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TECTONICS AND VOLCANISM OF EASTERN APHRODITE TERRA: NO SUBDUCTION, NO SPREADING.

Vicki L. Hansen, Myra Keep, Robert R. Herrick, and Roger J. Phillips, Department of Geological Sciences, Southern Methodist University, Dallas TX 75275, USA.

Introduction: Eastern Aphrodite Terra is approximately equal in size to the western North American Cordillera, from Mexico to Alaska. Its size and unique landforms make it an important area for understanding the tectonics of Venus, yet models for its formation are diametrically opposed. This region is part of the Equatorial Highlands, which was proposed as a region of lithospheric thinning, isostatic uplift, and attendant volcanism [1,2]. Head and Crumpler [3] suggested, on the basis of topographic symmetry and proposed cross-strike lineaments interpreted from Pioneer Venus data, that this area represents a zone of crustal divergence, analogous to terrestrial midocean ridges. Using Magellan SAR data, Suppe and Connors [4] proposed that Eastern Aphrodite Terra forms part of a circumglobal rift zone separating two major venusian plates. In contrast, McKenzie et al. [5] interpreted Eastern Aphrodite Terra as a region dominated by crustal shortening and subduction of venusian crust. They argued that structures resembling trenches display the same curvature and topographic asymmetry as terrestrial subduction zones. Sandwell and Schubert [6] modeled the trench and outer rise topography of the rim of Artemis and Latona coronae as a thin elastic plate subjected to a line load with a bending moment beneath the coronae. They calculated elastic thicknesses and bending moments, and used these values together with a yield strength model to estimate lithospheric temperature gradients. They concluded that the amplitudes of the trench and outer rise are too large to be explained by thermal subsidence alone, and they propose a lithospheric subduction model wherein the lithosphere outboard of the corona perimeter subducts as the corona diameter increases [7]. Thus, Eastern Aphrodite Terra has been interpreted as a region analogous to both a terrestrial midocean ridge extensional plate boundary and a terrestrial subduction plate boundary.

Observations: Structural mapping and kinematic interpretation of Magellan SAR imagery of Eastern Aphrodite Terra provide new evidence for the formation of this region. Eastern Aphrodite Terra comprises a band of predominantly circular structures and east-trending fractures that extends from Artemis corona to Atla Regio. The belt is approximately 1500 km wide and greater than 8000 km long. The circular structures vary in diameter from 100 to 2500 km and they fit the description of coronae as described by many workers and summarized by Stofan et al. [8]. The largest circular structure is Artemis corona, although Artemis does not exhibit many of the features discussed here. The curvature of these features generally varies between 180° and 270°, although 360° is preserved locally, particularly in structures of small diameter. The circular structures commonly display both radial and concentric fractures. A single circular structure may have as many as four nested sets of concentric fractures, each separated by a region marked by little or no deformation. Fractures from one structure commonly overlap with those of adjacent structures. The circular structures are the sites of extensive volcanism. Flows emanate from both the center of the structures and

the concentric fractures. Artemis corona is different from adjacent circular features; it is almost three times the size of the next largest feature and it does not show nested concentric fractures, although it has associated volcanism.

Detailed examination of one of these circular features with center at 14°S, 164°E, herein referred to as 14S/164, reveals that the structure is approximately 600 km in diameter, with at least three sets of concentric fractures stepping outward from the center (e.g., 11.5°S, 164°E). Locally, radial fractures <100 km in length form normal to concentric fractures (e.g., 12.5°S, 166.5°E). Lava flows emanate from the center of the circular structures into channels formed by radial fractures. Extensive lava flows also emanate from each set of concentric fractures and flow outward. The central radial flows are radar-dark whereas the youngest flows from the concentric fractures are radar-bright. Radar-dark flows are interpreted as generally less viscous than radar-bright flows because radar-dark regions appear to flood into preexisting fractures and are influenced by local topography, whereas radar-bright flows form lobate structures and define their own boundaries (e.g., 14.5°S, 168°E). The spatial and temporal relations between radar-bright and radar-dark flows may provide evidence for magma differentiation at depth. Examination of the outermost concentric fracture set reveals that radar-dark flows fill a moat outside this concentric fracture set as evidenced by the sharp truncation of earlier cross fractures. Radar-bright flows, ~30 km wide and greater than 100 km long, flow outward from the concentric fracture set. Flows from each of the concentric fracture sets are cross-cut by the next outward concentric fracture set. Therefore, the concentric fracture sets are interpreted to become younger outward, with the youngest fractures farthest from the center of the circular feature.

Radial fractures within the circular features are readily identifiable where flooded by volcanic material from the center of the structure (e.g., 16.5°S, 162.5°E). The radar look direction, as well as structure orientation, must be considered while mapping individual sets of structures and in interpreting the timing relations between structures. For example, north-trending lineaments, oriented perpendicular to the radar look direction, commonly appear dominant, and therefore they may be interpreted as cross-cutting less visible east-trending lineaments (e.g., 17.5°S, 163°E). In this particular circular structure, central radial fractures cut concentric fractures where the radial set is north trending, and lava flows following east-trending radial fractures are not apparently truncated by circular north-trending concentric fractures. We therefore interpret these lava-filled radial fractures as younger than the inner concentric fractures. The presence of lava flows makes these east-trending troughs visible; without the lava fill the east-trending troughs are difficult to see. The temporal relations, radial fractures younger than adjacent concentric fractures, imply that these radial fractures are relatively deep in order to act as lava conduits. It is possible that the central radial fractures and their attendant volcanic flows completely disguise early formed, inner-concentric fracture sets. The presence of volcanic flows in both the center and associated with the outermost concentric fractures indicates that volcanism played an important role in the formation of 14S/164.

East- to east-northeast-trending fractures overprint 14S/164. These fractures belong to a regional fracture set that trends northeast between Latona and Alta Regio, to the east west of Latona, and to the east-northeast west of Dali and Diana Chasmata. The relationship between 14S/164 and Diana and Dali Chasmata is not clear. The two outermost sets of concentric fractures of 14S/164 trend into parallelism with the trough of Diana Chasma, which is itself parallel to the set of regional east-trending fractures. Radar-bright volcanic

flows emanate and flow northward from east-trending fractures parallel to Diana Chasma. Radar-dark flows flooded the region north of Diana Chasma.

The circular structures comprising Eastern Aphrodite Terra are connected by east-northeast-striking fracture sets that dominantly postdate formation of the circular structures, although locally deformation related to the circular structures cross-cuts the regional fractures. The regional fracture set trends parallel to the radar look direction, and therefore the character of the fractures is difficult to distinguish. However, we interpret the regional fractures as troughlike features on the basis of their sharp boundaries and relatively straight and continuous character (i.e., they are not anastomosing). We further interpret these features as regional extensional fractures similar in nature to fractures of the Guor Linea trough region of Eistla Regio [9].

Formation of these structures is consistent with the model for coronae formation outlined by Squyres et al. [10]; however, we are able to document successive outward stepping of the nested concentric fractures with time. Initial circular uplift of the crust, caused by rising and spreading magma, leads to the formation of radial and concentric fractures. With further uplift the crustal welt grows in diameter and new concentric fracture sets are formed. Once the welt reaches a critical diameter, a moat forms around its perimeter, outward from the oldest concentric fracture set. Lava escapes out of the concentric fractures filling the moat. Within 14S/164 flows emanate from the concentric fracture sets with diameters of ~240, 380, and 510 km. Less viscous radar-dark flows may predate the escape of more viscous radar-bright flows, which can be traced back to individual vents. As the structure continues to expand outward the zone of concentric fractures steps outward and the earlier-formed fracture set and moat are uplifted. A new concentric fracture set and moat form. The newly formed concentric fractures deform earlier-formed volcanic flows, and new flows emanate from these new fractures. This process continues until the structure reaches an average diameter of ~600-800 km. The concentric fracture set may not be equally well developed around the entire 360° arc; in fact, structure 14S/164 is developed around an arc of ~270°. We interpret that the circular structures within Eastern Aphrodite Terra formed in a manner similar to that of 14S/164. This model is similar to a model of corona formation by blistering of the lithosphere as a result of the ascent of a magma diapir to the base of the lithosphere [9,10], although the sequence of deformation and volcanism proposed here is different. Magma diapirs rising passively within a region of crustal extension may be responsible for the circular structures that characterize Eastern Aphrodite Terra [e.g., 11].

Subduction and Spreading: Eastern Aphrodite Terra appears to lack the cross-strike discontinuities proposed from Pioneer Venus data. In addition, it lacks crustal or structural symmetry, which might be predicted for a terrestrial-type rift zone. The area is dominated by circular features as opposed to linear features transected by transform faults. The proposed transform fault [5] that joins Diana and Dali Chasmas is comprised of ridges with no apparent strike-slip or noncoaxial shear component preserved across the belt. In addition, the ridge zone appears to curve into parallelism with east-striking fractures in both Diana and Dali Chasmas; further, the orientation of the ridge belt with respect to the proposed extension troughs (Diana and Dali Chasmata) is kinematically infeasible to be a transform structure.

If Diana and Dali Chasmata are subduction zones as proposed [5], the presence of the radar-bright flows is puzzling as the region north of Diana Chasma should be a subducting lower plate. In addition, a subduction scenario requires a structural distinction

between upper and lower plates. However, radial fractures from the center of Latona can be traced through and across its southern boundary (e.g., 21°S, 167.7°E). The continuity of structures across the trough also argues against the interpretation of this trough as a subduction zone [i.e., 5–7]. Furthermore, terrestrial subduction zones are <180°, and generally <120° along their arc, whereas these circular structures are often preserved up to 270°, and locally up to 360°. Subduction along >180° is kinematically difficult; subduction along 270° is even more difficult. In addition, the diameters of the circular features within this region are much smaller than subduction zones on Earth. Artemis, the largest of the circular structures in this region, is equivalent in size to the Sandwich Islands subduction system [5–7], one of the smallest terrestrial subduction zones. Therefore, we believe that Eastern Aphrodite Terra does not represent a zone of major lithospheric spreading, nor does it represent a region of terrestrial-like subduction. Rather, detailed analysis of SAR imagery indicates that Eastern Aphrodite Terra may be the result of rising magma diapirs that blister the surface within a zone of lithospheric tension.

In conclusion, Eastern Aphrodite Terra is dominated by circular structures within which deformation and volcanism are intimately related. These structures are marked by radial and concentric fractures, and volcanic flows that emanate from a central vent, as well as from concentric fracture sets. Cross-cutting relations between flows and concentric fracture sets indicate that outer concentric fractures sets are younger than inner fractures sets. The circular structures are joined by regional northeast- to east-trending fractures that dominantly postdate formation of the circular structures. We propose that the circular structures "grow" outward with time. Although these structures probably represent addition of crust to the lithosphere, they do not represent significant lithospheric spreading or convergence, and the region does not mark the boundary between two distinct tectonic plates. This region is not easily explained by analogy with either terrestrial midocean rifts or subduction zones. It is perhaps best explained by upwelling of magma diapirs that blister the surface, but do not cause significant lithospheric spreading [1]. Further study of the structural and volcanic evolution of this region using Magellan altimetry and SAR data should lead to better understanding of the tectonic evolution of this region.

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WESTERN APHRODITE TERRA, TECTONICS, GEOLOGY, AND LINE-OF-SIGHT GRAVITY. John E. Hays and Paul Morgan, Department of Geology, Box 6030, Northern Arizona University, Flagstaff AZ 86011–6030, USA.

Aphrodite Terra is the largest area of high-standing topography on Venus, and isostatic considerations strongly suggest that this high topography is supported at least in part by thickened crust [1]. Previous studies of line-of-sight gravity data from the Pioneer Venus orbiter indicate rapidly changing apparent depths of compen-