Volcanism and resurfacing on Venus at the full resolution of Magellan SAR data

Peter M. Grindrod,[1,2] Ellen R. Stofan,[1,3] and John E. Guest[1]

[1] We examine the importance of localized volcanism in resurfacing on Venus by analyzing the results of geologic mapping of a 12° × 12° area at the full resolution of Magellan SAR data. Resurfacing due to corona-, ridge-, and small volcano-related volcanism accounts for 27%, 6%, and 10% respectively of the mapped area. Mapping at the resolution of Magellan data, rather than a regional scale, gives corona-related flow unit areas that can differ individually by almost an order of magnitude, with a total increase of 28%, and more than three times as many identifiable units. A total of 2919 small volcanoes or vents less than 10 km in diameter were identified in the F-Map, with a mean diameter of 1.59 (s.d. = 1.08) km and densities of up to 36 small volcanoes per 50 km^2. Taken together, coronae, ridge eruptions, and small volcanoes probably make a significant contribution to resurfacing on Venus. **Citation:** Grindrod, P. M., E. R. Stofan, and J. E. Guest (2010), Volcanism and resurfacing on Venus at the full resolution of Magellan SAR data, *Geophys. Res. Lett.*, *37*, L15201, doi:10.1029/2010GL043424.

1. Introduction

[2] Despite their similar size and composition [*Kaula*, 1994], the different geological histories recorded at the surface of Venus and Earth are evidence of their different heat loss regimes. The majority of heat loss on the Earth is due to plate tectonics [*Sclater et al.*, 1980] and gives rise to mantle cooling. The lack of plate tectonics on Venus [*Solomon et al.*, 1992] suggests that more heat is generated in the mantle than can be lost at the surface, resulting in a net warming of the mantle [*Nimmo*, 2002]. The apparently reduced surface heat flow on Venus is probably about 8–25 mW m^{-2} [e.g., *Nimmo and McKenzie*, 1998], and is most likely lost through a variety of methods, such as hotspots, large volcanoes, and rifting. Here we aim to determine new insights in the contribution of small-scale volcanism and resurfacing mechanisms on Venus by analyzing a recent geologic map made at the full resolution of the Magellan SAR data [*Grindrod and Guest*, 2006].

[3] Although full-resolution images (F-Maps) are used in the ongoing mapping program of Venus (VMAP) [*Tanaka*, 1994], the mapping procedure itself is conducted on a regional scale (1:5,000,000), rather than a local scale (1:1,500,000) [*Grindrod and Guest*, 2006]. To date, other than the regional map of the V43 quadrangle [*Bender et al.*, 2000], no detailed study has focused on, or made reference to, any volcanic feature in our F-Map study region (Aglaonice), which contains four coronae: Bhumidevi (B), Takus Mana (TM), Iyatik (I) and Qetesh (Q), with diameters of 150, 125, 200, and 80 km respectively. There are four impact craters in our study region, with diameters ranging from 2.4 to 17.2 km, which are all classified as pristine [*Schaber et al.*, 1998] indicating that they are amongst the youngest features present in the F-Map. Only the smallest crater, Dena, has an associated radar-dark halo, suggesting that this might be the latest impact event in the region [e.g., *Basilevsky et al.*, 2003]. The Aglaonice region (Figure 1a) is situated about 1200 km to the northwest of Alpha Regio, and was chosen for this study as it contains no large topographic rises, rifts, or large volcanoes, and does not show evidence for major tectonic alteration; instead this region appears to be fairly typical of corona and plains materials on Venus.

2. Volcanism

[4] This study concentrates on the volcanism observed in the F-Map, which can be categorized according to source region (Figure 1b): corona-related volcanism dominates the region, with shield and ridge flows also making a significant contribution. This section describes each type of volcanism, with particular reference to the scale and nature of resurfacing.

2.1. Corona-Related Volcanism

[5] In addition to corona-related fractured plains material, which may have originated from corona-related flows, several flow units are identified at each corona, based on gross morphology and stratigraphy. Corona-related flows have a total surface area of approximately 0.43 × 10^6 km^2, equivalent to about 27% of the total surface area of the F-Map. Most of the coronae have temporally distinct flow units which are identified by their appearance in the SAR image. Distinct lava flow textures, such as levées and channels, are only visible in about a quarter of all corona-related flow units and occur in the most stratigraphically recent flows at each corona. No definite source vents are visible at any of the flows, although in many cases units can be traced to a general area of small-scale volcanism or concentric fracturing.

2.2. Ridge-Related Volcanism

[6] One of the more surprising outcomes of the full-resolution mapping is the identification of nine individual occurrences of lava flows mapped regionally as plains material [*Bender et al.*, 2000], which appear to emanate from extensional fractures at broad, topographically-raised ridges. These flows vary in size from only about 10 km in width

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[1]Department of Earth Sciences, University College London, London, UK.
[2]Also at Centre for Planetary Sciences at UCL/Birkbeck, University College London, London, UK.
[3]Also at Proxemy Research, Rectortown, Virginia, USA.
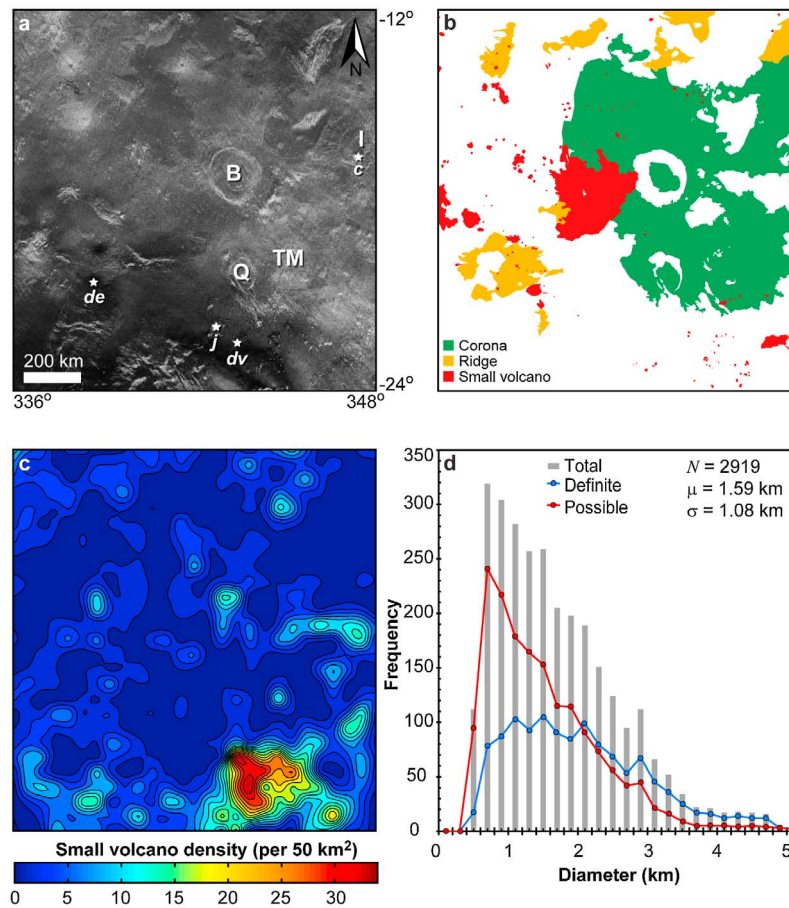
Figure 1. The Aglaonice F-Map region. (a) SAR image of the studied area, showing the location of the center of B, I, Q, and TM coronae, and impact craters (stars) Cynthia (*c*), Dena (*de*), Jerusha (*j*), and Devorah (*dv*). (b) Units attributed to corona-, ridge-, and small-volcano-related volcanism as identified by *Grindrod and Guest* [2006]. (c) Small volcano density map for the F-Map region, including all definite and possible small volcanoes and vents. Out of 2919 small volcanoes, 1250 are classified as definite, and 1669 as potential. Contours are 2 volcanoes or vents per 50 km². (d) Histogram of small volcano diameters, showing total, definite and possible small volcano diameters in bins of 200 m. N is the total number of small volcanoes, μ is the mean diameter, and σ the standard deviation. The skew towards smaller diameters of possible volcanoes is probably the result of the identification process.

to over 150 km in length, and account for approximately 6% of the total surface area of the F-Map, similar to several of the largest plains material units. Individual source vents for most of the ridge flows are not visible at Magellan SAR resolution, but source regions can usually be traced near to extensional fractures associated with a broad ridge (Figure S1).[1] These fractures are sometimes buried by the ridge flows themselves, thus obscuring the exact source region. The source ridges were identified in a synthetic stereo image pair, and are about 20–40 km in width, 50–150 km in length, and up to about 300 m in height.

2.3. Small-Scale Volcanism

[7] Small-scale volcanism, in the form of vents, volcanoes and fissures, is ubiquitous in the F-Map, contributing about 10% of the total surface area. This surface area value is a minimum, as it does not account for other units (e.g. plains material) which might also be the result of small

vents. A detailed analysis of the F-Map was conducted to identify and measure the diameter of all definite and potential small volcanoes and vent structures, based on features previously identified as indicative of small volcanoes on Venus [e.g., *Guest et al.*, 1992; *Crumpler et al.*, 1997; *Addington*, 2001; *Hansen*, 2005]. With a pixel size of 75 m, only volcanic structures with recognizable features greater than 3 or 4 pixels (i.e. ~300 m) could be identified. Definite small volcanoes and vents were identified by the presence of a summit caldera/vent and/or quasi-circular deposits and structures. Possible small volcanoes or vents were identified by the presence of a group of anomalously bright pixels in the SAR images, interpreted as a summit caldera/vent below the limit of resolution. Only those pixels which were sufficiently bright to stand out in the inherently speckly SAR image were selected. As small volcanoes and vents may exist below the resolution of Magellan SAR data, the small volcano density analysis represents a minimum value. A total of 2919 small volcanoes or vents less than 10 km in diameter were identified in the F-Map, of which 1250 were considered to be definite and 1669 to be potential.
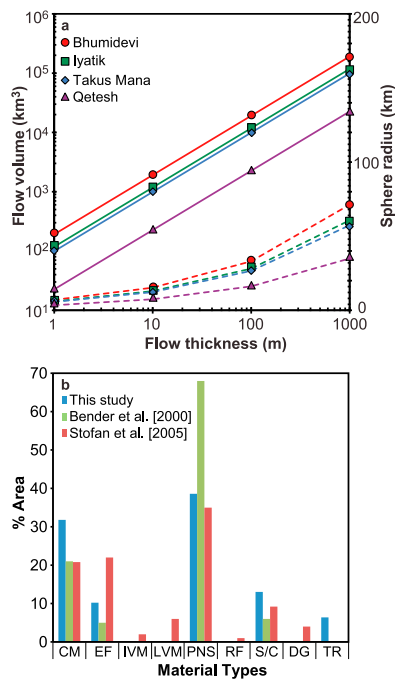
Figure 2. Implications for resurfacing. (a) The flow volumes generated at each corona for different flow thicknesses (solid lines, primary axis), and the diameter of the sphere required to account for the flow volume generated by the corresponding flow thickness (dashed line, secondary axis). (b) Histogram showing the percentage area covered by material types determined in the Aglaonice F-Map region at the full resolution of the SAR data (this study) and at a regional scale [*Bender et al.*, 2000], and of ~30% of the Venusian surface at a regional scale [*Stofan et al.*, 2005, and references therein]. The units are corona materials (CM), which includes 4% corona plains material, small edifice materials (EF), intermediate volcano materials (IVM), large volcano materials (LVM), plains with no identifiable source (PNS), rift flows (RF), structure and impact crater materials (S/C), data gaps (DG), and topographic ridge flows (TR).

Both the definite and potential density distributions are similar, with the highest concentrations (up to 36 small volcanoes in a 50 km^2 area) found in the south of the F-Map (Figure 1c). For the total of 2919 small volcanoes, the mean diameter is 1.59 km, with a standard deviation of 1.08 km. The mean diameters of the definite and possible populations are 1.93 (s.d. = 1.2) and 1.33 (s.d. = 0.9) km respectively, highlighting the difficulty in confidently identifying definite small volcanoes with diameters of less than about 2 km (Figure 1d). The lack of small volcanoes with diameters less than about 300 m is most likely due to reaching the limit of the Magellan SAR resolution.

3. Implications for Resurfacing

[8] *Roberts and Head* [1993] determined the flow field areas for 326 coronae identified by *Stofan et al.* [1992], which ranged from just under 1500 km^2 to 1.5×10^6 km^2, with a mean of 1.1×10^5 km^2. The flow areas at B, I, TM and Q Coronae are 1.8×10^5, 1.2×10^5, 9.9×10^4 and 2.3×10^4 km^2 respectively, totaling 4.2×10^5 km^2. Therefore the flow areas observed at the coronae in this study

are of a similar order to the global mean corona flow area. The flow areas determined here can also be compared with those determined previously for this region by *Bender et al.* [2000], who defined flow units associated with B, I, TM and Q Coronae with areas of approximately 6.4×10^4, 1.1×10^5, 1.6×10^5 and 0 km^2 respectively, totaling 3.3×10^5 km^2. Full resolution mapping yielded similar areas at B, I, TM and Q Coronae of 1.8×10^5, 1.2×10^5, 9.9×10^4 and 2.3×10^4 km^2 respectively, totaling 4.2×10^5 km^2. Mapping at the resolution of Magellan data, rather than a regional scale, has defined corona-related flow unit areas that differ individually by almost an order of magnitude, giving a total flow area greater by about 9.0×10^4 km^2 or 27%.

[9] Although it is not possible to determine the thickness of flow field units on Venus, previous estimates at Mylitta Fluctus vary from 10 to 400 m [*Roberts et al.*, 1992], whereas *Stofan et al.* [2005] estimated that a 1 km global lava unit would be required to obscure large impact basins. Therefore, by assuming end-member flow thicknesses, it is possible to estimate the possible volumes of the corona-related flows studied here (Figure 2a). A flow thickness of 10 m yields flow volumes of the order of 1000 km^3 for all but Q, which has a volume of only 200 km^3. These volumes are larger than those of volcanics associated with most terrestrial hotspots [*Stofan et al.*, 1995] and all but the largest flow episode observed at Mylitta Fluctus [*Roberts et al.*, 1992]. Assuming a constant flow thickness of 100 m yields volumes of the order of 10,000 km^3, comparable to the volumes of the topographic edifices of the large volcanoes Sif and Gula Montes [*Stofan et al.*, 2001]. Although it is unlikely that the flows are of a constant thickness, the above estimates suggest that coronae may be as significant as large volcanoes as regions of significant magma production. Bearing this in mind, it is interesting to speculate on the size of the magma bodies required to account for the above flow volumes (Figure 2a). Magma reservoirs most likely never empty completely during eruption [e.g., *Sharp et al.*, 1980; *Crisp*, 1984], and so if coronae are or were underlain by a plume or diapir of similar size to the corona diameter at the surface, then the extrusive volume is of the order of 1% that of the intrusive (magma body) volume. This high intrusive to extrusive ratio is more similar to those found in continental, rather than oceanic, regions on the Earth [*Crisp*, 1984] and if correct supports the idea of significant magma emplacement during the formation of coronae [*Dombard et al.*, 2007].

[10] The number and area of all units identified at a local scale can be compared to the regional scale study of *Bender et al.* [2000]. In the Aglaonice F-Map region, a local scale mapping approach identified 35 individual units [*Grindrod and Guest*, 2006], more than three times as many as a regional scale method that identified 11 individual units in the same area [*Bender et al.*, 2000]. Clearly, using the full resolution SAR data allow specific source regions to be identified more easily. However, comparing the flow areas in this study region according to material type (Figure 2b), rather than individual unit, shows that the differing mapping methods yield reasonably similar results. The main difference is that a local scale approach allows more source regions to be identified, thus reducing the amount of plains material that has no identifiable source by almost half. The ability to confidently identify source region at a local scale

has doubled the edifice flow material area to 10% of the FMap region, and has increased the material attributable to coronae from 21% to 32%. The flow areas identified here study can also be grouped according to material type, and compared to the large-scale study of *Stofan et al.* [2005], which assessed the resurfacing sources in eighteen VMAP quadrangles, an area covering about 30% of the planet. The material types identified in the Aglaonice region have a similar overall percentage distribution to that of *Stofan et al.* [2005], but also show some notable differences (Figure 2b). There are no intermediate or large volcanoes in our study area and therefore no associated material. The Aglaonice region contains about 11% more corona-related material, about 5% more ridge-related flow material, and approximately 4% more plains with no identifiable source, compared to areas found by *Stofan et al.* [2005].

[11] There is significantly less small edifice flow material identified in the F-Map than in the 18 quadrangles by *Stofan et al.* [2005]. Although variations are expected due to the differences in study area, several important points can still be made. Similarly to *Stofan et al.* [2005], we have found that almost two thirds of the units making up the F-Map region originate from identifiable sources. We have also found similar overall relative material type proportions to those of *Stofan et al.* [2005], specifically that although operating at very different scales, corona and small edifice materials make up almost half of the resurfacing sources. This suggests that the material type of most units on Venus can be identified through regional scale geologic mapping of large areas, but local scale geologic mapping offers a significant advantage in identifying individual source units.

[12] The small volcano density analysis can be compared with a recent full resolution study of small volcanoes [*Hansen*, 2005] that found mean definite and potential small volcano densities of 6255 and 23,445 shields/10^6 km^2 respectively. These densities are much larger than the definite and potential densities identified here (1250 and 1669 shields/10^6 km^2 respectively), due to our study being more representative of a 'typical' Venusian region, whereas *Hansen* [2005] scaled up a 2° × 2° area of shield terrain. If the small volcano densities determined here are more typical of the Venusian surface as a whole, then it is interesting to note the implications on a global scale. Scaling up the 2919 volcanoes observed in the F-Map to a surface area equivalent to the surface of Venus results in 973,000 small volcanoes or vents over the entire planet, a value similar to the exponential distribution estimate of 931,000 of *Crumpler et al.* [1997]. The total surface area of identifiable small volcanoes or vents in our study area is 8443 km^2, equivalent to 0.5% of the mapped region. This value is lower than the area resurfaced by the small volcano unit (10%), indicating either significant vent obscuration by self-burial, and/or large numbers of small volcanoes or vents below the resolution of Magellan SAR data. Given that this simple analysis is for a 'typical' area of Venus, with no high density shield fields similar to those studied by *Hansen* [2005], then we expect that small volcanoes probably make a significant, although by no means solitary, contribution to the resurfacing on Venus.

[13] The relatively high proportion of flows that can be sourced to fractures at broad ridges has not been previously reported, and may be significant. These flows of different relative ages originate from fractures or fissures associated with extension, and flow onto different plains material units. In the absence of volcanic centers, these flows are probably fed by a system of dikes, which are common in areas of extension and rifting in Iceland [e.g., *Gudmundsson*, 1995] and common as radial patterns on Venus [e.g., *Grosfils and Head*, 1994; *Grindrod et al.*, 2005]. The large range of relative ages of these flows suggests that eruptions were initiated and controlled by local stress regimes and melt production rates. The sometimes poorly-defined boundary between the ridge flows and plains material indicates that they may have contributed towards plains formation to some extent, and that the identified flows are only the latest eruptive phase. If the ridge flows did contribute large volumes to plains units, then the latest, identifiable, phases appear to be less voluminous. This possible declining pattern of effusion rates after an initial high is similar to the fissure-fed eruptions at Krafla, Iceland [*Harris et al.*, 2000], which are typical of many basaltic effusive eruptions [*Wadge*, 1981].

4. Conclusions

[14] We have analyzed the results of geologic mapping at the full resolution of Magellan SAR image data for a 12° × 12° region. Resurfacing due to corona-, ridge-, and small volcano-related volcanism is responsible for 27%, 6%, and 10% respectively of the F-Map surface area of 1.6 × 10^6 km^2. Mapping at the resolution of Magellan SAR data shows some important differences from a regional scale approach. Flow units attributable to coronae using a local scale mapping method increase by 28% compared with a regional scale mapping method. By estimating the thickness of these flow units, it appears that coronae are probably underlain by magma bodies of a similar size to those at large volcanoes on Venus, although they are most likely not emptied during eruption. The local scale mapping approach also identified more than three times as many units compared to a regional scale approach, although general material type sources have overall similar proportions at the different mapping scales. The main advantage of mapping at the full resolution of Magellan SAR data is that the unit source region can be more confidently identified. A total of 2919 small volcanoes or vents less than 10 km in diameter were identified in the F-Map, of which 1250 were considered to be definite and 1669 to be potential. The mean total small volcano diameter is 1.59 km, with a standard deviation of 1.08 km. The mean diameters of the definite and possible populations are 1.93 and 1.33 km respectively. Previously unidentified ridge flows may contribute to resurfacing in the absence of volcanic centers, and show possible declining patterns of effusion rates over time. When mapped at the full resolution of the Magellan SAR image data, independent sources of resurfacing, especially small volcanoes, are significantly more important than previously estimated, and may be an important resurfacing mechanism on Venus.

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J. E. Guest, P. M. Grindrod, and E. R. Stofan, Department of Earth Sciences, University College London, Gower St., London, WC1E 6BT, UK. (p.grindrod@ucl.ac.uk)