Idunn Mons: Evidence for Ongoing Volcano-tectonic Activity and Atmospheric Implications on Venus

P. D'Incecco[1,2] , J. Filiberto[3] , I. López[4] , D. A. Gorinov[5] , and G. Komatsu[1,6]

[1] Dipartimento INGEO, Università d'Annunzio, Viale Pindaro 42, 65127 Pescara, Italy
[2] Arctic Planetary Science Institute (APSI), Rovaniemi, Finland
[3] Lunar and Planetary Institute, USRA, 3600 Bay Area Boulevard, Houston, TX 77058, USA
[4] Departamento de Biología, Geología, Física y Química Inorgánica. Universidad Rey Juan Carlos, Madrid, Spain
[5] Space Research Institute of the Russian Academy of Sciences, Profsoyuznaya st., 84/32 Moscow, Russia
[6] International Research School of Planetary Sciences, Università d'Annunzio, Viale Pindaro 42, 65127 Pescara, Italy

Abstract

In 2010 the ESA Venus Express Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) instrument first observed 1 μm emissivity anomalies over the top and eastern flank of Idunn Mons (46° S; 146° W), a 200 km wide volcano located in Imdr Regio, a volcano-dominated large volcanic rise of Venus. The anomalies suggest the presence of chemically unweathered and fresh volcanic deposits, which provided the first hint that volcanism in this area may have been active during the past few million years. Subsequent studies have investigated the geologic and atmospheric evolution at Idunn Mons, but no study has comprehensively investigated the evolution and the implication for recent activity in Idunn Mons. Previous work, using both VIRTIS data and Magellan radar emissivity data, confirmed the occurrence of unaltered basaltic lava flows at Idunn Mons. Building on that previous work, experimental laboratory studies have revealed that chemical weathering on Venus may act much faster than previously expected, which suggests very young ages for these flows. This inference has been supported by investigations of the tectonic fracturing surrounding Idunn Mons. Finally, atmospheric data from VIRTIS also show regional anomalies in the speed of the winds in the lower atmosphere over Imdr Regio, which may be related to very recent or ongoing volcanism. In this paper, we take a comprehensive approach, using atmospheric to surface measurements, including recent laboratory experiments, to constrain the evolution of Idunn Mons. Our work suggests that Idunn Mons may be geologically both volcanically and tectonically active today.

Unified Astronomy Thesaurus concepts: Venus (1763); Volcanoes (1780); Planetary science (1255); Solar system (1528); Spectroscopy (1558); Planetary atmospheres (1244)

1. Introduction

Imdr Regio is one of the volcano-dominated large topographic rises of Venus (Stofan et al. 1995). The topographic rises are thought to be formed by mantle upwelling with a style of resurfacing comparable to that of terrestrial hotspots (Stofan et al. 1995; Stofan & Smrekar 2005). Based on its apparent depth of compensation, uplift, and limited amount of erupted volcanic material, the plume underlying the topographic rise of Imdr Regio is thought to be at a relatively early stage of evolution, given that a significant amount of pressure-release melting still has to be produced by its underlying mantle plume (Stofan et al. 1995). With its 200 km (120 miles) diameter and an elevation of 2.5 km (1.6 miles) above the plains, Idunn Mons (46° S; 146° W) is the major volcanic edifice of Imdr Regio (Figures 1(a) and (b)). It is a large shield volcano, characterized by a flat top with gently sloping lower flanks and a complex summit (Stofan et al. 1995; D'Incecco et al. 2017; López et al. 2021).

The volcanic edifice is arranged along the axis of a rift trend, Olapa Chasma. Near Idunn Mons, the rift fractures and graben are reoriented following the stress field responsible for the rift formation. Given their tectonic interaction, we define Olapa Chasma and Idunn Mons (OCIM) as a volcano-rift system. Multiple episodes of extensional fracturing and volcanic

eruptions have alternated and overlapped during the recent geologic past of the area (D'Incecco et al. 2020).

VIRTIS data showed high 1 μm emissivity anomalies over the top and eastern flank of Idunn Mons (Mueller et al. 2009; Smrekar et al. 2010). These anomalies indicate the presence of chemically unweathered surface deposits, which were thought to be less than 2.5 million years old or younger (Smrekar et al. 2010). The chemical weathering on Venus represents all the chemical reactions taking place at the surface–atmosphere interface. In this regard, the oxidation of Fe^{2+} to Fe^{3+} in silicate minerals is particularly important because it can be measured from orbit, including what VIRTIS measured (Dyar et al. 2020), and hematite coatings on rocks were potentially observed by the Venera images of the surface (Pieters et al. 1986). Recent experimental studies simulating the surface environment of Venus suggest that chemical weathering on the surface of Venus acts much faster than previously expected (Fegley et al. 1995; Berger et al. 2019; Filiberto et al. 2020; Cutler et al. 2020). The age of volcanic activity is particularly important, because Imdr Regio may be key to constraining the debate regarding Venus's resurfacing history. Venus is characterized by a dry atmosphere, while it is still an object of debate whether its mantle is comparably anhydrous (Strom et al. 1994; Nimmo & Mckenzie 1998; Filiberto 2014; Karimi & Dombard 2017). Understanding whether the most recent surface volcanic deposits on Venus formed from a hydrous or anhydrous interior might provide important clues about the current presence or absence of a weak Earth-like asthenosphere. A wetter interior might in fact favor the presence of a weak
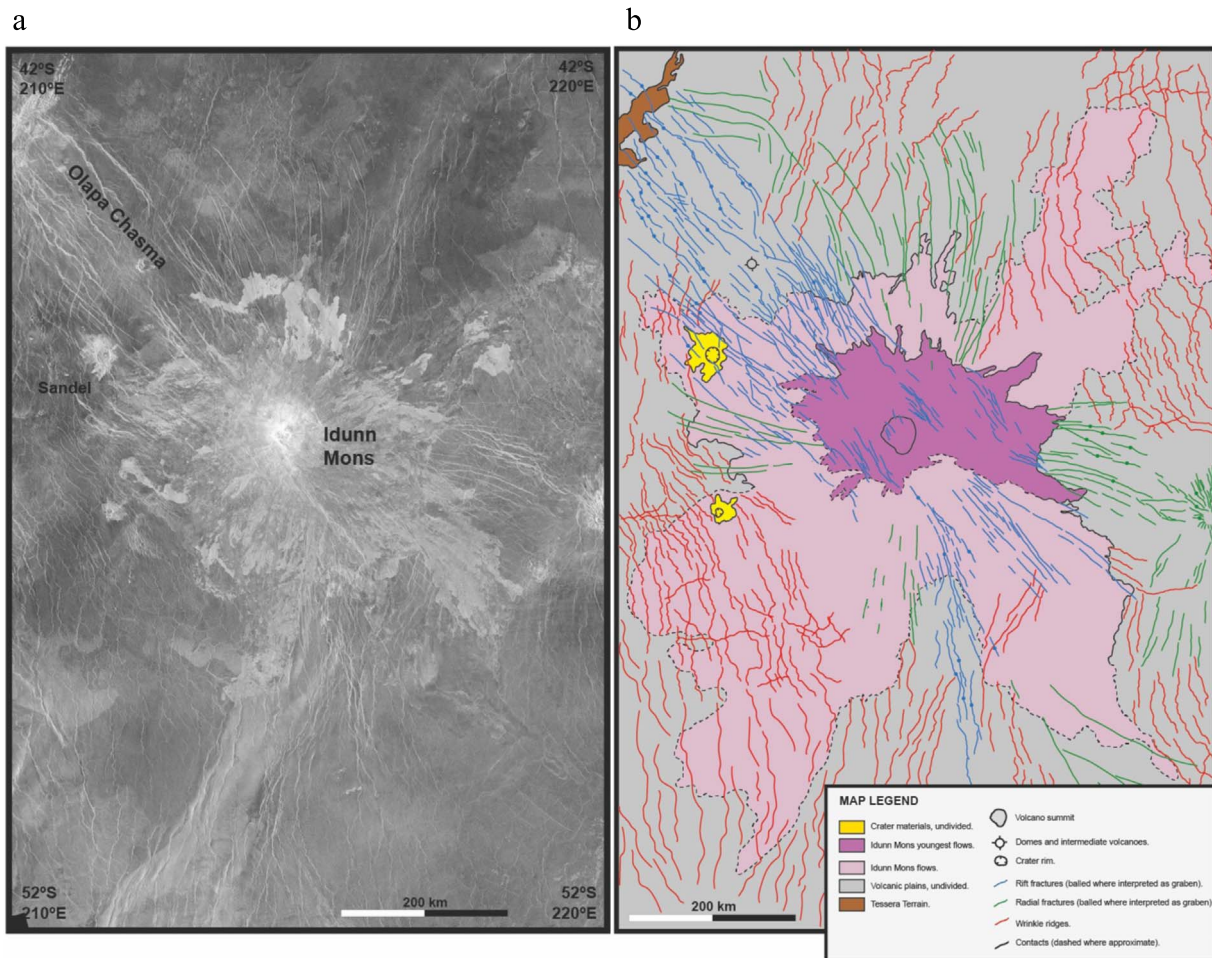
Figure 1. (a) Left-looking Magellan radar image of Olapa Chasma, Idunn Mons, and Sandel crater. (b) Simplified geologic map of the Olapa Chasma–Idunn Mons volcano-tectonic system.

asthenosphere and a more steady (Equilibrium) volcanic resurfacing (Phillips 1992; Phillips & Hansen 1994; Guest & Stofan 1999; Bjonnes et al. 2012; O'Rourke & Korenaga 2015), while a drier interior may overheat the mantle, causing a catastrophic resurfacing event (Schaber 1992; Strom et al. 1994; Nimmo & Mckenzie 1998; Turcotte et al. 1999; Romeo & Turcotte 2010).

Using a holistic approach, here we combine observations in surface geology, emissivity of the region, experimental studies, and atmospheric circulation in lower and upper clouds from IR (VIRTIS) and UV (VMC) observations above Imdr Regio, to constrain the possible age and evolution of Idunn Mons and Imdr Regio. In this paper, we combine and analyze previously published results from the literature and new recent results over the study area in a broader and more multidisciplinary perspective than previous work.

2. Evidence for Recent Volcanism Derived from Surface Studies

2.1. Recent Volcanic Activity at Idunn Mons Inferred from the Combination of Geologic Mapping, VIRTIS 1 μm Anomalies, and Magellan Low Radar Emissivity Signatures

Data from the Venus Express mission enabled the production of the first map of 1 μm surface emissivity for the southern hemisphere of Venus (Mueller et al. 2009). Preliminary studies from VIRTIS instrument data identified high emissivity anomalies over the top and eastern flank of Idunn Mons (Smrekar et al. 2010). Given the speed of chemical alteration that surface materials undergo on Venus owing to their interaction with the low atmosphere, these anomalies can be related to the presence of unweathered and fresh materials. Observing those anomalies over the summit area of a volcanic structure provided a first strong argument in favor of geologically recent (less than 2.5 million years old) volcanic activity at Idunn Mons (Smrekar et al. 2010).

Subsequent studies investigated the possible location and extent of the lava flows likely responsible for the emissivity anomalies (D'Incecco et al. 2017; Figures 2(a)–(c)). Five distinct lava flow units—one summit and four flank units—were mapped using full-resolution (75–100 m pixel^{-1}) Magellan SAR left-looking images. Eight configurations were then tested, assigning in each configuration varying values of simulated emissivity. The best-fit scenario—the one that better approximated the observations of the VIRTIS instrument—was number seven (Figures 2(b)–(c)), where high values of simulated emissivity had been assigned to the flank lava flow units. Hence, according to the emissivity modeling, the flank lava flow units would be more likely to be responsible for the observed 1 μm high emissivity anomalies.

Using the differences in radar brightness and the cross-cutting relationships between mapped lava flows and tectonic fractures, a post-eruption stratigraphic reconstruction was also
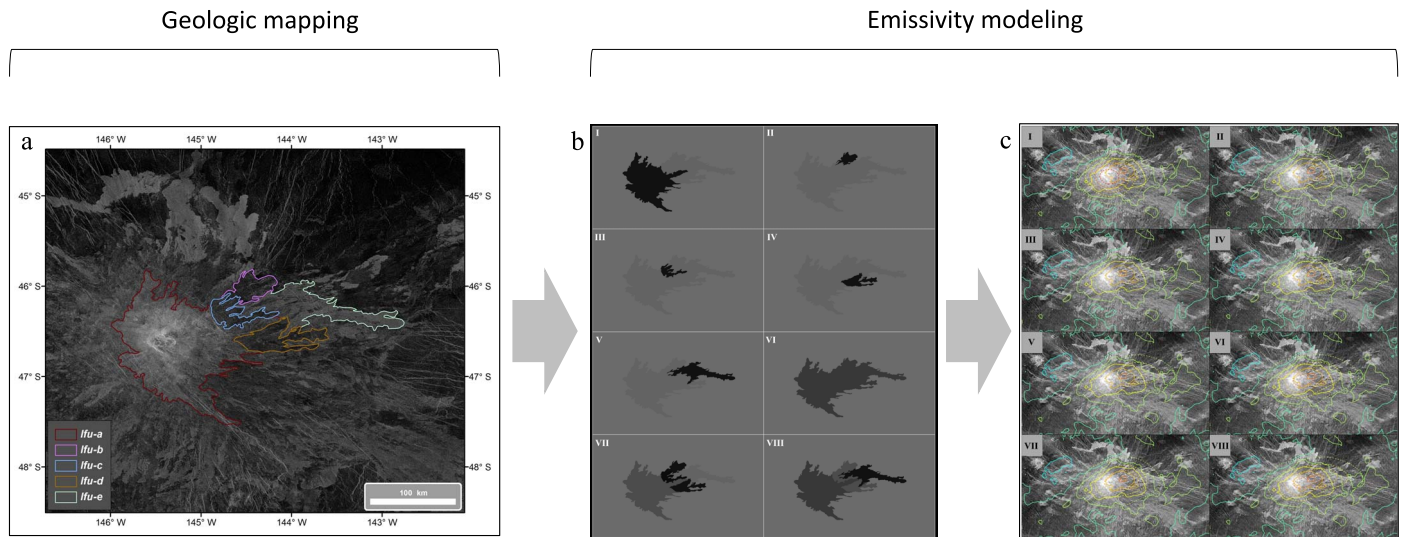
Geologic mapping

Emissivity modeling

Figure 2. The figure shows the iterative steps followed to derive location and extent of the lava flows possibly responsible for the high 1 um VIRTIS emissivity anomaly observed over the top and eastern flank of Idunn Mons (Smrekar et al. 2010). (a) The five lava flows units mapped over the area affected by the 1 mm emissivity anomalies. (b) The eight tested scenarios. In each scenario, a different value of simulated emissivity was assigned to each of the mapped lava flow units (black = higher emissivity). (c) Overlap between the emissivity anomalies observed by the VIRTIS instrument (solid lines) and the anomalies as derived from the simulation performed in each of the eight scenarios. Source: D'Incecco et al. (2017).
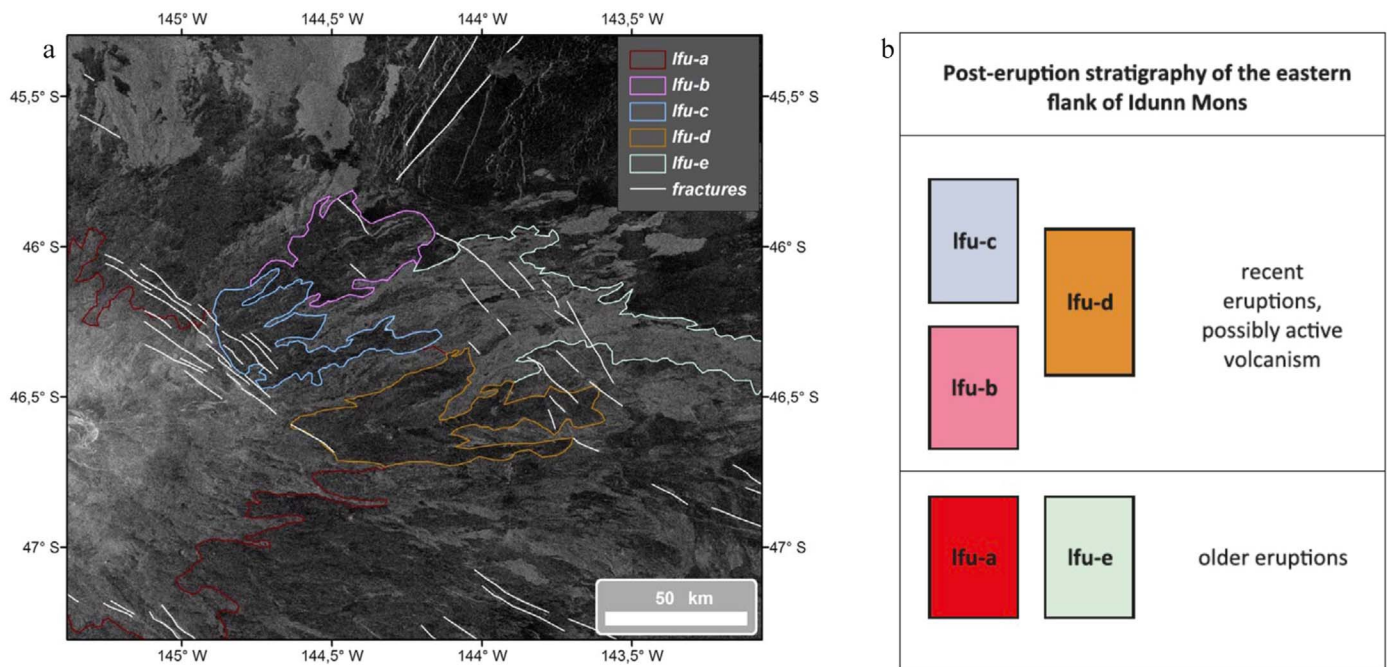

Figure 3. (a) Detailed image showing the five lava flow units and the tectonic fractures mapped over the top and eastern flank of Idunn Mons. Left-looking Magellan full-resolution SAR image. (b) The proposed post-eruption stratigraphic reconstruction for the study area. Source: D'Incecco et al. (2017).

determined in the same area, fully independent from the emissivity modeling (Figures 3(a)–(b)).

The independently performed tentative stratigraphic reconstruction agrees with the emissivity modeling, indicating that upper flank units are the likely source for the observed 1 μm high emissivity anomalies, with two of the flows (lfu-c and lfu-d; Figure 3(b)) possibly originating from the tectonic fractures of the OCIM system.

Recent detailed analysis using the Magellan low radar emissivity signatures was consistent with the observations based on VIRTIS data, indicating the presence of unweathered

and fresh volcanic deposits over the summit area of Idunn Mons (Brossier et al. 2020).

2.2. Recent Tectonic Activity as Shown by Local Stratigraphic Relations at Sandel Crater

Idunn Mons is situated within Olapa Chasma, a NW–SE trending rift. The tectonic interaction between the volcanic structure and the rift is complex, with the stress fields due to the formation of Olapa Chasma being dominant in determining the actual orientation of the fracture pattern of the OCIM system.
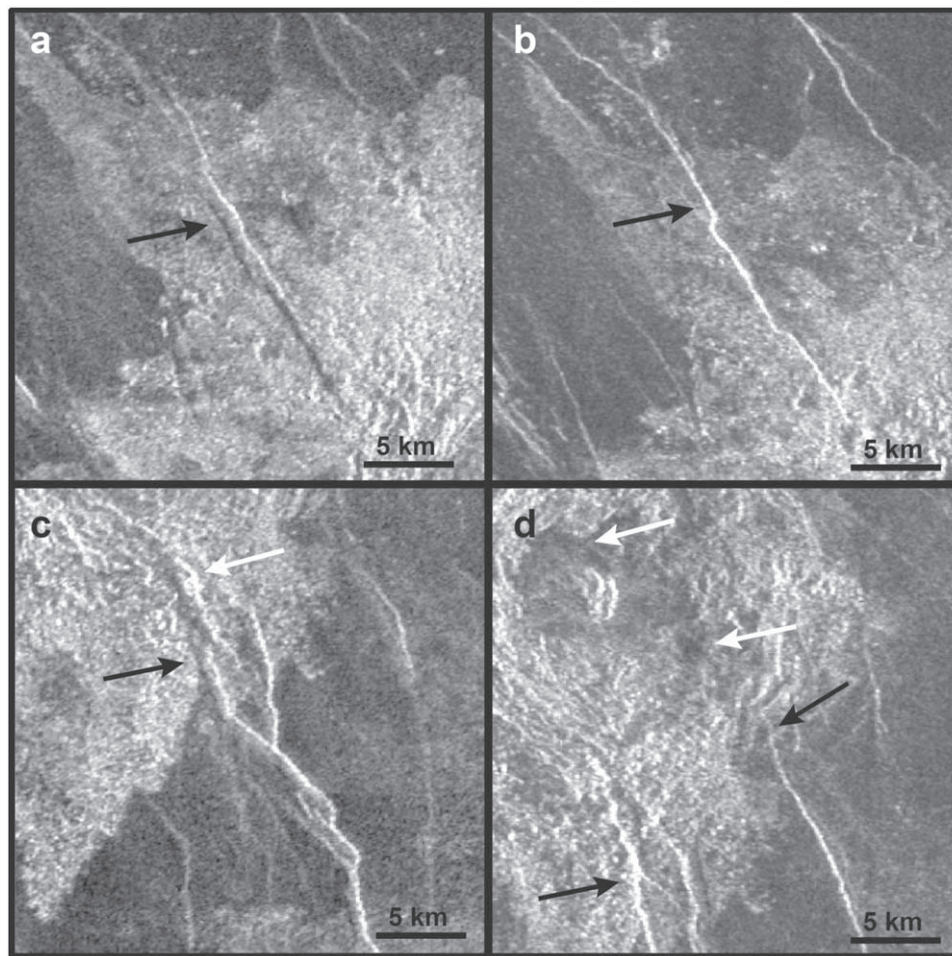
Figure 4. Detailed images of the fractures and graben intersecting Sandel crater (45.7°S/211.7°E). The white arrows indicate fractures and graben postdating the impact units, while the black arrows indicate uncertain stratigraphic interrelationship. (a) Graben intersecting the impact deposits in the NW portion of Sandel crater. Left-looking Magellan full-resolution SAR image. (b) Same graben as shown in panel (a), but observed from the right-looking Magellan full-resolution SAR image. (c) Graben (8.7 km in length) intersecting the impact deposits SE of Sandel crater, extending up to and cutting the crater rim. Left-looking Magellan full-resolution SAR image. (d) Two fractures disrupting the floor of Sandel crater. Right-looking Magellan full-resolution SAR image. Source: D'Incecco et al. (2020).

Sandel crater (45.7°S/211.7°E; Figure 1), a morphologically fresh and pristine impact structure situated NW of Idunn Mons (Schaber & Strom 1999), has been used as a stratigraphic marker to constrain the relative temporal interrelationships of the tectonic activity and its alternation with volcanic eruptions during the geologic history of the OCIM system (D'Incecco et al. 2020). Given the radiometrical properties of its only partially degraded but still well-visible dark halo (Izenberg et al. 1994), it is possible to constrain the formation of Sandel crater to be between $0.5\ T$ and $0.15\ T$, with T being the mean global surface age of Venus (Phillips 1992; Schaber 1992).

We found evidence for fractures and graben from the OCIM system intersecting impact deposits up to the southern portion of the rim of Sandel crater (Figures 4(a)–(c)), with two fractures extending onto the floor of the crater (Figure 4(d)). While the terracing may have extended enough into the external ejecta deposits so that eventually preexisting fractures and graben could be exposed, the presence of a graben disrupting the rim and the two aligned fractures onto the floor of the crater constitutes a direct piece of evidence for tectonic activity being reactivated or having continued after the formation of the fresh impact structure (Figure 4(d); D'Incecco et al. 2020).

Analyzing the fracturing SE of Sandel crater, we observed that the same lava flow can bury a fracture while being cut by another fracture (Figure 5). Even if it was not possible to stratigraphically relate those lava flows with Sandel crater, this provides evidence for the tectonic activity alternating in time with volcanic eruptions at the OCIM system.

2.3. Recent Volcanic Activity as Shown from the Eruptive History at Idunn Mons

Combining the evidence from emissivity, experimental studies, and geomorphology shows that the volcanic history of Idunn Mons is that of a complex volcano that has gone through different eruptive styles and phases. Initial geologic mapping of Idunn Mons flows shows that the first materials associated with the edifice are long sheet flows that reach more than 500 km (Figure 1(b)). The flows are texturally smooth but display differences in backscatter that can be related to differences in the small-scale texture and/or amount of alteration. These flows are contemporaneous with a suite of radial fractures that can be related to the emplacement of radial dikes during the initial phase of the volcanic plume responsible for the volcano (Grosfils & Head 1994; Ernst et al. 1995, 2001).
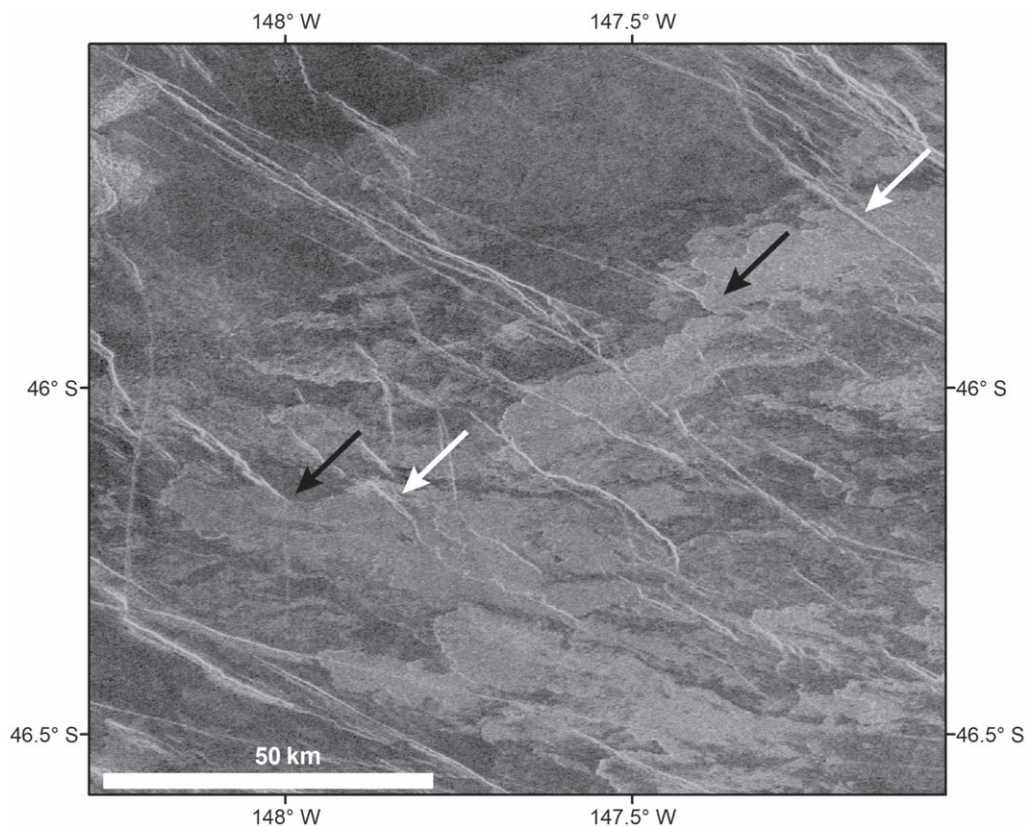
Figure 5. Southern area of Sandel crater. The figure shows two distinct lava flows, each of those buries (black arrows) and it is cut (white arrows) by a fracture from the OCIM system. Left-looking Magellan full-resolution SAR image. Source: D'Incecco et al. (2020).

Postdating these flows, and more restricted to the volcano flanks, several units of digitate volcanic flows form the summit and flanks of Idunn Mons and postdate the previous sheet flows. Though internal limit boundaries of the different individual flows are very difficult to delineate owing to the multiple overlapping flows, there is evidence of multiple effusive events on the summit and the volcano flanks. The youngest of these flows are coincident with the location of the 1 μm emissivity anomalies first identified by Smrekar et al. (2010), indicating the presence of fresh and unweathered lava flows on the summit and eastern flank of the volcano (see also the solid lines in Figure 2(c)). Hence, the stratigraphy of Idunn Mons based on the independent geological mapping is consistent with the observations made by the VEX VIRTIS instrument.

The existence of a complex caldera on the summit with multiple overlapping collapse events that migrate to the southwest is indicative of the existence of a shallow magma chamber that has gone through multiple collapse events that could be related to the emplacement of these digitate flows on the volcano flanks. The presence of large flows and dike emplacement, together with this late-stage summit evolution related to the presence of a shallow reservoir, has been described in other large volcanoes formed in large igneous rises (Keddie & Head 1995). This is fully consistent with the observations made by Stofan et al. (1995), who proposed that —based on the relation between uplift and amount of erupted volcanic material—Imdr Regio is at an early stage of evolution and still has to go through multiple stages of volcanism.

Idunn Mons has a flat-topped summit that can be observed in Magellan left- and right-looking images (Figure 6; López et al. 2021). Other large Venusian volcanoes also have this type of summit (e.g., Sapas Mons), but this structure is more common in smaller edifices such as domes and ticks. Scarps and small horse-shoe amphitheaters can be observed in its eastern lower summit (Figure 6). This morphology could be the result of the small lateral flank collapse events or be lateral parasitic vents partially embayed by younger flows sourced in the summit or in fractures in the volcano apron (D'Incecco et al. 2017). Although we cannot identify clear collapse-related deposits at the summit base, right-looking radar images of the eastern part of the summit show the presence of high backscatter materials that could be interpreted as an embayed hummocky terrain related to a previous lateral flack collapse event (Figure 6). The existence of collapse events in the history of Idunn Mons could be closely related to the syn-tectonic formation of Idunn Mons and Olapa Chasma (D'Incecco et al. 2017, 2020), with local tectonic-related instabilities and lateral flank collapse events formed during the volcano evolution. These lateral collapse events would predate the younger digitate flows that emanate from the summit and fractures on the volcano flanks, which have been interpreted as recent unweathered materials (Smrekar et al. 2010; D'Incecco et al. 2017; Cutler et al. 2020; Filiberto et al. 2020).

3. Temporal Constraints on the Age of Idunn Mons Lava Flows from Laboratory Analyses on the Oxidation and Alteration Rate of Igneous Materials

Orbital emissivity measurements of lava flows at Idunn Mons range from > 0.9 to < 0.8 (Smrekar et al. 2010), which is consistent with a change from fresh basalt to altered hematite coated basalt. While these flows were interpreted geologically
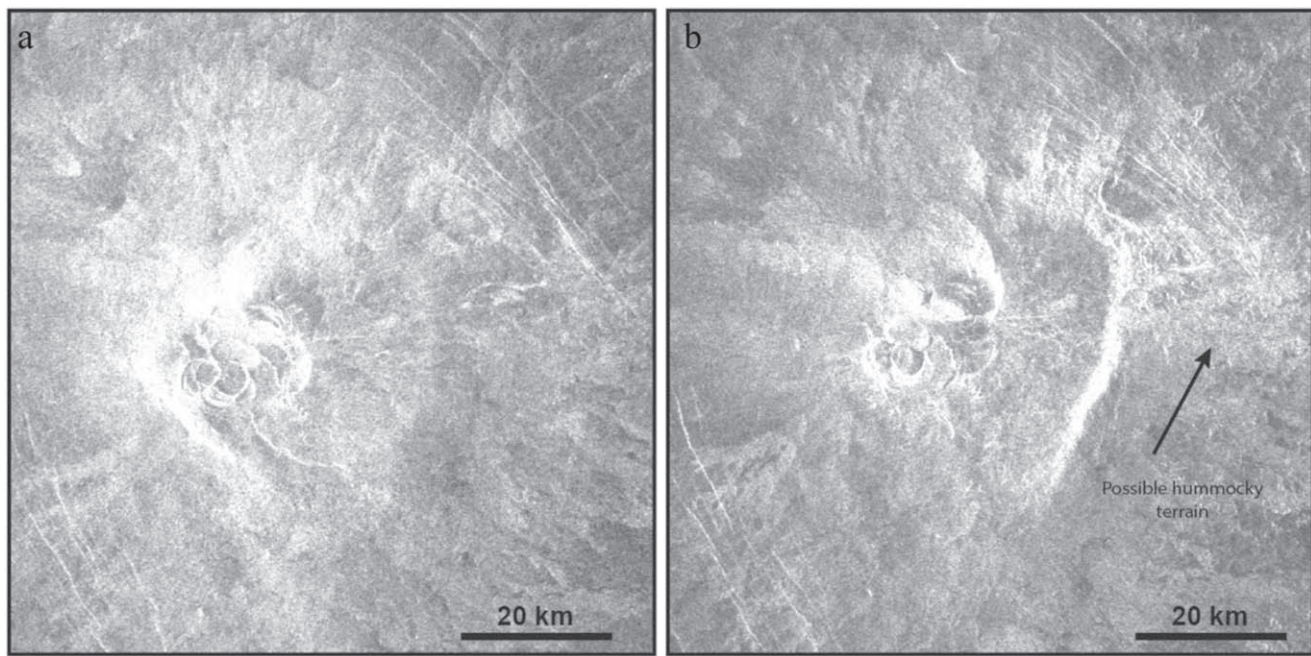
Figure 6. Detailed images of the summit area of Idunn Mons. High-reflectivity material is visible, which can be interpreted as a partially embayed hummocky terrain. Magellan full-resolution radar images: (a) left-looking; (b) right-looking.

young (at most 2.5 million years old or possibly even as young as 250,000 yr; Smrekar et al. 2010), in order to constrain the age of these flows and the most recent volcanism at Idunn Mons, experimental and geochemical weathering studies were needed to constrain the rate basalts alter at high surface temperatures in contact with the caustic, CO_2-rich, S-bearing Venus atmosphere; what alteration minerals form; and how the formation of alteration minerals changes the 1 μm emissivity.

Experimentally reproducing the high-temperature, high-pressure, and caustic nature of the Venus surface for a long duration is difficult, especially with large enough samples to be analyzed by spectroscopy; therefore, experiments typically reproduce some but not all of the exact conditions, and then experimental results from different approaches are combined and extrapolated accordingly (Fegley et al. 1995, 1997; Berger et al. 2019; Radoman-Shaw 2019; Santos et al. 2019; Filiberto et al. 2020; Cutler et al. 2020; Dyar et al. 2021; Reid et al. 2021; Teffeteller et al. 2021). Here we summarize two different approaches: (1) long-duration (up to 7 weeks) oxidation experiments at elevated temperatures with large sample size (Filiberto et al. 2020; Cutler et al. 2020; Knafelc et al. 2019; Fegley et al. 1997, 1995), and (2) shorter-duration (1–2 weeks) experiments under more directly applicable conditions (Berger et al. 2019; Radoman-Shaw 2019; Santos et al. 2019; Reid et al. 2021; Teffeteller et al. 2021). Geochemical modeling also provides vital information on surface alteration mineralogy (Zolotov 2018; Semprich et al. 2020; Dyar et al. 2021) and can be used to help extrapolate not directly applicable experimental results. We then combine these experimental and modeling results to constrain maximum and minimum age for these young flank lava flows on Idunn Mons.

Oxidation experiments have been conducted on a wide range of basaltic materials, including a range of silicate minerals and alkali basalt analogous to the rock analyzed at the Venera-13 landing site and at temperatures from Venus surface temperatures to significantly hotter (900°C) for specific minerals

(Fegley et al. 1997; Filiberto et al. 2020; Cutler et al. 2020). Hotter temperatures were chosen, as they mimic time speeding up the reaction and can be compared with lower-temperature experiments to predict how oxidation proceeds through time. The experimental results showed that iron diffuses quickly through olivine and basaltic glass to produce patchy iron-oxide coatings on the surface of rocks after weeks to months of oxidation. Such hematite (pigmentary or nanophase) coating the surface of rocks is consistent with the color of surface rocks and regolith on Venus at the Venera 9 and 10 landing sites (Pieters et al. 1986). Pyroxene oxidation produces mainly Fe^{+3} within the crystal structure with only minor iron-oxides on the surface (Cutler et al. 2020; McCanta & Dyar 2020).

Visible-to-near-infrared reflectance spectroscopic measurements of the run products show that while iron-oxides do not necessarily fully coat the surface of a sample, hematite starts obscuring the signature of both olivine and basalt after 1 month of oxidation at 600°C, and hematite dominates the spectral signature obscuring all igneous signature after ∼1 month of oxidation of olivine at 900°C and 7 weeks of oxidation of basalt at 600°C (Filiberto et al. 2020; Cutler et al. 2020). These results are consistent with experiments conducted under 92 bars of CO_2 atmosphere and Venus surface temperatures (Berger et al. 2019; Teffeteller et al. 2021), which produced iron-oxides forming on the surface of basaltic glass and olivine after 1–2 weeks of experimentation. Teffeteller et al. (2021) used the experimental results to suggest that lava flows would only appear "fresh" up to about 10,000 yr; however, the spectral signal of any basalt on the surface may change over that time (Filiberto et al. 2020; Cutler et al. 2020; Filiberto et al. 2021a, 2021b). However, these experiments did not contain S, which is likely the most reactive species in the atmosphere (e.g., Zolotov 2018; Dyar et al. 2021). Previous and ongoing experiments on basaltic and granitic rocks with added sulfur show that anhydrite can form even faster on the surface of Venus, but that iron-oxides form as well (Berger et al. 2019; Radoman-Shaw 2019; Santos et al. 2019; Reid et al. 2021).

Consistent with the experimental results, reaction modeling has shown that the surface of Venus should react to produce mainly calcium sulfates and iron-oxides (Zolotov 2018; Semprich et al. 2020; Dyar et al. 2021), with the exact iron-oxide (magnetite versus hematite) dependent on the oxidation state (which is currently not well constrained). Based on experimental results, time of alteration–magnetite forms first with a progression to hematite with time (Knafelc et al. 2019), which suggests that kinetics are dominating the reactions (Filiberto et al. 2020; Teffeteller et al. 2021). At higher latitudes, and therefore lower temperatures, the reaction products should include pyrite as well (Semprich et al. 2020). The combination of all the experimental and modeling results suggests that they can be extrapolated to understanding Venus alteration rates with the caveat that since anhydrite forms faster than hematite (e.g., Berger et al. 2019; Radoman-Shaw 2019; Santos et al. 2019; Reid et al. 2021; Dyar et al. 2021), estimates based on oxidation only may be maximum lava flow ages. However, modeling has suggested that if the surface coating is sulfates only, depending on the exact chemistry of the coating and the associated emissivity, the lava flows may be up to 500,000 yr old (Dyar et al. 2021).

Combining the experimental and modeling studies shows that lava flows on the flanks of Idunn Mons with "fresh" signatures (those with emissivities > 0.9) must be extremely young, with a minimum age of only a few years or less and a maximum age of ~10,000 yr based on the speed basaltic (and granitic) rocks experimentally alter (Berger et al. 2019; Radoman-Shaw 2019; Santos et al. 2019; Filiberto et al. 2020; Cutler et al. 2020; Zolotov 2018; Teffeteller et al. 2021; Reid et al. 2021) and up to 500,000 yr based on modeling results (Dyar et al. 2021). The ranges of emissivity signature from 0.9 to 0.8 (Smrekar et al. 2010) and the correlation with lava flow rheology (D'Incecco et al. 2017) are consistent with a progression of lava flow ages. Emissivity measurements of Idunn Mons and other potentially active or recently active volcanoes from future missions with higher spatial resolution may be able to resolve lava flow stratigraphy at Idunn Mons, which in turn could be used to constrain lava production rate, which is critically needed to constrain Venus's resurfacing history.

4. Variations of Atmospheric Circulation above Imdr Regio in the Lower Clouds from Infrared Observations

Recent studies have shown that on Venus's surface topography can influence atmospheric circulation, with the most prominent observed effects caused by Aphrodite Terra on the cloud top level circulation (Patsaeva et al. 2019; Khatuntsev et al. 2017; Bertaux et al. 2016; Fukuhara et al. 2017). Much less is known about the influence of smaller mountains. In averaged longwave infrared images faint thermal features were associated with various topographic rises in the equatorial region (Fukuya et al. 2019). Irregular behavior of oxygen nightglow in the upper mesosphere (both in emission intensity and in circulation patterns) was suggestively attributed to highlands in the southern hemisphere, such as Phoebe Regio (Gorinov et al. 2021).

The proposed explanation for these effects is the influence of stationary gravity waves, emerging from the surface, where the atmospheric flow interacts with the topographic rises. In the case of ongoing volcanism, the overheated surface of the lava flows could create additional influence on the atmospheric circulation through vertical propagation of the waves. A recent analysis of the infrared images in 1.74 μm (Gorinov et al. 2018)

from VIRTIS has shown that longitudinal variations exist in the lower cloud layer of Venus (44–48 km). In middle latitudes a notable deceleration of the mean zonal component by 4–5 m s^{-1} in the longitudes of 220°E–260°E was reported. It was the most prominent change of zonal speed magnitude across the southern hemisphere, also exceeding any possible local time bias. A longitudinal profile in the 40°S–50°S latitude range illustrated that this deceleration occurs at the same longitudes as the peak of Imdr Regio, its eastern slopes, and about 50° further eastward. Despite other highlands present in the same latitude bin (Themis Regio, southern part of Aphrodite Terra), a significant change of zonal speed is only observed at the coordinates of Imdr Regio.

This zonal wind deceleration could be caused by the aforementioned mechanism of stationary gravity waves. Effects of such topographic influence are expected to be less noticeable in the lower clouds compared to the cloud top (Yamamoto et al. 2019). However, it is not clear why in the lower clouds a dynamic signature suggestively attributed to Imdr Regio is much stronger than that of Themis Regio despite almost the equal topographic altitudes. This leads us to the suggestion that another mechanism could be involved, and one hypothesis is higher-than-average surface temperature at Imdr Regio. Simulating effects of localized lava flows on atmospheric dynamics can be promising for future research.

5. Discussion

Previously published work from a range of scientific disciplines suggested recent and possibly ongoing volcanic and tectonic activity on Venus (and Idunn Mons in particular), such as spectroscopy (Smrekar et al. 2010; D'Incecco et al. 2017; Cutler et al. 2020; Filiberto et al. 2020, 2021a), radar observations (Brossier et al. 2020), and geology (D'Incecco et al. 2020), with some anomalies also being shown by the wind circulation in the lower atmosphere of Venus, as shown by the VIRTIS-M infrared images (Gorinov et al. 2021). We also showed a new simplified high-resolution geological map of Idunn Mons and atmospheric data on the wind circulation in the lower cloud of Venus (Gorinov et al. 2021). However, all these works and results analyzed each aspect of active volcanism, tectonism, and atmospheric circulation at Imdr Regio from a very specific and usually single perspective.

Instead, here we consider all the previously published and new results under the broader view of what they tell us in terms of ongoing volcano-tectonic activity at Idunn Mons.

Using Sandel crater (Figure 1(a))—a fresh impact structure situated NW of Idunn Mons—as a stratigraphic marker, D'Incecco et al. (2020) found evidence for volcano-tectonic activity at the OCIM system taking place after the formation of the crater. They constrained the age of this activity between 0.5 T and the present day, with T being the mean global surface age of Venus (Phillips 1992; Schaber 1992).

The independent stratigraphic reconstruction provided by the preliminary and simplified high-resolution geological mapping of Idunn Mons (Figure 1(b)) identified the lava flows on the summit and eastern flank of the volcano as the youngest ones (López et al. 2021). This result fully supports previous observations on the age, location, and extent of the youngest lava flows at Idunn Mons, based on the 1 μm VIRTIS emissivity anomalies (Smrekar et al. 2010; D'Incecco et al. 2017). Another important aspect is also constituted by the presence of multiple caldera collapses on the top of Idunn Mons, which indicates the presence of a shallow magma

chamber. Based on the relation between apparent depth of compensation, uplift, and limited amount of erupted volcanic material, Stofan et al. (1995) suggested that—unlike all the other volcanic rises—the active plume underlying Imdr Regio may still be in an early stage of evolution, a unique case for Venus and implying that significant quantities of pressure-release melt still must be produced. Considering that (1) the limited amount of plume-related volcanic deposits in Imdr Regio is mainly localized over Idunn Mons and (2) the youngest flows of Idunn Mons are located just on its summit calderas and eastern flank, those observations are consistent with volcanism being ongoing on Idunn Mons and with multiple episodes of volcanic eruptions occurring just on its summit caldera. Modeling results constrained the age of the youngest lava flows at Idunn Mons up to 500,000 yr (Dyar et al. 2021), which in terms of geologic time is consistent with an ongoing volcanic activity. However, experimental results from laboratory analyses on the oxidation and alteration rate of igneous minerals have provided more precise temporal constraints and suggested that the youngest (unweathered) lava flows on the top and eastern flank of Idunn Mons (*Idunn Mons youngest lava flows* unit, Figure 1(b)) must have a minimum age of only a few years or less and a maximum age of ∼10,000 yr (Berger et al. 2019; Santos et al. 2019; Radoman-Shaw 2019; Filiberto et al. 2020; Cutler et al. 2020; Zolotov 2018; Teffeteller et al. 2021; Reid et al. 2021). Finally, the infrared images from the VIRTIS instrument in the 1.74 μm spectral band (Gorinov et al. 2018) have provided evidence for longitudinal variations occurring in the lower cloud layer of Venus (44–48 km). Interestingly, a remarkable zonal wind deceleration has been observed over Imdr Regio. Future missions will surely unveil the causes of this wind deceleration. However, as of now, a direct relation between active volcanism and zonal wind deceleration in the lower atmosphere of Venus cannot be ruled out. These combinations of observations and experimental results are consistent with Idunn Mons being volcanically active at the present day.

6. Conclusion

The ESA Venus Express mission focused the attention of the science community on Imdr Regio since high 1 μm emissivity anomalies were observed over the top and eastern flank of its major volcanic structure, Idunn Mons, suggesting the occurrence of possibly geologically young unweathered basaltic lava flows. Here we combine the spectral observations and modeling, laboratory analyses, geologic interpretation, and atmospheric data to discuss the age and evolution of Idunn Mons and Imdr Regio. The combination of all these different data sets shows a panoramic vision of Idunn Mons, which indicates that the volcano-tectonic activity at Imdr Regio and—in particular—at the OCIM system, not only may be recent in terms of geological time, as already suggested by previous studies (Smrekar et al. 2010; D'Incecco et al. 2017, 2020; Filiberto et al. 2020; Cutler et al. 2020), but also is likely ongoing at present. The comparison of the geologic history with the atmospheric data (deceleration of zonal speed above Imdr Regio) for the first time is notable and may suggest active processes; however, its connection to the ongoing volcanic activity remains uncertain. Further studies and future mission data are needed to investigate the extent to which potentially active or recent lava flows can influence atmospheric circulation such as seen above Imdr Regio.

The young volcanic rises are believed to be the surface manifestation of actively upwelling mantle plumes (Smrekar et al. 2010; Stofan & Smrekar 2005; Stofan et al. 1995). The volcano-tectonic activity affecting those areas postdates the formation of the wrinkle ridges (the stratigraphic marker for the mean surface age of Venus); therefore, the volcanic rises can be rightly considered among the geologically youngest areas on the surface of Venus. It is vital that future missions not only measure the surface properties of Idunn Mons but also make repeat measurements of the region, as well as investigate the atmospheric characteristics combined with the surface geology of Venus (Brossier et al. 2020, 2021; Filiberto et al. 2021a; D'Incecco et al. 2021a, 2021b). This holistic approach will be needed to constrain the age, origin, and evolution of Idunn Mons and other young volcanic rises, as well as to use this data set to constrain Venus's resurfacing history.

Finally, future missions should target measuring the atmospheric regions of potentially volcanically active areas on Venus to the search for the presence of trace gases (i.e., sulfur species, phosphine, halogens; e.g., Zolotov 2018; Cordier et al. 2019; Truong & Lunine 2021; Baines et al. 2021; Greaves et al. 2021; Milojevic et al. 2021). The specific amount of such trace gases above active volcanoes is needed to constrain whether an abiotic (Truong & Lunine 2021) or biotic origin (Baines et al. 2021; Greaves et al. 2021) would be needed to produce the trace gases.

ORCID iDs

P. D'Incecco ⓘ https://orcid.org/0000-0002-4002-3878
J. Filiberto ⓘ https://orcid.org/0000-0001-5058-1905
I. López ⓘ https://orcid.org/0000-0003-4608-2606
D. A. Gorinov ⓘ https://orcid.org/0000-0003-2034-1518
G. Komatsu ⓘ https://orcid.org/0000-0003-4155-108X

References

Baines, K. H., Dragan, N., Cutts, J. A., et al. 2021, AsBio, 21, 1316
Berger, G., Cathala, A., Fabre, S., et al. 2019, Icar, 329, 8
Bertaux, J. L., Khatuntsev, I. V., Hauchecorne, A., et al. 2016, JGRE, 121, 1087
Bjonnes, E. E., Hansen, V. L., James, B., & Swenson, J. B. 2012, Icar, 217, 451
Brossier, J. F., Gilmore, M. S., & Toner, K. 2020, Icar, 343, 113693

Brossier, J., Gilmore, M. S., Toner, K., & Stein, A. J. 2021, JGRE, 126, e06722
Cordier, B. D. A., Port, S., et al. 2019, ApJ, 880, 82
Cutler, K. S., Filiberto, J., Treiman, A. H., & Trang, D. 2020, PSJ, 1, 21
D'Incecco, P., Filiberto, J., López, I., et al. 2021a, JGRE, 126, e06909
D'Incecco, P., Filiberto, J., López, I., et al. 2021b, SoSyR, 55, 315
D'Incecco, P., López, I., Komatsu, G., Ori, G. G., & Aittola, M. 2020, E&PSL, 546, 116410
D'Incecco, P., Muller, N., Helbert, J., & D'Amore, M. 2017, P&SS, 136, 25
Dyar, M. D., Helbert, J., Cooper, R. F., et al. 2021, Icar, 358, 114139
Dyar, M. D., Helbert, J., Maturilli, A., Müller, N. T., & Kappel, D. 2020, GeoRL, 47, e90497
Ernst, R. E., Grosfils, E. B., & Mège, D. 2001, AREPS, 29, 489
Ernst, R. E., Head, J. W., Parfitt, E., Grosfils, E., & Wilson, L. 1995, ESR, 39, 1
Fegley, B., Klingelhöfer, G., Brackett, R. A., et al. 1995, Icar, 118, 2
Fegley, B., Zolotov, M. Y., & Lodders, K. 1997, Icar, 125, 416
Filiberto, J. 2014, Icar, 231, 131
Filiberto, J., D'Incecco, P., & Treiman, A. H. 2021a, Elements, 17, 1
Filiberto, J., D'Incecco, P., & Treiman, A. H 2021b, Elements, 17, 67
Filiberto, J., Trang, D., Treiman, A. H., & Gilmore, M. S. 2020, SciA, 6, eaax7445
Fukuhara, T., Futaguchi, M., Hashimoto, G. L., et al. 2017, NatGe, 10, 85
Fukuya, K., Imamura, T., Taguchi, M., Fukuhara, T., & Kouyama, T. 2019, EPSC, 13, 397
Gorinov, D. A., Khatuntsev, I. V., Zasova, L. V., Turin, A. V., & Piccioni, G. 2018, GeoRL, 45, 2554
Gorinov, D. A., Zasova, L. V., Khatuntsev, I. V., Patsaeva, M. V., & Turin, A. V. 2021, Atmos, 12, 186
Greaves, J. S., Richards, A., Bains, W., et al. 2021, NatAs, 5, 655
Grosfils, E. B., & Head, J. W. 1994, GeoRL, 21, 701
Guest, J. E., & Stofan, E. R. 1999, Icar, 139, 55
Izenberg, N. R., Arvidson, R. E., & Phillips, R. J. 1994, GeoRL, 21, 289
Karimi, S., & Dombard, A. J. 2017, Icar, 34, 282

Keddie, S. T., & Head, J. W. 1995, JGR, 100, 11729
Khatuntsev, I. V., Patsaeva, M. V., Titov, D. V., et al. 2017, JGRE, 122, 2312
Knafelc, J., Filiberto, J., Ferré, E. C., et al. 2019, AmMin, 104, 694
Lopez, I., D'Incecco, P., Komatsu, G., & Filiberto, J. 2021, LPSC, 52, 1329
McCanta, M. C., & Dyar, M. D. 2020, Icar, 352, 113978
Milojevic, T., Treiman, A. H., & Limaye, S. 2021, AsBio, 21, 1250
Mueller, M., Helbert, J., Hashimoto, G. L., et al. 2009, LPICo, 1470, 45
Nimmo, F., & Mckenzie, D. 1998, AREPS, 26, 23
O'Rourke, J. G., & Korenaga, J. 2015, Icarus, 260, 128
Patsaeva, M. V., Khatuntsev, I. V., Zasova, L. V., et al. 2019, JGRE, 124, 1864
Phillips, R. J. 1992, LPICo, 789, 89
Phillips, R. J., & Hansen, V. L. 1994, AREPS, 22, 597
Pieters, C. M., Head, J. W., Pratt, S., et al. 1986, Sci, 234, 1379
Radoman-Shaw, B. G. 2019, PhD thesis, Case Western Reserve Univ.
Reid, R. B., McCanta, M. C., Filiberto, J., et al. 2021, LPSC, 52, 1293
Romeo, I., & Turcotte, D. L. 2010, P&SS, 58, 1374
Santos, A. R., Lewis, J. A., McCubbin, F. M., et al. 2019, LPSC, 50, 2579
Schaber, G. G. 1992, JGR, 97, 13257
Schaber, G. G., & Strom, R. G. 1999, LPSC, 30, 1221
Semprich, J., Filiberto, J., & Treiman, A. H. 2020, Icar, 346, 113779
Smrekar, S. E., Stofan, E. R., Mueller, N., et al. 2010, Sci, 328, 605
Stofan, E. R., & Smrekar, S. E. 2005, in GSA Special Papers: Plates, Plumes and Paradigms, Vol. 388, ed. G. R. Foulger et al. (McLean, VA: Geological Society of America), https://doi.org/10.1130/0-8137-2388-4.841
Stofan, E. R., Smrekar, S. E., Bindschadler, D. L., & Senske, D. A. 1995, JGR, 100, 23317
Strom, R. G., Schaber, G. G., & Dawson, D. D. 1994, JGR, 99, 10899
Teffeteller, H., Filiberto, J., McCanta, M. C., et al. 2021, Icar, submitted
Truong, N., & Lunine, J. I. 2021, PNAS, 118, 2021689118
Turcotte, D. L., Morein, G., Roberts, D., & Malamud, B. D. 1999, Icar, 139, 49
Yamamoto, M., Ikeda, K., Takahashi, M., & Horinouchi, T. 2019, Icar, 321, 232
Zolotov, M. Y. 2018, RvMG, 84, 351