Venus records a rich early history

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ABSTRACT

The distribution and character of Venus's impact craters led to the widely accepted idea that Venus underwent global catastrophic resurfacing ca. 500 Ma, and thus Venus records only a short history, encompassing surface evolution since postulated catastrophic resurfacing. Ribbon tessera terrain (RTT), a structurally distinctive unit, represents some of Venus's oldest surfaces, and is widely accepted as forming prior to postulated global catastrophic resurfacing. We constructed a global geologic map of RTT unit exposures and structural trends using National Aeronautics and Space Administration (NASA) Magellan data. Map relations illustrate that RTT displays planet-scale patterns that, together with altimetry, record a rich geologic history that predates proposed global catastrophic resurfacing.

INTRODUCTION

About 15 yr ago, the National Aeronautics and Space Administration (NASA) Magellan mission revealed that Venus lacks plate tectonic processes (Solomon et al., 1992; Phillips and Hansen, 1994), yet Venus's evolution and operative geodynamic processes remain elusive. Two classes of geologic features provide substantial clues to Venus's evolution: impact craters and ribbon tessera terrain (RTT; Hansen and Willis, 1996, 1998) representing distinctive remnants of ancient surfaces. The record of remarkably well preserved craters influenced thinking about Venus's history because few craters show substantive embayment by external flows or tectonic disruption (Phillips et al., 1992; Schaber et al., 1992; Herrick et al., 1997). Total craters, crater spatial distribution, and crater flux models indicate a global average model surface age (AMSA) of ca. 750 +350/–400 Ma (McKinnon et al., 1997). A wide range of different surface histories could accommodate this global AMSA (Hansen and Young, 2007) that include, but are not limited to, a single global-scale event. The assumption that this AMSA records a single global event led to the widely accepted global catastrophic resurfacing hypothesis: that ca. 500 Ma, ~80% of Venus's surface was completely renewed in a period of 10–100 m.y. Postulated surface renewal could have occurred either through (1) extensive deep volcanic burial (Strom et al., 1994; Basilevsky and Head, 1998, 2002, 2006; Bullock et al., 1993), or (2) wholesale lithospheric recycling (Turcotte, 1993; Herrick, 1994; Turcotte et al., 1999). In either case, little record of the pre-catastrophic surface should be preserved, and any preserved pre-catastrophic record would be mostly limited to high-standing crustal plateaus, which escaped either deep burial or lithospheric recycling. The proposed thickness of deep burial has evolved, ranging from >3 km to >1 km, but ≥1 km is required to bury Venus's large impact craters (Stofan et al., 2005). We present results of detailed, but global scale, geologic mapping of RTT. Geological relations reveal that RTT records a rich geologic history that predates units attributed to global catastrophic resurfacing, and could challenge the occurrence of such an event.

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RIBBON TESSERA TERRAIN

Unit RTT (Hansen and Willis, 1998) constitutes Venus's locally oldest surface unit (Basilevsky and Head, 1998; Head and Basilevsky, 1998), although globally not all RTT formed at the same time (Bindschadler et al., 1992; Bindschadler, 1995; Hansen and Willis, 1996; Hansen et al., 2000). Unit RTT is marked by a distinctive tectonic fabric and high surface roughness, and characterizes crustal plateaus, but also occurs as lowland inliers, widely interpreted as remnants of collapsed crustal plateaus (Phillips and Hansen, 1994; Ivanov and Head, 1996). The fabric includes short- to long-wavelength folds (1–50 km) that record layer shortening, and orthogonal structures that record layer extension, including so-called ribbon ridges and troughs, and grabens (Fig. 1A). Locally, volcanic deposits flood structural lows (Bindschadler et al., 1992; Bindschadler, 1995; Hansen and Willis, 1996, 1998; Ivanov and Head, 1996; Gilmore et al., 1998; Hansen et al., 2000; Romeo et al., 2005; Hansen, 2006). Although there is debate about whether folds dominantly predate or postdate ribbons, most workers agree that (1) fold and ribbon formation broadly overlapped in time, (2) grabens formed late, and (3) volcanic activity accompanied RTT fabric formation. Ribbon character and spacing, functions of brittle layer thickness (Hansen and Willis, 1998), require a high geothermal gradient (minimum heat flow similar to average terrestrial mid-ocean ridges) during ribbon formation (Gilmore et al., 1998; Ruiz, 2007). Regular ribbon spacing across 10^6 km^2 (Ghent and Tibuleac, 2000) implies a thermal control for the base of the upper strong layer corresponding to a regional brittle-ductile transition depth (Hansen and Willis, 1998; Hansen, 2006; Ruiz, 2007). Calculated heat-flow values for ribbon formation and the estimated depth to the crustal solidus require either extremely thin crust, or a crustal magma reservoir across areas of RTT formation; thus RTT records regional-scale environmental conditions different than those of contemporary Venus (Ruiz, 2007).

RTT GLOBAL GEOLOGIC MAP: OBSERVATIONS AND IMPLICATIONS

We constructed a global geologic map of RTT using Magellan SAR (synthetic aperture radar) and altimetry data, and estimated the global distribution of shallowly buried RTT (i.e., RTT buried <1 km; Fig. DR1 in the GSA Data Repository[1]). RTT is exposed across 53 × 10^6 km^2, or 12% of the surface; shallowly buried RTT constitutes an additional 21%–38% of the surface. The distribution of RTT and/or shallowly buried RTT together with global topography provide clues for the global-scale evolution of Venus, revealed through first-order observations as follows (Fig. 1B; Videos DR1 and DR2 in the Data Repository). (1) RTT is strongly correlated with crustal plateaus, as widely recognized. (2) RTT inliers occur within all volcanic rises, except Imdr and Themis. (3) RTT occurs within most lowland basins. (4) RTT inliers occur independent of basin topography. (5) Groups of RTT inliers describe regional-scale linear to arcuate patterns, many of which (6) show no obvious correlation with long-wavelength topography; i.e., some patterns track across lowland basins and highland rises. (7) Few large (>7 × 10^6 km^2) RTT-poor regions exist. (8) RTT inliers are rare across one extensive region centered at ~30°S, 180°E, including the area that encompasses Artemis, Diana-Dali, Parga, and Hecate Chasmata. We focus on observations 1–6 here.

The lack of spatial correlation of RTT outcrop patterns with long-wavelength (>1000 km) topography that marks lowland basins and volcanic rises indicates that the processes forming these features likely operated independent of RTT formation. Parallelism of RTT outcrops

[1]GSA Data Repository item 2010084, Figure DR1 and Videos DR1 and DR2 (Quicktime movies of global views), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

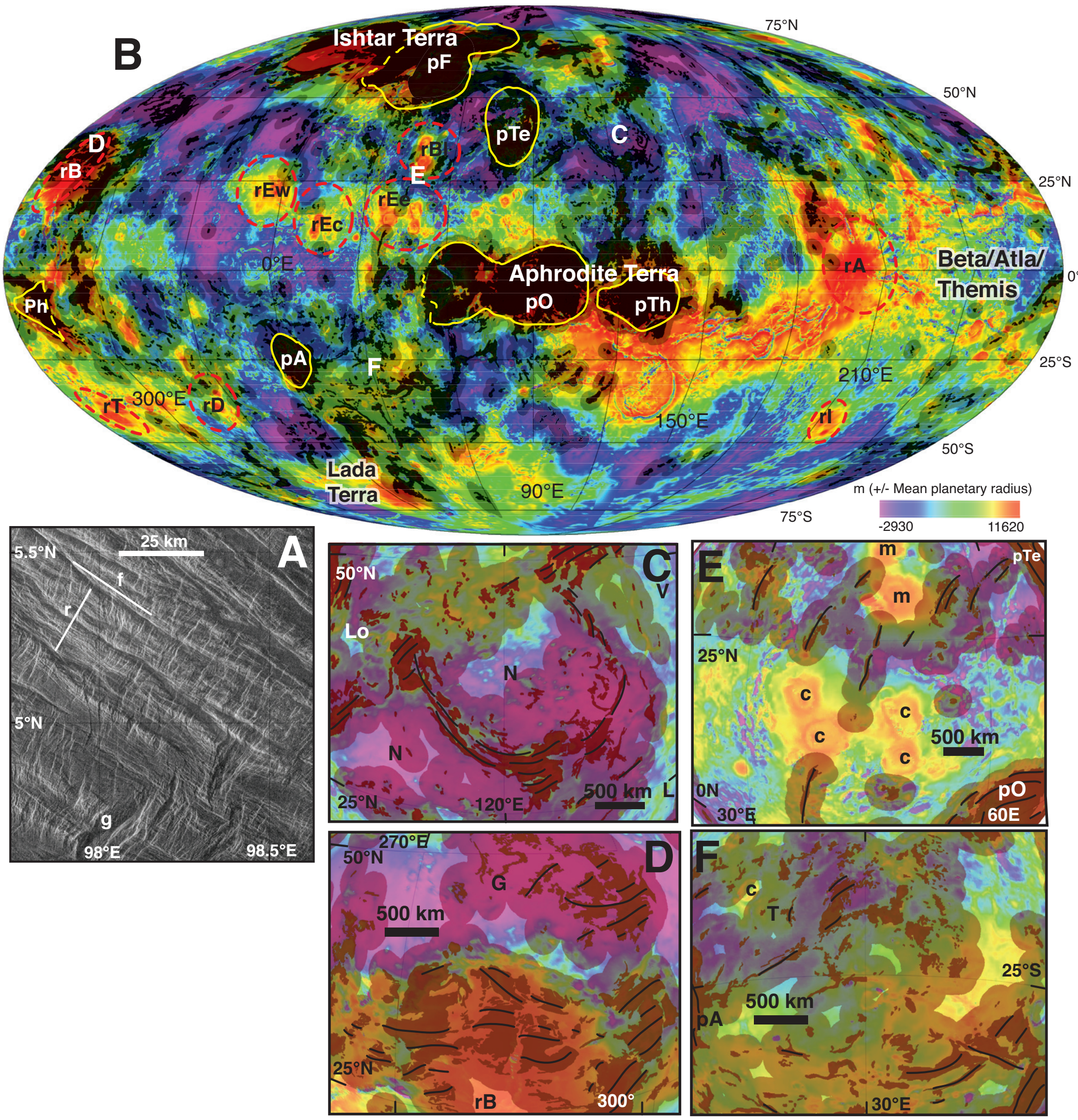

Figure 1. A: Magellan synthetic-aperture radar image of ribbon tessera terrain (RTT) fabric. Ribbons (bright-dark paired lineaments 20–100 km long, parallel to r line) define alternating flat-topped ridges and narrow, steep-sided, flat-bottomed troughs; folds (gently sloping ridges, parallel to f line) with wavelength <1 km up to 50 km; grabens (g, with aspect ratios ~1:3, and ~60° walls) typically parallel ribbons. B: Mollweide projection of Venus with Magellan altimetry, RTT (black), shallowly buried RTT (gray; see Fig. DR1 for method [see footnote 1]), and major geomorphic features including all regions: isostatically supported crustal plateaus (yellow outlines: pA—Alpha; pF—Fortuna; pO—Ovda; pTe—Tellus; pTh—Thetis); thermally supported volcanic rises (red outlines: rA—Atla; rB—Beta; rBl—Bell; rD—Dione; rEc—central Eistla; rEe—eastern Eistla; rEw—western Eistla; rI—Imdr; rT—Themis); and Phoebe (Ph) with plateau and rise characteristics (Simons et al., 1997). Letters C–F indicate locations of regional views of global surface; RTT (dark brown) and shallowly buried RTT (light brown); fold trends (black lines). C: Lowland planitiae: Lowana (Lo), Niobe (N), Vellamo (V), and Llorona (L) preserve temporal relations between two suites of RTT. D: Lowland-highland transition between Beta rise (rB) and Guinevere Planitia (G). E: Montes (m) of Bell and coronae (c) of eastern Eistla disrupt early formed RTT; Tellus (pTe) and Ovda (pO) show different RTT fabric trends. F: Tinatin Planitia (T) and mesoland east of Alpha (pA); coronae (c) locally disrupt RTT.

and RTT fabrics within isolated outcrops across lowland basins and highland rises suggests that a regional surface decorated by RTT fabric was downwarped and upwarped during basin and rise formation, respectively.

In contrast, strong spatial correlation of RTT and individual topographically defined crustal plateaus suggests a genetic relationship between the plateau formation and the RTT they host, consistent with earlier conclusions (Bindschadler et al., 1992; Bindschadler, 1995; Ghent and Hansen, 1999; Hansen et al., 2000). Some plateaus apparently lost topographic support, positioning RTT for possible burial (Phillips and Hansen, 1994; Ivanov and Head, 1996) or, alternatively, some (or all) tracts of lowland RTT were never greatly elevated above their surroundings. Tellus Regio truncates linear to arcuate patterns defined by adjacent RTT inliers, suggesting that Tellus Regio formed after the RTT inliers, consistent with diachronous, rather than coeval, RTT formation (Bindschadler, 1995).

Further clues emerge from a closer look at four large areas. In the first region, an extensive lowland across four planitiae hosts two dominant features: an ~2000-km-diameter circular feature, and a northeast-trending belt that extends for thousands of kilometers beyond the map area (Fig. 1C). Both topography and RTT fabrics define each feature. RTT inliers typically correspond to local topographic highs, although several RTT inliers show little topographic expression, and some local highs lack RTT; RTT preserved within the circular feature interior suggests that RTT underlies this entire feature. RTT fabrics parallel the elongate form of RTT outcrops and topographic trends that define the circular feature; RTT fabrics also parallel highs that mark the northeast-trending belt. The circular feature shows both structural and topographic truncation by the northeast-trending belt, suggesting that the two suites of RTT represent different events, formed at different times. Most of the area is underlain by shallowly buried RTT, consistent with geologic mapping indicating that a thin cover of shield terrain likely overlies RTT (Aubele, 1996, 2009; Hansen, 2005); thus this area is difficult to reconcile with extensive flooding (>1 km). Although this region includes several million square kilometers of the lowland, geologic relations cannot be reconciled with interpretations that it hosts extensive thick (>1 km) flows, or represents newly formed lithosphere replacing older recycled lithosphere.

A second region straddles a highland-lowland transition marking the boundary between Beta Regio and Guinevere Planitia (Fig. 1D). Fracture zones and flows disrupt coherent RTT fabric within Beta rise, whereas RTT occurs even at low basin elevation within Guinevere Planitia. RTT exposed in Beta Regio and Guinevere Planitia could record two events, or a single event based on current map relations. Shallowly buried RTT extends across much of this area, with only isolated regions potentially preserving cover >1 km. Thus, geologic relations are consistent with local shallow burial of RTT prior to Beta rise and Guinevere basin formation. The geologic history that emerges includes (1) early formation of RTT (by one or more events), (2) local shallow burial of RTT, (3) upwarping and downwarping of the RTT and/or shallow cover surface within Beta Regio and Guinevere Planitia, respectively, and (4) local fracturing and burial of RTT within Beta Regio. Map relations are inconsistent with interpretations that Guinevere Planitia hosts extensive flows >1 km thick, or represents a large tract of young lithosphere; thick flows are inconsistent with shallowly buried RTT estimates; new young lithosphere would lack RTT.

A third region, which includes portions of Bell and eastern Eistla Regiones (Fig. 1E), preserves narrow elongate exposures of RTT (hundreds of kilometers long) that collectively extend thousand of kilometers in a north-northeast direction, and define a strike-normal belt >2000 km wide. Individual exposures, separated by hundreds of kilometers, display parallel structural fabrics; fold crests parallel the long axes of outcrops and ribbons trend perpendicular to the folds. The RTT inliers, and their internal fabrics, track across and beyond Bell and Eistla rises. Viewed globally, crustal plateaus Tellus and Ovda Regiones and their respective RTT fabrics truncate the elongate RTT inliers and their internal fabrics (Fig. 1B), suggesting that Tellus and Ovda Regiones formed after this suite of RTT. Relative timing of Tellus versus Ovda formation is unconstrained. Montes and coronae, which characterize Bell and Eistla Regiones, respectively, obliterated local RTT, consistent with the history derived from 1:5,000,000-scale geologic mapping (Campbell and Campbell, 2002; Campbell and Clark, 2006). However, the lack of RTT in the surrounding lowlands is not the result of montes and coronae. These lowlands are characterized by intermediate-wavelength topography similar in character to that of RTT inliers. Deep, extensive, post-RTT flooding of the adjacent lowland region is difficult to reconcile with this topographic character. Deep flooding would be expected to bury intermediate-wavelength topography; if not, then RTT should be preserved in the local topographic highs that escape burial. If the surrounding lowland represents young lithosphere, then the similarity in topographic character of the lowland and RTT inliers would be coincidental. The geologic history that emerges includes (1) RTT formation, (2) local burial of RTT that preserves isolated kipukas of RTT yet shallowly buries other portions of the RTT, preserving intermediate topography (shield terrain emplacement [Hansen, 2005; Stofan et al., 2005)] is one process that could accommodate these requirements), and (3) regional uplift at Bell and Eistla Regiones and emplacement of montes and coronae. The relative timing of Bell and Eistla Regiones is unconstrained based on this study. The elongate inliers and their internal RTT fabrics trend parallel to, and line up globally with, the northeast-trending RTT belt within Niobe Planitia discussed here (Fig. 1C). These two suites of RTT could be correlative; however, more mapping is required to test this hypothesis.

The fourth region is in the mesoland-lowland east of Alpha Regio (Fig. 1F); here RTT inliers preserve several patterns defined by intermediate-wavelength topography and RTT fabrics. Large tracts of RTT display crosscutting fabrics recording different events or phases of fabric development; elsewhere RTT inliers are small (at the scale of data effective resolution; Zimbelman, 2001), and more detailed study is required to establish the regional extent of various fabric domains and possible temporal relations. However, the distribution of RTT inliers provides evidence that (1) RTT is shallowly buried across the region, (2) cover material could have numerous sources, and (3) long-wavelength topography formed after RTT, and likely after emplacement of cover deposits. Locally coronae obliterate RTT. RTT fabrics within Alpha Regio trend at a high angle to inliers with northeast outcrop and fabric trends, indicating that Alpha Regio likely formed later. The intermediate-wavelength topographic character is similar to that of the lowland adjacent to Bell and Eistla Regiones. Map relations are inconsistent with interpretations that this region hosts extensive flows >1 km thick, or represents young lithosphere.

SYNTHESIS

Geologic relations gleaned from global observations and region-scale map areas lead to the following implications for the global to regional scale evolution of Venus's surface. (1) The unit RTT records a rich geologic history that broadly predated the formation of long-wavelength rises and basins. (2) Crustal plateaus formed individually via a process that formed both RTT fabric and plateau topography. (3) Suites of RTT inliers collectively define coherent patterns based on outcrop exposure, topography, and RTT fabric trends; these suites describe linear to arcuate patterns that cover millions of square kilometers. The spatial extent of suites is not yet defined, and it is likely that many suites of coherent RTT have yet to be recognized. It is unclear whether individual suites of RTT were once topographically elevated, like crustal plateaus, and subsequently collapsed, or if they never attained elevated status, or both. (4) Crosscutting relations indicate that at least some crustal plateaus are younger than the suites of RTT preserved in adjacent lowlands (e.g., Tellus, Alpha, and Ovda Regiones). (5) Suites of RTT formed via multiple events through time and space, and record a rich history that can be unraveled by further detailed mapping.

Volcanic rises and lowland basins each preserve RTT inliers. The occurrence of RTT inliers in several rises, thermally supported contemporary features (Simons et al., 1997), requires that these areas of RTT inliers either somehow escaped catastrophic resurfacing (whether through deep burial or lithospheric overturn) before rise formation, or resurfacing occurred after rise formation. The same can be stated of lowland basins, although with inverse topographic development. Given that lowland basins preserve RTT and/or shallowly buried RTT, these regions either did not undergo catastrophic resurfacing, or resurfacing occurred after basin formation. If the basins did not undergo catastrophic resurfacing, then it is difficult to justify global resurfacing; if resurfacing occurred after basin formation, then basin RTT should not be preserved. These results provide a serious challenge to (1) global resurfacing hypotheses, whether by the emplacement of extensive flows >1 km thick, lithospheric overturn, or global subduction, with or without pulsating continents (Romeo and Turcotte, 2008), and (2) the implication that Venus records only a temporally limited geologic history.

The picture that emerges is one in which Venus's surface records a rich and prolonged history (e.g., Guest and Stofan, 1999); this study serves to highlight the history that awaits discovery. RTT formed during a specific geologic era, marked by relatively unique environmental conditions, conceptually similar to Earth's Archean. RTT records a regional-scale history of deformation phases or events that vary in space and time. At a global scale, patterns within RTT outcrops and fabrics extend over millions of square kilometers, and individual suites record variable temporal evolution, which could potentially be used to correlate temporally distinct events over large regional scales.

Our ability to understand terrestrial planet evolution relies on the preserved geologic record. Earth's limited ancient record is dismembered due to plate tectonic processes, and eroded and buried due to surface processes. The record of Mars' early history has been obscured by bolide impact, surface burial, or reworking by volcanic, hydrologic, or atmospheric processes. In contrast, Venus's surface might preserve a novel record of terrestrial planet evolution given its lack of plate tectonics and a hydrologic cycle, and its dense atmosphere that protected the surface from extensive bolide impact. Renewed study of Magellan's spectacular global data sets has the potential to reveal this history.

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