Recent volcanic resurfacing of Venusian craters

Jennifer L. Whitten and Bruce A. Campbell
Center for Earth and Planetary Studies, Smithsonian Institution, MRC 315, PO Box 37012, Washington, D.C. 20013-7012, USA

ABSTRACT
Ejecta from impact craters on Venus are a major source of fine-grained materials across the planet, and crater spatial distribution has been studied as a guide to the relative age and resurfacing rates of large regions. Of particular interest is the potential intersection of distal crater deposits and tesserae, highly deformed landforms that may be the oldest materials on Venus. The composition of tesserae is unknown, but is key to understanding whether water played a role in crustal differentiation. Thus, tesserae are ideal sites for future landed missions to identify possible felsic materials, but the short lifespan of surface landers means that efforts must be made to avoid contaminating surface materials from craters. Here we develop a method to detect distal crater ejecta on tessera terrain across Venus using NASA Magellan radar data. Our results show that fine-grained ejecta are unevenly distributed in the tesserae with respect to nearby craters. Many tesserae within a few hundred kilometers of plains craters do not have evidence for thick (>5–10 cm) mantling material, indicating that eolian or mass-wasting processes have moved the debris off the highland ridge slopes. At Sudenitsa Tesserae, within the young Beta-Atla-Themis region, we observe a radar signature of mantling debris, but there is no apparent source crater to which this material can be traced. We infer that the source crater has been resurfaced by volcanic activity within the past 80 m.y., and suggest that similar fine-grained ejecta deposits may have built up over time in other tesserae across Venus.

INTRODUCTION
Tesserae cover ~7%–8% of the surface of Venus (Ivanov and Head, 1996) and are interpreted to be the oldest terrains on the planet (Campbell et al., 1992; Izenberg et al., 1994; Ivanov and Basilevsky, 1993). Tesserae are classified as radar-bright, topographically high materials that have undergone two or more tectonic deformation events and, as a result, have at least two sets of near-orthogonal fractures and/or folds (Fig. 1A, inset) (Barsukov et al., 1986; Ivanov and Head, 1996). The composition of tesserae is unknown despite previous landed missions to Venus (Basilevsky et al., 2007). Based on orbital data, researchers have proposed both a basaltic (Ivanov, 2001) and granitic composition (Mueller et al., 2008; Gilmore et al., 2015) for the tesserae. A granitic lithology would suggest that water played a substantial role in magma differentiation and tessera formation earlier in Venusian history. To definitively determine the composition of the tesserae, a landed mission is required.

Future landed missions would aim to sample tessera terrain uncontaminated by materials such as ejecta from craters in the low-lying basaltic plains (e.g., Surkov et al., 1987). On Venus, features known as crater ejecta parabolas (Fig. 1A) were identified during the NASA Magellan mission (Phillips et al., 1991; Campbell et al., 1992). All of the ~60 radar-dark, east-west–oriented parabolic features are hypothesized to have formed immediately following an impact event as fine-grained ejecta was thrown into the upper atmosphere, carried westward by zonal winds, and deposited over distances of up to ~2000 km from the source crater (Campbell et al., 1992; Vervack and Melosh, 1992; Schaller and Melosh, 1998). These fine-grained ejecta deposits smooth the surface, resulting in a dark radar signature in Magellan data. Owing to the large areal extent of the individual parabolic ejecta deposits, and their ubiquitous formation for craters >~3 km in diameter (Schaller and Melosh, 1998), these fine-grained ejecta deposits could easily contaminate tessera surfaces across much of the planet.

Over time, eolian or volcanic processes erode and redistribute the parabolic ejecta deposits in the plains (Izenberg et al., 1994; Bondarenko and Head, 2009). Some of this redistributed material likely contributes to mantling deposits associated with wrinkle ridges (McGill and Campbell, 2006), dome fields, and dune fields across the surface of Venus (Carter et al., 2004). Estimates of the time scale for parabolic-deposit removal in the plains are 35 ± 15 m.y., but evidence for their occurrence and lifetime in the tesserae have been sparse until recent Earth-based radar studies.

Previous studies using Magellan synthetic aperture radar (SAR) data found little evidence of parabolic ejecta in tesserae, leading to suggestions that tesserae are too rough to detect the deposits or that mass wasting off ridges modified the mantling debris (Arvidson et al., 1992; Campbell et al., 1992). Analyses of tessera terrain in eastern Alpha Regio using European Space Agency Venus Express Visible and
Infrared Thermal Imaging Spectrometer emissivity data did not detect reflectance differences potentially linked with such ejecta (Gilmore et al., 2015). Recently, however, Earth-based same-sense circular (SC) radar data have detected distal, fine-grained ejecta in eastern Alpha Regio, exploiting the sensitivity of this radar polarization to mantling of centimeter- to decimeter-scale surface roughness or rocks. A layer of fine-grained material at least ~5 cm deep, and perhaps much thicker, was mapped across the eastern half of Alpha Regio, continuing with the plains parabolic ejecta sourced from Stuart Crater (Campbell et al., 2015) (Fig. 1A). Traces of other parabolic ejecta have been detected at Gegute Tessera and Clotho Tessera with Magellan SAR data (Campbell et al., 1992), and with Earth-based SC data in two other tessera regions, Zirka and Manzan-Gurme (Campbell et al., 2015) (Fig. DR1 in the GSA Data Repository1).

The detections of large regions of fine-grained ejecta in tesserae indicate that plains materials may complicate compositional measurements made by a future landed mission, and certainly any analysis from orbital infrared observations. It is thus necessary to study the tesserae using the near-global Magellan SAR data because Earth-based radar data only partially cover one hemisphere (250°E to 50°E). We have developed a methodology for detecting mantling debris from the radar brightness of tessera ridge slopes, and confirmed the reliability of this technique by comparison with the Earth-based SC polarization data.

METHODS

The Magellan SAR left- and right-look data sets [75 m/pixel, 12.6 cm wavelength, HH polarization (horizontal transmitting, horizontal receiving)] were used to measure the tesserae radar properties in five different regions (Fig. DR1). These data were used to map the extent of tesserae, as defined by Ivanov and Head (1996), and to measure the backscatter coefficient (referred to as radar brightness, either radar-dark for a low, or radar-bright for a high backscatter coefficient) of the surface (Campbell, 1995, his equation 1). Backscatter coefficient measurements were compiled for the backslopes of ridges in the tesserae. The term backslope refers to the side of a ridge facing away from the sensor (i.e., the eastern slope for left-looking Magellan data). Due to their orientation, backslope echoes are not saturated like the radar-facing ridge slopes, making them more amenable for measuring backscatter variations. Our measurements were taken near the ridge crests to avoid possibly sampling material deposited in the troughs between ridges.

Due to the changing incidence angle of the Magellan left-look SAR data set (14°–46°), there is a latitudinal dependence to the calculated backscatter coefficient values, resulting in a systematic variability for the tessera regions analyzed in this study. To compare results among regions, we classify echoes with respect to the local backslope mean (see the standard deviation legends in Figs. 1–3). Backslopes were considered radar-dark if their backscatter coefficient was >1.5 σ (or 3 dB) lower than the local mean backscatter value.

RESULTS

Confirmation of Earth-Based Radar Data at Alpha Regio

Alpha Regio has been imaged in both Magellan and Earth-based data, making it an ideal location to validate the detection of radar-dark materials. Fine-grained ejecta from Stuart Crater were detected on the eastern half of Alpha Regio in Earth-based data (4.2 × 105 km2; Campbell et al., 2015; Fig. 1A, white line). Radar-dark backslopes in Alpha Regio mapped from Magellan SAR data (2.4 × 105 km2, 24 km3; Table DR1) are concentrated in the northeastern part of the highlands (Fig. 1B), and correlate with the radar-dark region first identified in the Earth-based images (Fig. 1A). Calculated fine-grained ejecta volumes in the tesserae represent ~0.9% of the total ejecta volume (see the Data Repository). The lack of correlation between five tectonic subunits in Alpha Regio (Bender et al., 2000) and the radar-dark backslopes indicates that tectonic modification of tessera ridge slopes (e.g., local generation of regolith from the bedrock) is not controlling the distribution of radar-dark materials. Two other tesserae adjacent to known parabolic ejecta deposits, Viritis Tesserae and Husbishag Tesserae (Fig. DR2), also show evidence for fine-grained material.

Detection of Distal Ejecta in Tesserae Outside of Earth-Based Coverage

Tellus Tessera

At Tellus, a high density of radar-dark backslopes occurs in the central region of the tessera (Fig. 2A; 2.6 × 105 km2, 26 km3; Table DR1). A small circumferential region of dark backslopes was also identified around the impact crater Khatun (44.1 km in diameter; Fig. 2A). The areally extensive concentration of radar-dark backslopes in the center of Tellus is located east of Bernhardt Crater (25.3 km in diameter; Fig. 2A); none of the other 4 nearby craters >3 km in diameter have associated patterns of radar-dark backslopes.

Bernhardt Crater, which formed in plains southeast of Tellus Tessera, has a floor partially covered with radar-dark material, and there is no obvious parabolic ejecta pattern in these plains (Fig. 2). The predicted extent of a parabolic ejecta associated with Bernhardt, however (Fig. 2A, black dashed line; Table DR2), encompasses most of the radar-dark backslopes in the central region of Tellus. These data suggest that fine-grained Bernhardt ejecta have been eroded from the plains, but remains preserved in the nearby tessera terrain. If the fine-grained ejecta on the plains were removed entirely by eolian processes, then the lifespan of similar deposits in the tesserae appears to be longer than the proposed age distribution of parabolic ejecta superposed on the plains (i.e., >35 Ma). It is also possible that the fine-grained materials were partially or

---

1GSA Data Repository item 2016175, methodological details for calculation of deposit volume and eruption rates, and figures of study region locations, additional backslope analyses, and Sudentissa elevation information, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

---

Figure 2. Radar-dark backslopes at Tellus Tessera, Venus. A: Tellus backslope radar brightness values. Dots are color coded by the standard deviation of the backscatter coefficient value; the darkest materials are shown in red and the brightest materials are shown in blue. K denotes location of Khatun Crater. White star marks location of Bernhardt Crater. Black dashed line shows the extent of the predicted parabolic ejecta deposit for Bernhardt (Table DR2 [see footnote 1]). Location of Tellus Tessera is in Figure DR1. B: Bernhardt Crater.
completely removed by volcanic resurfacing, which left the elevated tesserae and the Bernhardt rim exposed.

**Sudenitsa Tesserae**

Two regions of radar-dark backslopes occur in Sudenitsa Tesserae (Fig. 3), located on the north-northeastern edge of the Beta-Atla-Themis (BAT) region (Phillips et al., 1992) (Fig. DR1). One concentration is located circumferential to the crater Sanger (83.6 km in diameter); radar-dark material is also evident on the plains west of this crater (Fig. 3A). The second, more areally extensive, concentration of radar-dark backslopes is on the western side of Sudenitsa, concentrated at 260°E (Figs. 3A–3C). The area of radar-dark backslope signatures extends for ~1155 km east-west and ~1276 km north-south, and covers an area of ~1.7 × 10^6 km² (17 km²; Table DR1). There are no radar-dark patterns associated with the ~15 other impact craters across this region.

**DISCUSSION: TIME SCALE OF RECENT VOLCANISM**

The concentration of radar-dark backslope signatures in Sudenitsa Tesserae is interpreted as preserved parabolic ejecta material, based on our studies of other tesserae (Figs. 1 and 2; Fig. DR1; Campbell et al., 2015). There is no obvious mechanism for creating smooth (radar-dark) surfaces on these ridge slopes over such an areally extensive region other than airfall ejecta emplacement. Local erosion may produce a fine-grained regolith in the tesserae, but there is no obvious reason (e.g., ridge-deflected winds, compositional variations) for this type of erosion to preferentially occur in certain areas. Tessera ridge slopes could be another cause for diverse radar signatures, but the lack of correlation with the tectonic subunits in Alpha Regio (Bender et al., 2000) argues against this mechanism.

There is no candidate source crater for the area of radar-dark signatures at 260°E in Sudenitsa (Fig. 3D; Fig. DR3). Based on the extent of these signatures (Figs. 3B and 3C; see the Data Repository) and morphologic relationships derived from the observed population of parabolic ejecta deposits (Schaller and Melosh, 1998), the source crater is expected to be 20–30 km in diameter (Table DR2). Around the predicted location of the source crater there is no evidence (e.g., part of the crater rim protruding from the plains, circular tectonic features) of either a partially or completely buried crater (Fig. 3D). In addition, the surrounding plains are not covered with radar-dark material (Figs. 3A–3C).

There are two end-member scenarios to explain these observations: (1) the fine-grained ejecta and source crater were completely resurfaced by volcanic flows, or (2) the fine-grained parabolic ejecta material on the plains was eroded by eolian processes and the source crater was removed by volcanic flows. Based on eolian erosion rates, parabolic ejecta deposits on the plains have an average age of 35 ± 15 Ma (Schaller and Melosh, 1998). If the plains part of the Sudenitsa parabolic ejecta deposit has been removed by the wind, then its removal likely occurred within, at most, the past 80 m.y. Eolian processes clearly do not remove source craters. The location of Sudenitsa within the BAT region, with its concentration of volcanic features 2–4x the global average (Head et al., 1992) and evidence of relatively younger terrain (Phillips et al., 1992), makes it plausible to suggest the removal of both features by volcanic resurfacing. For example, Polik-mana Mons, south of Sudenitsa, erupted north-trending lava flows that may have resurfaced a portion of the initial parabolic ejecta deposit on the plains (Fig. DR3).

These two scenarios constrain estimated eruption rates for flows originating in the BAT region (see the Data Repository), based on a maximum age of 80 Ma for parabolic ejecta deposits on the plains, a resurfaced area of ~10^6 km² (scenario 1), and ~10^5 km² (scenario 2), and predicted source crater rim heights. If the eruptions were continuous over 80 m.y., average volume rates of 3.8 × 10^3 km³/yr (scenario 1) and 1.3 × 10^5 km³/yr (scenario 2) are required. Scenario 2 is the favored resurfacing model due to the more reasonable areal extent of the proposed volcanic flows. The presence of a well-developed pattern of wrinkle ridges (Fig. 3D) suggests that the resurfacing occurred earlier within the 80 Ma age limit, in order to provide enough time for lava flows to undergo deformation aligned with the regional stress regime. A period of 8 m.y. (10% of the maximum age estimate and ~25% of the 35 Ma age for plains parabolic ejecta) would entail an average rate for scenario 2 of ~1.3 × 10^-4 km³/yr. This value is <1% of an estimated global eruption volume of 2 km³/yr (Phillips et al., 1992; Greeley and Schneid, 1991), and generally consistent with
eruptive rates for terrestrial volcanoes ($10^{-5} - 10^{0}$ km$^3$/yr; White et al., 2006).

Detects of recent volcanic events (e.g., Smrekar et al., 2010; our study) have implications for whether major resurfacing on Venus can be explained by a catastrophic (Scherber et al., 1992) or equilibrium (Phillips et al., 1992) model. The area of the resurfaced region in Sudenitsa (~$10^3$ km$^2$ for scenario 2) is consistent with model area estimates (Phillips et al., 1992; Bjonnes et al., 2012) of local and regional resurfacing associated with the equilibrium resurfacing model, and with the scale and duration of mare volcanism on the Moon (Hiesinger et al., 2000) (see the Data Repository; Fig. DR3). Substantially larger volumes over more limited time scales are expected for the catastrophic resurfacing model.

This analysis shows that Magellan SAR data can be used to detect radar brightness variations in tessera terrains linked with distal ejecta of impact craters, which must be factored into studies by future orbital or landed missions to assess highland compositions on Venus. At Tellus, fine-grained ejecta within the tessera has been preserved longer than ejecta on surrounding low-lying plains. This observation, coupled with the paucity of parabolic ejecta deposits associated with other adjacent craters, indicates that parabolic deposits superposed on low-lying plains have a shorter lifetime compared with ejecta in tessera. A region of radar-dark backslips associated with a volcanically buried source crater was identified at Sudenitsa Tesserae. A recent low-eruption-rate lava flow complex sourced from the adjacent BAT region is capable of the area of the resurfaced region in Sudenitsa (~$10^3$ km$^2$ for scenario 2) is consistent with model area estimates (Phillips et al., 1992; White et al., 2006). Venus surface thermal emission at 1 um in VIRTIS imaging observations: Evidence for variation of crust and mantle differentiation conditions: Journal of Geophysical Research, v. 113, E00B17, doi:10.1029/2009JE003118.


Manuscript received 13 January 2016
Revised manuscript received 9 May 2016
Manuscript accepted 10 May 2016

Printed in USA