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Venus tesserae feature layered, folded, and eroded rocks

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ABSTRACT

Tesserae on Venus are locally the stratigraphically oldest units preserved on the planet. These regions are characterized by pervasive tectonic deformation including normal faults, grabens, thrust faults, and folds. In multiple tesserae, sets of (often highly) curved, parallel linear features are also present. These features strongly resemble terracing in layered volcanic or sedimentary sequences on Earth having arcuate or sinuous outcrop patterns that follow undulating topography. Should this analogy hold for Venus, then these outcrop patterns imply some erosion of the tessera units in which these strata occur; radar-dark materials filling proximal lows might be deposits of that eroded material. This outcrop pattern is seen in geographically dispersed tessera units, so the preservation of layering could be common for this terrain type. If so, then tesserae record the culmination of volcanic and/or sedimentary deposition, folding, and erosion—complex geological histories that should be considered in future studies of this enigmatic terrain.

INTRODUCTION

Tesserae occupy ~7% of the surface of Venus and locally are always stratigraphically older than surrounding plains units (e.g., Ivanov and Head, 2011). Tessera units occur as both large plateaux thousands of kilometers across and as smaller inliers—isolated, high-standing regions hundreds of kilometers in horizontal extent that are surrounded and embayed by younger volcanic deposits (Ivanov and Head, 2011). Venus' tesserae are characterized by numerous sets of intersecting tectonic features, interpreted as mixes of extensional and shortening structures that record complex strain histories for individual exposures (e.g., Barsukov et al., 1986; Ghent and Hansen, 1999). Indeed, tessera units boast areal densities of tectonic structures not observed over comparable scales on any other planetary body (aside, perhaps, from highly tectonized Archean and Proterozoic rocks on Earth, such as those in northern Canada and Greenland).

One hypothesis for tessera formation is that the surficial material is basaltic and was the cooling crust of a voluminous subsurface magma pond (e.g., Hansen, 2006). Another view is that tesserae may be Venus' counterparts of continents on Earth, inferred on the basis of morphology, gravity anomaly signature, and composition (e.g., Hashimoto et al., 2008; Romeo and Capote, 2011). Indeed, data from the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) instrument on the European Space Agency *Venus Express* spacecraft (Helbert et al., 2008) indicate that the Alpha Regio tessera has a lower overall surface emissivity than the adjacent basaltic plains, and so it may differ in rock type or surface mineral assemblage (Gilmore et al., 2015). The 1 µm emissivity of this tessera is consistent with low Fe^{2+} content, corresponding to such lithologies as granitoids, anorthosites, and carbonates and sulfates derived from the chemical weathering of basalt under a higher atmospheric partial pressure of water than today (Gilmore et al., 2015).

LAYERING

When resolved with NASA *Magellan* synthetic aperture radar (SAR) left- and right-looking global radar mosaics, which have a spatial resolution of ~100 m per pixel (m/px), there are, within multiple tesserae, sets of curved, parallel lines of high radar backscatter (Senske and Plaut, 2000, 2009) that are crosscut by extensional and shortening structures. For example, in Tellus Tessera, an exposure of this terrain type at mid-northern latitudes in Venus' eastern hemisphere, subparallel, radar-bright linear features appear to follow local changes in topography and can be traced continuously for tens of kilometers (Fig. 1). Where these features strike approximately perpendicular to the radar look direction, their spacing decreases, likely a result of radar foreshortening (a distortion common in radar images of mountainous terrain facing the SAR antenna by which slopes appear steeper in map view than they really are).

These linear features bear a strong morphological resemblance to strata in layered sequences on Earth that have an arcuate or sinuous, terraced outcrop pattern from having been

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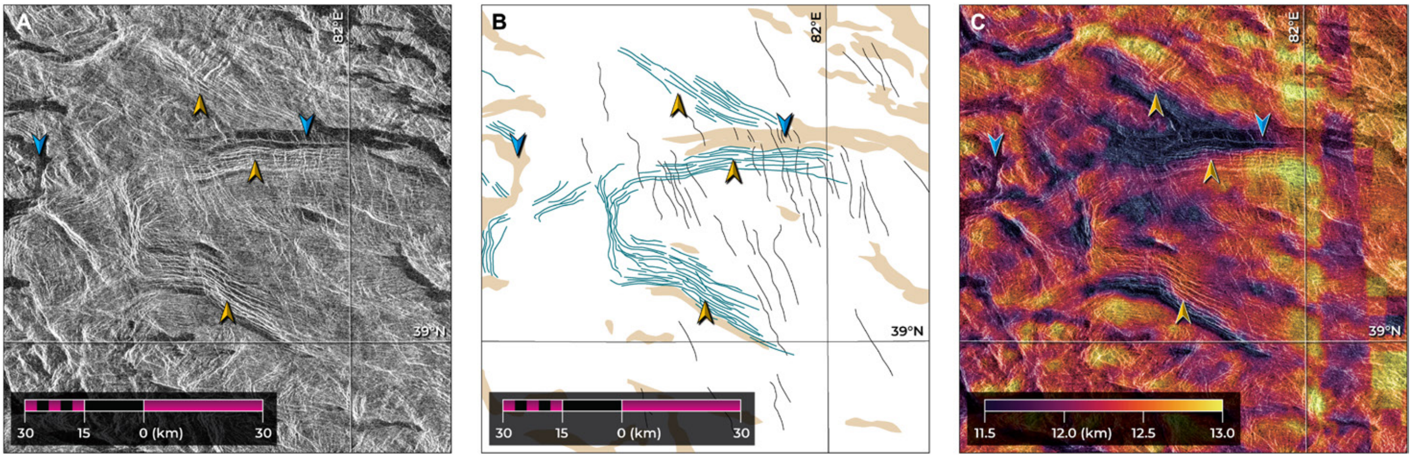

Figure 1. (A) Portion of a NASA *Magellan* global radar mosaic showing examples in Tellus Tessera, Venus, of arcuate lines of high radar backscatter (marked by gold arrows). Intratessera radar-dark material is marked with blue arrows. (B) Sketch map of these arcuate features (teal lines), which tend to differ substantially in strike from linear structures that appear to be extensional fractures (thin black lines). Radar-dark material is shown as tan fill. (C) Topographic data (from Herrick et al., 2012) overlain on radar imagery showing how arcuate features follow local topography; topographic data have a resolution of ~1 km/px. All images are in azimuthal equidistant projection, centered at 39.3°N, 81.5°E; radar look direction in A and C is from the left.

exposed by erosion on the flanks of ridges or valleys (Figs. 2A and 2B). The irregular, curvilinear patterns in tesserae may thus, by analogy, be indicative of exposed layers that follow undulating ridge-and-trough topography with length scales of tens of kilometers.

On the basis of *Magellan* radar image resolution, these candidate strata are tens to hundreds of meters thick, although fainter lines that parallel the more prominent examples suggest that thinner layers are also present. In addition to those examples within Tellus Tessera (Senske and Plaut, 2000, 2009), we have identified this curvilinear outcrop pattern in Ovda Regio (Figs. 2C and 2D) and Alpha Regio (Figs. 2E and 2F) tesserae, as well as in Manatum Tessera (e.g., at 8°S, 67°E) and Thetis Regio tessera (e.g., at 11°S, 130°E).

The nature of these strata is unclear, although they could be volcanic or sedimentary units. If sedimentary, the lithology of such units is difficult to ascertain. Under current Venus surface atmospheric conditions at typical elevations (~740 K and 9.3 MPa), there is no means by which fluvial or shallow-marine sediments could form, and carbonate rocks are not thermodynamically stable (e.g., Fegley and Treiman, 1992). The atmosphere is well capable of transporting sediment (Greeley et al., 1984), but few definitive eolian landforms and deposits have been recognized in *Magellan* data, and most of those are associated with impact ejecta (Craddock, 2011). Water-derived sedimentary rocks might perhaps have formed under different environmental conditions from those that prevail today, particularly if the climate of Venus was once more clement (e.g., Way and Del Genio, 2020). Without in situ chemical analyses and high-resolution images of tessera rocks, however, such inferences are difficult to test.

Explosive volcanism on Venus today is generally thought to be inhibited by the high surface pressure (e.g., Head and Wilson, 1986), although at least two possible candidate pyroclastic deposits have been identified (Ghail and Wilson, 2015; Campbell et al., 2017). Alternatively, the tessera layers could be stacked flood lava flows (e.g., Gilmore et al., 2015). Up to 70% of the planet's surface is occupied by plains lavas (Ivanov and Head, 2011), and widespread (if episodic) volcanism was likely responsible for the average model crater age of the Venus surface of 800–700 Ma (McKinnon et al., 1997). If the layers are flood basalts, then tesserae represent substantial accumulations of effusive flows akin to large igneous provinces (LIPs) on Earth, e.g., the mafic Deccan or Siberian Traps (in India and Russia, respectively).

FOLDING OF TESSERAE

Whatever the surface composition of tesserae, the map patterns we observe are readily explained as folded stacks of layered rocks. Both short- and long-wavelength folds have been widely seen in tesserae (e.g., Ghent and Hansen, 1999; Romeo and Capote, 2011; Cofrade et al., 2019). Horizontal shortening of tessera units (or the precursor rocks) is predicted to yield periodic fold trains of antiforms and synforms (possibly featuring flexural slip along the interfaces of any layers). Under this scenario, strata should dip away from ridges and toward the troughs, but neither *Magellan* altimetric (Ford and Pettengill, 1992) nor stereo-derived (Herrick et al., 2012) topographic data (with effective horizontal resolutions of ~10 km/px and ~1 km/px, respectively) are of sufficient resolution to measure reliably the dip angles of the features we interpret as exposed layers.

Nonetheless, under the assumption that these ~10-km-scale ridges and valleys are indeed upright antiforms and synforms, we used stereo-derived topography to estimate the shortening they represent by assessing the geometry of ridges and valleys along two ~400-km-long transects, one each in Tellus Tessera (from 36.8°N, 78.6°E to 40.6°N, 78.0°E) and Ovda Regio (from 6.9°S, 82.3°E to 3.3°S, 82.2°E). We approximated each assumed fold limb as triangular in cross section, such that the horizontal shortening strain is $\Delta L = L_{\text{final}} - L_{\text{initial}}$, where L is length, $L_{\text{final}} = \lambda/4$, $L_{\text{initial}} = [(\lambda/4)^2 + a^2]^{0.5}$, λ is fold wavelength, and a is fold amplitude. With wavelengths of 10–20 km and amplitudes of 200–300 m, these landforms are gentle folds with interlimb angles of ~175° that likely represent shortening strains of only ~0.2%–0.5%, a finding consistent with earlier work (e.g., Ghent and Hansen, 1999).

Folding also accounts for distinctive lenticular features that occur widely within tesserae, such as the examples in Figures 3A and 3B. These features morphologically resemble eroded periclinal folds, i.e., folds with double-plunging fold axes. Periclines are common within major shortening systems on Earth, such as in Iran's Zagros Mountains (Molinaro et al., 2005), in southern China (Li et al., 2016), and in the Sulaiman Range of Afghanistan and Pakistan (Figs. 3C and 3D; Reynolds et al., 2015). Given that the tesserae were formed at least in part by horizontal shortening (e.g., Romeo and Capote, 2011), it would be surprising if such folds were absent on Venus. The "circular troughs" discussed by Cofrade et al. (2019), and attributed by those authors to local diapirism, may also be eroded periclinal folds. Further, polyphase deformation can readily generate complex fold interference patterns (Ramsey, 1967) and has been invoked, for instance, to account for the "basin-and-dome" topography at the center of Alpha Regio (Hansen and Willis, 1996).

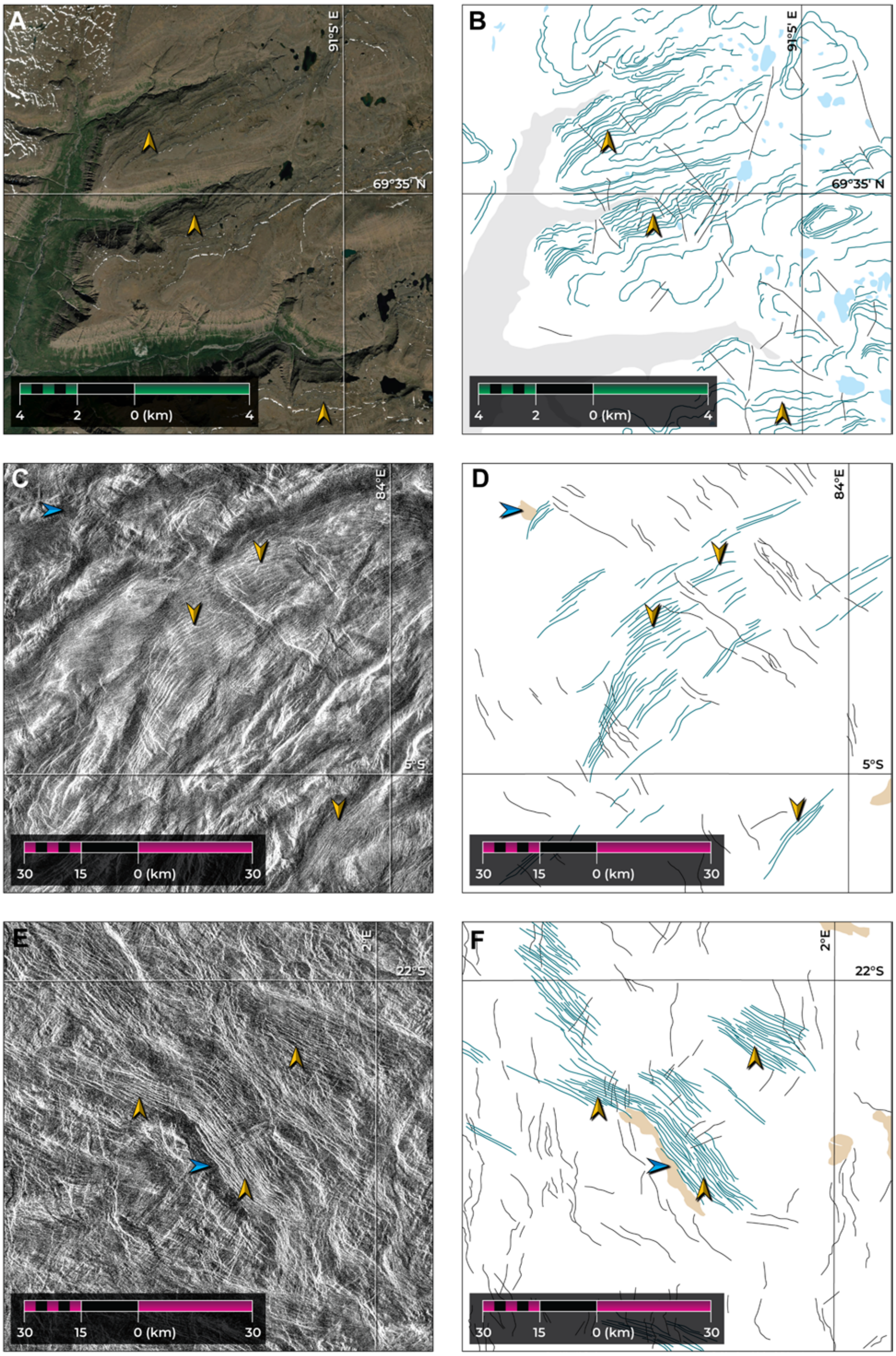

Figure 2. (A) TerraColor NextGen *Landsat 8* satellite (NASA/U.S. Geological Survey) image mosaic of a portion of the Siberian Traps in northern Russia. Exposed lava formations follow topography and show arcuate outcrop patterns (gold arrows). (B) Sketch map of scene in A; thin black lines mark extensional fractures, gray fill is vegetation cover, and blue fill corresponds to perched lakes. (C) Portion of *Magellan* global radar mosaic with examples of arcuate lines (gold arrows) and radar-dark deposits (blue arrows) in Ovda Regio. (D) Sketch map of these features and extensional structures (teal and thin black lines, respectively). Tan fill is radar-dark material. (E) NASA *Magellan* radar imagery of curving lines in Alpha Regio. (F) Sketch map of scene in E. All images are in azimuthal equidistant projection, centered at (A) 69.5°N, 91.7°E; (C) 4.6°S, 83.5°E; and (E) 22.4°S, 1.6°E. Solar illumination in A is from the south, and radar look direction in C and E is from the left. Satellite view in A was provided by Earthstar Geographics (https://www.terracolor.net/) and has a resolution of 15 m/px.

EROSION OF TESSERAE

The arcuate map patterns we report within tessera are consistent with gently dipping or near-horizontal layers. Yet, even with horizontal shortening sufficient to produce folds with amplitudes as great as 500 m (as for the example in Fig. 1), some erosion is required to expose the constituent strata of layered tesserae and so account for outcrop patterns that follow local topography, as well as generate the eroded periclines postulated above.

The prospect for erosion on Venus at present is equivocal, especially given the apparent dearth of eolian deposits on the planet (Craddock, 2011). Nonetheless, some transport of fine material by wind takes place on Venus. For instance, sand-sized particles were seen to be removed from the NASA *Venera 13* lander over approximately one hour, with wind the most likely cause of movement (Selivanov et al., 1985). Even a very low wind erosion rate—for instance, 10^{-6} m yr^{-1}, comparable to the sedimentation rate on the North Atlantic abyssal plain (Carvalho et al., 2011)—will remove 700–800 m of material over the average model age of the planet's surface (McKinnon et al., 1997). Given that tesserae tend to be the stratigraphically oldest units where they are observed, they are likely to have been subjected to eolian erosive action for the greatest amount of time of any portion of the currently exposed surface of Venus.

Erosion of tessera therefore provides a means by which layered units may be exposed within this terrain type. Erosion also accounts for the radar-dark materials (e.g., those marked by blue arrows in Figs. 1A, 2C, 2E, and 3A) that fill local lows in tesserae and have commonly been interpreted as volcanic (e.g., Ivanov, 2001). Some of these materials might instead be sediments, sourced from tessera rocks, that are fine grained at the *Magellan* radar wavelength (12.6 cm) and thus have low backscatter. If so, these radar-dark units may more closely resemble the blocky, stratified outcrops observed at the *Venera 13* and *14* landing sites (Basilevsky et al., 1985).

CONCLUSIONS AND OUTLOOK

There is morphological evidence for layers within numerous tessera units on Venus. The nature and attitude of these strata remain unclear. Layered units are not readily compatible with interpretations of tesserae as exposures of intrusive igneous rock, such as granitoids or anorthosites, given the vast (>1000 km) spatial extent of the tesserae in which layering is seen. In contrast, the largest layered igneous intrusion on Earth, the Bushveld Complex in South Africa (comprising both mafic and felsic lithologies), is <300 km in its longest dimension. If flood basalts, then the layered rocks in Alpha Regio may have lower 1 μm emissivity values than the surrounding basaltic plains because of differences in grain size or weathering, especially if tessera rocks were chemically altered under a different climate regime from today (Gilmore et al., 2015).

In summary, layered tesserae might be flood lavas or sedimentary sequences; they may be

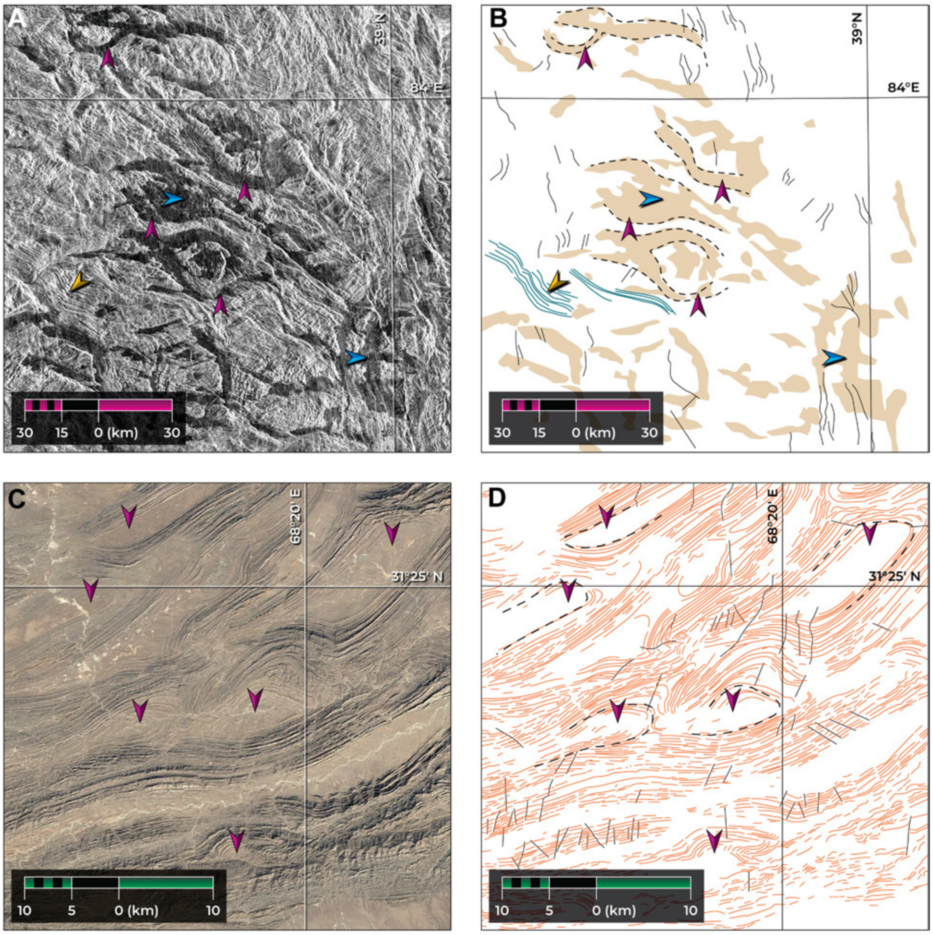

Figure 3. (A) NASA *Magellan* global radar data showing examples of features we interpret as eroded periclinal folds (purple arrows) in Tellus Tessera, Venus; arcuate lines (gold arrow) and radar-dark deposits (blue arrows) are also shown. (B) Sketch map of scene in A; dashed black lines delimit exemplar periclinal folds. (C) *Landsat 8*/*Copernicus Sentinel-2* (European Space Agency) satellite image data of the region within the Sulaiman Mountains in western Pakistan, where sequences of Mesozoic-to-younger sediments are shortened and periclinal folds (purple arrows) abound. (D) Sketch map of scene in C, where prominent, exposed strata and minor fractures are mapped as orange and thin black lines, respectively; several periclinal folds are outlined by dashed black lines. Image in A is in azimuthal equidistant projection, centered at 38.5°N, 83.0°E; image in C is in orthographic projection, centered at 31.4°N, 68.4°E. Radar look direction in A is from the right, and solar illumination in C is from the southeast. Satellite imagery in C was provided by Maxar Technologies/CNES/Airbus and has a resolution of 30 m/px.

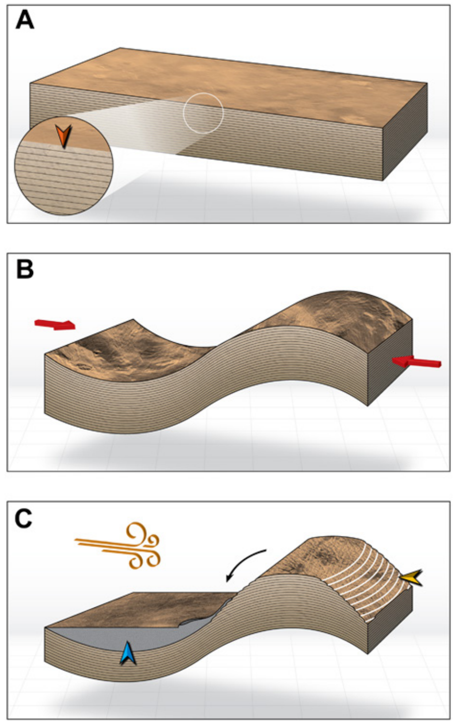

Figure 4. Schematic illustration of how a combination of folding and erosion leads to the outcrop patterns we report. (A) A set of horizontal layers (orange arrow) is emplaced. (B) These layers are folded in response to regional horizontal compression (red arrows), forming troughs and ridges. (C) Eolian action erodes these local highs, exposing constituent layers (gold arrow) and depositing sediments in subjacent lows (blue arrow).

horizontal or gently folded; they may have formed after Venus experienced a runaway atmospheric greenhouse (Ingersoll, 1969), or they may date from an earlier, more temperate climate (Way and Del Genio, 2020). However, the presence and map patterns of layering denote a complex formational history for these enigmatic units that includes volcanic and/or sedimentary deposition, at least one phase of folding, and exhumation by some erosive action (Fig. 4). These geological characteristics must be considered when formulating interpretations for tessera formation.

Importantly, tesserae are distinguished in geological maps on the basis of morphology, but there is no requirement that this terrain type has the same lithology at all locations, or that is the product of a single formational or deformational history (cf. Hansen and Willis, 1996). It is also not clear how many large tessera exposures show evidence for low 1 µm emissivity and an inferred low ferrous iron content. A fuller understanding of the nature of these units must await high-resolution radar and multispectral imaging, as well as in situ chemical analyses, by future orbiter and lander missions.

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