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GEOLOGY AND STRUCTURE OF BETA REGIO, VENUS: RESULTS FROM ARECIBO RADAR IMAGING

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Abstract. Arecibo radar images of a portion of the equatorial region of Venus provide the first high resolution (1.5- to 2.0-km) synoptic coverage of Beta Regio. Within this area, tessera, a complex deformed terrain, is identified as a major geologic unit with the largest region corresponding to a plateau on the east flank of the highland. Three models are proposed to explain the origin and evolution of Beta Regio and are identified as *Mantle Plume/Passive Crust*, *Mantle Plume/Active Crust*, and *Mantle Plume/Crustal Spreading*. The Mantle Plume/Passive Crust model appears to be the most consistent with the geology in this region and suggests that a plume disrupts a preexisting region of tessera.

Introduction

Studies of the geology of highlands on Venus have shown that the equatorial region and northern high latitudes are characterized by different tectonic styles. Northern high latitude highlands (e.g. Ishtar Terra) contain broad zones interpreted to be associated with the lateral movement of crust, convergence, and processes forming orogenic belts [Crumpler, et al., 1986; Vorder Bruegge and Head 1989; Vorder Bruegge et al., 1990; Head, 1990a] while the equatorial region typically consists of long interconnecting linear zones of extension, possible crustal divergence, and spreading [Schaber, 1982; Campbell et al., 1984; Head and Crumpler, 1987; Senske, 1990]. In order to understand better differences between highlands on different parts of the planet, we use Earth-based Arecibo radar images to map the geology of Beta Regio and to propose a range of models to account for its geology and topography.

Recent studies of Beta Regio have concentrated on the analysis of the volcanic and tectonic history of the rift valley Devana Chasma and propose that the high topography and rifting are associated with either a simple hot spot [McGill et al., 1981; Esposito et al., 1982] or a hotspot and lithospheric extension [Stofan et al., 1989]. Radar images obtained from the Arecibo Observatory provide new details of areas previously identified and offer a basis for the first high resolution (1.5- to 2.0-km) [Campbell et al., 1989] regional overview of the geology of Beta (Figure 1a).

In order to understand better the processes acting to form and modify Beta, an analysis of the image data has been carried out so as to 1) determine the regional geologic character of Beta Regio, 2) examine the relation between volcanism and tectonism for this part of the planet, and 3) assess the significance of the east flanking upland plateau [Senske, 1990] to the formation of this highland. On the basis of mapping, a range of models to explain the structure and geology of Beta Regio are proposed and assessed.

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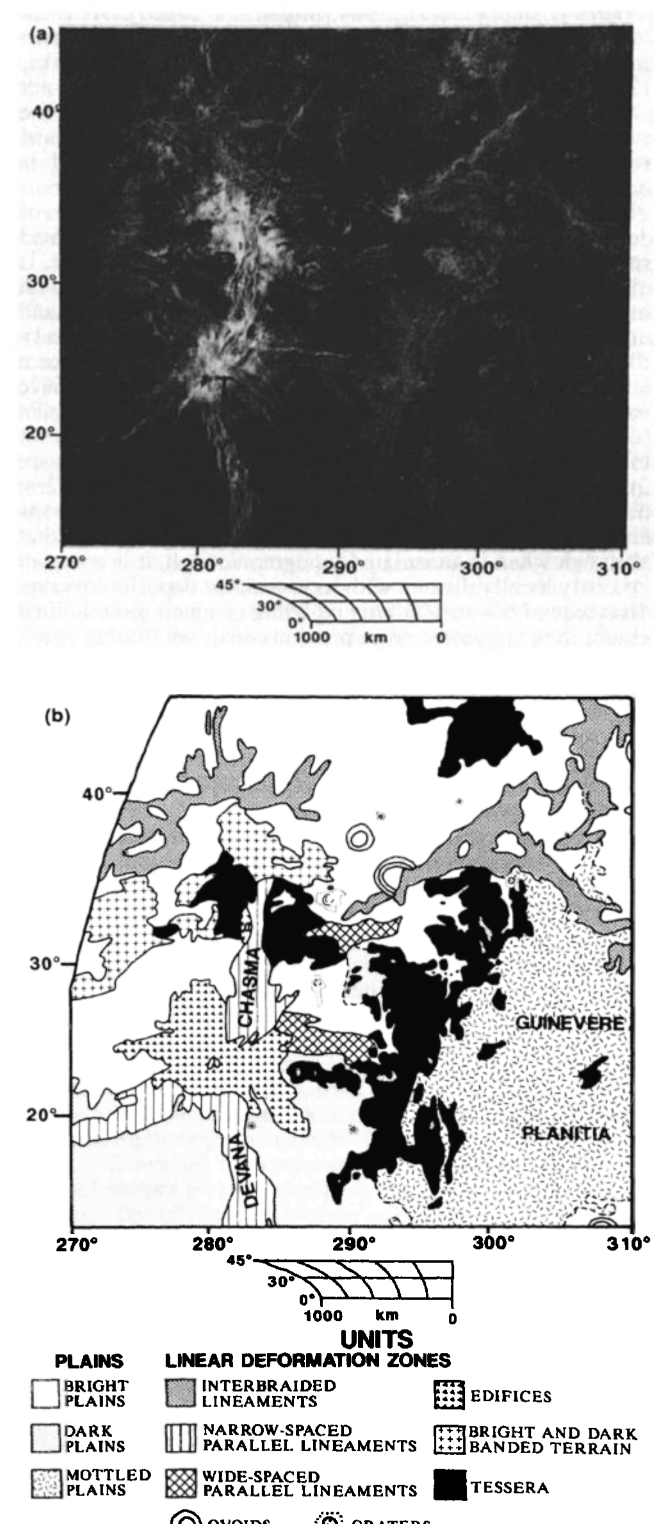

Fig. 1. a) Arecibo image of Beta Regio. Theia and Rhea Montes are labelled "T" and "R". b) Geologic units mapped on Beta Regio. The units are described in the text.

Geologic Characteristics of Beta Regio

Beta Regio is a polygonal region 2300 km x 2000 km rising to an elevation of 4.0 km above the surrounding plains. Located on its crest is the 1.0 km deep rift valley Devana Chasma on which are located the volcanoes Theia and Rhea Montes [Campbell et al., 1984; Stofan et al., 1989]. At Theia Mons the rift forms a tectonic junction, splitting into two arms, one extending to the south and the other SW [Senske, 1990] (Figure 1). A second region of high topography, not previously imaged at high resolution and located on the eastern flank of Beta is made up of interconnecting ridges and valleys with multiple directions of deformation and is interpreted to be tessera-like [Bindschadler et al., 1990].

Ten geologic units have been mapped on the basis of degree of radar brightness, texture, and presence of associated structures (Figure 1b). The most abundant unit, *plains*, is divided into bright, dark, and mottled plains (i.e. areas with uniformly high and low radar backscatter cross sections and ones with variable backscatter over relatively short distances). Plains on Beta range from bright to dark and have a uniform texture. In contrast, mottled plains in Guinevere Planitia have variable textures and contain cones, domes, and flow units [Campbell, et al., 1989]. On the basis of the presence of lobate flows and embayment relations, all the plains units are interpreted to be volcanic in origin. Theia and Rhea Montes, mapped as *edifices*, are flanked by radar-bright deposits arrayed around each peak. The new images show that although Rhea is an isolated topographic high, it is complex and only locally distinct with its associated deposits covering distances of 50- to 100-km and being of much more limited extent than suggested from previous analyses [Stofan et al., 1989]. Bright material surrounding the peak is tessera-like [Ford and Senske, 1990], suggesting that Rhea and its deposits have been heavily modified by tectonism. Deposits associated with Theia Mons are asymmetric, extend for distances of 550- to 700-km to the NW and SE and form a butterfly pattern [Campbell, et al., 1989] (Figure 1b). This relation suggests that within the zone where Devana Chasma intersects the volcano, faulting and the deposition of volcanics probably occurred nearly contemporaneously, with the flows disrupted by faulting along a NE/SW direction and those on the NW/SE flanks preferentially flowing down the raised flanks of the rift. The summit of Theia is cut in a nearly north-south direction by scarps indicating that, like Rhea, Theia has been split by faulting [Campbell et al., 1989], and that at least limited lithospheric extension has occurred. *Linear deformation zones*, belts of radar-bright lineaments, are divided into three classes: 1) *Narrow-spaced parallel lineaments* which include Devana Chasma and are interpreted to be scarps associated with rifting and normal faulting [Campbell, et al., 1984]; 2)*Wide-spaced parallel lineament zones*, regions of lineaments observed for the first time, located within topographic depressions on the eastern flank of Beta striking perpendicular to Devana Chasma; and 3) *Interbraided lineament zones*, located along the northern edge of Beta, made up of anastomosing bright lineaments. A belt intersecting the NE edge of Beta is locally elevated (~0.5 km) with one segment trending NNE and another NNW. The set of lineaments is generally oriented 45° to the orthogonal trends of the Devana/wide-spaced lineament zones. *Ovoids*, 200- to 250-km diameter ring to arcuate structures are generally composed of two radar-bright concentric rings. Two ovoids NE of Rhea Mons are similar to coronae, but due to the inability to clearly identify an annulus of concentric ridges they have not been mapped as coronae. On the basis of their morphologic similarity to coronae, ovoids are interpreted to have formed in association with regions of mantle upwelling.

Three regions of *tessera* are identified in the vicinity of Beta (Figure 1b). The northernmost, mapped from Venera 15/16 images, is centered near 44° N, 300° [Barsukov et al, 1986], contains ridges with a general NE orientation and topographic relief of less than 500 m. Embayment relations suggest that it predates the surrounding plains. The new data reveal that the most extensive region of tessera corresponds with the east flanking topographic rise which is separated into northern (1.5 km high) and southern regions (2.5 km high) by a 500 m deep NW/SE trending valley (Figure 2a). Its eastern edge forms a steep slope which is embayed by mottled plains while the western edge is embayed by bright plains. Lineaments in the southern part of the tessera are generally north-south and parallel to Devana Chasma and its internal structure (Figure 2b), while those in the northern region are more chaotic. Small outliers of tessera are located within the valley, interpreted as a zone of disruption, separating the two larger regions of tessera. Both the tessera (outliers and large blocks) and the valley are flooded by plains material. Although there is no indication of faulting within the zone of disruption, it is suggested that this was an early event and has been subsequently covered by plains. Where the southern wide-spaced parallel lineament zone intersects the tessera a number of lineaments extend into it forming a cross-cutting relation (Figure 2b), suggesting that some of the lineaments may be faults which postdate the tessera. On the basis of its elevation and its interpreted tectonic origin, we suggest that this flanking high represents an area of thick crust as has been suggested for other regions of tessera [Smrekar and Phillips, 1990; Head, 1990b]. Stratigraphic relations indicate that the tessera predates episodes of plains flooding and faulting. The third region of tessera occurs near Rhea Mons, flanking Devana Chasma, and is similar to trough and ridge tessera [Bindschadler and Head, 1991]. Ridges within the unit on the western flank of the rift are oriented in a NE direction while those on the eastern flank are oriented in a north-south direction. A second, less abundant, set of dark lineaments orthogonal to Devana Chasma are also present. North/south trending faults associated with rifting at Devana cut across the tessera indicating that the tessera predates rift formation.

A unit identified as *bright and dark banded terrain*, located adjacent to the tessera flanking Devana Chasma, is made up of alternating NW trending 10- to 20-km wide radar-bright and radar-dark bands and forms a gradational boundary with tessera. This unit, tessera, and plains lying to the north of Rhea Mons are all crosscut by scarps associated with Devana Chasma. Embayment relations indicate that it predates plains flooding. On the basis of these relations we conclude that the tessera and banded terrain are the oldest units and that the

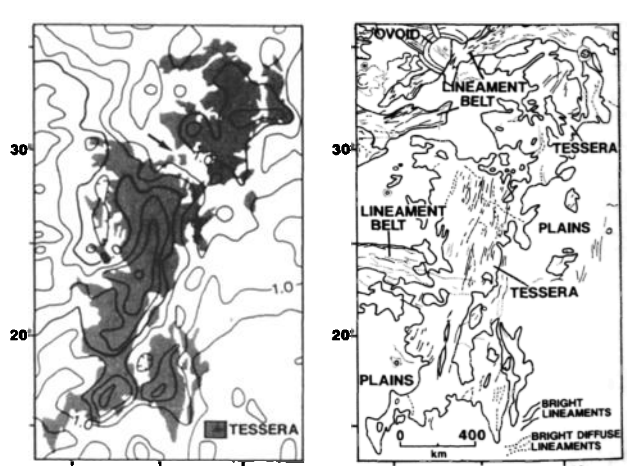

Fig. 2. a) Pioneer Venus topography superposed on east flanking unit of tessera. The arrow indicates the location of a valley separating the tessera into two regions. b) Geologic units and lineaments associated with the tessera.

cross-cutting scarps indicate that faulting and rifting are the youngest events within this region.

Models

Models proposed to explain the formation and evolution of Beta Regio must account for the following observations and characteristics: 1) broad domal rise (~2000 km in diameter); 2) large positive gravity anomaly [apparent depth of compensation (ADC) of 330 km [Esposito, et al., 1982]]; 3) central rift zone; 4) volcanoes associated with the rifting; 5) distributed plains volcanism; 6) tectonic junction; 7) polygonal outline of topography; 8) relatively steep bounding slopes of the plateau; 9) occurrence of tessera and its positive correlation with topography; 10) wide-spaced parallel lineament zones oriented normal to Devana Chasma and the tessera fabric; 11) interbraided lineament zones; and 12) variation in orientation of the tectonic fabric from northern to southern parts of Beta.

Three models are proposed and evaluated for the origin and evolution of Beta, all involve a mantle plume to account for the very great ADC and widespread volcanism. The first model, *Mantle Plume/Passive Crust* (Figure 3a), suggests that a mantle plume disrupts preexisting structure producing rifting and volcanism. Analyses from Pioneer Venus image data suggest that material to the west of Beta, in the area not imaged with the Arecibo system, is tessera-like [Senske, 1990]. In the initial step, we suggest the presence of a region of tessera, interpreted as a thick crust [Smrekar and Phillips, 1990; Head, 1990b] extending from the west at Asteria Regio to present eastern Beta as the passive site of a mantle plume. This stage may have similarities to Alpha Regio, an isolated region of tessera surrounded by plains [Campbell et al., 1991]. Updoming and volcanism begin to disrupt the structure; plains volcanism covers part of the tessera along with building edifices. Tesserae located adjacent to Devana Chasma are interpreted as high standing remnants. Finally, the tessera is split into western and eastern regions due to limited extension associated with the formation of Devana Chasma. The polygonal nature of topography is related to deformation of the preexisting structure and the surface geology and structure are largely unrelated to the plume. This model accounts for the relative age of units, polygonal outline of topography, and volcanism forming plains and edifices, but does not provide a mechanism for the initial formation of the tessera. It does not explicitly explain why the fabric within the east flanking region of tessera is parallel to Devana Chasma, but it may be related to deformation and rift formation along a preexisting zone of weakness.

In the second model, *Mantle Plume/Active Crust* (Figure 3b), an upwelling plume causes uplift and underplating to account for the high topography and results in volcanism producing the edifices and plains on the topographic high. The tessera fabric is caused by gravity sliding or is related to mantle flow and is not necessarily associated with large crustal thickness variations. Like the previous model, rifting is localized to Devana and extension is limited. This model predicts that the topography for a simple plume should be relatively symmetric. The polygonal outline of the rise would suggest that this is not just simple updoming. Deformation along the periphery of the east flanking tessera may result from gravity sliding; however, this mechanism cannot fully explain its high standing plateau morphology.

The third model, *Mantle Plume/Crustal Spreading* (Figure 3c), suggests that Beta is initially a site of crustal spreading. Elevation of upper mantle temperature by the superposition of a hotspot on the spreading axis enhances crustal thickness in a manner similar to that proposed for Aphrodite by Sotin et al. [1989]. The flanking tessera represent analogs to abyssal hills and their elevation is related to regions of thicker crust; the orthogonal lineaments represent fracture zone-like structures. The parallelism between the fabric in the tessera and Devana Chasma can be explained by the tessera having once resided at the spreading axis and subsequently moved laterally. The extrusion of lava forming plains have covered the area between the tessera and Devana. Assuming that spreading is symmetric about Devana, then this model predicts that a region of tessera similar to that on the eastern flank should be present on the western flank of Beta. Although part of this area has tessera-like properties, there is presently no evidence for a north-south fabric similar to that on the eastern flank. This area is near the edge of Arecibo image coverage; additional imaging is required in order to clearly define trends in its structure. The topography is not symmetric about Devana, although this is not required for a spreading model since asymmetric spreading and crustal formation has been suggested to occur at terrestrial spreading centers [Rohr et al., 1988]. The image data show no evidence for lateral offset of the east flanking tessera along the wide-spaced parallel lineament zone (several of the lineaments cut nearly all the way across the tessera). This may not be expected if both segments of the rift are spreading at the same rate. At Devana Chasma there is local evidence of features split by rifting (Rhea and Theia Montes). The absence of large-scale split and separated features (separated by distances of 100's to 1000's of km) suggests that extension is restricted to the 60- to 200-km wide zone of the rift.

All three models can account for the variety of features identified on Beta Regio. The mantle plume/crustal spreading model requires assumptions regarding the style of spreading before it can fit the observed geology and topography of this region. The mantle plume/active crust model provides a mechanism to explain the range of volcanic features observed on Beta, but does not adequately explain the plateau structure of the east flanking region of tessera. The simplest model which makes the fewest assumptions to explain the geology and structure of Beta Regio is the mantle plume/passive crust model, although it does not offer a mechanism for the initial formation of the tessera.

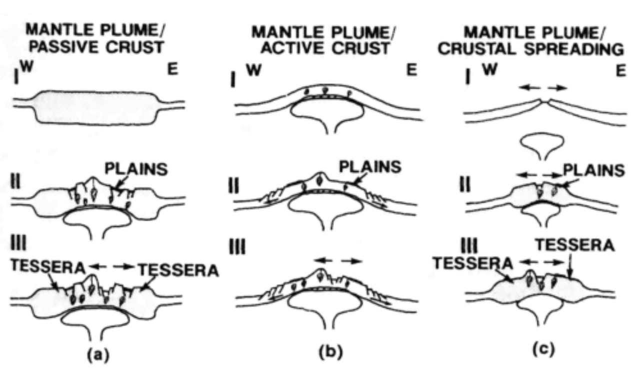

Fig. 3. Models of formation for Beta along East-West cross-sections. a) A region of preexisting tessera is the site of a mantle plume, is disrupted, and split into eastern and western blocks. b) A plume causes uplift and underplating; tessera fabric is the result of gravity sliding or flow in the mantle. c) The region is initially characterized by spreading, elevation of upper mantle temperature by superposition of plume on the spreading center, enhances crustal thickness. The tessera fabric is analogous to abyssal hills.

Conclusions

Geologic mapping from Arecibo radar imagery has shown that tessera is a major unit within Beta Regio. Tesserae on the eastern flank of the highland are interpreted as regions of thick crust and its plateau morphology suggests that it did not form completely by gravity sliding. Stratigraphic relations between units in this area suggest a geologic history in which: 1) the tessera was split into northern and southern regions along NW trending faults with evidence of faulting subsequently covered by plains flooding; 2) additional plains volcanism has embayed the edges of the tessera; and 3) faulting along the southern wide-spaced lineament zone has crosscut the tessera. On the basis of the lack of lateral offset along these lineaments, their enhanced radar brightness due primarily to roughness, the lack of radar backslopes (bright/dark pairs to suggest ridges), and their location in a trough, these lineaments are interpreted as scarps associated with normal faulting. Crosscutting and embayment relations suggest that tesserae are typically the oldest units on Beta. The nature of topography and the complex interrelation of tectonism and volcanism suggests that the formation of Beta is not just a consequence of simple updoming. We suggest that models of formation for Beta need to take into account both dynamic support of topography along with variations in crustal thickness. On the basis of stratigraphic relations and evidence for only limited extension at Theia and Rhea, we conclude that the mantle plume/passive crust model best accounts for the observed geology in this region. Additional imaging of this highland by the Magellan spacecraft [Saunders et al., 1990] will provide data to: 1) determine the lateral extent of tessera to the west of Devana, 2) examine the characteristics of the linear deformation zones by identifying faults, scarps, and ridges, and 3) assess the relative contributions of tectonic and volcanic units at Rhea Mons and quantify the amount of extension that has occurred.

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References

Barsukov, V. L., et al., The Geology and Geomorphology of the Venus Surface as revealed by the Radar Images Obtained by Veneras 15 and 16, *J. Geophys. Res.*, 91, D378-D398, 1986.

Bindschadler, D. L., M. A. Kreslavsky, M. A. Ivanov, J. W. Head, A. T. Basilevsky, and Yu. G. Shkuratov, Distribution of Tessera Terrain on Venus: Prediction for Magellan, *Geophys. Res. Lett.*, 17, 171-174, 1990.

Bindschadler, D. L. and J. W. Head, Tessera Terrain, Venus: Characterization and Models for Origin and Evolution, *J. Geophys. Res.*, in press, 1991.

Campbell, D. B., J. W. Head, J. K. Harmon, and A. A. Hine, Venus Volcanism and Rift Formation in Beta Regio, *Science*, 226, 167-170, 1984.

Campbell, D. B., J. W. Head, A. A. Hine, J. K. Harmon, D. A. Senske, and P. C. Fisher, Styles of Volcanism on Venus: New Arecibo High Resolution Radar Data, *Science*, 246, 373-377, 1989.

Campbell., D. B., D. A. Senske, J. W. Head, A. A. Hine, and P. C. Fisher, Venus Southern Hemisphere: Geologic Character and Age of Terrains in the Themis-Alpha-Lada Region, *Science*, 251, 180-183, 1991.

Crumpler, L. S., J. W. Head, and D. B. Campbell, Orogenic belts on Venus, *Geology*, 14, 1031-1034, 1986.

Esposito, P. B., W. L. Sjogren, N. A. Mottinger, B. G. Bills, and E. Abbott, Venus Gravity: Analysis of Beta Regio, *Icarus*, 51, 448-459, 1982.

Ford, P. G. and D. A. Senske, The Radar Scattering Characteristics of Venus Landforms, *Geophys. Res. Lett.*, 17, 1361-1364, 1990.

Head, J. W., Formation of Mountain Belts on Venus: Evidence for large-scale convergence, underthrusting, and imbrication in Freyja Montes, Ishtar Terra, *Geology*, 18, 99-102, 1990a.

Head, J. W., Processes of Crustal Formation and Evolution on Venus: An Analysis of Topography, Hypsometry, and Crustal Thickness Variations, *Earth, Moon and Planets*, 50/51, 25-55, 1990b.

Head, J. W. and L. S. Crumpler, Evidence for Divergent Plate-Boundary Characteristics and Crustal Spreading on Venus, *Science*, 238, 1380-1385, 1987.

McGill, G. E., S. J. Steenstrup, C. Barton, and P. G. Ford, Continental rifting and the origin of Beta Regio, *Geophys. Res. Lett.*, 8, 737-740, 1981.

Rohr, K. M., B. Milkereit, and C. J. Yorath, Asymmetric deep crustal structure across the Juan de Fuca Ridge, *Geology*, 16, 533-537, 1988.

Saunders, R. S., G. H. Pettengill, R. E. Arvidson, W. L. Sjogren, W. T. K. Johnson, and L. Pieri, The Magellan Venus Radar Mapping Mission, *J. Geophys. Res.*, 95, 8339-8355, 1990.

Schaber, G. G., Venus: Limited Extension and Volcanism Along Zones of Lithospheric Weakness, *Geophys. Res. Lett.*, 9, 499-502, 1982.

Senske, D. A., Geology of the Venus Equatorial Region From Pioneer Venus Radar Imaging, *Earth, Moon, and Planets*, 50/51, 305-327, 1990.

Smrekar, S. E. and R. J. Phillips, Geoid to Topography Ratios for 14 Venusian Features: Implications for Compensation Mechanisms, *LPSC XXI*, 1176-1177, 1990.

Sotin, C., D. A. Senske, J. W. Head, and E. M. Parmentier, Terrestrial spreading centers under Venus conditions: evaluation of a crustal spreading model for Western Aphrodite Terra, *Earth Planet. Sci. Lett.*, 95, 321-333, 1989.

Stofan, E. R., J. W. Head, D. B. Campbell, S. H. Zisk, A. F. Bogomolov, O. N. Rzhiga, A. T. Basilevsky, and N. Armand, Geology of a rift zone on Venus: Beta Regio and Devana Chasma, *GSA Bull.*, 101, 143-156, 1989.

Vorder Bruegge, R. W. and J. W. Head, Fortuna Tessera, Venus: Evidence of Horizontal Convergence and Crustal Thickening, *Geophys. Res. Lett.*, 16, 699-702, 1989.

Vorder Bruegge, R. W., J. W. Head, and D. B. Campbell, Orogeny and Large-Scale Strike-Slip Faulting on Venus: Tectonic Evolution of Maxwell Montes, *J. Geophys. Res.*, 95, 8357-8381 1990.

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