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Key Points:

- We map deposits on Venus formed by collapse of volcanic eruption columns
- Radar properties suggest that the deposits are made up of coarse clastic debris
- We propose that these deposits mark sites of renewed magmatic activity

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Pyroclastic flow deposits on Venus as indicators of renewed magmatic activity

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Abstract Radar bright deposits on Venus that have diffuse margins suggest eruptions that distribute debris over large areas due to ground-hugging flows from plume collapse. We examine deposits in eastern Eistla, western Eistla, Phoebe, and Dione Regiones using Magellan data and Earth-based radar maps. The radar bright units have no marginal lobes or other features consistent with viscous flow. Their morphology, radar echo strength, polarization properties, and microwave emissivity are consistent with mantling deposits composed of few centimeters or larger clasts. This debris traveled downhill up to ~100 km on modest slopes and blanketed lava flows and tectonic features to depths of tens of centimeters to a few meters over areas up to $40 \times 10^3 \text{ km}^2$. There is evidence for ongoing removal and exhumation of previously buried terrain. A newly identified occurrence is associated with a ridge belt south of Ushas Mons. We also note radar bright streaks of coarse material west of Rona Chasma that reflect the last traces of a deposit mobilized by winds from the formation of Mirabeau crater. If the radar bright units originate by the collapse of eruption columns, with coarse fragmental material entrained and fluidized by hot gases, then their extent suggests large erupted volatile (CO_2 or H_2O) amounts. We propose that these deposits reflect the early stage of renewed magmatic activity, with volatile-rich, disrupted magma escaping through vents in fractured regions of the upper crust. Rapidly eroding under Venus surface conditions or buried by subsequent eruptions, these markers of recently renewed activity have disappeared from older regions.

Plain Language Summary We map deposits on Venus formed by the collapse of volcanic eruption plumes or fire fountains. These deposits are made up of small rocks fragmented during the eruption, extend up to 100 km from their sources, and cover areas of up to 40,000 km^2 . The rough material covers older lava flows and is being eroded relatively quickly in the harsh environment. We propose that these deposits are evidence for the first stage of eruptions from new batches of magma and that their locations represent some of the youngest volcanically active places on Venus.

1. Introduction

Volcanic deposits dominate the landscape of Venus. At least three quarters of the planet is composed of smooth plains with volcanic dome fields, coronae, and shield volcanoes. Most of these units are associated with morphologies such as lobate flow fronts, channel and levee structures, and pit-like or linear vents. Their surface roughness, as inferred from radar backscatter strength and polarization properties, is consistent with that of Hawaiian basalts of the pahoehoe to a'a types [Campbell and Campbell, 1992]. With the exception of "pancake" domes and narrow channels (canali) of enormous length, there are few features that have no obvious terrestrial parallel.

One type of deposit not explained by simple flow emplacement exhibits strong radar echoes, diffuse margins, and a lack of internal lobes or channels. These features have been identified on volcanoes in Dione Regio [Keddie and Head, 1995], on corona margins in western Eistla Regio [Campbell and Clark, 2006], and surrounding hybrid volcano-tectonic features near Sappho Patera in eastern Eistla Regio [McGill, 2000] (Figure 1). All authors suggest some type of pyroclastic or ignimbritic process to explain their distribution and radar scattering properties. A very different type of landform at Scathach Fluctus, suggested to be an ignimbrite-like deposit by Ghail and Wilson [2013], has distinct lobate margins more similar to those of lava flows than the diffuse margins of the units studied here. To date, there has been no subsequent effort to

Figure 1. A Magellan left-looking radar map labeled with locations of features noted in this study (approximate area 48°S to 25°N latitude, −85.5°E to 55°E longitude).

examine the radar bright, diffuse margined deposits as a group, search for additional occurrences, and consider the implications of their stratigraphic position.

Work based on Venus Express VIRTIS data shows 1.02 μm emissivity enhancements interpreted as evidence for recent (though of indeterminate age) eruptions [Smrekar *et al.*, 2010]. These sites include Hathor and Innini Montes, two of the Dione Regio volcanoes noted as having radar bright, diffuse margin summit deposits. In contrast, Ushas Mons has neither enhanced 1.02 μm emissivity nor radar bright summit material. This correlation suggests a potential role of the radar bright terrain in creating the infrared emissivity anomalies.

Radar measurements are the primary method of investigating the surface properties of Venus. The data used here come from the Magellan orbital radar mission and Earth-based radar mapping. Magellan collected near-global image coverage, in one sense of radar polarization (horizontal transmit and horizontal receive), with about 100 m spatial resolution. Between radar mapping bursts, Magellan measured the microwave thermal emission from the surface, which is related to the dielectric permittivity and small-scale roughness of the terrain [Pettengill *et al.*, 1992; Campbell, 1994]. The spatial footprint of the emissivity measurements is 20–30 km in the latitude range studied here, though the global gridded data set is resampled at a 4.6 km posting. The radar bright units studied below span at least two emissivity footprints along their N-S and E-W axes.

Earth-based radar mapping can achieve 1–2 km spatial resolution and measure echoes in both the opposite-sense (OC) circular polarization and the same-sense circular (SC) mode. The OC echoes are very similar to Magellan measurements and are strongly modulated by slopes that face toward the radar. The SC echoes are much more sensitive to small-scale surface roughness than to topographic slopes. We can also form the circular polarization ratio ($\text{CPR} = \text{SC}/\text{OC}$), which allows for simple comparisons with rough surfaces on the Earth. The utility of these data was demonstrated in mapping of fine debris in the Venus highlands [Campbell *et al.*, 2014; Whitten and Campbell, 2016], and we now have coregistered coverage of the side of Venus that faces Earth at inferior conjunction from 1988, 2012, and 2015 (the relevant part of which is shown in Figure 2).

In this work, we further document the locations, physical properties, planform, and stratigraphic position of radar bright deposits with diffuse margins, using Magellan data for high-resolution mapping and Earth-based data, where available, for polarimetric analysis. These analyses are used to constrain the stratigraphy and spatial scale of emplacement with respect to geologic setting. Finally, we discuss the implications of our results for plume collapse models, recent and future studies of infrared surface emissivity, and the inference of ongoing volcanic activity.

Figure 2. Earth-based radar data summed from observations of the southern hemisphere in 1988, 2012, and 2015. Opposite-sense polarization (OCP) radar echoes, so echoes from areas closer to the center of the planet are much brighter. Approximate area 48°S to 11°S latitude, −85.5°E to −11°E longitude. Blurred region at upper left is due to radar echoes from Beta Regio that are “folded over” by the delay-Doppler imaging method.

2. Locations and Properties of Radar Bright Units

2.1. Eastern Eistla Regio

Campbell and Clark [2006] noted occurrences of radar bright material with diffuse margins in eastern Eistla Regio, many on the western flank of Pavlova Corona (units P1 to P3, Figures 3 and 4). Two other nearby deposits are associated with a densely ridged area (unit R1) and with an unnamed small corona southwest of Pavlova (unit C1). The units have wispy or diffuse margins, moderate to very high backscatter coefficients,

Figure 3. Regional (10.8°N–16.0°N, 35.3°E–40.0°E) view of radar bright deposits (outlined in orange) in the vicinity of Pavlova Corona. Magellan left-looking radar image data. Black line denotes trace of topographic profile in Figure 5.

and appear to cover preexisting volcanic and tectonic features. In their central regions there may be no distinguishable features, but closer to the margins the outlines of buried lava flows, graben, or fractures emerge from a thinning cover. Similar properties are associated with a unit on the southwest flank of Didilia Corona, and in each case the radar bright materials appear to have moved downhill from corona margins or ridged terrain (Figure 5). A topographic profile through unit P3 shows that the bright materials cover a distance of about 100 km over slopes no larger than $\sim 0.3^\circ$ (Figure 6). The total area covered by this single unit is about 7600 km².

Two locales (northern unit P2 and southeastern unit D1) have prominent patterns of radar dark streaks, which we infer to be fine-grained material moved by the wind onto the radar bright materials [Greeley *et al.*, 1992]. On unit D1, the dark

Figure 4. Three-dimensional perspective view of the region shown in Figure 3, based on Magellan image and altimetry data. View is from the south. Note the downslope emplacement of labeled units away from corona rims and densely ridged terrain.

material has moved westward (the direction of the prevailing wind at the surface) from a 65 km diameter volcanic edifice with a radar dark summit region. The radar bright unit covers the west flank of this volcano, so the wind streaks must reflect ongoing aeolian mantling of unit D1 (Figure 5). It is interesting that such a small volcano summit region supplies the required volume of streak material, perhaps implying a fine-grained, localized pyroclastic deposit. In the case of northern unit P2, the streaks form a roughly radial pattern suggesting a source to the north, but their orientation is nearly orthogonal to the prevailing wind (Figure 7).

The most dramatic remote sensing property of these units is their high radar backscatter strength. Within eastern and western Eistla Regiones the deposits have echoes stronger than any edifice-related lava flows:

Figure 5. View of the southwest flank of Didilia Corona, with a radar bright, diffuse unit labeled D1; unit P2 from Figure 3 is visible at the lower right. Magellan left-looking radar image data, image area 15.5°N–17.6°N, 35.8°E–38.4°E. Note the pattern of dark streaks running west from the 65 km volcanic edifice at the right center.

Figure 6. Topographic profile of the southwest flank of Pavlova Corona, from (left) 12.87°N, 36.79°E to (right) 13.90°N, 38.30°E. Vertical offset is in kilometers from a reference radius of 6051 km. The radar bright material of unit P3 covers approximately 100 km from the corona rim. Data are from the Magellan GTDR data set. Raw along-track footprint values are smoothed and gridded at a horizontal posting of 4.6 km. Vertical accuracy can be as fine as about 20 m over smooth terrain.

backscatter coefficient or “sigma-zero” values at $\sim 46^\circ$ incidence angle are about -9 dB for unit P3. Such backscatter coefficients imply either (1) rough terrain (expressed as either a continuous topographic profile or a field of discrete objects) at the scale of the radar wavelength or (2) an enhanced Fresnel reflectivity due to an increase in the real permittivity of the materials. The 12.6 cm wavelength, horizontal-polarized emissivity, E_H , for radar bright units near Pavlova and Didilia are 0.80 to 0.85 at incidence angles around 44° . These values correspond to a dielectric permittivity, ϵ' , range of about 3 for a plane surface to about 6.5 (similar to bare rock) for a surface that is rough at the wavelength scale [Campbell, 1994]. Most of the bright units have slightly higher E_H values relative to the surrounding flows, which is consistent with a higher degree of wavelength-scale roughness rather than an increase in permittivity. For comparison, the mean emissivity value for Venus is 0.845, and high-elevation regions of Maxwell Montes have typical values of ~ 0.3 due to surface-atmosphere chemical reactions [Pettengill *et al.*, 1992].

Figure 7. Full resolution, Magellan left-looking radar view of wind streaks in northern part of radar bright, diffuse unit P2 (lower left). Image width about 25 km; north at top. Note the outlines of lava flows emerging from the northwestern margin of the radar bright deposit.

Figure 8. Regional (9°N–18°N, 10°E–22°E) view of radar bright deposits (outlined in orange) on Irnini and Anala Montes. Magellan left-looking radar image data.

Absent enhanced reflectivity, the high radar backscatter values must come from significant roughness, expressed as the RMS height/slope of either a continuous rough profile or a field of discrete objects, on the 12.6 cm horizontal scale. The necessary RMS height/slope would be comparable to that of terrestrial *a'a* flows or to a field of clasts with diameters up to at least about 4 cm [Campbell, 2001]. The lack of any obvious structure (at the few hundred meter scale) within the deposits suggests a blanket of clastic debris that is always the locally highest stratigraphic unit. The actual size-density distribution of the clasts cannot be determined; there may be a sorting process during emplacement that leaves larger rocks close to the vent or deposits them preferentially at the base of a downslope deposit. The presence of wind streaks would suggest clast sizes toward the smaller end of the range in those locales, since the fine-grained windblown material would not easily cover more rugged terrain.

2.2. Western Eistla Regio

The two major hybrid volcano-tectonic constructs of western Eistla Regio, Anala Mons and Irnini Mons (with Sappho Patera at its summit), have large, radar bright deposits with diffuse margins emanating radially and extending downslope from their corona-like, densely ridged annuli [McGill, 2000] (Figures 8 and 9). A profile through unit I1 shows that the area of continuous bright material covers about 70 km from a point on the Irnini Mons flank and extends onto nearly flat terrain to the north (Figure 10). The average slope of the Irnini flank in this area is 1.2°. The margins of units I1, I2, and A1 are uncertain where they meet the densely fractured terrain, but there is some evidence that diffuse deposits extend onto the floor of Sappho Patera. The contacts between the floor units and the radar bright terrain are poorly defined, and it is difficult to determine whether there is embayment by the lava flows or exhumation of these flows by erosion of the mantling debris. Very thin streaks, inferred here to form by aeolian movement of fine material, on the radar bright units, and subtle diffuse patterns overlapping dark flows just inside the dense fracture belts are more consistent with the latter scenario. A minimum area for the bright deposits around Anala (units I1 and I2) is about 41,000 km². Radar brightness (the average sigma-zero value for central unit I1 is −9.7 dB at 45° incidence angle) and emissivity properties for unit I1 are similar to those observed in eastern Eistla Regio.

The northwestern portion of unit I1 shows that the mantling unit thickness must be a few meters or more to cover flows with central channels as well as lobate margins high enough to produce a glint from the radar-facing slope (Figure 11). This view illustrates the apparent erosion of the mantling material in the dense

Figure 9. Three-dimensional perspective view of the region shown in Figure 8 based on Magellan image and altimetry data. View is from the north. Note the downslope emplacement of units I1, I2, and A1 away from densely lineated rims. Unit I3 is isolated in the nearby plains.

pattern of linear streaks, trending north-northwest, and the patchy brighter areas on the radar dark flow to the northwest. There are also areas of darker radar signature within units I1 and I2. We infer that these may be localized areas where the initial deposit was thin, which seems unlikely for a surge deposit traveling such distances, or that subsequent breakdown of the coarse material has begun to remove the mantle.

Unit I3 is anomalous among radar bright deposits noted thus far (Figure 12). It is situated in a topographic low of a region characterized by both plains-forming (broad with indistinct or nonlobate margins) and edifice-derived (narrow with lobate margins) flows (Figure 9). The deposit mantles tectonic fractures and ridges, as well as a moderate backscatter flow complex from the southwest. There is no evident direction of transport, and the margins are a collection of linear “spines” that parallel the local tectonic fabric. At no point along its margin does unit I3 appear to be embayed by a later flow. It also lies just beyond the farthest extent of flows that emerge from the margin of unit I1, so we cannot make a stratigraphic connection from that relationship. We suggest that I3 is an erosional remnant of a once larger I1 deposit, perhaps protected to some degree by its location in the lowest local topography. This would be consistent with the “spiny” appearance

Figure 10. Topographic profile of the northern flank of Irnini Mons at 15.1°E longitude, running from 16.92°N at left to 14.70°N at right. Vertical offset is in kilometers from a reference radius of 6051 km. The radar bright material in this locale covers approximately 70 km of the flank and adjacent flat terrain, but in other areas the deposit extends to 80–100 km. Data are from the Magellan GTDR data set. Raw along-track footprint values are smoothed and gridded at a horizontal posting of 4.6 km. Vertical accuracy can be as fine as about 20 m over smooth terrain.

Figure 11. Full-resolution, left-looking Magellan image of radar bright, diffuse deposit northwest of Irnini Mons. Image width 188 km; north at top. Note the lobate flows that disappear southward beneath the bright mantling unit (northern part of unit I1) and the dense streaks and residual patches that suggest ongoing erosion of the mantle and exhumation of the flows.

that suggests formation (and perhaps aeolian removal) of fine material by erosion of the original rocky mantle.

These observations confirm the inferences from Pavlova and Didilia Coronae that the radar bright, diffuse deposits are superposed on all other geologic features. Even more than in those instances, the deposits at Irnini Mons suggest substantial removal of clastic mantling material by breakdown of the rocks and redistribution of resulting fines by the wind. While they are thus stratigraphically “young,” the diffuse deposits have undergone a considerable degree of weathering. The rate of that breakdown might be high under Venus conditions [Fegley *et al.*, 1997].

2.3. Dione Regio

Keddie and Head [1995] present a detailed analysis of volcanic stratigraphy for the major edifices within Dione Regio (Figures 1 and 2). They note radar bright, diffuse margin material near the summits of Hathor and Innini

Figure 12. Full-resolution, Magellan left-looking radar image of unit I3. Image width 120 km; north at top.

Figure 13. (a) Earth-based opposite-sense circular (OC) radar image of Dione Regio (approximately 20.5 to 45°S latitude, 316 to 335°E longitude); simple cylindrical projection. White arrows denote locations of radar bright, diffuse deposits. (b) CPR color overlay on OC image of the same region shown in Figure 11a. Note that CPR values in the ridge-belt region at center and some parts of the Hathor Mons deposits are 0.4 to 0.5, suggesting high few centimeter-scale roughness.

Montes, and perhaps on Nepthys Mons. Only near the summit of Innini Mons does the radar bright signature appear to arise in part from altitude-dependent surface-atmosphere effects on the dielectric permittivity. They further note that these materials blanket underlying features, including lava flows and tectonic features such as graben, and infer a pyroclastic or ignimbrite style of emplacement. Dione Regio is the only major location of radar bright, diffuse terrain within the Earth-based radar coverage (Figure 2), and our combined data from 1988, 2012, and 2015 offer a view of polarimetric scattering behaviors (Figure 13) at a signal-to-noise ratio much higher than that available in *Keddie and Head* [1995].

We note multiple areas of radar bright units with diffuse margins on Hathor and Innini Montes, but nearby Ushas Mons appears to have no major instances of this type of deposit (Figure 13a). Those on Innini Mons are relatively concentric to the cluster of radar bright domes on the summit, while those on Hathor Mons extend away from an oval summit region toward the north and west. We also note a large (maximum dimensions of ~230 km on NW-SE axis and ~100 km SW-NE), radar bright feature along the densely fractured terrain south of Ushas Mons that appears to superpose the ridge structure and some extensional features. This large radar bright unit has not been previously discussed, perhaps due to its location away from the major edifices and gaps in Magellan image coverage.

Topographic profiles (Figure 14) show that the radar bright material south of Ushas Mons extends ~70 km from a modest topographic high east of the ridge belt. In both profiles the western extent of the deposit occurs near or within a local depression. The local slope, dipping to the west, is only about 0.14° along the northern transect, while the southern transect has what might be (extrapolating through the data gap) up to about a 0.3° slope at its eastern edge. The area of the bright deposit is about 21,000 km².

In both the Magellan image and the Earth-based SC data, the ridge-related material is very bright (an average sigma-zero value of −10 dB at 33° incidence angle), suggesting a high degree of surface roughness (Figure 15). The circular polarization ratio, which is sensitive to the degree of scattering by wavelength-scale roughness, shows enhanced values for the radar bright units on Hathor Mons and the ridge-belt area (Figure 13b). The deposits near the summit of Innini Mons are only modestly enhanced. The ridge-belt feature and the bright deposit on the west flank of Hathor Mons have CPR values of 0.4 to 0.5 at incidence angles around 40°. These values are consistent with the upper range of few centimeters to decimeter-scale

Figure 14. (a) Magellan left-looking radar image of the radar bright material south of Ushas Mons: area covered is 33°S to 28°S, 321°E to 326°E. White lines indicate locations of topographic transects in Figure 14b. Gaps are due to missing data in the Magellan coverage. (b) Topographic profiles across the radar bright material south of Ushas Mons: (1) at 30.35°N, running from 321°E at the left to 326°E at the right, and (2) at 31.04°N, running from 321°E at the left to 326°E at the right. Vertical offset is in kilometers from a reference radius of 6051 km; profile (1) is offset by an additional 500 m for clarity. The radar bright material covers ~70 km downhill of a topographic high just east of the ridged terrain. Data are from the Magellan GTDR data set. Raw along-track footprint values are smoothed and gridded at a horizontal posting of 4.6 km. Vertical accuracy can be as fine as about 20 m over smooth terrain. Gaps are due to missing data in the Magellan coverage.

about 60 km along a SE-NW axis (Figure 20). The streaks occur on a patch of volcanic plains with very low radar backscatter that appears to be the oldest rift-related flow unit superposing the regional plains. These very smooth flows are superposed by radar bright (i.e., rougher) flow fields from fractures on the western side of Rona Chasma. Where the radar bright streaks meet the later flows, the margins of those flows are less distinct than elsewhere, suggesting that the streak material has banked up against the flow lobes. In at least one locale (noted in Figure 20), a streak crosses over a flow and causes an increase in the radar echo. This

roughness for basaltic flows on the Earth [Campbell, 2009] and stand out markedly against the background of lower CPR values for the plains- and edifice-forming flows. As with the radar bright deposits in Eistla Regio, there is no evidence of the low microwave emissivity expected if these brightness changes came from an increase in the Fresnel reflectivity.

Keddie and Head [1995] noted that Nephtys Mons, which formed on the north flank of a ridge belt, has a 40 km diameter region of enhanced radar echoes near its highest elevation. The SC image shows an oblong region of enhanced echoes in the same region, though the strength of this echo with respect to the surrounding flows is not as distinguishing as those on Hathor Mons or the ridge belt south of Ushas Mons (Figure 16). Some parts of the radially fractured flanks of Mielikki Mons might be mantled by radar bright material, but the SC echo shows only modest enhancement across the whole edifice (Figure 17). Finally, one site noted in the VIRTIS study of Smrekar *et al.* [2010] but not visible in the Earth-based coverage, Idunn Mons (Figure 18), may have radar bright, diffuse material on the north-western parts of its summit, but even at the full resolution of the Magellan images, we cannot confirm the mantling relationships evident in other locales.

2.4. Phoebe Regio

Rona Chasma is part of the long rift zone of Phoebe Regio, trending roughly SW-NE in our study locale (Figure 19). Associated with the rift zone are numerous volcanic flow fields. Centered on 0.5°S, 286°E is a field of radar bright streaks extending

Figure 15. (top) Magellan left-looking radar image of radar bright materials astride a ridge belt south of Ushas Mons. (bottom) Earth-based SC polarization image. Region shown is approximately 32.3°S to 28.6°S latitude, 322°E to 325.6°E longitude.

Montes. The radar bright streaks near Rona Chasma may likewise have once extended to the outer fractures of this rift zone.

In the larger occurrences, we find evidence for mantling of preexisting lava flows and tectonic features by clastic debris up to several meters thick, which thins and perhaps is sorted to finer particle sizes downslope of the highest elevations. We also note evidence for erosion of this material, exhumation of flow features, and isolated outliers that implies larger initial extents. The smaller occurrences exhibit some of these attributes

shows that the streaks form by redistribution of coarse, clastic debris rather than by removal of a regolith cover to expose the rock beneath [e.g., Greeley *et al.*, 1992].

The streak materials appear to have traveled from NW to SE, which is not consistent with the prevailing wind pattern. Even if they were oriented from east to west, it is unlikely that the Venus surface winds can mobilize such large particles. A plausible scenario is that these streaks formed as a result of winds associated with the formation of the 23.8 km diameter crater Mirabeau (Figure 19). The center of Mirabeau (1.1°N, 284.3°E) is about 260 km from the farthest extent of the streaks, which trend nearly radial to the crater. Figure 21 presents the likely sequence of events in this region, with the inference that the streaks are the remnants of a once contiguous deposit that may have extended eastward to the fractures of Rona Chasma.

3. Discussion and Implications

The existence of radar bright deposits with diffuse margins in a few locations on Venus has been known since initial mapping efforts [Keddie and Head, 1995; McGill, 2000; Campbell and Clark, 2006]. Our work shows that these deposits comprise moderate-scale units along fractures near the summits of classic shield volcanoes like Hathor and Nephtys Montes and perhaps Mielikki and Idunn Montes. Similar deposits are related to densely fractured terrain south of Ushas Mons, the flanks of Pavlova and Didilia Coronae, and surrounding the hybrid volcano-tectonic features Anala and Irnini

Figure 16. (top) Magellan radar image of Nephtys Mons at center right, with (bottom) Arecibo SC-polarization image. Region shown is approximately 35°S to 31°S latitude, 313.5°E to 321°E longitude. Image width 780 km.

but often have less enhanced SC radar echoes; we speculate that these deposits are older or were not as initially extensive or thick, such that subsequent erosion has left less distinct traces.

In most cases there is no clear evidence for embayment of the mantling deposits by later flows, so they are the locally youngest units except for radar dark wind streak material. Only near Rona Chasma do we infer significant superposition of radar bright, clastic material by lava flows, and here the debris is confined to streaks aligned with winds from the Mirabeau impact.

These deposits of clastic material are clearly ephemeral, since they are typically observed only at the top of the local stratigraphy rather than interleaved with the flows that make up the other deposits from the ridge belts or volcano summits. The bright streaks west of Rona Chasma are a rare glimpse of an older deposit preserved on early flows from the major regional source, and the total amount of material is small with respect to the inferred initial coverage. We conclude that the clastic debris is most often a recent volcanic phenomenon in each area, where the “recent” term can only have a quantitative meaning if the rate of erosion is known.

Smrekar et al. [2010] modeled the surface emissivity at 1.02 μm from VIRTIS data and Magellan topography and found some degree of enhancement from Idunn, Meilikki, Hathor, and Innini Montes; no such signature was noted for Ushas Mons. The first-order correlation with the enhanced backscatter signatures might suggest that the radar bright material plays a role, perhaps due to grain size or compositional properties, in modulating the 1.02 μm emissivity. An issue with this interpretation is that the modeled emissivity [*Smrekar et al.*, 2010, Figure 2B] does not suggest enhancement from the large radar bright unit on the ridge belt south of

Figure 17. Magellan left-looking radar image of Mielikki Mons, with Arecibo SC-polarization image of surrounding region as inset. Image width 422 km.

Ushas Mons. If the radar bright units are of generally similar composition and particle size, then the lack of correlation in $1.02\ \mu\text{m}$ properties between the Hathor Mons summit and the ridge-belt unit suggests little sensitivity of the modeled emissivity to these youngest materials.

It is unlikely that, given the density of the lower atmosphere, that fallout from a lofted plume could emplace such extensive, clastic deposits [Fagents and Wilson, 1995; Wilson and Head, 1981; Carter *et al.*, 2006]. A more plausible mechanism for significant (tens of kilometers) lateral transport, especially of coarse particles, is plume collapse, where a low (up to a few kilometers), volatile-driven column creates an outer ring of cooler material falling away from the peak rise altitude [Thornhill, 1993; Campbell *et al.*, 1998; Glaze, 1999]. A linear chain of vents on Venus would be even more effective than circular vents, for the same eruption rates, in producing such collapsing columns, and thus pyroclastic flows [Glaze *et al.*, 2011]. This mechanism is also more consistent with the asymmetric distribution of mantling material downhill of its sources at volcano summits

Figure 18. Magellan left-looking radar image of Idunn Mons. Image width 195 km.

Figure 19. Regional view from Magellan radar data of Rona Chasma and Mirabeau crater (23 km diameter). Image area approximately 1.7°S to 2.5°N latitude, 284 to 290°E longitude. Arrow notes region of radar bright streaks on smooth plains unit.

or in the densely fractured terrain. At the Magellan image resolution of ~100 m, we cannot further pursue characterization of the possible vent geometries.

If our interpretation of a generally thin mantling layer of coarse debris is correct, then the closest terrestrial comparisons are low aspect ratio features like the Taupo ignimbrite (dated to ~186 Common Era). From a strictly morphologic perspective, the parallels with the large radar bright unit south of Ushas Mons are striking. The total range from the vent for the Taupo deposit is ~80 km, the volume is about 30 km³ over an area of

Figure 20. Magellan radar view of radar bright streaks west of Rona Chasma. Image width 190 km. Black arrow notes location of brighter echo from lava flows where a streak crosses the lobe.

Figure 21. Sketch maps showing the inferred sequence of geologic events west of Rona Chasma. (a) A smooth, radar dark flow unit (black) from fractures along Rona Chasma floods a region of regional plains. (b) A deposit of clastic material (yellow) from the Rona Chasma fractures is emplaced on the smooth flows. (c) Rougher lava flows (red) superpose part of the clastic deposit, which is also eroding from its initial thickness and extent. (d) Mirabeau crater forms, and the resulting winds redeposit the remaining clastic material into streaks that bank against, and sometimes cross, the radar bright lava flows.

about 20,000 km², and there is few centimeter-scale clastic debris [Wilson, 1985; Dade and Huppert, 1996]. The Venus example covers around 21,000 km², extends 70–100 km, has inferred thickness as little as tens of centimeters to a meter (i.e., a volume of 21 km³ for a constant 1 m depth), and is characterized by clast sizes of perhaps a few centimeters.

Highly silicic eruptions like Taupo are not expected on Venus based on existing compositional data. There is evidence, however, of terrestrial basaltic eruptions that produce deposits of similar morphology. Two such units were identified by Williams [1983], with the larger covering an area of 1200 km². The dense, hot atmosphere of Venus may create significant differences in how clasts are entrained and transported, allowing emplacement over greater distances. Large explosive eruptions have also been linked with the Columbia River Basalt province [Brown *et al.*, 2014], supported by models of volatile accumulation and explosive events in such ancient flood basalt eruptions [Glaze *et al.*, 2017].

Even the smaller units mapped here, assuming they were originally up to a few meters thick, imply a substantial total mass of volatiles (concentrations of up to 5% H₂O or CO₂) in the rising magma [Airey *et al.*, 2015] and a chain of vents extending along the fractured terrain [Glaze *et al.*, 2011]. In general, discharges of volatile-rich magma occur during the early phases of a magma source's interaction with the surface. For example,

fire-fountain activity was typical of the early stages of lunar mare volcanism. Subsequent eruptions were depleted of volatiles, yielding the more classic plains-forming lava flows. Due to this timing, the largest surviving lunar pyroclastic deposits occur only in elevated regions (such as the Aristarchus Plateau) where the later flows did not cover them [Zisk *et al.*, 1977].

Venus has a much more active cycle of magmatic activity, with the expectation of many batches of magma rising to the surface in any one region over time. Given their stratigraphic position and requirement for enhanced volatile content, the radar bright clastic deposits may reflect the early phases of renewed magmatic activity. All of the occurrences are related to elevated, fractured terrain within regions of extensive volcanism, consistent with such new batches of magma contributing to uplift and extensional tectonism in an area. There is evidence for erosion and removal of the coarse-grained debris (perhaps quite rapid), so those we observe are only the thickest or youngest deposits. There may have been many more such deposits over time, each marking sites of renewed eruptive phases.

4. Conclusions

We examine radar bright deposits with diffuse margins in eastern Eistla, western Eistla, Phoebe, and Dione Regiones using Magellan data and Earth-based radar maps. The radar bright units have no marginal lobes or other features consistent with viscous flow. Their morphology, radar echo strength, polarization properties, and microwave emissivity are consistent with extensive mantling deposits composed of few centimeter-scale clasts. This coarse debris traveled downhill up to about 100 km on modest slopes and blanketed preexisting lava flows and tectonic features to depths of tens of centimeters to perhaps a few meters. The coarse material thins with downhill distance from the highest elevations, and there is evidence for ongoing removal and exhumation of previously buried terrain. A newly identified occurrence lies astride a ridge belt south of Ushas Mons, mirroring a similar correspondence with densely fractured terrain in Eistla Regio. We also note radar bright streaks of coarse material on lava flows west of Rona Chasma and suggest that these reflect the last traces of an earlier, more extensive deposit that was mobilized by winds from the formation of Mirabeau crater. If the radar bright units originate by collapse of eruption columns, with coarse fragmental material entrained and fluidized by hot gases, then their extent and volume suggests large erupted volatile (CO_2 or H_2O) amounts. We propose that these deposits reflect the early stage of recently renewed magmatic activity that supplies the volatiles and contributes to uplift and extensional tectonism in an area. Rapidly eroding under Venus surface conditions, or buried by subsequent volatile-poor eruptions, these markers of renewed activity have largely disappeared from older regions. Their short erosional timescale may offer new insights on surface chemical and aeolian processes. Future Earth-based observations and orbital missions could target these sites for evidence of crustal deformation or active eruptions. Future landed missions could better constrain the overall range of Venus surface composition as a guide to the volatile budget and physical properties of erupted material.

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