

**SOME VENUS TESSERAE FEATURE LAYERED, FOLDED, AND ERODED ROCKS.** Paul K. Byrne<sup>1</sup>, Richard C. Ghail<sup>2</sup>, Martha S. Gilmore<sup>3</sup>, A. M. Celâl Şengör<sup>4</sup>, Christian Klimczak<sup>5</sup>, Sean C. Solomon<sup>6</sup>, David A. Senske<sup>7</sup>, Jennifer L. Whitten<sup>8</sup>, Sara Khawja<sup>9</sup>, and Richard E. Ernst<sup>9,10</sup>, <sup>1</sup>Planetary Research Group, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA ([paul.byrne@ncsu.edu](mailto:paul.byrne@ncsu.edu)); <sup>2</sup>Royal Holloway, University of London, Egham, TW20 0EX, UK; <sup>3</sup>Wesleyan University, Middletown, CT 06459, USA; <sup>4</sup>Istanbul Technical University, 34469 Ayazaga, İstanbul, Turkey; <sup>5</sup>University of Georgia, Athens, GA 30602, USA; <sup>6</sup>Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA; <sup>7</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA; <sup>8</sup>Tulane University, New Orleans, LA 70118, USA; <sup>9</sup>Carleton University, Ottawa, ON K1S 5B6, Canada; <sup>10</sup>Tomsk State University, Tomsk, 634050, Russia.

**Introduction:** Tessera units occupy ~7% of the surface of Venus [1] and are characterized by pervasive tectonic deformation. Numerous sets of lineaments, interpreted as mixes of extensional and shortening structures, record complex strain histories for individual tessera exposures [e.g., 2–4]. On the basis of gravity anomaly, morphology, and inferred composition, it has been proposed that tesserae are the Venus counterparts to continents on Earth [5–7]; indeed, surface emissivity data from the ESA Venus Express mission provide supporting evidence that the Alpha Regio tessera is more felsic than adjacent basaltic plains [8]. A better understanding of Venus' tessera units is therefore key to determining if, for example, these units formed in the presence of abundant volumes of water [9].

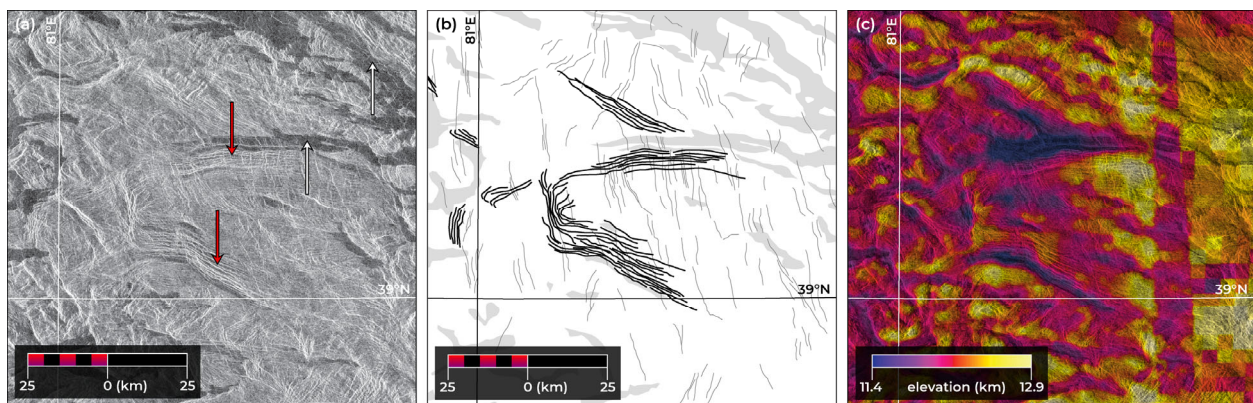
**Interior Layering:** In numerous tessera units, e.g., Tellus Tessera, in addition to the recognized extensional and shortening structures, a set of (often highly) curved, parallel lineaments is seen in radar images [10,11] (red arrows in Figure 1a). These structures strongly resemble strata in layered sequences on Earth that have an arcuate or sinuous outcrop pattern having been exposed by erosion on the flanks of ridges or valleys.

The irregular, curvilinear patterns of these lineaments in tesserae may thus be indicative of layers that follow undulating ridge-and-trough topography with length scales of tens of kilometers (Figure 1b). These candidate strata are ~100–200 m thick, although

fainter lineaments that parallel the more prominent examples suggest some thinner layers, perhaps <10 m thick, as well. In addition to the lineaments within Tellus Tessera [10,11], we have identified this outcrop pattern in Manatum Tessera (e.g., at 8°S, 67°E), as well as in Alpha, Ovda, and Thetis Regiones (with exemplar outcrops at 26°S, 1°E; 3°S, 86°E; and 11°S, 130°E, respectively). Curving lineaments within tesserae are thus widespread across Venus, rather than being confined to a single exposure of this terrain type.

The nature of these strata is unclear, although by analogy with Earth they could be stacked lava flows (i.e., trap terrain) [8,11] or sedimentary units. The map patterns in Tellus Tessera, for example, are consistent with gently dipping or near-horizontal layers. Yet, for such layers to be visible, some volume of material must have been removed: the difference in relief between the troughs and ridges in Figure 1c is ~1 km, requiring erosion even if these troughs originally formed by tectonic processes (e.g., crustal extension).

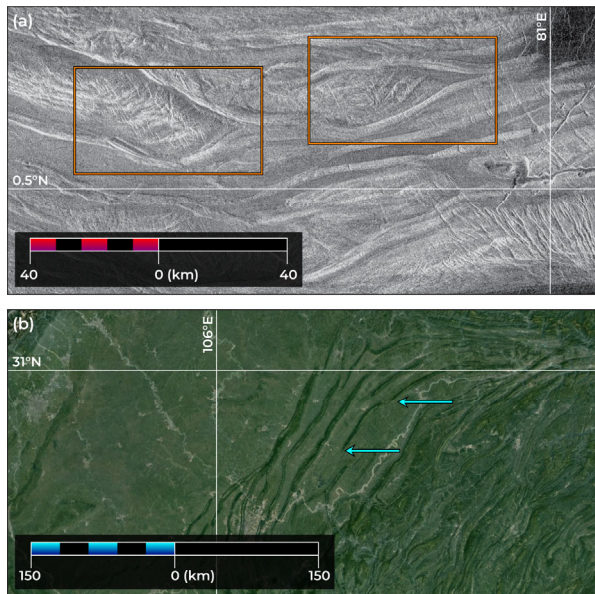
**Folding of Tesserae:** Folding offers an alternative explanation for the map patterns we report. Both short- and long-wavelength folds have been widely observed in tessera [7,12–14]. Horizontal shortening of tessera units (or the precursor rocks) yields periodic fold trains of antiforms and synforms, possibly featuring flexural slip along the interfaces of the interior layers. Under this scenario, then, the exposed strata dip away from ridges



**Figure 1:** (a) Examples of arcuate structures in Tellus Tessera (marked by red arrows); intra-tessera radar-dark material marked with white arrows. (b) Sketch map of these arcuate structures (black lines), which tend to differ substantially in strike from lineaments that appear to be extensional fractures (grey lines). Radar-dark material is shown as grey fill. (c) Topographic data [17] show how the arcuate lineaments follow local topography. All images are in orthographic projection, centered at 39.3°N, 81.5°E; the radar look direction is from the left.

and towards the troughs—although neither Magellan altimetric [15] nor stereo-derived [16] topography is of sufficient resolution to test this inference.

Nonetheless, folding accounts for distinctive lenticular features within tesserae; the examples in **Figure 2a** (orange boxes) morphologically resemble periclinal folds, i.e., with double-plunging fold axes. Periclinal folds abound in shortening systems on Earth, e.g., in the Zagros Mountains [17] and in southern China [18] (cyan arrows in **Figure 2b**), so it is not surprising that they be present on Venus. The “circular troughs” discussed by Cofrade et al. [14] may also be periclinal folds. Further, polyphase deformation can readily generate complex fold interference patterns [19] and has been invoked for instance to account for the “basin-and-dome” topography at the center of Alpha Regio [20]. However many phases of deformation have shaped the tesserae, we find that these folds represent shortening strains of  $\sim 0.1\%$  (consistent with earlier work, e.g., [4]).



**Figure 2: (a)** A set of lenticular landforms along the northern margin of Ovda Regio that we interpret as periclinal folds. The image is in orthographic projection, centered at  $0.5^\circ\text{N}$ ,  $80.5^\circ\text{E}$ ; Radar look direction is from the left. **(b)** Periclinal folds in southeast Sichuan basin, China (arrows mark two examples). Image is in orthographic projection, centered at  $30^\circ\text{N}$ ,  $107^\circ\text{E}$ .

**Erosion of Tesserae:** Even with horizontal shortening sufficient to produce folds with amplitudes as great as 1 km, some erosion is required to expose the constituent strata of layered tesserae. The prospect for erosion on Venus is unclear: although the atmosphere is well capable of transporting sediment [21], few definitive aeolian landforms and deposits have been recognized with Magellan data [22]. Yet some mobility of fines via wind takes place on Venus: sand-sized particles were seen to be removed from the Venera 13 landing ring over about an hour [23]. And even a very

low erosion rate—say,  $0.001\text{ mm yr}^{-1}$ , comparable to the rate of sedimentation within the North Atlantic abyssal plain [24]—will remove 700–800 m of material over the average model age for the planet surface [25].

Invoking erosion of tessera (whatever the rate) therefore allows for the exposure of lithostratigraphic units within this terrain type. Erosion also provides another explanation for the radar-dark materials (white arrows in **Figure 1a**) that fill local lows in tesserae and are commonly interpreted as volcanic [e.g., 26]: at least some of these materials might instead be sediments that are fine-grained at radar wavelengths, resembling the layered strata at the Venera 13 and 14 landing sites [27].

**Conclusions and Outlook:** There is morphological evidence for the presence of layers within numerous tessera units. The nature and attitude of these strata remain unclear: they might be lava traps or sedimentary formations; they may be sub-horizontal or folded; perhaps they formed after Venus entered a runaway greenhouse effect [28], or date from before that time. But given their widespread occurrence, the preservation of interior strata could characterize this terrain type in general. If so, the presence and map patterns of such layering denotes a complex formational history for Venus’ enigmatic tesserae of volcanic and/or sedimentary deposition, at least one phase of folding, and exhumation by some erosive agent.

**References:** [1] Ivanov M. A. and Head J. W. (2011) *Planet. Space Sci.*, 59, 1559–1600. [2] Barsukov V. L. et al. (1986) *JGR*, 91, D378–D398. [3] Basilevsky A. T. et al. (1986) *JGR*, 91, D399–D411. [4] Ghent R. R. and Hansen V. L. (1999) *Icarus*, 139, 116–136. [5] Hashimoto G. L. and Sugita S. (2003) *JGR*, 108(E9), 5109. [6] Hashimoto G. L. et al. (2008) *JGR*, 113, E00B24. [7] Romeo I. and Capote R. (2011) *Planet. Space Sci.*, 59, 1428–1445. [8] Gilmore M. S. et al. (2015) *Icarus*, 254, 350–361. [9] VEXAG Goals, Objectives, and Investigations (2019) NASA. [10] Senske D. A. and Plaut J. J. (2000) *Lunar Planet. Sci.*, 31, abstract 1496. [11] Senske D. A. and Plaut J. J. (2009) *Lunar Planet. Sci.*, 40, abstract 1707. [12] Banks B. K. and Hansen V. L. (2000) *JGR*, 105, 17,655–17,667. [13] Ghent R. and Hansen V. L. (2005) *Icarus*, 139, 116–136. [14] Cofrade G. et al. (2019) *Planet. Space Sci.*, 178, 104706. [15] Ford P. G. and Pettengill G. H. (1992) *JGR*, 97, 13,103–13,114. [16] Herrick R. R. et al. (2012) *Eos*, 93, 125–126. [17] Molinaro M. et al. (2005) *Tectonics*, 24, TC3007. [18] Li J. et al. (2016) *JGR*, 121, 3048–3080. [19] Ramsey J. G. (1967) *Folding and Fracturing of Rocks*. McGraw-Hill, New York. [20] Hansen V. L. and Willis J. J. (1996) *Icarus*, 123, 296–312. [21] Greeley R. et al. (1984) *Icarus*, 57, 112–124. [22] Craddock R. A. (2011) *Prog. Phys. Geog.*, 36, 110–124. [23] Selivanov A. S. et al. (1982) *Sov. Astron. Lett.*, 8, 235–236. [24] Carvalho F. P. et al. (2011) *ICE J. Mar. Sci.*, 68, 427–435. [25] McKinnon W. B. et al. (1997) in *Venus II* (Bougher S. W. et al., eds.), Univ. Ariz. Press, pp. 969–1014. [26] Hansen V. L. et al. (1999) *Geology*, 27, 1071–1074. [27] Basilevsky A. T. et al. (1985) *GSA Bull.*, 96, 137–144. [28] Ingersoll A. P. (1969) *J. Atmos. Sci.*, 26, 1191–1198.