_2O_3	15.8	6.0	17.9	5.2	16.0	3.6
FeO^T	9.3	4.4	8.8	3.6	7.7	2.2
MnO	0.2	0.2	0.2	0.2	0.1	0.2
MgO	11.4	12.4	8.1	6.6	11.5	7.4
CaO	7.1	2.0	10.3	2.4	7.5	1.4
K_2O	4.0	1.2	0.2	0.1	0.1	0.2

SO_3	1.6	2.0	0.4	0.6	1.9	1.2
Cl	< 0.3		<0.4		≤0.3***	
Sum	96.1		95.8		90.6	
Na_2O*	4	2	3	2	3	2
Na_2O**	2	1	2.4	0.8	2	

*estimated based on terrestrial analogs as compared in Filiberto (2014)
** calculated by Surkov et al. (1984; 1986) based on the K_2O, MgO, and FeO^T abundances
*** Barsukov et al. (1986b) reported 0.3 wt% Cl; while Surkov et al. (1986) reported < 0.3 wt% Cl
FeO^T = Total iron (FeO + Fe_2O_3) as oxidation state was not determined

Table 1b. Radioactive Element Abundances (ppm by weight)

	Venera 8	+/- 2 σ	Venera 9	+/- 2 σ	Venera 10	+/- 2 σ	Vega 1	+/- 2 σ	Vega 2	+/- 2 σ
K	40000	24000	4700	1600	3000	3200	4500	4400	4000	4000
U	2.2	2.4	0.6	0.32	0.46	0.52	0.64	0.94	0.68	0.76
Th	6.5	0.4	3.65	0.48	0.7	0.74	1.5	2.4	2	2

We note an important point for future Venus missions: these studies using the Venera and Vega geochemical data assume that the material analyzed is known to be igneous or isochemically altered (except for sulfur) basalts; however, as has been recently shown on Mars by both Mars Science Laboratory Curiosity and Mars 2020 Perseverance rovers, determining the origin and petrogenetic history of a rock without detailed mineralogy and texture may *not* be conclusive (e.g., the debate over rock Jake_M at Gale Crater and whether it represents a Martian mugearite or a sedimentary rock) (Edwards et al., 2017; McLennan et al., 2014; Stolper et al., 2013). Mineralogy, in combination with bulk composition, would be needed to determine whether a rock is igneous, metamorphic, or sedimentary (e.g., Treiman et al., 2020).

4) Atmospheric phenomena as signs of volcanism

On Earth, local, regional, and sometimes global atmospheric properties provide evidence of volcanic eruptions, as they release volcanic and fumarolic gases, pyroclastic materials, and fine-grained ash particles. The distinct compositions of volcanic gases (CO_2, H_2O, CO, SO_2, H_2S, OCS, S_2, HCl, and HF) and stable isotopes (H, C, O, S, Cl, He, etc.) (Giggenbach, 1996; Oppenheimer et al., 2014; Symonds et al., 1994) compared to the N_2-O_2 rich and SO_2-poor air results in compositionally distinct plumes. These differences facilitate chemical interactions between volcanic and atmospheric compounds. In the troposphere, 'acidic' volcanic gases (SO_2, H_2S, HCl, HF) are removed from the atmosphere quickly. This removal includes interaction with atmospheric moisture, oxidation of SO_2 in sulfate aerosol, and acid rain (e.g., Mather, 2015), as well as interaction with geological materials (tephra, lava) (e.g., Bagnato et al., 2013). If volcanic plumes reach the stratosphere, the complex photochemical oxidation of SO_2 leads to the formation of acid sulfate aerosols, which could persist for over a year (Mather, 2015; Oppenheimer et al., 2011; Schmidt and Carn, 2022; Warneck, 1999). Stratospheric sulfate aerosols affect the radiation balance and can cause global cooling. Degassing of trace elements (Edmonds et al., 2022) affects the composition of air, clouds, and fallouts. Tephra can alter the optical properties of the atmosphere, thereby impacting heat transfer, clouds, and precipitation. Lightning typically occurs above active vents and within eruptive columns, and lightning networks can be used to monitor eruptions (Van Eaton et al., 2016). The listed compositional and physical atmospheric phenomena can inform the location, efficiency, eruption style, tectonic settings of eruptions, and the composition of magma and its degassing products. The differences between the atmospheres and volcanic activities on Earth and Venus imply significantly different manifestations of volcanic eruptions in their respective atmospheres.

Venus' atmosphere is nearly two orders of magnitude denser than Earth's (Prinn and Fegley, 1987). Unlike Earth's 6 to 18 km thick troposphere, which varies as a function of latitude and season, Venus' troposphere is 58 to 62 km thick, with an almost adiabatic temperature-pressure profile below the cloud deck at 43 to 47 km (Limaye et al., 2018; Seiff et al., 1985). At the mean planetary radius [6051.4 km, 95.6 bars, 740 K; 467°C (Ford and Pettengill, 1992)], the atmospheric density is 66.8 kg m^{-3} (Seiff et al., 1985), which is 55 times that of air at sea level on Earth. The atmospheric pressure, which is equivalent to the pressure at ~ 1 km ocean depth on the Earth, should suppress volcanic degassing (e.g., Gaillard and Scaillet, 2014; Garvin et al., 1982; Head and Wilson, 1986), which is consistent with uncertain signs of pyroclastic volcanic activity in Magellan radar images (Campbell et al., 1997; Head et al., 1992; see Section 2).

Compared to Earth's atmosphere, Venus' atmosphere is rich in CO_2, SO_2, HDO, N_2, and non-radiogenic noble gases (^{4}He, ^{20}Ne, ^{22}Ne, ^{36}Ar, ^{38}Ar) and depleted in O_2, H_2O, and ^{40}Ar [**Table 2,** (Fegley, 2014; Marcq et al., 2018; Mills et al., 2007)]. Higher relative abundances of carbon, nitrogen, and non-radiogenic ^{36}Ar in Venus' atmosphere than in the combined atmosphere-ocean-crust reservoir on Earth suggest a higher degree of overall degassing of the interior; however, the lower abundance of ^{40}Ar may imply degassing earlier in its evolution than for the Earth (see review by Gillmann et al., 2022). It has been suggested that the observed CO_2 and N_2 in Venus' atmosphere are generated by ongoing and protracted volcanism, linked to differing tectonic regimes (e.g., Prinn and Fegley, 1987; Weller et al., 2023). In addition to CO_2 and N_2, atmospheric SO_2 could reflect significant volcanic degassing (e.g., Bullock and Grinspoon, 2001; Fegley and Treiman, 1992; Zolotov, 2025) during the formation of vast volcanic plains that are thought to have occurred in a geologically short period within 0.6 to 0.8 Ga (Korycansky and Zahnle, 2005; McKinnon et al., 1997). Abundant sulfur in otherwise basaltic probes of surface rocks (**Table 1a)** suggests possible partial trapping of degassed S-bearing species into secondary minerals since the global volcanic resurfacing during the formation of plains and other volcanic features. Lower atmospheric Cl/S and F/S ratios (**Table 2)** compared to terrestrial volcanic gases (Oppenheimer et al., 2014; Symonds et al., 1994) imply more efficient trapping of volcanic halogens than S-bearing gases. The trapping of halogens via gas-solid-type reactions at the surface is consistent with ≤ 0.3 wt% Cl reported from the Vega 2 descent probe analysis (**Table 1a)** and with a thermodynamic drive for the interaction of HCl and HF gases with rock-forming minerals (Fegley and Treiman, 1992; Lewis, 1970; Zolotov, 2018).

The bulk composition and speciation of planetary volcanic gases mainly depends on abundances of C, S, H, Cl, and F in magma, the redox state (fO_2) of the magma, and the effect of pressure on the solubility of corresponding species in the melt (CO_2, CO, SO_2, H_2O, H_2, etc.) (Gaillard et al., 2021; Gaillard and Scaillet, 2014). Although abundant atmospheric SO_2, sulfuric acid in cloud aerosols, and exogenic sulfur (and possibly chlorine) in surface materials indicate volcanic degassing, the composition of Venus' volcanic gases is uncertain. If the magmatic fO_2 is between the QFM (quartz-fayalite-magnetite) and IW (iron-wüstite) buffers inferred from the Fe/Mn ratio in three surface probes (**Table 1a**) (Schaefer and Fegley, 2017), oxidized volcanic gases (CO_2, SO_2, and H_2O) should dominate over reduced species (CO, OCS, H_2S, S_2, and H_2); however, as on Earth (McCammon, 2005), fO_2 could vary depending on tectonic settings and magma sources. Importantly, the amount of H-bearing species in melts and volcanic gases is a significant unknown. Given the scarcity of atmospheric water vapor (**Table 2**), H-depleted melts at fO_2 levels between the QFM and IW buffers could degas S-Cl, S-Cl-O, and S-F (e.g., SCl, S_2Cl, Cl_2S, SCl_2, $SOCl_2$) species instead of H_2O, H_2S, HCl, and HF present in terrestrial gases, as modeled for H-depleted Io (Fegley and Zolotov, 2000) and Venus (Zolotov and Matsui, 2002). The atmospheric pressure of ~92 bars suppresses the degassing of high-solubility water compared to low-solubility CO_2, CO, and H_2 (Dixon and Stolper, 1995; Dixon et al., 1995; Hirschmann et al., 2012; Holloway et al., 1992; Mysen et al., 2009). Gaillard and Scaillet (2014) and Gaillard et al. (2021) modeled a significant suppression of SO_2 degassing at ~100 bars, resulting in a CO_2/SO_2 mixing ratio of $\sim 10^3$. In contrast, Fegley and Treiman (1992) and Bullock and Grinspoon (2001) suggested a supply of magmatic sulfur to the Venusian atmosphere, that includes oxidation of pyrrhotite by atmospheric CO_2 and H_2O. Zolotov (2025) referred to the SO_2 solubility models of Boulliung and Wood (2023) and Ding et al. (2023) to argue for comparable mixing ratios of SO_2 and CO_2 released from vents and lava flows at Venus-relevant pressures. The latter estimates align with the atmospheric abundance of S-bearing species (**Table 2**) and the presence of apparently exogenic sulfur in surface materials (**Table 1a**). **Table 2** illustrates that Venus' volcanic gases can be characterized by C, S, Cl, and F abundances and redox states typical of terrestrial basaltic eruptions; however, the bulk H abundance and the speciation of S, Cl, and F gases are more uncertain, especially when H is strongly depleted (H/C atomic ratio $< 8 \times 10^{-3}$, Zolotov and Matsui, 2002).

The vast volume of volcanic formations inferred largely from Magellan radar images (Section 2) and abundant sulfur in surface materials (**Table 1a**) suggest volcanic degassing followed by sequestration of atmospheric sulfur into secondary minerals (e.g., Fegley and Treiman, 1992; Johnson and Fegley, 2002; Prinn and Fegley, 1987; Treiman and Schwenzer, 2009; Zolotov, 2025). The inconsistency of abundant SO_2 in the atmosphere with the instability of basalt in contact with Venus' SO_2 (Section 6) indicates incomplete trapping of degassed S-bearing gases, which is also supported by low (<1) and variable S/Ca atomic ratios in surface probes (**Table 1a**) (e.g., Fegley and Treiman, 1992; Zolotov, 2025; Zolotov and Khodakovsky, 1989). This inconsistency implies a faster volcanic supply of S-bearing gases than their sequestration into secondary minerals. A scarcity of experimental data on the rates of SO_2 interaction with geological materials under Venus' conditions (Section 6) limits the interpretation of atmospheric abundances of SO_2 in terms of ongoing or recent volcanism.

Fegley and Prinn (1989) experimentally inferred the geological rapid sequestration of current atmospheric SO_2 through the sulfatization of calcite to anhydrite (1 μm yr^{-1} $CaSO_4$ formed) when calcite is present on the surface. Based on these values, Fegley and Treiman (1992) noted that atmospheric SO_2 could deplete to fSO_2 at the $CaSO_4$-$CaCO_3$ equilibrium in ~ 1.9 Ma. Fegley and Prinn (1989) and Fegley and Treiman (1992) demonstrated that experimental data on SO_2 interaction with diopside indicate much slower SO_2 sequestration via the sulfatization of silicates in basalts. They stated that maintaining SO_2 in the atmosphere requires volcanic degassing at rates comparable to the rate of sulfatization and suggested a steady state concerning atmospheric SO_2. Based on the rate of calcite alteration, Fegley and Prinn (1989) estimated the rate of current volcanism in the range of 0.4-11 km^3 yr^{-1}, with a nominal value of ~1 km^3 yr^{-1}. Fegley and Treiman (1992) noted that estimates based on diopside alteration data suggest significantly lower rates of volcanic activity. Bullock and Grinspoon (2001) developed a climate model that simulated the fate of atmospheric SO_2 and H_2O following a global volcanic resurfacing into the present and future. In their models, the degassed SO_2 interacted with calcite, which was assumed to be present in permeable surface materials. They found that sustaining existing sulfuric acid-rich clouds necessitates the outgassing of S-bearing volcanic species over the past 20–50 Myr. Although these approaches are methodologically viable, applying such models to volcanic degassing is questionable considering the instability of calcite, and limited understanding of potential pathways for calcite production, in contact with atmospheric SO_2, S_2, and CO (Fegley and Treiman, 1992; Zolotov, 2018, 2025, for reviews) and the morphological evidence for widespread basaltic materials (Section 2) that do not contain calcite. In summary, a meaningful use of the global abundances of atmospheric gases to constrain the volcanic degassing rate requires data on the kinetics of the advanced stages of gas-solid reactions in basalt (Section 6), and the resurfacing rate.

The detection of current volcanic activity through atmospheric measurements is hindered by several factors: limited high-pressure degassing of mafic magma, restricted pyroclastic activity, a denser atmosphere, the thick cloud layer, and the presence of abundant atmospheric gases that are expected in volcanic emissions (CO_2, SO_2, CO, OCS, S_2, etc.). The dominance of basaltic eruptions, evidenced by the current state of radar imaging (Barsukov et al., 1986c; Ghail et al., 2024; Hahn and Byrne, 2023; Head et al., 1992; Ivanov and Head, 2025; Ivanov and Head, 2013 and as described in section 2), implies neither significant degassing nor the formation of eruptive columns typical of volcanoes at convergent plate boundaries on Earth. The dense atmosphere confines the formation of eruptive columns that could deliver volcanic gases and ash/tephra to higher altitudes (Airey et al., 2015; Glaze et al., 2009; Glaze et al., 2011). Atmospheric CO_2 absorbs in the near-infrared (NIR) spectral range, limiting the measurement of SO_2, CO, OCS, and H_2O below an altitude of ~33 km (Arney et al., 2014; Marcq et al., 2013; Marcq et al., 2023; Marcq et al., 2018; Pollack et al., 1993), though H_2O may be measurable down to ~10km in certain transparency windows (Evdokimova et al., 2025). Suppressed volcanic degassing and a dense atmosphere suggest a low volcanic/atmospheric gas ratio in the near-surface gas phase affected by volcanism. Consequently, the initially scarce volcanic gases become further diluted, forming shallow plumes aligned with the west-band atmospheric circulation pattern. All this reduces the chances of detecting volcanic gases and particulates via remote and in situ measurements above the near-surface atmosphere in the vicinity of eruptions.

Table 2. Volume ratios of chemically active gases in the near-surface atmosphere and possible volcanic gases on Venus.					
	Atmosphere at 740 K, 467 °C, 95.6 bars	Volcanic gas at 1500 K, 1227 °C, 92.1 bars			
		H-rich-QFM	H-poor-QFM	H-rich-IW	H-poor-IW
CO_2	**0.965**	0.316	0.689	0.0879	0.167
N_2	(0.035)	1.23×10^{-4}	2.73×10^{-4}	1.36×10^{-4}	3.45×10^{-4}
SO_2	$\mathbf{1.3 \times 10^{-4}}$	0.106	0.224	2.89×10^{-6}	4.22×10^{-5}
H_2O	$\mathbf{3 \times 10^{-5}}$	0.518	2.01×10^{-12}	0.207	1.05×10^{-13}
OCS	2.8×10^{-5}	1.33×10^{-3}	6.17×10^{-3}	6.24×10^{-3}	0.173
CO	$\mathbf{1.7 \times 10^{-5}}$	0.0118	0.0256	0.278	0.53
HCl	$\mathbf{4 \times 10^{-6}}$	1.45×10^{-3}	1.10×10^{-5}	1.64×10^{-3}	2.01×10^{-5}
S_2	2.3×10^{-7}	9.36×10^{-3}	0.0421	3.67×10^{-4}	0.0781
H_2S	1.1×10^{-7}	0.025	2.06×10^{-13}	0.168	1.24×10^{-12}
S_2O	3.2×10^{-8}	1.55×10^{-3}	6.97×10^{-3}	7.45×10^{-7}	1.52×10^{-4}
H_2	3.5×10^{-9}	7.32×10^{-3}	2.84×10^{-14}	0.248	1.26×10^{-13}
HF	$\mathbf{5 \times 10^{-9}}$	1.45×10^{-3}	3.44×10^{-5}	1.64×10^{-3}	3.76×10^{-5}
S_3	8.4×10^{-10}	1.05×10^{-4}	1.00×10^{-3}	8.16×10^{-7}	2.53×10^{-3}
CS_2	6.5×10^{-11}	1.32×10^{-6}	1.30×10^{-5}	1.05×10^{-4}	0.0423
SO	3.1×10^{-11}	2.82×10^{-4}	5.98×10^{-4}	6.56×10^{-7}	9.57×10^{-6}
S_4	7.0×10^{-12}	3.66×10^{-6}	7.41×10^{-5}	5.63×10^{-9}	2.55×10^{-4}
S_5	2.0×10^{-12}	1.20×10^{-8}	5.18×10^{-6}	3.67×10^{-12}	2.42×10^{-6}
HS	1.0×10^{-12}	1.36×10^{-4}	5.68×10^{-10}	1.57×10^{-4}	1.63×10^{-9}
SO_3	3.3×10^{-13}	5.15×10^{-7}	1.11×10^{-6}	1.67×10^{-13}	2.44×10^{-12}
S_6	1.6×10^{-13}	1.88×10^{-9}	1.71×10^{-7}	1.14×10^{-13}	1.09×10^{-6}
$\log_{10} fO_2$	-21.31	-7.76	-7.76	-11.62	-11.62

Note. A volume mixing ratio is the volume fraction of a gas in a gas mixture. The atmospheric composition corresponds to the Vernadsky chemical equilibrium model from Fegley et al. (1997b) for the conditions of mean planetary radius (6051.4 km). Values in bold correspond to measured mixing ratios extrapolated to the surface. S_2O is from Model 8 in Zolotov (2025). These values serve as anchors to calculate the concentrations of other gases in the near-surface atmosphere. The volcanic gas models from Zolotov and Matsui (2002) correspond to ideal gas phase chemical equilibria, constrained by atomic abundances of elements and selected fO_2 controlled by mineral buffers. H-rich models for volcanic gases possess an H/C atomic ratio of 3.4, as in the Kilauea 1918-1919 volcanic gas (Gerlach, 1980). As in Venus' atmosphere, H-poor volcanic models have a C/H atomic ratio of 6.3×10^{-5}. fO_2 is in bars. QFM, quartz-fayalite magnetite fO_2 buffer; IW, iron-wüstite fO_2 buffer.

Despite the difficulties, some volcanic products could be delivered to the sub-cloud atmosphere (~ 35 to 48 km) and clouds (~ 48 to 70 km) by equatorial upwelling in the Hadley-cell type circulation suggested from latitudinal variations of COS, CO, and SO_2 contents measured in the middle and lower atmosphere (Arney et al., 2014; Marcq et al., 2008; Marcq et al., 2005; Marcq et al., 2023; Oschlisniok et al., 2021; Tsang et al., 2008; Tsang and McGouldrick, 2017) and from wind direction data in the lower clouds (Gorinov et al., 2021). Possible polar vortices upwelling (Limaye et al., 2009; Luz et al., 2011; Oschlisniok et al., 2021) also provides such an opportunity. Another possibility is delivery by atmospheric gravity waves (e.g., Navarro et al., 2018) that form through the interaction of the near-surface gas layer with elevated topography regions. The existence of gravity waves is evidenced by the UV and IR features at cloud tops (Bertaux et al., 2016; Fukuhara et al., 2017; Fukuya et al., 2022; Kitahara et al., 2019; Kouyama et al., 2017), CO abundances in the middle and lower atmosphere (Marcq et al., 2023), and winds in the upper mesosphere (Gorinov et al., 2018). Remote detection of SO_2, OCS, and CO below ~30 km is impossible from both ground-based and Venus' orbital spectroscopic observations (Arley et al. 2014; Marcq et al., 2021, 2023). Volcanic gases can be remotely detected above 30 km (and possibly down to 10km for H_2O) in the equatorial atmosphere, polar regions, and areas with gravity waves associated with large highlands (e.g., Aphrodite Terra). The highlands are especially important because the convective layer above them is expected to be strong (Lebonnois et al., 2018), facilitating the vertical transport of gases. Even without ash reaching above 30 km, a tephra-rich plume raised to a few kilometers could be detected in the NIR within CO_2 spectral windows, as it "would produce a dark feature resembling a mountain" (Arney et al., 2014). Likewise, an ash-rich plume could potentially be distinguished via polarimetric radar imaging by disrupting the microwave emissivity from surface materials (and hence their complex dielectric permittivity). Repeated polarimetric SAR imaging will inform any changes to plume characteristics. A disturbance in global atmospheric circulation above a hot lava flow, especially in near-surface layers (D'Incecco et al., 2021a), also allows for the detection of active eruptions. For example, Gorinov et al. (2021) analyzed the Venus Express VIRTIS dataset, which inferred a deceleration of the zonal wind in the lower clouds above the potentially volcanically active Imdr Regio, as suggested by Smrekar et al. (2010). They noted that the deceleration cannot be explained solely by the propagation of vertical stationary gravity waves, as no other highland has been shown to affect the lower cloud winds. Although an influence of a propagating thermal plume above a hot lava flow is possible, it has yet to be verified by further observations in the Southern hemisphere and plume modeling.

The compositional difference between volcanic and atmospheric gases (**Table 2, Fig. 4**) potentially allows for detecting volcanic tracers in diluted plumes (Wilson et al., 2024). Except for CO_2, which is abundant in the atmosphere, all modeled volcanic gases could serve as markers if their concentrations significantly differ from atmospheric values. Notably, abundant CO and OCS detected remotely or in situ could be such tracers, especially in reduced volcanic gases with elevated CO/SO_2 and OCS/SO_2 ratios (Zolotov and Matsui, 2002). If volcanic abundances of CO_2 and SO_2 are compatible, locally elevated SO_2/CO_2 mixing ratios exceeding atmospheric 2×10^{-4} would indicate active volcanic degassing. Even if H_2O is present in the melt, it would not then generate significant volcanic gas but still may act as a potential (short-lived; temporally and spatially) volcanic tracer (e.g., Weller and Kiefer, 2025). H-poor magmas and gases provide more opportunities for testing due to the presence of other gases not typically abundant in the atmosphere. Given the low atmospheric HCl and HF abundances (**Table 2**), which imply trapping in secondary minerals (Fegley and Treiman, 1992; Zolotov, 2018), their concentrations beyond 10 ppm and 10 ppb levels, respectively, would suggest ongoing volcanic degassing.

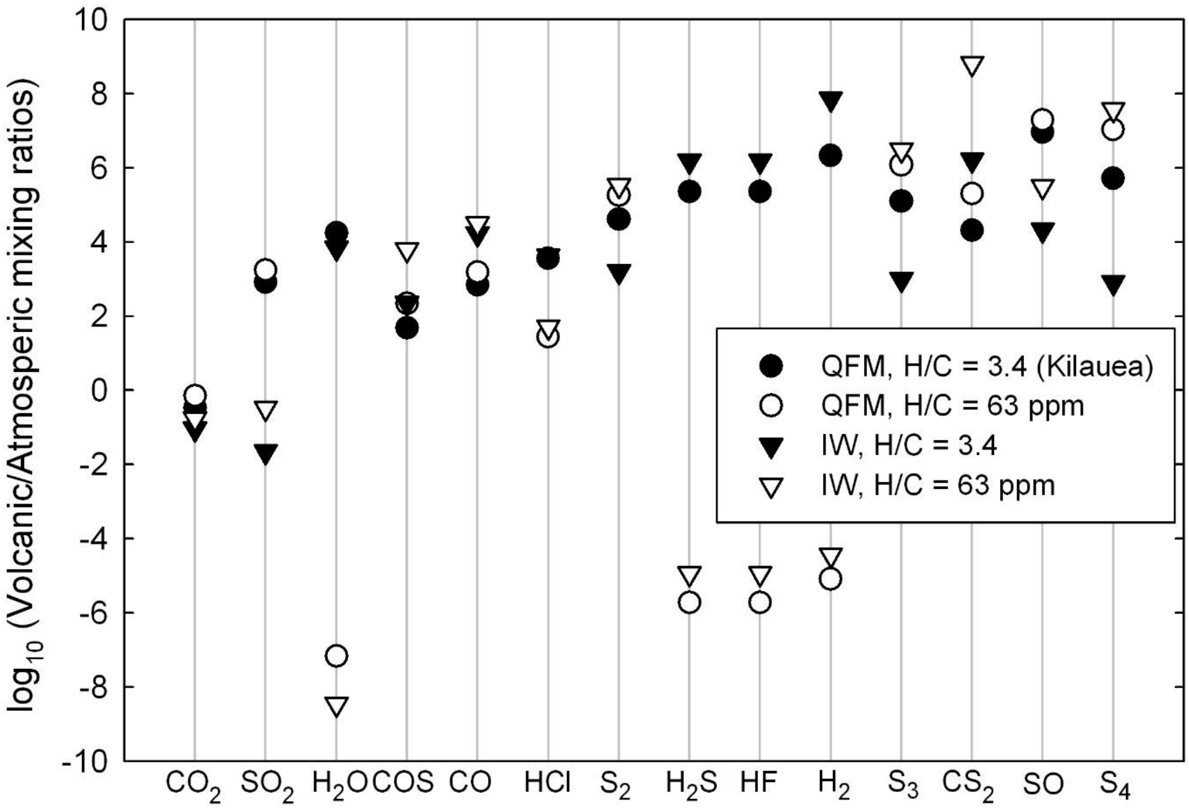

Fig. 4. Venus' volcanic/atmospheric gas ratios. The atmospheric and volcanic gas compositions are from Table 2. The plot illustrates that, except for CO_2 and SO_2, the supposed Venusian volcanic gases are of orders of magnitude more (or less) abundant than their atmospheric counterparts. The difference suggests that they could be distinguished in moderately diluted plumes. The figure is modified after Wilson et al. (2024).

It is unclear whether global Hadley-type cell circulation, oligarchic waves, or polar upwellings transport volcanic products faster than the gravitational settling of ash particles, dilution, and consumption in chemical reactions with gases and solids (ash, surface, and permeable crustal materials). The difference in chemical equilibrium speciation between atmospheric and volcanic gases **(Table 2**, **Fig. 4)** suggests that previous volcanic gases have been chemically altered and consumed through reactions with each other and atmospheric gases. Re-equilibration of volcanic gases at surface conditions changes key gas ratios. Interaction with atmospheric gases leads to the consumption of most degassed reduced species (CO, OCS, S_2, CS_2) into oxidized species (CO_2, SO_2) that are abundant in the atmosphere (**Fig. 5)**. Volcanic CO_2 and SO_2 are more likely to be affected by dilution than by gas-phase chemical consumption. The thermodynamic instability of S-Cl, S-Cl-O, and S-F species in the lower atmosphere implies their consumption, likely via reactions with water vapor, leading to the formation of HCl and HF gases (Wilson et al., 2024), which are the most thermodynamically stable Cl- and F-bearing atmospheric gases (**Table 2**). Considering suppressed degassing via non-explosive eruptions and a dense near-surface atmosphere, fractions of SO_2, HCl, and HF in moderately diluted plumes could also be sequestered via gas-solid reactions. At the same time, the rest of these gases contribute to the atmospheric inventory of these species. In summary, the physics and chemistry of volcanic-atmospheric gas interactions would decrease the COS/SO_2, CO/SO_2, and S_2/SO_2 ratios in plumes due to dilution and gas-phase redox reactions.

On Earth, the stable isotopic composition of H, He, C, N, O, S, Cl, and Ar in volcanic gases differs from that in the atmosphere (Oppenheimer et al., 2014). This composition varies depending on tectonic setting, volcano type, magma source, eruption style and stage, and crustal contamination. While Venus' volcanic gases may have a more uniform isotopic composition, predicting their makeup is difficult without a better understanding of local and global specific geological history. Nonetheless, local isotopic anomalies near potential eruptions could not only support the presence of degassing but also provide insight into magma sources and the fate of magmatic volatiles, particularly C-O-S-H species.

Possible signs of lightning have been suggested by data from various missions, including the Venera 11 and 12 probes, Pioneer Venus Orbiter, Venus Express, Akatsuki orbiters, and ground-based observations (Grebowsky et al., 1997; Ksanfomaliti et al., 1983; Lorenz, 2018; Russell, 1991). In his critical review, Lorenz (2018) discussed the complexities and challenges of detecting and interpreting lightning signals and suggested that only events detected in the visible range can be reliably attributed to lightning. No lightning was detected in Akatsuki's optical emission data during the first three years of observations, suggesting that the electromagnetic signals observed by other missions were unrelated to lightning (Lorenz, 2018). Interpretations of lightning from Parker Solar Probe and Pioneer Venus orbiter have also been challenged or eliminated (George et al., 2023; Taylor Jr and Cloutier, 1992). These results suggest that the occurrence rates of lightning inferred from current data are likely overestimated and tentative at best. While a definitive lightning detection does not necessarily indicate active volcanic plumes, such findings could still serve as volcanic markers when complemented by other independent data, such as zonal and vertical winds, NIR and microwave imaging, and more.

Although no definitive signs of volcanic activity have been observed within the atmosphere to date, several datasets have been discussed suggesting ongoing or recent volcanic degassing. The decrease in SO_2 abundance at the cloud tops, from ~500 ppb to ~20 ppb, observed from 1978 to 1992 with UV spectroscopy with the Pioneer Venus Orbiter, was initially interpreted as evidence of variable volcanic degassing (Esposito, 1984; Esposito et al., 1988); however, the dense atmosphere and limited volcanic degassing (e.g., Head and Wilson, 1986) suggest that volcanic plumes would not reach the cloud tops (65 to 70 km) (Glaze, 1999). The SO_2 mass in the atmosphere (10^{17} kg) is unlikely to be significantly affected by even major volcanic events over years [the flux of volcanic SO_2 on Earth is ~2×10^{10} kg/yr (Carn et al., 2017; Schmidt and Carn, 2022)]. Subsequent long-term (2007-2012) observations of changes in cloud-top SO_2 content by the Venus Express orbiter (Marcq et al., 2013) and the Hubble Space Telescope (Jessup et al., 2015) did not show a correlation with the relatively uniform SO_2 mixing ratio of (1-2) × 10^{-4} measured via gas chromatography (Gelman et al., 1980b; Oyama et al., 1980) and remote observations of the lower atmosphere (Arney et al., 2014; Bézard et al., 1993; Marcq et al., 2021; Marcq et al., 2008; Marcq et al., 2023; Pollack et al., 1993) and lower clouds (Oschlisniok et al., 2021). The anti-correlation of SO_2 and H_2O at cloud tops reported by Encrenaz et al. (2020) suggests an atmospheric phenomenon. Earth-based and HST observations of SO_2 in upper clouds over the last two decades reveal both short- and long-term variability in plume intensity (Encrenaz et al., 2019; Jessup et al., 2015; Marcq et al., 2020). Periods of high SO_2 abundance could have caused by multiple low-latitude plumes, as suggested by Marcq et al. (2020). Other models explained the long-term SO_2 viability by periodic changes in effective eddy diffusion in clouds (Krasnopolsky and Krasnopolsky, 1986) and in global circulation (Clancy and Muhleman, 1991). According to models of Kouyama et al. (2019) and Kitahara et al. (2019), the variability may reflect momentum deposition from propagating atmospheric gravity waves induced by topography. In summary, the long-term SO_2 trends observed at the cloud tops since the 1960s likely reflect changes in the cloud circulation regime influenced by low-altitude plumes.

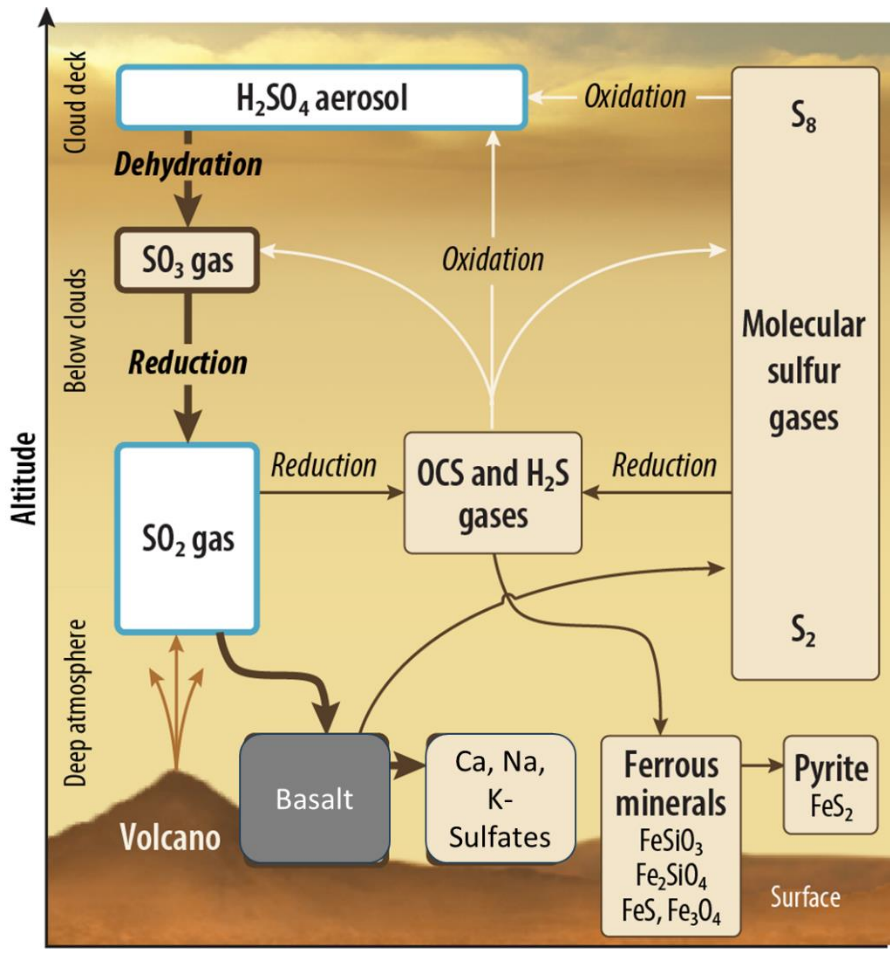

Fig. 5 A simplified sulfur cycle in the atmosphere-surface system on Venus focused on volcanic outgassing. Note that volcanic gases also contain OCS, H_2S, and S_2 (Table 2). The figure is modified from Garvin et al. (2022) and updated based on Filiberto and McCanta (2024). For more detailed geochemical cycles see Prinn (1985); Prinn and Fegley (1987); Fegley et al. (1995b), and Zolotov (2025).

5) Evidence for potential volcanic and tectonic activity from Magellan and Venus Express datasets.

NASA's Magellan orbital mission performed moderate-resolution Synthetic Aperture Radar (SAR) mapping of almost the entire surface (Ford et al., 1993), showing a complex surface geology with likely recent volcanic activity (Section 2) and tectonism playing a vital role in its recent geologic evolution (< ~0.7 Ga). Combined analysis of the Magellan radar datasets (SAR, altimetry, and microwave emissivity) and the datasets provided by the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) (Piccioni et al., 2007) and Venus Monitoring Camera (VMC) (Markiewicz et al., 2007) instruments mounted onboard ESA's Venus Express spacecraft (Svedhem et al., 2007b) have provided evidence of geologically recent and possibly ongoing volcanic, as well as tectonic, activity (Bondarenko et al., 2010; Brossier et al., 2021; Brossier et al., 2022; Brossier et al., 2020; D'Incecco et al., 2021; D'Incecco et al., 2020; D'Incecco et al., 2017; D'Incecco et al., 2022; Filiberto et al., 2021; Mueller et al., 2008; Shalygin et al., 2012; Shalygin et al., 2015; Smrekar et al., 2010; Stofan et al., 2016).

5.1 Idunn Mons: a possibly active volcano with the most complete data coverage currently available

Smrekar et al. (2010) observed locally high "model-based" NIR emissivity anomalies over the summit area and eastern flank of Idunn Mons (46° S; 146° W, **Fig. 6**), the most prominent volcanic structure of Imdr Regio (López et al., 2022; López et al., 2024; López et al., 2023; Stofan and Smrekar, 2005; Stofan et al., 1995), suggesting that these NIR anomalies are possible evidence for unweathered and potentially recently erupted basaltic rocks. Combining 1-μm emissivity modeling (100 km scales) and radar mapping (100 m scales) using cross-cutting relationships between the mapped units, D'Incecco et al. (2017) attempted to constrain the location and extent of the lava flows possibly responsible for the VIRTIS emissivity anomalies observed by Smrekar et al. (2010). Based on this, D'Incecco et al. (2017) proposed that flank rather than summit flows may be responsible for the observed emissivity anomalies. Brossier et al. (2020) focused on the Magellan radar emissivity signatures over Idunn Mons, which are consistent with the observations made by the VIRTIS instrument that indicate the presence of fresh and relatively unweathered basalt. D'Incecco et al. (2020) used the potentially geologically recent 17.9 km diameter Sandel crater (45.7°S/211.7°E, **Fig. 6**), situated NW of Idunn Mons, as a stratigraphic marker to assess the relative age of the geologic activity in the area surrounding Idunn Mons and proposed that it should have: 1) been both volcanically and tectonically active in recent geologic times, and 2) that the volcanic and tectonic activity are likely contemporaneous. This assertion was based on the relative freshness of its impact deposits (in Magellan SAR), and the cross-cutting interrelationships showing some tectonic fractures and graben locally disrupting the impact deposits associated with Sandel crater and its crater floor. The observation that Idunn Mons and its surroundings can be seen as an area of relatively recent volcano-tectonic activity is further supported by the morphology and structural geology of Idunn Mons with Olapa Chasma, the rift zone along which Idunn Mons is situated (D'Incecco et al., 2020; López et al., 2022; 2024; 2023) (**Fig. 6**).

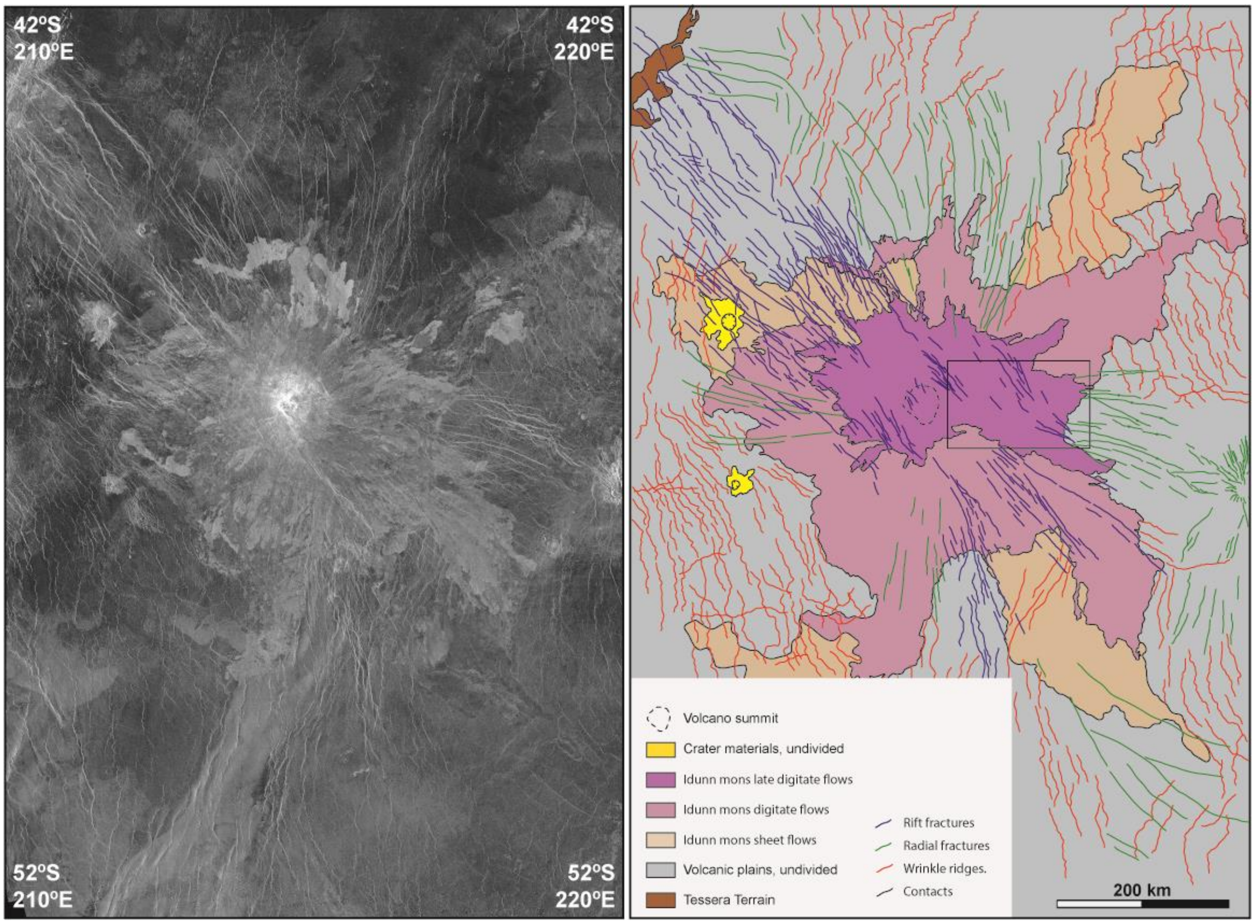

Fig. 6. Regional view of the Olapa Chasma–Idunn Mons (OCIM) volcano-tectonic system. The rectangle marks the location of the recent volcanic materials on the flank of Idunn Mons (Smrekar et al., 2010; D'Incecco et al., 2017). The image is a left-looking normal Magellan SAR image processed from the Magellan SAR FMAP Left Look Global Mosaic 75m. Image from USGS.

https://astrogeology.usgs.gov/search/map/venus_magellan_sar_fmap_left_look_global_mosaic_75m

5.2 Maat Mons & Ganis Chasma in Atla Regio: other possible volcanically active areas

Using microwave active and passive data from NASA's Magellan mission, several studies revealed that some large volcanoes exhibit abnormal declines in the S-band microwave emissivity at their summits (Bondarenko et al., 2010; Brossier et al., 2020; Klose et al., 1992; Pettengill et al., 1992). This phenomenon is commonly ascribed to minerals having high dielectric permittivity (and hence higher than typical loss tangents), produced or stabilized by temperature, such as ferroelectric minerals (Brossier and Gilmore, 2021; Brossier et al., 2020; Treiman et al., 2016). In this model, the altitude of the emissivity excursion is a function of composition, while its magnitude is a function of the volume of ferroelectric minerals (Shepard et al., 1994). Brossier et al. (2021) showed that specific ferroelectric signatures correlate with individual large lava flows, suggesting that ferroelectric minerals are related to rock composition, as opposed to the regional deposition of atmospheric precipitates for these volcanic systems. Sites with strong microwave emissivity excursions at high altitudes are thought to have had enough time to produce the ferroelectric minerals responsible for the dielectric anomalies in those regions. Conversely, sites with subtle or no microwave emissivity excursions at high altitudes are considered young or possibly active since they have limited ferroelectric minerals (Brossier et al. 2021). Interestingly, microwave emissivity signatures at Maat, Idunn, and Otafuku Montes, as well as the novae within Pavlova and Didilia coronae, are consistent with lower volumes of ferroelectric minerals and may indicate relatively recent and less weathered basaltic lava flows (Brossier et al., 2020).

Detailed geological mapping (from Magellan SAR) and relative lithostratigraphic analysis across Ozza and Maat Montes at Atla Regio (Mason et al., 2025) have revealed that lava flows erupted from Maat Mons are likely between 9 and 60 Ma in apparent "age", the suggested age range for the Uvaysi impact (Brossier et al. 2021). All these volcanic edifices are associated with presumably active hotspots and smaller plumes/diapirs that are among the most likely sites for recent or current volcanic activity based on geophysical and morphological data (Herrick and Hensley, 2023; Smrekar, 1994; Stofan et al., 1995). Relatively unweathered basaltic flows have also been suggested for some flank deposits on Idunn Mons based on 1-µm VIRTIS data (D'Incecco et al., 2017; D'Incecco et al., 2021a; Smrekar et al., 2010). Thus, the microwave emissivity data provide an independent constraint on recent volcanic activity on the planet in agreement with NIR 1-µm modelled emissivity. The spatial scales of these datasets are many tens of km in contrast with Magellan's S-band SAR imaging.

Brossier et al. (2022) extended their survey to Ganis Chasma (**Fig. 7**), a rift valley in Atla Regio where recent volcanic activity was previously suggested based on the superposition of rift structures on young impact deposits (Basilevsky, 1993). Shalygin et al. (2015) analyzed the VMC NIR data from Venus Express to reveal multiple sites in the region showing an elevated (1-µm) emission with varying intensity over several days or months. Shalygin et al. (2015) suggested that these transient high- NIR emissivity sites are possibly associated with short-lived effusive activity, locally causing significant increases in surface temperatures relative to the already elevated Venus surface. According to Brossier et al. (2022), the microwave emissivity signatures in these sites are also consistent with the presence of ferroelectrics with subtle differences in the regional mineral composition, in agreement with the other volcanoes in Atla Regio (Brossier et al., 2021). They also demonstrated that the microwave emissivity signatures of these sites are broadly consistent with relatively young and unweathered basaltic materials, providing independent corroboration of ongoing (rift-associated) volcanism in Ganis Chasma.

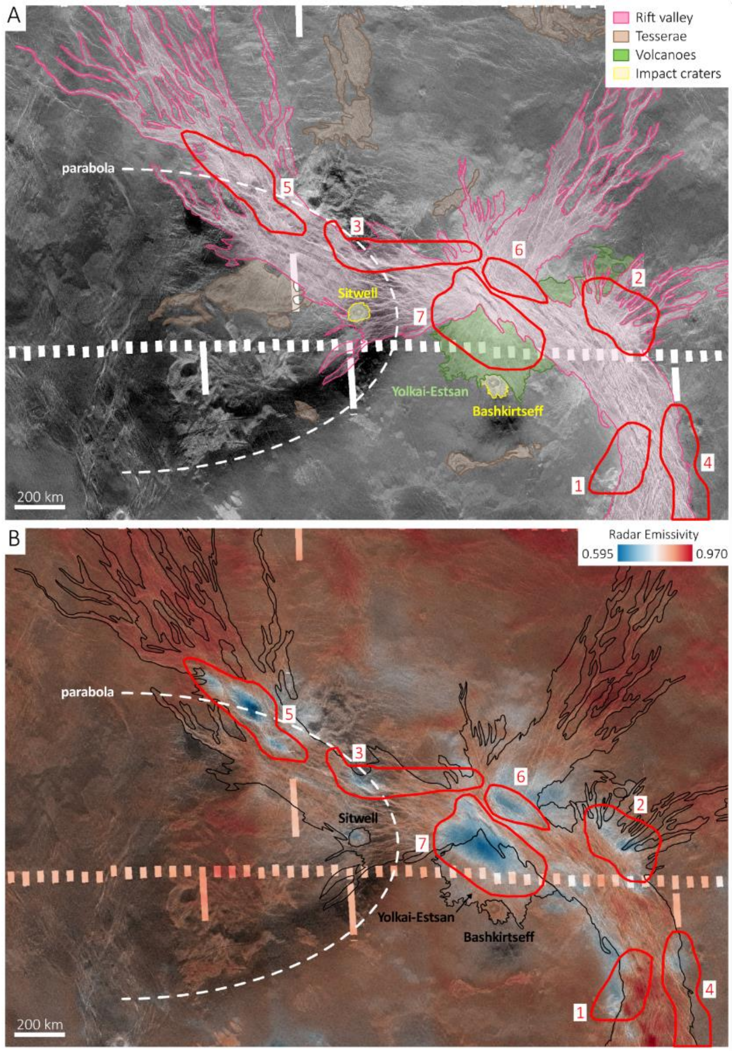

Fig. 7. Ganis Chasma through (A) Magellan SAR image and predominant morphologic features, and (B) microwave emissivity map (adapted from Brossier et al., 2022). The seven sites of interest defined by VMC observations (Shalygin et al., 2015) are outlined in red.

5.3 Active volcanism in coronae and other large tectono-magmatic features.

Most studies looking for evidence of active volcanism on Venus focus on large volcanoes and rift systems. Yet, there are other tectono-magmatic features with potential associations of active volcanism with tectonic activity: coronae. Coronae are large circular to elliptical volcano-tectonic features characterized by an annulus of tectonic structures (**Fig. 8**) (Copp et al., 1998; Stofan et al., 1992). The number of coronae (Gülcher et al., 2025; Stofan et al., 2001) and their global distribution suggests that they must have played an important role in as a source for resurfacing on the volcanic plains (DeLaughter and Jurdy, 1997; Namiki and Solomon, 1994), and contributing to the release of heat from the interior of the planet (Smrekar and Stofan, 1997; Stofan et al., 2001). Further, Aramaiti Corona, which will be discussed in more detail, is considered to be underlain by an active volcanic plume (Gülcher et al., 2020). This makes it very important to constrain whether some coronae are geologically active.

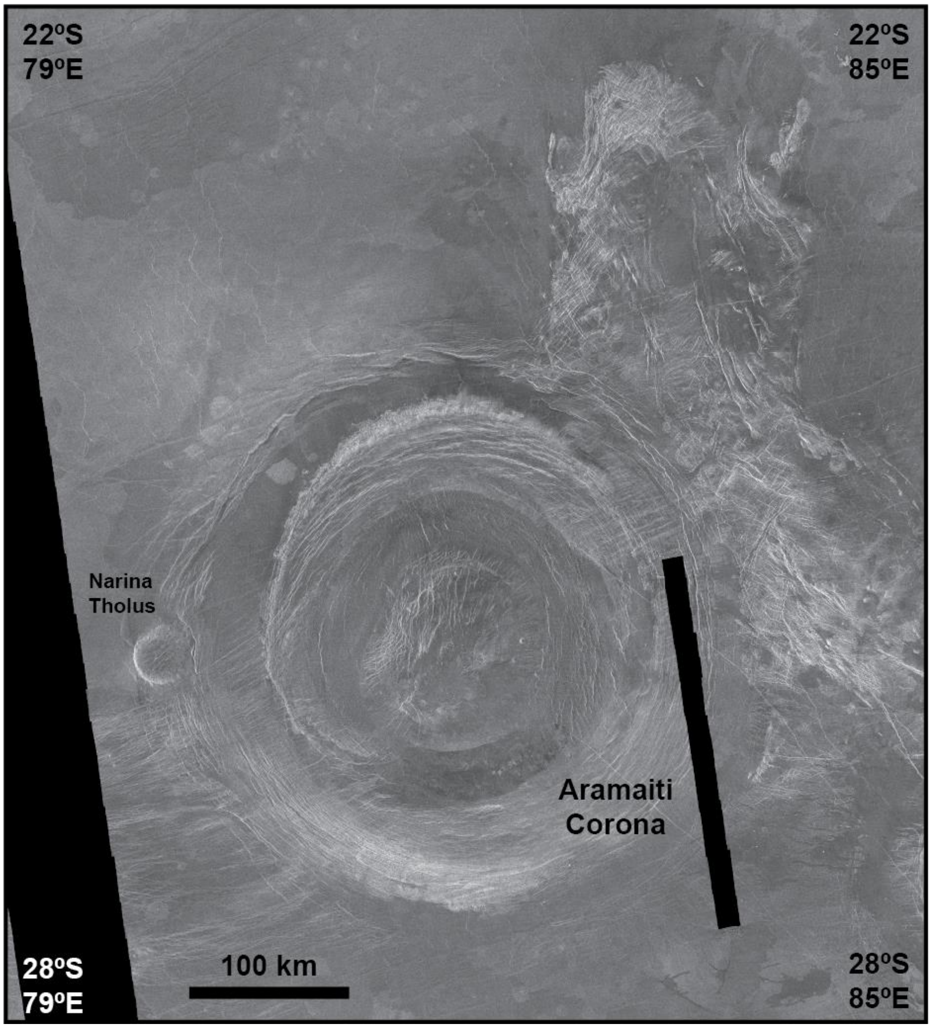

Fig. 8. Aramaiti Corona, Venus. This corona represents a classic example of this type of tectono-magmatic structure, composed of a ring of deformation structures or annulus and different types of associated volcanism. Narima Tholus, a steep-sided dome formed in the corona annulus has been proposed as an area of potential active volcanism (Russell and Johnson, 2021). The image is a left-looking normal Magellan SAR image processed from the Magellan SAR FMAP Left Look Global Mosaic 75m. Image from USGS.

https://astrogeology.usgs.gov/search/map/venus_magellan_sar_fmap_left_look_global_mosaic_75m

The type of volcanism associated with coronae is diverse in scale and style, from extensive sheet flows surrounding the corona (Magee Roberts and Head, 1993; Stofan et al., 1992) to steep-sided-domes and clusters of small edifices located in their annuli and the interior of coronae (Lang and López, 2015; Stofan et al., 1992). Studies on the lithospheric flexure and heat flow associated with Narina Tholus, a steep-sided dome in the annulus of Aramaiti Corona (**Fig. 8**), suggest an elevated heat flow that would be consistent with late-stage and possibly recent volcanism (Russell and Johnson, 2021). Active volcanism in this corona, located in the volcanic plains of Tahmina Planitia, is important for being in a completely different tectonic setting than the other candidate sites for active volcanism. Further, recent work has suggested that at least 37 coronae present morphologies are compatible with active plumes and present-day activity (Gülcher et al., 2020; Gülcher et al., 2025). Recent work by Cascioli et al. (2025) furthers the case for recent activity at coronae on Venus, which suggests the potential for active seismicity (De Toffoli and Mazzarini, 2025).

Some coronae are also associated with high microwave emissivity, as those interpreted to be unweathered basaltic flows associated with large volcanoes (Brossier et al., 2020; D'Incecco et al., 2017; D'Incecco et al., 2021a; D'Incecco et al., 2021b; Smrekar et al., 2010) (see Section 5). Quetzelpetlatl and Boala Coronae in Lada Terra, which have large sheet flows with high emissivity values (Helbert et al., 2008; Ivanov and Head, 2010), are thought to be associated with a mantle plume near the south pole, far from the low latitude large topographic rises where active volcanism has been proposed. Themis Regio is a corona-dominated large topographic rise (Smrekar et al., 1997; Stofan et al., 2016) with coronae that also have emissivity anomalies in VIRTIS images (e.g., Mertseger Mons; Stofan et al., 2016), associated with Parga Chasma. To understand Venus' evolution, it is essential to constrain the existence of active volcanism in all these different sites, related to different types of mantle plumes and geologic environments (Stofan et al., 2016).

6) Alteration of Basalts to Constrain Spectroscopic Evidence

To estimate the relative age of lava flows from orbital measurements, it is critical to constrain alteration mineralogy, rate of alteration, and how secondary minerals affect specific spacecraft measurements (such as microwave and NIR emissivity) (e.g., Dyar et al., 2021). Since the surface is in contact with the hot dense, and caustic atmosphere, this causes the progressive formation of alteration minerals, which should, in turn, affect emissivity values of the crust [**Fig. 5;** (Filiberto and McCanta, 2024; Zhong et al., 2023; Zolotov, 2019; Zolotov, 2018)]. On Earth, the surface conditions on Venus equate to low-grade hornfels and greenschist metamorphic facies (e.g., Mueller, 1964; Semprich et al., 2020; Semprich et al., 2025). This would produce alteration minerals such as andalusite, garnet, cordierite, epidote, tremolite, and others (Semprich et al., 2020). Metamorphism of the crust may limit the crustal thickness to ~ 40 kilometers (Jull and Arkani-Hamed, 1995; Namiki and Solomon, 1993; Semprich et al., 2025), and depending on the thermal gradient and crustal composition can cause either delamination and crustal recycling or melting of the base of the crust causing volcanic eruptions (Semprich et al., 2025). This may provide a mechanism to produce volcanism today (Semprich et al., 2025) with a wide range of lava compositions (Semprich, 2024). However, metamorphic reactions at these facies are kinetically driven, and water and CO_2 play an important role in driving these reactions (e.g., Semprich et al., 2020; Semprich et al., 2025). On Venus, liquid water is not currently stable on the surface, and there is low water vapor content (~30 ppm by volume) in the atmosphere (see Section 4 and Table 2) (Esposito et al., 1997; Johnson and de Oliveira, 2019; Marcq et al., 2018). Instead, the surface materials should react quickly with the atmosphere to produce Na-, K-, Ca- sulfates, iron oxides (hematite and magnetite), and possibly pyrite. Therefore, the alteration is largely controlled by CO_2, S_2, and O_2 instead of water (Berger et al., 2019; Esvan et al., 2022; Fegley et al., 1995a; Fegley and Prinn, 1989; Filiberto and McCanta, 2024; Johnson and Fegley, 2002;

McCanta et al., 2014; Radoman-Shaw et al., 2022; Reid et al., 2024; Santos et al., 2023; Semprich et al., 2020; Teffeteller et al., 2022; Zhong et al., 2023).

Predicting such changes in mineralogy through experimental and geochemical modeling approaches has been a recent focus of the community as we prepare for the coming decade of Venus exploration—especially how these changes affect measurements that will be made from orbit. Since the surface is dominated by basaltic lava flows (Section 2), the focus of experimental studies has, to date, been on how basalt and associated mafic minerals and glasses react with the atmosphere at surface conditions (P and/or T). An important note is that Venus' atmosphere is so caustic that 'no experimental approach has been able to fully replicate the necessary conditions and sustain them for a significant length of time' (Filiberto and McCanta 2024). Therefore, experimental studies take targeted approaches focusing on: a) oxidation at temperature and at ambient pressure in a terrestrial atmosphere (Cutler et al., 2020; Filiberto et al., 2020), b) alteration at temperature and a CO_2-rich environment at 1-bar (Fegley et al., 1995a; Fegley and Prinn, 1989) or Venus-relevant pressure (Berger et al., 2019; Esvan et al., 2022; Teffeteller et al., 2022; Zhong et al., 2023), or c) the most difficult to sustain consistently for significant lengths of time alteration at Venus-relevant temperature, pressure, and atmosphere (gas-phase) (Berger et al., 2019; Esvan et al., 2022; Radoman-Shaw et al., 2022; Reid et al., 2024; Santos et al., 2023). Despite the different approaches, these studies have shown that alteration proceeds quickly (within days to months) to produce alteration minerals: sulfatization occurs faster than oxidation and basaltic glass typically alters faster than crystalline minerals. Alkaline basalt alters faster than tholeiitic basalt (Reid et al., 2024). Alteration minerals formed as coatings on the surface of rocks and minerals, as well as along pre-existing cracks in rocks, and along dislocations and impurities in the original crystal **(Fig. 9)** (Knafelc et al., 2019). Alteration zones have been described within samples showing cation mobility with Na, K, Ca, and Fe^{2+} being enriched near the surface of the reacted samples **(Fig. 9)** (Reid et al., 2024; Teffeteller et al., 2022). Alteration mineralogy is dominated by Na-, K-, Ca-, sulfates and iron oxides (magnetite and/or hematite) with the exact mineralogy and mineral abundances produced dependent on numerous variables such as the protolith composition and mineralogy, as well as the gas phase (atmospheric) composition (Berger et al., 2019; Esvan et al., 2022; Filiberto and McCanta, 2024; Johnson and Fegley, 2002; McCanta et al., 2014; Radoman-Shaw et al., 2022; Santos et al., 2023; Semprich et al., 2020; Zhong et al., 2023; Zolotov, 2018). Such hematite-rich coatings were suggested by Pieters et al. (1986) in their treatment of the color of Venus from imaging and spectrophotometry for Venera landing sites in comparison with the NIR spectra of heated hematite. The absence of reliable fO_2 data at these sites limits further conclusions until new lander missions address both fO_2 and direct measurement of mineralogy (Section 9).

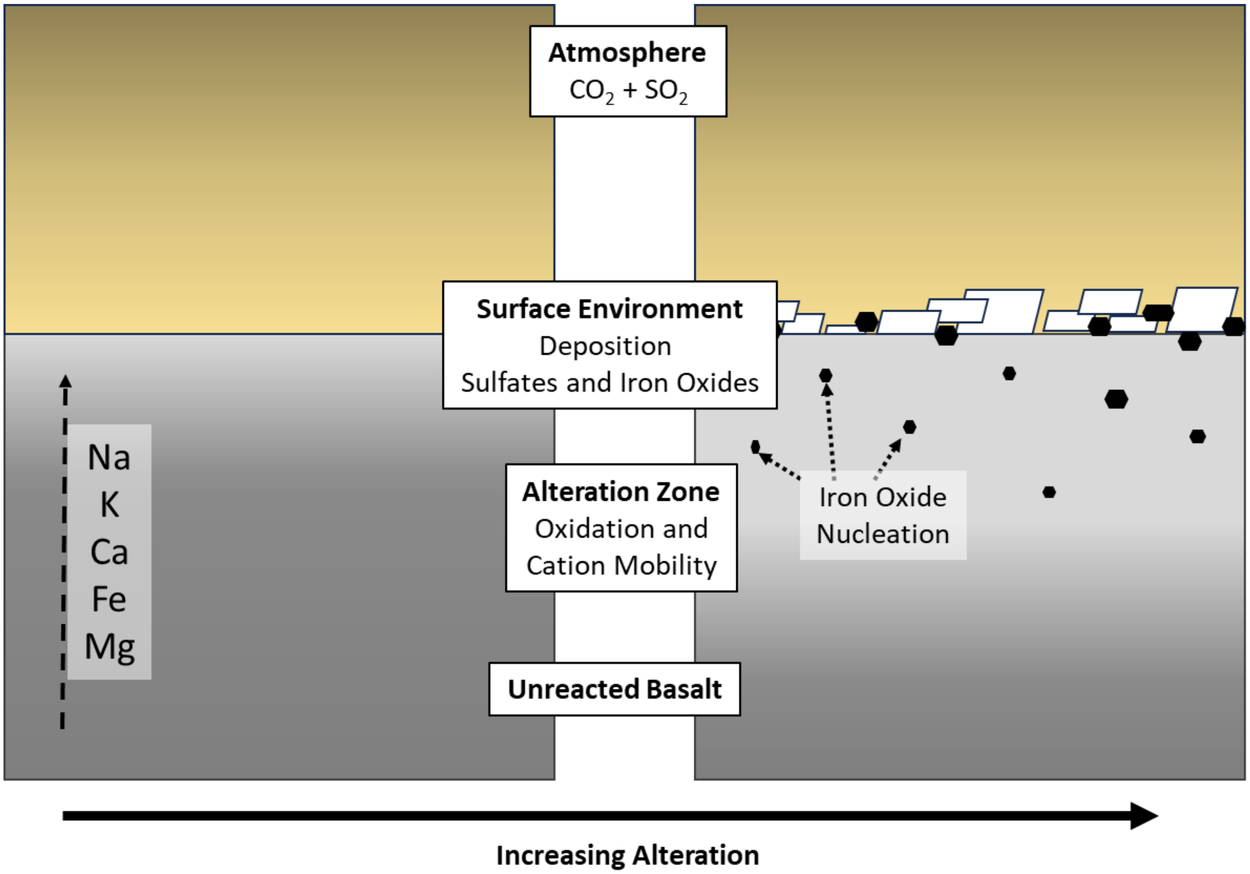

Figure 9. Cartoon (not to scale) detailing the progressive alteration (left to right) of a basalt (gray) in contact with a Venus-atmosphere (yellow) based on experimental and geochemical modeling studies (Berger et al., 2019; Esvan et al., 2022; Filiberto and McCanta, 2024; Johnson and Fegley, 2002; McCanta et al., 2014; Radoman-Shaw et al., 2022; Santos et al., 2023; Semprich et al., 2020; Zhong et al., 2023; Zolotov, 2018). Labels (white boxes) shown between unaltered and altered basalt represent the regions, from top down, atmosphere (yellow), surface environment, basalt (gray). The increase in the alteration zone after experimentation (left to right) into the rock's interior is shown by the vertical white to gray gradation transition, which increases with alteration (labeled oxidation and cation mobility). Cation mobility based on diffusion coefficients experiments (e.g., D(Na) > D(Mg)) in basaltic samples reacting with a CO_2 and SO_2-bearing atmosphere (e.g., Reid et al. 2024) is shown in the left panel (in decreasing order of mobility: Na→K→Ca→Fe→Mg) by the dashed arrow moving towards the surface. In the right panel, white crystals at the surface environment represent Na-, K-, and/or Ca-sulfates. Black hexagons represent iron oxides – magnetite changing to hematite with progressive alteration (e.g., Knafelc et al. 2019). Iron oxides form on the surface and within the interior of a sample –along cracks and within crystal structures (e.g., Berger et al. 2019; Knafelc et al. 2019; Zhong et al. 2023). Arrows (dotted lines) point out the iron oxides forming within the sample. Specific details, including the exact minerals to form, and the alteration rate, are dependent on numerous factors as described in the text.

Following the detection of Venus' hot CO_2-rich atmosphere, seminal work by R. Mueller and J. Lewis assumed gas-mineral equilibria in efforts to constrain the secondary mineralogy of upper crustal materials based on atmospheric compositional data (Lewis, 1968, 1970; Mueller, 1964, 1965). This work suggested that calcite is present in contact with the atmosphere where SO_2 is less abundant than reduced S-bearing gases: OCS and H_2S (Lewis, 1968, 1970; Mueller, 1964, 1965). In situ data on the lower atmosphere's composition obtained from the Pioneer Venus Large Probe and Venera 12 (Gelman et al., 1980a; Gelman et al., 1980b; Oyama et al., 1980) (reliably down to 22 and 12 km, respectively) enabled a more detailed evaluation of mineral stability and alteration pathways. Building on the work of Miller and Lewis, one approach involved comparing the conditions of selected gas-solid equilibria with T-P-f(gas) conditions at Venus' surface (e.g., Fegley and Treiman, 1992; Johnson and Fegley, 2002). Another approach included calculations of gas-solid type chemical equilibria in multicomponent systems (e.g., basalt-CO_2-CO-SO_2-H_2O) to constrain the secondary mineralogy of altered surface rocks (Barsukov et al., 1986a; Barsukov et al., 1980; Barsukov et al., 1982; Klose et al., 1992; Semprich et al., 2020; Semprich et al., 2025). The results of these 60 years of effort are outlined in several reviews (Fegley et al., 1997a; Fegley et al., 1992; Johnson and Fegley, 2002; Zolotov, 2025; Zolotov, 2018). The work on mineral stability demonstrated that the calculated secondary mineralogy depends on the bulk rock composition, atmospheric composition, and accuracy of thermodynamic data used to calculate chemical equilibria, as illustrated in **Figures 10 and 11**. For example, Semprich et al. (2020) showed slightly different calculated equilibrium alteration mineralogy from basalt and alkali-basalt protoliths. Pyrite, magnetite and/or hematite could be stable depending on the temperature, pressure, and atmospheric composition. The equilibrium alteration assembly is more affected by small changes in fO_2 than it is by changes in fS_2 (**Fig. 10, 11**) (Semprich et al., 2020; Zolotov, 2019; Zolotov, 2018).

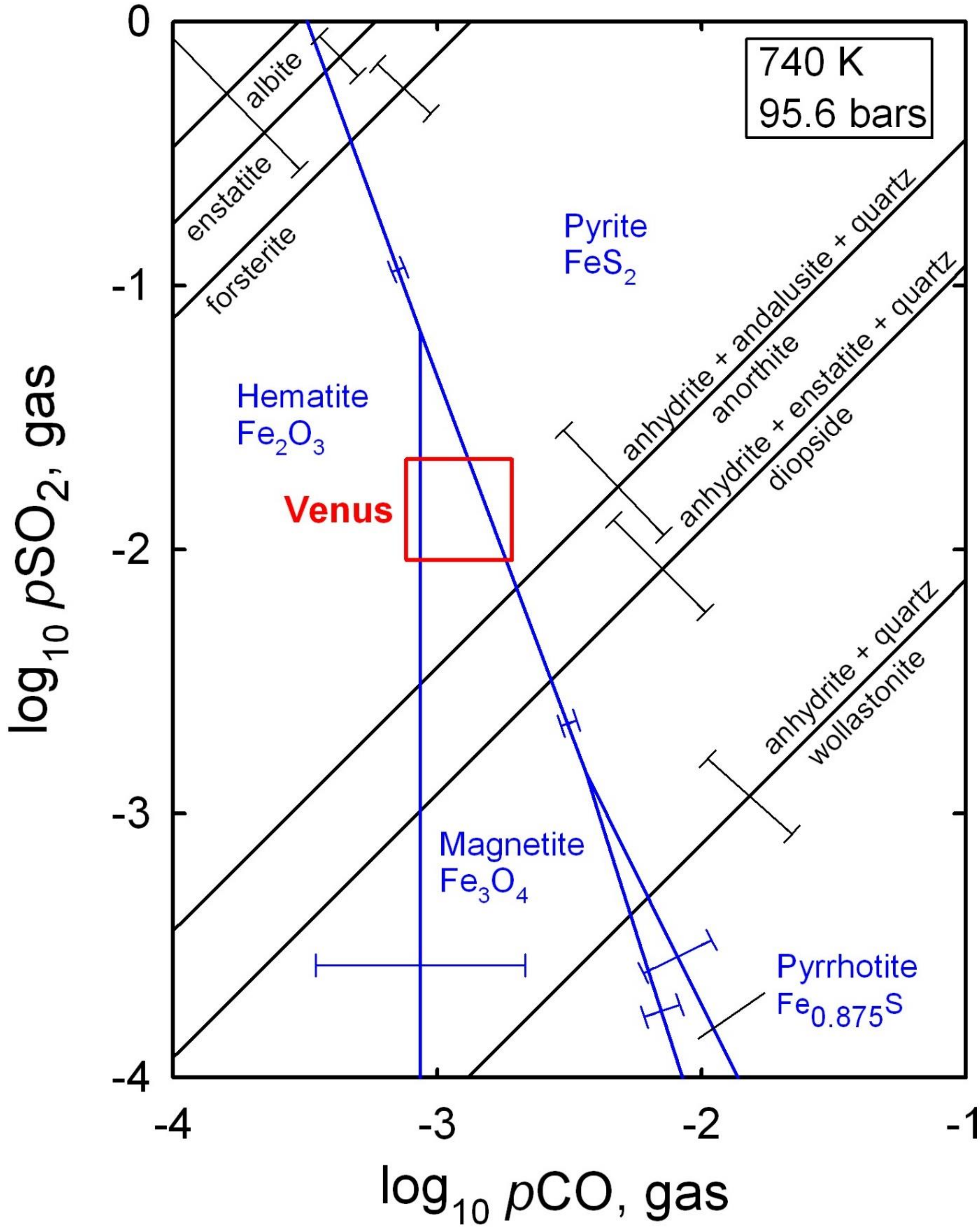

Fig. 10. Stability of iron oxides and sulfides, and silicate-sulfate equilibria at conditions of the modal radius of Venus (740 K, 467 °C, 95.5 bars, 6051.4 km). The forsterite line corresponds to chemical equilibrium between forsterite, $MgSO_4$, and enstatite. The enstatite line shows

equilibrium between enstatite, $MgSO_4$, and quartz. The albite line is for equilibrium between albite, thernadite (Na_2SO_4), andalusite, and quartz. The error bars in phase boundaries are due to uncertainties in thermodynamic data. The Venus' box corresponds to partial pressures of SO_2 and CO inferred from measurements in the lower atmosphere. Venus' surface conditions favor oxidation and/or pyritization of ferrous iron, as well as sulfurization of Ca-rich pyroxenes in exposed minerals. Ca-Na plagioclase can be stable for sulfatization. The figure is modified after Zolotov (2018).

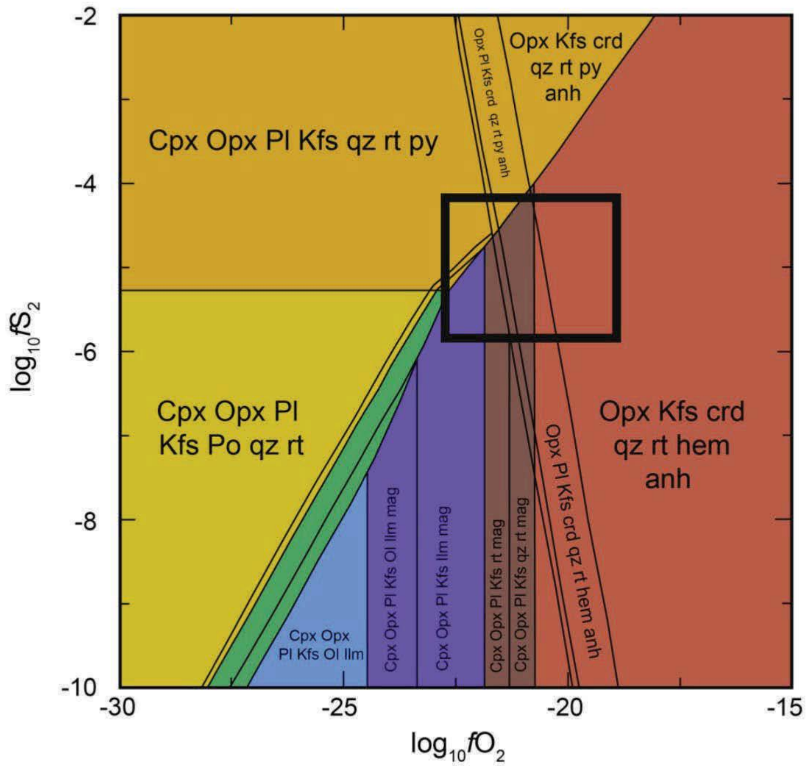

Figure 11. Metamorphic phase equilibria for a basalt composition as a function of oxygen and sulfur fugacities and at temperature-pressure conditions (470 °C, 743 K, 96.6 bars) applicable to the basaltic plains on Venus. The black boxes represent the most likely fugacities (fO_2: 10^{-19} to 10^{-23} bars and fS_2: $10^{-4.2}$ to 10^{-6} bars). Hematite = red; magnetite = brown; pyrite = dark yellow; pyrrhotite = bright yellow; ilmenite + magnetite = purple; ilmenite = blue; ilmenite + pyrrhotite = green. The figure is from Semprich et al. (2020).

The key question is whether mixed sulfate and oxide coatings affect orbital NIR and/or microwave measurements of surface materials (Barmatz et al., 2024; Dyar et al., 2021). Much of this related work is ongoing, but limited results show that iron oxides and Na-K- Ca-sulfates affect laboratory spectroscopic and NIR emissivity measurements, depending on the thickness of the coating layer. Iron oxide coatings obscured Visible and Near Infra-Red (VNIR) reflectance of forsteritic olivine after months of alteration at Venus' surface conditions and may completely encase the grains within tens to hundreds of years (Filiberto et al., 2020; Knafelc et al., 2019;

Zhong et al., 2023). Similarly, oxide coatings on basalt dominate the VNIR reflectance spectra after months of oxidation/alteration in terrestrial (O_2-rich) and CO_2-rich atmospheres at 1-bar experiments and Venus' surface temperature (Cutler et al., 2020; Fegley et al., 1995a); however, the effect on clinopyroxene VNIR reflectance spectra is much less pronounced, with changes in the crystal structure affecting the spectral shape (Cutler et al., 2020; McCanta and Dyar, 2020). Ongoing work (Leight et al., 2024; McCanta et al., 2024) is investigating the effect of physical mixtures and coatings of basalt plus sulfates (anhydrite and thernadite) on reflectance NIR spectroscopy. These results have shown that adding sulfates results in a higher reflectance (lower emissivity) than the basalt alone and that, depending on the sulfate composition, 10 to 20 vol. % sulfate may be sufficient to affect the spectral shape. Adding hematite to the basalt-sulfate mixture further obscures the spectral shape, masking features from the basalt (Leight et al. 2024). Therefore, sulfate coatings on basaltic slabs are likely to obscure measurements of reflectance of basalt, even when thin (0.1, 0.2, and 1.3 mm) (McCanta et al., 2024), and small amounts of alteration should alter reflectance measurements (Leight et al. 2024); however, most of these measurements were made at room temperature, and not at Venus surface temperatures. First-order laboratory measurements show that reflectance spectra at 850 and 950 nm and 400 °C–500 °C of Venus-relevant rocks are similar to those at 25 °C, except pigmentary hematite, which appears darker in the visible range (Pieters et al., 1986; Treiman et al., 2021; Yamanoi et al., 2009). Therefore, based on the results so far, a fresh basaltic lava should react with the atmosphere to produce an alteration rind of sulfates and/or iron oxides that may be measurable within tens to tens of thousands of years of exposure from orbit depending on spatial scales (Cutler et al., 2020; Filiberto et al., 2020; Reid et al., 2024; Teffeteller et al., 2022; Zhong et al., 2023). This suggests that the larger lava flows with high NIR emissivity at Idunn Mons are consistent with very young basaltic materials, and Idunn Mons can be considered an active volcano, if the laboratory measurements are directly applicable to VIRTIS emissivity measurements (D'Incecco et al., 2017; D'Incecco et al., 2021a; Filiberto et al., 2021; Filiberto et al., 2020; Smrekar et al., 2010). Note that most laboratory measurements were made in reflectance mode, which is related to NIR emissivity but may not be directly comparable (e.g., Dyar et al., 2022; Leight et al., 2023).

7) Change detection of surface morphology from radar (SAR) images

The gold standard for investigating and constraining volcanic activity involves regular monitoring and holistic analysis with complementary instruments physically deployed all over a volcanic construct, such as on Earth (Scarpa et al., 1996). For other planets, deploying such instruments is far more challenging and costly, and we, therefore, rely on indirect observations, such as repeated imaging (multi-temporal spatial monitoring at the scale of changes) and the detection of changes to the imaged or measured features, such as spikes in measured temperature and/or newly erupted or collapsed volcanic features. For example, on the Jovian moon Io, we have seen such changes through increases in surface temperature associated with the turnover of a magma lake and the changing color of volcanic plume deposits (Davies, 2003; Davies et al., 2010) and in recent JunoCam images of active volcanoes (Perry et al., 2025). For Venus, it would be difficult to observe such changes, as we only have a few orbital cycles of Magellan radar data, and the repeated SAR images had different viewing geometries (look directions and incidence angles). Thus, these measurements were <u>not</u> optimized for reliable image matching and comparison. While microwave emissivity measurements from Magellan S-band radar and NIR VIRTIS spectrometer suggested geologically recent volcanic activity (as described above), identifying new lava flows from local changes in radar backscatter amplitude is challenging, even on Earth at meter scales. Although very large changes to the shape of the terrain can be observed in radar backscatter amplitude changes (Herrick and Hensley, 2023), smaller features, including relatively horizontal lava flows or new lava flows erupting over older but very similar flows, are difficult to detect, even on Earth.

Herrick and Hensley (2023) presented strong evidence of a volcanogenic feature with a shape and spatial extent that changed between Magellan imaging cycles 1 (east-looking) and 2 (west-looking), plus a robust and critical analysis of the potential for such shape changes to be an artifact of viewing geometry and/or radar system changes (**Fig. 12**). Supported by a simulation model, they concluded that a sizeable vent (from ~1 to ~2 km diameter) on the northwestern flank of the Maat Mons volcano has changed morphology in the eight months between the two radar images, which they interpreted as a signature for ongoing volcanic activity; however, Herrick and Hensley (2023) noted that with only one such time-variable feature we currently cannot constrain how common current volcanism with this expression may be. Earth-based Arecibo polarimetric radar observations (with ~25% Venus coverage) have not detected any such changes so far (at km scales), but the best spatial resolution of Arecibo polarimetric radar images using the S-band transmitter is 1 to 2 km and 8 km in a lower-resolution mode (Campbell and Campbell, 2022).

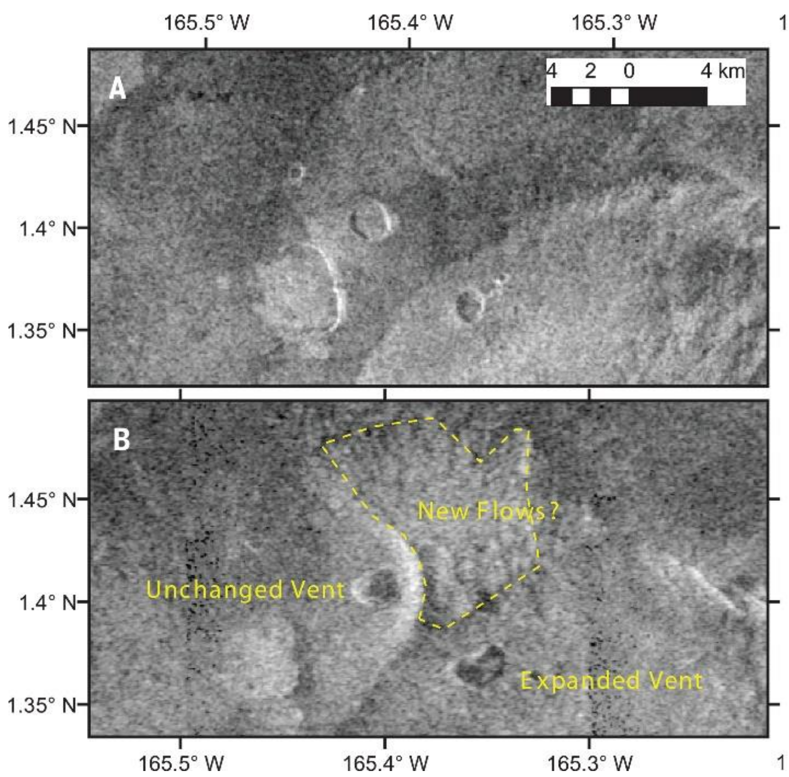

Fig. 12. Magellan Radar images (A) east-looking image from cycle 1 and (B) west-looking image from cycle 2 of a putative vent on a domed shield volcano that is part of Maat Mons in Atla Regio. Images from cycles 1 and 2 were taken 8 months apart and show changes in the morphology of one vent and potentially a new lava flow(s) (radar-bright feature outlined with a dashed yellow line). From Herrick and Hensley (2023).

Sulcanese et al. (2024) reported variations in the radar backscatter measured from different volcanic-related flow features on the western flank of Sif Mons and in western Niobe Planitia, using Magellan radar images acquired at different viewing geometries. Like Herrick and Hensley (2023), they presented an interpretation for evidence of a change in backscatter (brightness) between inter-cycle Magellan radar images and interpreted them as new lava flows that were emplaced during the mission. However, the only measured change presented in this recent work is the degree of backscatter ($\sigma°_{HH}$, i.e., HH backscattering coefficient), while several previous studies (Campbell, 2002; Campbell and Hensley, 2024; Campbell and Shepard, 1996; Gallardo i Peres et al., 2024) clearly demonstrate that such backscatter variations are primarily a function of the radar viewing geometry (i.e., local incidence angle and look direction), and do not represent the wavelength-scale properties of the surface. Moreover, the 'new flows' as reported by Sulcanese et al. (2024) perfectly match the boundaries of the older (prior) flow, which is fundamentally unusual and physically unlikely in volcanological terms, since the new flows will always be affected by the topography created by the previous flows (i.e., conforming to their local relief) and will thus flow differently (e.g., Schaefer et al., 2016). Considering these very real limitations to the search for active volcanism using observations from SAR amplitude data alone, we suggest that the requirements for demonstrating geologically significant feature changes must be more rigorously evaluated and verified in their 3D context. Morphological changes, in addition to changes to brightness and backscatter, are required for robust change detection and require well-calibrated SAR backscatter data with appropriate sensitivity (NES0). Moreover, change detection between Magellan data and new SAR imagery acquired by the upcoming radar orbiter missions (VOM, EnVision, VERITAS, VOICE), across a 40-year divide, will be even more challenging. New methods must account for the differences in wavelength, look direction, incidence angles, number of looks, radar sensitivity (as NES0) and spatial resolution (which depends on RF Bandwidth of the instrument). Reliable change detection between two SAR images relies on images of equivalent spatial resolution which, for images from Magellan and EnVision or VERITAS, for example, will involve very different number of looks (amongst other differences) (e.g., Campbell and Hensley, 2024; Widemann et al., 2023). Gallardo i Peres et al. (2024) present a method that derives the ratio of two images with a different number of looks. If there are changes between the two images, these will appear as two statistically significant histogram peaks that can be separated. Depending on the amount of change that has occurred, the larger peak will represent the shared information, and the smaller one will contain unique or changed information, allowing for at least semi-automated (supervised) detection of changes.

Previous terrestrial studies suggest that polarimetric SAR (PolSAR) and Interferometric SAR (InSAR) techniques are very effective for mapping lava flows (Campbell et al., 1993; Campbell and Shepard, 1996; Dietterich et al., 2012; Poland, 2022) and can be used when changes cannot be distinguished in radar amplitude data alone. Radar backscatter is affected by the cm- to dm-scale morphology (3D textures) of the surface, and if this morphology changes over time, this could be used for the relative dating of surfaces. While Bruno et al. (1992) suggested that the fractal dimensions of some Venusian lava flows are more indicative of aʻā flows, Kratter et al. (2007) observed that the radar-bright flow field associated with Quetzalpetlatl corona on the south flank of Lada Terra resembles terrestrial pāhoehoe flows in terms of roughness. Campbell and Campbell (1992) note that the large lava flows imply high volume eruption rates, where the flow surface is continuously disrupted during emplacement, which favors the formation of rougher a'a flows. Polarimetric radar parameters such as the circular polarization ratio (CPR) and signal decomposition methods (e.g., m-chi) have been widely used in characterizing terrestrial lava flows to understand the local variations in texture and dominant scattering mechanisms (e.g., Campbell et al., 1993; Sreejith et al., 2024). A single lava flow may comprise both pāhoehoe and aʻā forms with no compositional variations (Dutton, 1884; Sigurdsson et al., 2015). For example, erupting as pāhoehoe flows, lavas of the December 1974 Kilauea eruption (Hawaii) underwent a textural transition to aʻā at a distance of ~6 km from the vent, attaining a maximum flow length of ~13 km wide (Gaddis et al., 1990). Extensive pāhoehoe lavas that erupted across the Reykjanes peninsula in Iceland over the last few years show very complex surface textures that have a rough (apalhraun) appearance like aʻā flows, but instead represent zones of inflation where the frozen, uppermost surface of the flow has been shattered by repeated injection of fresh lava beneath (**Fig. 13**). Recently, polarimetric radar analysis of a fresh lava flow channel associated with the NE rift zone on Mauna Loa volcano (2022 eruption) revealed a transition between smooth pāhoehoe and rough aʻā flow textures along its current extent (Sreejith et al., 2024). Additionally, on Venus, potential mechanisms for reducing cm- and decimeter-scale roughness associated with lava flow fields include aeolian erosion and deposition (Bondarenko and Kreslavsky, 2018; Greeley et al., 1992; Kreslavsly and Bondarenko, 2017) and chemical weathering (Fegley et al., 1997a; Filiberto and McCanta, 2024; Zolotov, 2018). These and other ongoing studies indicate that characterizing the surface roughness plays an important role in dating the surfaces, which can be enabled by new polarimetric radar measurements aided by high-resolution topography (ie., as will be possible from the DAVINCI mission via descent imaging at 1-10 m scales; Garvin et al., 2022).

Moreover, several terrestrial studies indicate that Interferometric Synthetic Aperture Radar (InSAR) is highly effective for the mapping of lava flows, particularly where changes in radar backscatter are not easily discernible (e.g., Poland et al., 2008; Poland, 2022; Zebker et al., 1996). Potential InSAR approaches for change detection include differential interferometry derived by Repeat Pass InSAR (RPI) measurement and/or temporal decoherence. InSAR operates by detecting changes to surface elevation (in the line-of-sight of the radar instrument) by calculating a map of the phase difference, or interferogram, between two SAR images of the same area. Two SAR images (acquired simultaneously or close together in time) are needed to derive the phase variations representing elevation or topography. A third SAR image acquired later (after an event that causes ground motion) is required to derive the differential phase difference representing ground deformation, such as would be caused by an earthquake (causing changes in line-of-sight distance). In this way, small-scale surface displacements that produce line-of-sight motions greater than ~1/10 of the radar wavelength can be detected, i.e., on the order of a few centimeters (Meyer and Sandwell, 2012; Zebker et al., 1994). The emergence of new lava flows would then also be detectable using coherence, a measure of the local spatial correlation between two SAR images. The new flow alters the surface scatterers' arrangement entirely, resulting in complete coherence loss in any interferogram made from images acquired before and after the flows' arrival (**Fig. 13**). Surface decoherence could be caused if a new lava flow is emplaced between the times of the reference and secondary (repeat) SAR image orbital passes. As demonstrated for terrestrial lava flows (e.g., Poland et al., 2008; Zebker et al., 1996), small changes that are not apparent in the radar backscatter images either due to the superposition of a new flow or inflation of an existing flow will cause nearly complete surface decoherence (Meyer and Sandwell, 2012), and illustrated in **Fig. 13**. SAR decoherence caused by natural processes is cumulative in time, so the coherence decreases as the temporal baseline between two images increases. On Earth, temporal decoherence is caused by many factors that alter the arrangement of the ground-scattering objects, such as vegetation growth, sediment transport, and fault movement. For Venus, we can rule out some of these processes, but the expected rates of surface change will need to be considered with respect to the likely temporal interval of repeated imaging. Any degree of temporal coherence loss between two SAR images would be a potentially huge scientific discovery, providing some vital constraints on the likely activity rate, whether volcanic, tectonic, or geomorphologic in origin.

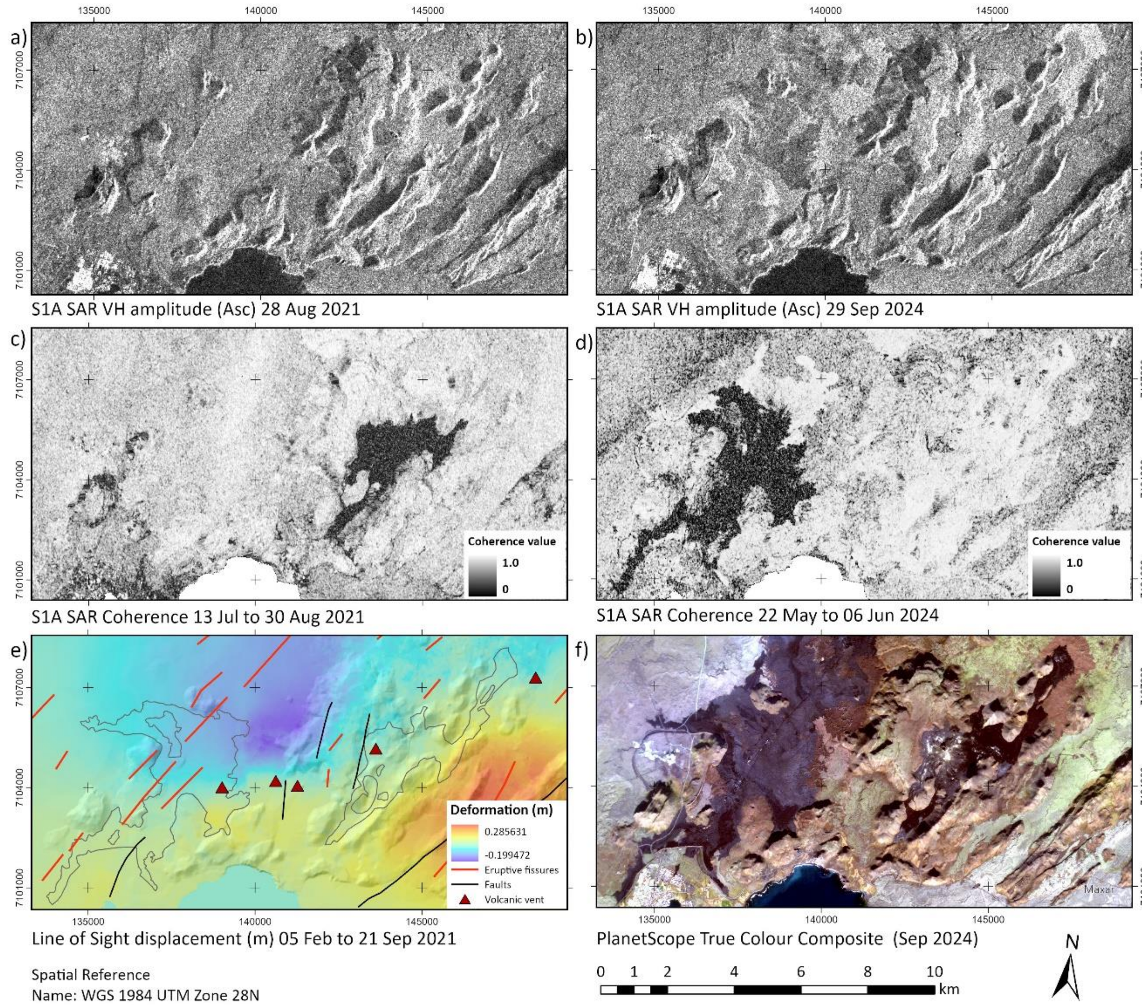

Fig. 13. The power of SAR coherence illustrated through analysis of Sentinel-1 ascending orbit SAR images across lava flows erupted between Mar 2021 and Sep 2024 at Fagradalsfjall, SW Iceland, illustrating the difficulty of detecting change from SAR amplitude images alone: a) and b) SAR 30 m VH amplitude images from 2021 and 2024 respectively; c) and d) SAR coherence calculated for the periods of 13 Jul to 30 Aug 2021 and 22 May to 06 Jun 2024 respectively; e) Unwrapped Line of Sight (LoS) displacement, showing ground deformation associated with the fissure eruptions of 2021 overlain on DEM hillshade (Natural Science Institute of Iceland); and f) PlanetScope 3 m true-colour composite for reference, acquired in Sep 2024. Backscatter variations in the SAR images (a and b) are subtle and complex, and new lavas do not necessarily produce distinct backscatter patterns. Hence, they can be confused with bright slopes facing the radar sensor. Conversely, SAR coherence loss reveals, very clearly, the profoundly altered backscatter caused by each new lava flow; in c) and d), coherence is almost zero across the new flows and is highest where no change has occurred (some coherence loss is also caused here by vegetation growth and anthropogenic activity).

8) Implications of potential active volcanism for resurfacing history and volcanic activity

The potential for active and ongoing volcanism has substantial implications for understanding Venus' evolution. The Magellan orbiter mission provided the most comprehensive and robust view of the surface, which allowed moderate to large-sized craters to be cataloged globally. Over 900 impact craters of ~2 to ~280 km in diameter were identified (Schaber et al., 1992). If impact characters showed clustered regions globally, this would imply substantial age variation in surface units as the older terrains *should* record greater impact fluxes. However, an apparently near-random distribution of impact craters was observed [**Fig. 14a**; (e.g., Herrick et al., 2023; Phillips et al., 1992)], which suggests the surface is broadly similar in age. This observation has led to an inferred globally near-uniform resurfacing age of ~240 to ~1000 Ma (Herrick et al., 2023; Le Feuvre and Wieczorek, 2011; McKinnon et al., 1997). A key implication of these putative surface ages is that the resurfacing rate has changed over the last Gyr, from an early higher rate sufficient to destroy or otherwise obscure previous impact craters; however, the current rate of volcanism, let alone the rate after plains formation (which cover ~ 80% of the surface), remains poorly constrained.

Early in the Magellan mission, only ~10% of the observed craters were thought to have been partially resurfaced by embaying volcanic flows (e.g., Schaber et al., 1992; Strom et al., 1994). Most impact craters showing no apparent post-impact modification led to an assumption of highly variable and peaked volcanic activity having occurred (or variable impact melt production). This assumption directly led to the establishment of models of so-called 'catastrophic' outpouring of lavas that occurred effectively instantaneously and globally, inundating ~ 80% of the planetary surface (perhaps in multiple cycles), with limited to no volcanism after the event (McKinnon et al., 1997; Romeo, 2013; Schaber et al., 1992); however, competing models of so-called equilibrium volcanism also exist and can match the crater observations at least as well [**Fig. 14b;** (Bjonnes et al., 2012; Hauck et al., 1998; O'Rourke et al., 2014; Phillips et al., 1992; Stofan et al., 1992)].

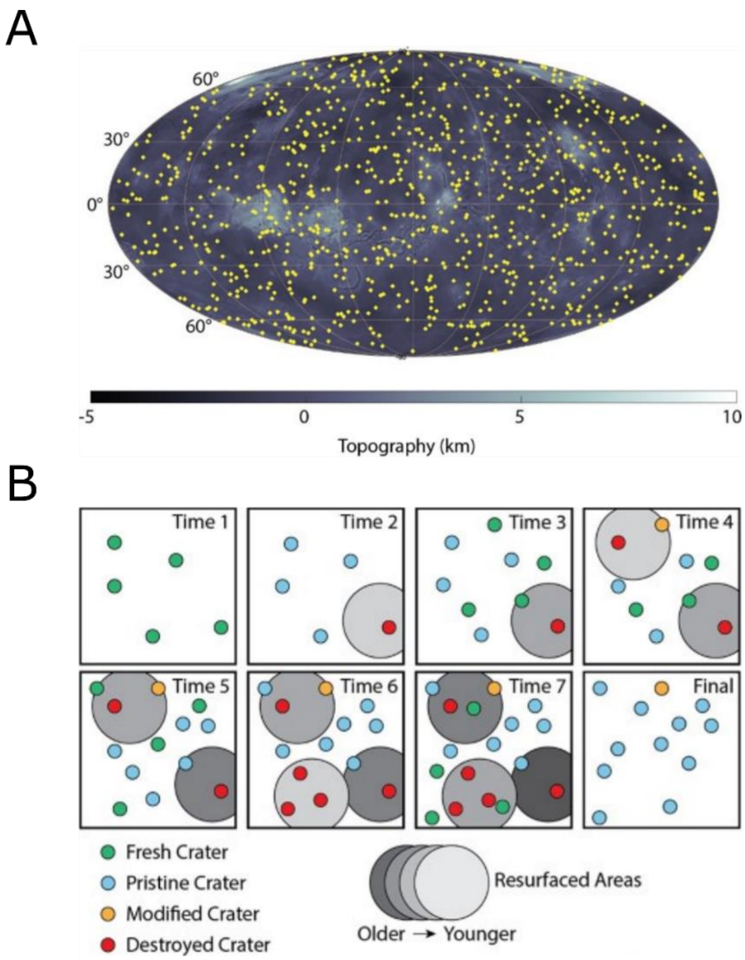

Fig. 14. Random impact crater distribution (yellow) on the surface with topography from the Magellan mission (A). Random crater generation and resurfacing cartoon. Craters within resurfacing zones (grey circles) are either modified or destroyed by volcanic processes over time (B; taken from the results of Bjonnes et al., 2012). The last time slice indicates an observed distribution of pristine and modified craters that matches the crater catalog. Modified from Herrick et al. (2023).

Follow-up analysis of many impact craters using much more detailed stereo SAR topography has indicated that many of them may have up to several hundred meters of post-impact volcanic fill or impact melt flooding (Herrick and Rumpf, 2011; Herrick and Sharpton, 2000). The loss of "halos" and ejecta deposits around craters further indicates ongoing resurfacing (Phillips and Izenberg, 1995). It has been further argued that impact crater densities are reduced from the global average in areas associated with volcanic lava shields, coronae, and rifts, which suggests recent to perhaps ongoing regions of volcanic resurfacing (Namiki and Solomon, 1994; Price et al., 1996).

The specific rate of volcanism over time is impossible to accurately quantify due to the uncertainty of the average age of the surface. Stofan et al. (2005) assessed resurfacing sources in the plains units that span ~30% of the surface and found a bulk resurfacing rate of ~1 km^3 per year, (ranging from ~0.6 to 4.5 km^3 per year, dependent on emplacement time scales). Recent work (Byrne and Krishnamoorthy, 2022) attempted to estimate observable volcanic events by scaling Earth's recent volcanic rate to Venus, and suggested resurfacing rates a factor of a few greater than bulk resurfacing rate estimate of ~1 km^3 per year; however, van Zelst (2022) argued Byrne and Krishnamoorthy (2022) overestimated the contribution of subduction zone volcanism while underestimating rift zone volcanism to Venus' volcanic rate. Accounting for these differences between Earth and Venus, van Zelst (2022) determined resurfacing rates of ~1 km^3 per year (ranging from ~0.3 to 1.5 km^3 per year, dependent on the dominate form of volcanism). Both approaches are within the uncertainty of the resurfacing rate estimates of (Stofan et al., 2005), which is similar to the intra-plate volcanism rate of the Earth today (Deligne and Sigurdsson, 2015; Turcotte and Oxburgh, 1978; Weller et al., 2023), and matches predictions from long-term models of thermal evolution of Venus (**Fig. 15**). This rate is comparable with post-impact volcanic fill of several hundred meters identified in many impact craters (Herrick and Rumpf, 2011). Further, specific spatial extents of identified resurfacing in the plains units show extreme variation, ranging from up to a hundred km^2 for smaller volcanic constructs to up to a million km^2 for large volcanic features and flow fields as well as coronae (Stofan et al., 2005).

Considering the surface holistically, impact cratering observations do not favor so-called "catastrophic" models of resurfacing (at least in the last era of Venus geological evolution), which require global resurfacing at one time. Instead, these observations along with inferences of potentially geologically recent volcanic events, as discussed throughout this paper, are much better explained by both ongoing, and much smaller regional-scale volcanic events. Further, the resurfacing rate has declined, perhaps precipitously, over the last Gyr. It challenges so-called equilibrium resurfacing models that allow for smaller resurfacing patch sizes but require near-constant, generally high resurfacing rates.

The volcanic resurfacing and production rates have been used to infer Venus' geodynamic evolution within the last Gyr. Therefore, volcanism and resurfacing are linked to, and may be critical, along with other metrics, to the tectonic state of the planet (**Fig. 15**). In a broad sense, inferences of "catastrophic" and steady-state volcanism have canonically led to two end-member tectonic scenarios, models of "catastrophic" overturning mantle convection (e.g., Rolf et al., 2022; Schaber et al., 1992; Strom et al., 1994; Turcotte, 1993) and those of steady-state (equilibrium) stagnant lid convection (e.g., Guest and Stofan, 1999; O'Rourke and Korenaga, 2015; Rolf et al., 2022). Neither endmember model has satisfactorily explained all observables, including volcanism, resurfacing rates, putative subduction under some coronae, rifting, or other markers of high-strain-rate environments (for recent reviews see Ghail et al., 2024; Rolf et al., 2022). Expanding on these end members, additional models have been proposed to address end member model limitations. These include models of some form of heat-pipe volcanism, in which the vast majority of melt generated is extracted from the interior through extrusive volcanism (e.g., Ghail et al., 2024; Moore and Webb, 2013; Rolf et al., 2022), and so-called "squishy-lid" tectonics, where the vast majority of melt remains trapped within the lithosphere as intrusive volcanism (Ghail et al., 2024; Lourenço et al., 2020; Rolf et al., 2022). These models are somewhat limited as they are designed to explain specific characteristics at a given time in the planet's evolution but are not meant to explain Venus' evolution over time. Critically, both heat-pipe and squishy-lid models extend and modify steady-state or equilibrium resurfacing assumptions.

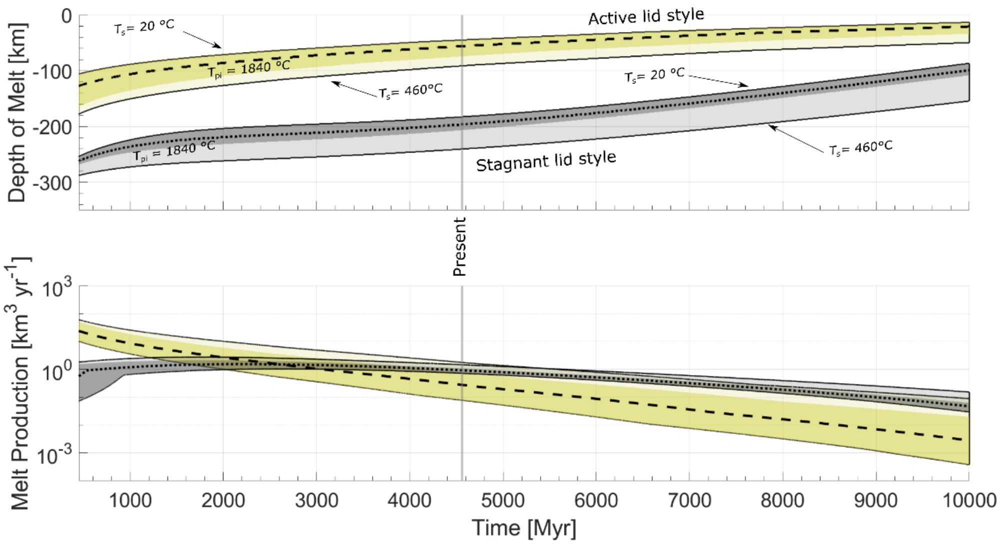

Fig. 15. Depth of melting (top) and melt production rate (bottom) for endmember (*equilibrium*) volcanic models, here intrinsically linked to the style of tectonics and 1D parameterized models (Weller et al., 2023). Active lid style should be thought of as the style of volcanism associated with active lid convection (yellow) and Stagnant lid style should be thought of as the style of volcanism associated with a single plate stagnant lid (grey). Dashed and dotted lines represent the initial mantle potential temperatures (T_{pi}) selected for each model bounded to 1840±200°C (solid shaded regions). Surface temperatures (T_s) here range from a global average of 20°C to near current Venusian values of 460°C (lighter shaded regions). In the first few billion years, volcanism was suppressed in the stagnant lid, whereas active lid volcanism has been relatively enhanced. For nearly 5 Gyr, from ~1.2 to ~6.2 Gyr both volcanic styles may be indistinguishable from each other in volcanic rates. After 6.2 Gyr, stagnant lid style of volcanism is likely to produce greater volcanism. Despite the depth of melting shallowing with time for both endmembers, melt in single plate styles of volcanism is sourced deeper. Critically, both endmembers show that melting and volcanism do not cease at present and indeed persist over at least 10 Gyr. Current estimated volcanic production rates (Stofan et al., 2005) fall where the present grey vertical bar intersects both the active and stagnant style melt production rates (omitted for figure clarity), indicating that volcanism alone may be insufficient to determine tectonic-volcanic styles at present with endmember (*equilibrium*) models.

The critical limitation of "catastrophic" models (aside from failing to match the cratering record from which they were initially derived to explain) is that they are ad hoc and potentially non-physical. They require volcanism to initiate and cease globally on very short time scales, almost like a step function. Melt and, consequently, volcanism generated on a planetary scale is predominantly accomplished via decompression melting. For Venus, models that invoke global volcanism require a large-scale overturn of the mantle. Such an overturn results in dramatic thinning of the mantle lithosphere, which is often accompanied by the yielding of the surface. An overturn event allows for the upwelling mantle to decompress adiabatically as it approaches the surface, and thus it may generate substantial melt. Other processes in mantle convection can allow for this rapid removal or thinning of the lithosphere, such as thermal erosion due to impinging plumes (Weller and Kiefer, 2025; Weller and Kiefer, 2020).

From a Venusian geologic standpoint, the initiation of volcanism linked to overturn and mantle source melting would be rapid, from within a few to ~30 Myr; however, while no mechanism will cause volcanism to cease globally (other than the planet losing all its heat and convection ceasing entirely), there are two major processes and two major timescales that operate to reduce volcanism immediately after an overturn event. Both fundamentally work by limiting decompression melting in the mantle. The first is to cause a temperature inversion in the mantle due to the cessation of surface yielding, which slows the ascent rate of the mantle, reducing the flux of adiabatic decompression melt (Rolf et al., 2022; Weller and Kiefer, 2020). The second is a fundamental limitation of heat transfer and convection - the thermal boundary layer (here the lithosphere) thickens largely by conductive processes, which is a rate-limiting step. Both processes operate over 100 Myr timescales (Rolf et al., 2022; Weller and Kiefer, 2025; Weller and Kiefer, 2020), which then require initiation to reduction of large-scale volcanism to occur over a few hundred Myr timescales. Large volcanic events then are controlled by the physics of convection, and heat transfer and have distinct time scales as a result. So-called "catastrophic" models fail to adhere to these fundamental physical constraints. Further, it cannot be understated that all physics-based models predict some form of ongoing volcanism on Venus today (**Fig. 15**). The only uncertainty in this prediction is in the current and time-averaged volcanic rates.

While "catastrophic" and equilibrium volcano-tectonic models have substantial limitations, there recently has been an attempt to develop a model using a single evolutionary framework to reconcile disparate observations. The approach of Weller and Kiefer (2020) is to revisit these classic endmember models within a robust and more holistic physics-based framework. Venus' evolution is explored as a change in tectonic regimes, from an earlier Earth-like mobile plate tectonic-like state [consistent with inferences from Way and Del Genio (2020) and Weller et al. (2023)] to a stagnant lid state [consistent with Guest and Stofan (1999) and O'Rourke and Korenaga (2015)]. Interestingly, a transition in tectonics is accompanied by an oscillatory tectonic state, often termed an episodic lid, in which multiple overturn events can occur over order 100 Myr to order 1 Gyr time scales (**Fig. 16**). Within this oscillatory state, volcanic rates can vary by several orders of magnitude over ~40 Myr time scales. Resurfacing events are non-global and restricted to hemispheric (for the largest event), sub-hemispheric, and regional scales (for the smallest events) (**Fig 16c** lower plots). Over sufficient time, multiple events can resurface most of the planet (Weller and Kiefer, 2025; Weller and Kiefer, 2020). However, portions of the planetary surface may record extreme volcanic activity, while most of the surface reflects volcanic (relative) quiescence. While there are limitations to this model (see Weller and Kiefer, 2020; Rolf et al., 2022; Weller and Kiefer, 2025), it does appear consistent with many observables, such as hemisphere-scale differences in volcanism (e.g., the BAT region versus the rest of the surface), the presence of multiple styles of plumes and upwellings (e.g., large coronae and rifting regions), and the partial resurfacing of impact crater floors across the Venusian surface.

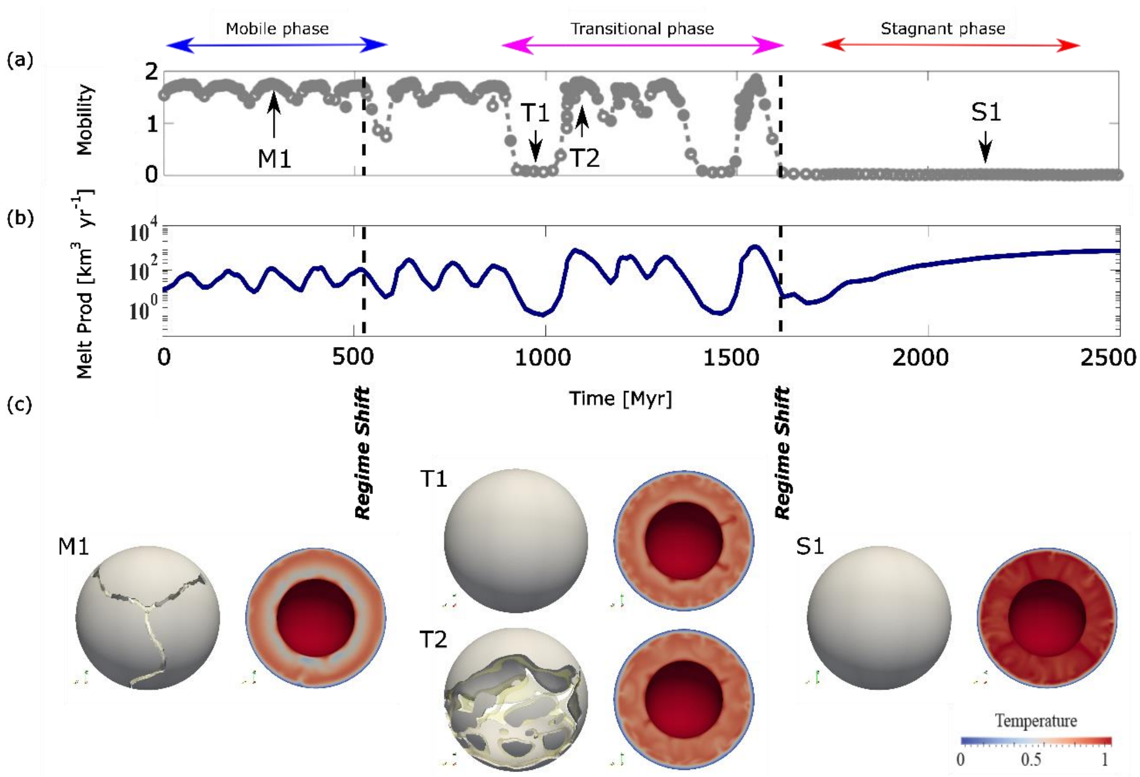

Fig. 16. Example of oscillatory tectonics and transitions in global tectonic regime using dynamic 3D thermo-tectonic models (Rolf et al., 2022; Weller and Kiefer, 2020). The transition follows from a plate tectonics-like active lid, through an episodic or transitional lid, into a single plate-like stagnant lid state. (a) Time series of surface mobility. Mobility is defined as the surface velocity normalized by the internal velocity. Mobility > 0.8 are considered mobile, and < 0.1 are considered stagnant. Dashed lines indicate regime changes. (b) Time series of volcanic melt production rates, with low production values in the transitional phase matching inferences of Venus today (and current volcanic melt production from 1D models for both active and stagnant lid volcanism, Fig. 15). (c) Snapshots of surface viscosities (left) and internal temperatures (right) for: mobile (M1), transitional (T1, T2), and stagnant (S1) regimes. Grey shells indicate high viscosity "plates" whereas yellow bands are regions of active yielding. Temperature is normalized to the temperature drop across the mantle (0 to 1).

Critically, what transitioning model suites illustrate is that a planet that transitions global tectonic states cannot be classified as either "catastrophic" or steady-state (equilibrium); instead, they should be considered models of *dynamic disequilibrium* (Weller and Kiefer, 2020). Interestingly, the end-stage stagnant lid results are not entirely inconsistent with general equilibrium models. Melt production rates in a stagnant lid long after the transition ceases may be enhanced relative to a plate tectonic-like rate, which agrees with the requirement that equilibrium models have generally higher volcanic fluxes (e.g., Rolf et al., 2022; Weller et al., 2023) than observed today. If volcanism is as low as currently inferred (Herrick and Rumpf, 2011; Stofan et al., 2005) then this model predicts Venus recently experienced an overturn event within the last several 100 Ma; consistent with the geologic record and current estimates of volcanic rates ~ 1 km^3/yr (Stofan et al., 2005), (**Fig. 16**). The potential volcanic events as described here may have occurred during, or near to, a volcanic minimum, and the globally averaged volcanic rate should increase into the future (Weller and Kiefer, 2025). This activity can be seen between labels T1 and T2 in **Fig. 16,** where production rates increase by as much as a factor of 1000 over a ~60 Myr time frame (e.g., ~1 to ~1,000 km^3 per year). This prediction suggests that Venus may be nearing or just entering a period of globally increasing rates of resurfacing and activity. This prediction may be testable at a global level with a long enough baseline (e.g., decades) of remote observations and direct missions, of which the currently slated missions are just the vanguard for Venus' era of discovery.

9) Lessons Learned for Future Missions in the Decade of Venus

With the upcoming exploration of Venus, several missions are poised to revolutionize our understanding of the planet's surface and geological processes, including past and potentially present-day volcanic activity on Venus. NASA's DAVINCI (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging), and VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) missions, along with ESA's EnVision mission and Indian Space Research Organization's (ISRO) Venus Orbiter Mission (VOM) have been selected to provide high-resolution data that will greatly enhance our ability to detect and understand volcanism on Venus. These missions are highly complementary, each addressing key scientific questions about Venus's geology, surface processes, and atmosphere, with a particular emphasis on surface evolution and volcanic activity.

DAVINCI will acquire measurements during an atmospheric descent (upper-clouds to surface), analyzing the composition of Venus's atmosphere frequently to infer the atmospheric history including volcanic emissions, while also providing NIR imagery of the planet's surface below the clouds to provide topographic and compositional information at new scales between those of Venera landers and those possible from orbit (Garvin et al., 2022). In addition, DAVINCI will employ two Venus flybys for detailed UV and NIR compositional observations of the atmosphere and night-side surface. VERITAS will use interferometric X-band radar to produce detailed 3D maps of Venus's surface, track surface deformation, and measure variations in surface composition at 100 km scales, directly searching for active or recent volcanism (Smrekar et al., 2022). ESA's EnVision, with its spectroscopic instruments and US-provided synthetic aperture radar, will allow for long-term monitoring of geological activity, providing dual-polarization, high-resolution and repeat-pass S-band SAR imaging necessary for detecting changes in the surface over time (Widemann et al., 2023). ISRO's Venus Orbiter Mission (VOM) will similarly carry a GPR instrument that can penetrate the Venus surface up to a km (Sundararajan, 2021). Other missions in stages of development are: Roscosmos' Venera-D mission (Eismont et al., 2019; Zasova et al., 2019), China's VOICE mission (Wang et al., 2022), and the privately funded Morning Star short-cloud-level probe mission (Seager et al., 2022). Together, these missions aim to resolve key questions about Venusian volcanism, crustal dynamics, and the planet's geodynamic evolution, contributing significantly to future exploratory strategies.

To reliably detect and characterize active or recent basaltic volcanism on Venus, there are specific measurement-based needs that these or other future missions must provide. These include high-resolution imaging, repeat observations – both in radar and emissivity, polarimetry, evidence of outgassing (trace gases and isotopic ratios), and topographical data (crucial to enable orthorectification and co-registration of radar images). The ability to capture and interpret these data is essential for understanding Venus's geological activity, particularly in regions where volcanic processes are suspected to be ongoing. While we focus on the upcoming fleet of missions and specific instruments in development, the discussion and caveats below apply to all missions aimed at detecting active volcanism. Other instrumentation such as traditional long-lived seismometers on the surface, detection of infrasonic waves in the atmosphere from a floating platform or balloon, or using an orbiting spacecraft to detect electromagnetic signatures could also be useful to constrain volcanic and tectonic activity (e.g., Brissaud et al., 2021; Kremic et al., 2020; Krishnamoorthy and Bowman, 2023; Lorenz, 2012; Stevenson et al., 2015). Additionally, ultra-high resolution SAR imaging at Venus is feasible, providing 1-3 m scale stripmaps of key areas to amplify what the constellation of radar orbiters discovers.

In addition to missions focused on Venus, this serves as the basis for understanding and interpreting detections of volcanism in current and future exoplanet characterization missions (e.g., Foley, 2024; Kaltenegger et al., 2010; Ostberg et al., 2023; Way et al., 2023). Several observational and theoretical studies suggest that many rocky exoplanets may follow evolutionary pathways similar to Venus, dominated by dense CO_2-rich atmospheres and intense volcanic activity (Brachmann et al., 2025; Kane et al., 2019; Ostberg et al., 2023; Quick et al., 2020; Way and Del Genio, 2020; Way et al., 2016; Way et al., 2023; Weller et al., 2023; Weller and Lenardic, 2018) (Fortin et al., 2022; Misra et al., 2015; Quick et al., 2020). Understanding the geological and atmospheric history of Venus, particularly its volcanic resurfacing and greenhouse evolution, offers critical insights into the possible fates of exo-Venus planets and their potential for habitability (Arney, 2020; Arney and Kane, 2020; Kane et al., 2019; Kite and Barnett, 2020; Krissansen-Totton et al., 2021; Oosterloo et al., 2021; Ostberg et al., 2023; Teixeira et al., 2023; Warren and Kite, 2023; Way and Del Genio, 2020; Way et al., 2016; Way et al., 2023; Weller et al., 2023; Westall et al., 2023). Upcoming ESA missions such as PLATO (e.g., Rauer et al., 2025), aimed at detecting terrestrial planets in habitable zones, and ARIEL (e.g., Tinetti et al., 2018), focused on atmospheric characterization, along with NASA's Habitable Worlds Observatory (HWO) (e.g., Vaughan et al., 2023), are poised to provide extensive datasets for rocky exoplanets (see review Foley, 2024). Many of these targets are expected to present surface and atmospheric conditions analogous to those observed on Venus. Comparative planetology using Venus as a reference, especially through terrestrial analog research efforts (e.g., D'Incecco et al., 2023; D'Incecco et al., 2024a; D'Incecco et al., Submitted; D'Incecco et al., 2024b; Garvin et al., 2025; Nunes et al., 2024), will be critical for interpreting spectroscopic and imaging data from these missions. In particular, the investigation of volcanic and tectonic processes on Venus will inform models of exoplanetary resurfacing and volcanism (e.g., Dorn et al., 2018; Kaltenegger et al., 2010; Ostberg et al., 2023; Weller et al., 2023; Weller and Lenardic, 2018), contributing to our understanding of how geological activity shapes planetary atmospheres beyond the Solar System.

9.1 The Atmosphere

Measurements of atmospheric composition from orbit or with deep atmospheric probes can also help constrain evidence for active or recent volcanism (Section 4). Planned orbital missions will be capable of detecting chemically active atmospheric trace gases at the cloud tops (~63-70km) and upper portion of the lower atmosphere (above ~35 km, and potentially lower for H_2O) via spectroscopic measurements in the UV and infrared spectral ranges (Widemann et al., 2023). Some trace gases (SO_2, OCS, CO, H_2O, Section 4) will help identify current volcanism, as Wilson et al. (2024) discussed in detail. Recent work of (Dias et al., 2025) has suggested that orbital nightside 2.3 μm thermal emission measurements could detect H_2O, CO and OCS from volcanic plumes given a minimum required signal-to-noise ratio of 50. These trace gases will be measured with DAVINCI (in situ) and EnVision (from orbit), where both missions will measure the sub-cloud atmosphere at different scales and sensitivities. Water vapor in the lower atmosphere can also be measured in the NIR range from the VERITAS orbiter (Widemann et al., 2023). DAVINCI's altitude-resolved trace gas and H, O, C, S isotopologue data will provide atmospheric "ground truth" to the orbital spectroscopy in the UV and NIR.

Although the DAVINCI entry probe will enable detailed in situ measurement of such gases as often as every 200 m (Garvin et al., 2022), passing through a recent volcanic plume is unlikely over Alpha Regio tesserae. Despite that, DAVINCI's in situ measurements of atmospheric noble gases (specifically ^{40}Ar, ^{4}He, ^{129}Xe, and ^{136}Xe) can help constrain the timing and rate of volcanic outgassing in the past and present (Garvin et al., 2022). Specifically, volcanic outgassing releases ^{40}Ar and ^{4}He (Namiki and Solomon, 1998; O'Rourke and Korenaga, 2015), which will be measured by DAVINCI and can be used to constrain volcanic outgassing over time (Garvin et al., 2022; Kiefer et al., 2020). Uncertainties with existing measurements of ^{40}Ar and ^{4}He are too high to constrain the volcanic history (Namiki and Solomon, 1998).

In addition to measurements of atmospheric gases, orbital NIR imaging (Arney et al., 2014) and microwave data aimed at studying geological materials could provide insights into ash-rich volcanic plumes in the lower atmosphere, should they occur.

9.2 Spectroscopy and Emissivity of Surface Materials in the NIR

Future missions will include a range of spectrometers to measure emissivity near the 1 μm region, which is the wavelength where light emitted from the surface can be viewed through the CO_2 atmosphere in one of several spectral windows (e.g., Widemann et al., 2023). The 1 μm region is particularly sensitive to crystal field transitions arising from Fe-bonding, which can be used to track both compositional differences and mineralogy (e.g., Gilmore et al., 2023). Specifically using the 1 μm feature, NIR emissivity measurements can be used to distinguish between basalt and granite and basalt and weathered basalt (Dyar et al., 2020; Gilmore et al., 2023; Gilmore et al., 2015; Hashimoto et al., 2008; Helbert et al., 2021; Mueller et al., 2008; Treiman et al., 2021). As described above, night-time emissivity measurements of Idunn Mons from VIRTIS on ESA's Venus Express mission have been used to suggest active volcanism because the emissivity of some lava flows are consistent with an unweathered basalt (Smrekar et al., 2010).

Calculated reflectance spectra for simulated measurements for the VenDI camera on DAVINCI (Garvin et al., 2022), using the Spectral Mapping Atmospheric Radiative Transfer Model (Meadows and Crisp, 1996) and the retrieval model described in Lustig-Yaeger et al. (2023), show that VenDI will easily be able to distinguish basalt from granite (Garvin et al., 2022; Garvin et al., 2025), which is critical for determining the petrogenesis of Alpha Tesserae where DAVINCI will touch-down (Garvin et al., 2022; Gilmore et al., 2015). Further, VenDI measurements will also be able to distinguish fresh basaltic surfaces from heavily altered (e.g., hematite) materials (D'Incecco et al., 2023; D'Incecco et al., 2024a; D'Incecco et al., Submitted). Laboratory high temperature emissivity analog measurements from the Planetary Spectroscopy Laboratory of the Deutsches Zentrum von Luft- und Raumfahrt (DLR) in Berlin have shown that basalt and granite will be easily distinguishable by Venus Emissivity Mapper (VEM) on NASA's VERITAS and VenSpec suite on the ESA EnVision mission; further based on their calibration, FeO^T can be calculated for basaltic rocks from orbital measurements providing not only rock characterization but first order classification (Dyar et al., 2020; Helbert et al., 2021). DAVINCI's band-ratio imaging methods will provide mapping scales as fine as ~ 5 m from beneath the clouds for tesserae surfaces in 3D context from digital elevation models (DEMs) derived from multi-frame descent imaging (Anderson et al., 2025; Garvin et al., 2022; Garvin et al., 2025). This will provide traditional-scale ground-truth for the powerful orbital NIR emissivity mapping from

EnVision and VERITAS, for example (which will be at 100 km spatial scales) (e.g., Smrekar et al., 2022; Widemann et al., 2023).

To determine the age of a flow, experimentally constrained rates of alteration will need to be correlated with how surface coatings affect NIR emissivity measurements (Dyar et al., 2021; Leight et al., 2024; McCanta et al., 2024). Experimental work has shown that surface coatings form rapidly at Venus surface conditions producing a sulfates and iron oxides, which will affect the spectroscopic measurements (Berger et al., 2019; Cutler et al., 2020; Esvan et al., 2022; Fegley et al., 1995a; Fegley and Prinn, 1989; Filiberto et al., 2020; Radoman-Shaw et al., 2022; Reid et al., 2024; Santos et al., 2023; Teffeteller et al., 2022); however, the rate is dependent on numerous things including bulk composition of the rock, crystallinity, rock textures, and others, which complicates determining an exact rate (see recent perspectives Filiberto and McCanta, 2024). Studies combining experimental alteration and spectroscopy are needed to better constrain the properties that affect alteration rate and how alteration affects emissivity. Based on experimental studies to date, calculations suggest that basaltic rocks will look altered in emissivity after a few years to hundreds of thousands of years, with most estimates below 100,000 years. Therefore, measurements of the emissivity of a lava flow showing a fresh basaltic signature can be assumed to be 'young' (likely less than 100,000 years old), but the exact age of the flow cannot be determined without other data sets. One caveat to determining a precise and accurate age is by using repeat measurements of the same region and 1) either a new feature shows up with high emissivity suggesting the formation of a new lava flow, or 2) decreasing emissivity of the same feature with multiple passes, which would suggest weathering of a lava flow that could be used to back calculate the age. Therefore, it is vital to obtain time-sequenced measurements from future missions of volcanic regions that are suggested to be volcanically active (e.g., Idunn Mons, Maat Mons, Aramaiti Corona). Future missions should make measurements of the same flows repeated throughout the mission and then compare measurements from one mission to another to look for either new high emissivity features, or a decrease in emissivity of any given flow.

9.3 Radar

High-resolution SAR imaging is essential to detect small-scale volcanic features. VERITAS, EnVision, and VOM are expected to provide imagery with a spatial resolution exceeding Magellan's (< 100 m), allowing detailed observations of volcanic flows and vents in multiple wavelengths and with polarimetry. SAR imagery with resolutions of around 30 m and 10 m will enable the detection of key volcanic features and their evolution. Frequent repeat pass imaging is crucial for detecting surface changes at < 100 m scales. VERITAS can provide a one-month turnaround for repeat-pass radar observations at X-band, while EnVision offers a ~6-month repeat cycle. Both cadences will contribute to observing volcanic activity, especially rapid events like lava flow emplacement or surface deformation, and more gradual, though still fast acting changes surface features and geodynamic processes (Widemann, et al., 2023). Repeat pass Interferometric SAR techniques, employed by both VERITAS and EnVision, will enable measuring surface deformation with centimeter-level accuracy (Widemann, et al., 2023). Polarimetric imaging, accomplished with the VenSAR and VSAR instruments on EnVision and VOM respectively at 30 m resolution, will help differentiate between surface features (including textures) and materials, providing insights into the composition of volcanic features and identifying areas of recent resurfacing (Widemann et al., 2023). Regions such as volcanic highlands, rift zones, and plains suspected of recent volcanic resurfacing, should be prioritized for repeated observations. These include targets such as Idunn Mons, Themis Regio, and others mentioned in Section 5, where active volcanism has been suggested. Further, microwave emissivity will be measured in orbit or on flybys with all missions. These measurements should be focused on the same volcanic regions to investigate how emissivity of different lava flows and volcanic features changes through time or if new emissivity-bright regions appear (D'Incecco et al., 2022; Shalygin et al., 2012; Shalygin et al., 2015). To ensure the success of future missions in detecting and monitoring volcanic activity on Venus, a significantly improved Digital Elevation Model (DEM) is vital. The current Magellan GDTR product lacks the spatial resolution (i.e., 8-12 km x, y posting) needed to properly orthorectify images at the level required for precise change detection. An order-of-magnitude improvement in topographic data will allow for more accurate interpretation of surface features ensuring that the observed changes are real and not artifacts of image geometry. Recent work with Magellan Stereo SAR DEM's and using Arecibo with improved Magellan radargrams (Garvin et al., 2023) enable 0.5-1 km scale topography in advance of the improvements to come from VERITAS InSAR and EnVision.

While coherent change detection does not rely on terrain correction using an accurate digital elevation model (only two SAR image passes with suitable baseline separation are needed to calculate coherence), the requirements for constructing differential interferograms are much more stringent in that they require a consistent DEM with comparable and high spatial resolution to remove the topographic phase contribution and thus to isolate the deformation signal (Meyer and Sandwell, 2012). Furthermore, the exploration of Venus presents distinct challenges for Repeat Pass InSAR measurements, given the typical highly elliptical orbits for Venus spacecraft missions (which increase the physical perpendicular baselines) as well as the slow rotation, which restricts the temporal baseline thereby limiting the number of repeat passes achievable during the mission lifetime. The Venus Interferometric Synthetic Aperture Radar instrument (VISAR) instrument on board the VERITAS mission is such an instrument that operates at X-band with a single pass radar interferometry mode (to generate topography at < 300 m x, y posting), and can also detect active surface deformation through repeat pass (differential) interferometry at some locations across the surface where baselines permit (Campbell and Hensley, 2024; Smrekar et al., 2022; Widemann et al., 2023). EnVision's current orbital configuration means that RPI will only be feasible at a few isolated (opportunistic) locations and times during the nominal mission, where/when the perpendicular baselines are small enough to be suitable for differential InSAR (Widemann et al., 2020). During the extended mission, circularizing the orbit and conducting targeted RPI measurements may be possible.

While radar imaging at a spatial resolution of ~ 30 m, as from the upcoming EnVision (VenSAR), VERITAS (VISAR), and VOM (VSAR), will provide surface imaging at unprecedented detail and scope, there are other important ways that surface changes can be detected, albeit at lower spatial resolutions. These complementary detection methods will be achievable by EnVision and VERITAS using the radar instrument as a passive microwave radiometer and using high temporal frequency observations from the VenSpec-M and Venus Emissivity Mapper (VEM) NIR spectroradiometers' multi-spectral and emissivity data at ~100 km spatial resolution. Radar-based (microwave) and NIR emissivity measurements have been used to detect spatiotemporal variations in complex dielectric permittivity and reflectivity caused by recent volcanic activity and new lava flows (Brossier et al., 2021; Brossier et al., 2022; Brossier et al., 2020; D'Incecco et al., 2021; D'Incecco et al., 2022). NIR emissivity anomalies can reveal the signatures of unweathered basalt at 100 km scales; such anomalies have been correlated with a number of volcanic features (D'Incecco et al., 2020; D'Incecco et al., 2017; D'Incecco et al., 2021a; Helbert et al., 2008; Smrekar et al., 2010). The modification of scattering properties across lava flows over time, by chemical weathering and progressive burial by transported sediments or pyroclastic cover, can also be detected through observations of backscatter variations in repeated polarimetric SAR imagery from new missions and in comparison to 40-year-old Magellan imagery. Finally, as noted above (Section 9.1), orbital microwave data can be used to identify, characterize, and monitor ash-rich volcanic plumes.

9.4 Terrestrial Analogs

The Earth provides a natural laboratory of easily accessible active volcanoes that can be monitored and studied in greater scientific detail than on other planetary bodies. Studies of terrestrial volcanism can be used to test both instrument capabilities in natural settings and scientific hypothesis. Further, testing instrument capabilities in natural settings provides real-world limitations of instrument functionality, data interpretation, and opportunity for validation. Preparation for the upcoming Venus missions will require this additional data to support and test approaches for investigating volcanic activity analysis. Programs like AVENGERS (Analogs for VENus' Geologically Recent Surfaces) initiative, the VERITAS 2023 Iceland Analog Campaign, and DAVINCI drone field tests (NM, FL, UT) provide essential comparative datasets (e.g., D'Incecco et al., 2023; D'Incecco et al., 2024a; D'Incecco et al., Submitted; D'Incecco et al., 2024b; Garvin et al., 2025; Nunes et al., 2024). By studying Earth analogs of active basaltic volcanism, we can better understand and interpret data, as well as refine our models of volcanic processes.

The AVENGERS project is investigating numerous active volcanoes on the Earth to provide a comparative study of recent and potentially ongoing volcanic activity on Venus (D'Incecco et al., 2023; D'Incecco et al., 2024a; D'Incecco et al., Submitted). Besides its scientific relevance, the AVENGERS initiative acts as a bridge for international scientific collaboration, between the leadership and/or team members from the currently selected missions to Venus and future missions being considered (D'Incecco et al., 2023; D'Incecco et al., 2024a; D'Incecco et al., Submitted). The first investigation focused on Mount Etna, as an analog for Idunn Mons and as a test case for the AVENGERS initiative (D'Incecco et al., 2024b). Mount Etna was chosen because it offers the opportunity to analyze multiple eruption styles (effusive and explosive) and is one of the most actively monitored volcanoes on Earth (e.g., Marchetti et al., 2019). Further, samples with known ages are being investigated to constrain how terrestrial alteration affects spectroscopic measurements and show, at a first order, that spectroscopy can determine the alteration stage, and therefore relative age, of a basalt from Mount Etna (Eggers et al., 2023). The initiative is expanding to La Palma and Kamchatka, including in situ operational tests for future orbital and lander Venus missions (D'Incecco et al., 2024c). Similarly, the VERITAS team, in collaboration with the German Aerospace Center (DLR), which includes members of the EnVision team, have been investigating Iceland as a Venus scientific and operational analog for X band and NIR data (Nunes et al., 2024). The work involved airborne radar mapping with surface characterization to ground truth their interpretations of radar backscatter and NIR emissivity, in preparation for orbital measurements at Venus (Adeli et al., 2024; Keller et al., 2024). The DAVINCI team is similarly using drone-based descent and horizontal imaging experiments in New Mexico near Las Cruces to establish training sites for spatial scales for discrimination and recognition of primary geologic features for DAVINCI (Garvin et al., 2025). Future targets in Iceland and elsewhere are being established so that the DAVINCI descent imaging approach under the Venus clouds is adequately evaluated as an approach for providing the Venus community with high-integrity ground-truth data at scales not possible from the radar orbiters (< 10 m x, y).

Beyond analog field work, analog laboratory experiments that simulate Venus-like conditions, such as high temperatures and pressures, are needed to help support the interpretation of mission data (see perspectives Filiberto and McCanta, 2024 and Zolotov, 2025). This is especially important for understanding how volcanic materials behave in Venus' extreme surface environment and how they might appear in microwave, VNIR, and optical data (e.g., Barmatz et al., 2024; Dyar et al., 2021; Gilmore et al., 2017; Gilmore et al., 2023; Santos et al., 2021; Treiman et al., 2021). Additionally, experimental work on surface/atmospheric interactions will assist in the characterization of atmospheric chemistry measurements to better determine if measurement values are driven by volcanic activity or are the result of natural variability (e.g., Fegley and Treiman, 1992; Prinn and Fegley, 1987). Advanced models of volcanic and tectonic processes will provide a framework for understanding the data from future missions. These models can help predict the rates of crustal motion, lava flow dynamics, and the thermal evolution of volcanic regions, informing both data interpretation and mission planning. Together, these data and tools will be essential for robust change detection and advancing our understanding of Venusian volcanism.

10) Conclusions

We find that the combination of all currently available evidence strongly indicates that Venus is volcanically active today; however, no single data set alone confirms active volcanism and its present rate. Instead, the best evidence for active volcanism comes from combining data sets and approaches – specifically at Idunn Mons, Maat Mons, and Aramaiti Corona – and not from a single study or data set alone. This is an important lesson for future missions: unless we observe an active volcanic plume or flow during its emplacement, it will require an interdisciplinary approach that involves comparing complementary data sets from different missions and instruments to determine how volcanically active Venus is today. Comparing data sets across missions with different instruments introduces the potential for significant errors and misinterpretations that must be addressed. We present techniques throughout to help address these potential errors – specifically we have focused on techniques for orbital radar measurements with different look geometries. Further, using terrestrial analogs in addition to experimental and modeling approaches is critical for understanding data from future missions. A volcanically active Venus would place important constraints on the geodynamics of the interior, depending on the volcanism rate today. Considering the evidence for activity that we have today, observations do not favor so-called "catastrophic" models of resurfacing, instead they are better represented by ongoing regional scale events. To reliably detect and characterize active or recent basaltic volcanism the new missions must collect high-resolution imaging, repeat observations, polarimetry, evidence of outgassing, deep atmospheric trace gas compositional data (including fO_2), and topographical data that provide insights into surface changes over time. Most importantly, understanding whether active volcanism is occurring will require correlating complimentary data sets from different missions to understand the planet holistically.

Open Research Data

Magellan data used here include SAR imagery original data records and mosaics, and the Global Topographic Data Record (GTDR-SINUS 2;2) or the PDS4 bundled data records.

Natural Science Institute of Iceland, ÍslandsDEM, v.1.0, https://dem.gis.is/mapview/?application=DEM

Copernicus Data Space Ecosystem (Sentinel-1 image data) https://browser.dataspace.copernicus.eu/.

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