Structural deformation of northern Ovda Regio, Venus: Implications for venusian tectonics.

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INTRODUCTION

Ovda Regio is an equatorial highland on Venus, extending from roughly 15° south to 10° north latitude, and from 70° to 100° east. It comprises an area of about 3000 by 2000 kilometers, and rises up to four kilometers above the mean planetary radius of about 6051 kilometers [*Kiefer and Hager*, 1991]. Ovda Regio, together with Thetis Regio to the east, forms one of the largest physiographic provinces of Venus; together they define Aphrodite Terra [*Kiefer and Hager*, 1991]. Ovda Regio is primarily composed of tessera terrain. Tessera terrain is characterized by multiple, highly deformed ridges, with depressions cutting these at high angles [*Ivanov and Head*, 1996]. These ridges appear radar bright in Magellan images, implying that they are rough [*Ivanov and Head*, 1996]. For Magellan data, rough implies terrain that is composed of blocks that are on the order of the radar wavelength, i.e. about 12.6 cm [*Ford et al.*, 1993]. Tessera terrain covers only about ten percent of the venusian surface area [*Head et al.*, 1994], and is the oldest observable stratigraphic unit [*Ivanov and Head*, 1996]. The regions of tessera are surrounded by vast volcanic plains, which terminate abruptly against the tessera at some margins, and overlap or embay the tessera in other regions [*Head and Ivanov*, 1993]. The plains are therefore inferred to be younger in age than the tessera [*Head and Ivanov*, 1993]. Some authors believe that the embayed nature of the tessera, along with small outcrops of tessera throughout the plains, implies that they are more expansive beneath the younger volcanic plains [*Head and Ivanov*, 1993]. Several authors think that tessera terrain was formed by compression and shortening of the venusian crust [e.g. *Tormanen*, 1993; *Head*, 1995], while the plains were emplaced relatively quickly, and on a global scale [*Schaber et al.*, 1992; *Strom et al.*, 1994], shortly after the tessera were formed [*Head and Ivanov*, 1993]. The tectonic mechanism necessary to produce both the tessera and plains is still debated.

METHODS

Radar interpretation and mapping. Radar images of Venus, as provided by Magellan, record the surface in terms of relative roughness. Morphological features on Venus can be inferred from the patterns of bright and dark visible within the data, but to develop a geological interpretation depends on an understanding of the radar data.

Without any interpretation, geological structures in radar data appear as a series of lineaments, both dark and bright. Radar data in Magellan appears bright for two primary reasons: either there is an object that reflects most of the energy back to the spacecraft (e.g. the face of a ridge facing the spacecraft), or the surface is rough on about the same scale of the radar wavelength (about 12.6 cm), and this roughness scatters the energy, returning a relatively high amount of energy to the spacecraft [*Ford et al.*, 1993]. Dark patterns are produced when relatively less energy is received back to the radar. With this understanding of the operation of the side-looking synthetic-aperture radar (SAR) on Magellan, the patterns of bright and dark can be correlated to positive and negative features. Positive features, such as ridges, should follow a pattern of bright, and then dark. This first bright lineament is due to the face of the ridge reflecting the radar back, while the radar-dark area is due to the ridge blocking the radar from this area. This pattern is indeed evident within the Magellan data. There are many such areas in which a bright lineament turns sharply to a dark partner, indicative of a ridge crest. The opposite -- a pattern of a dark lineament followed by a bright one -- is characteristic of a depression. The first, dark lineament is dark for the same reason as with positive

Table 1. Caldera diameter, basal altitude, and volcano height for all 15 volcanoes		
Caldera Diameter (km)	Basal altitude* (m)	Volcano height (m)
***a.* 10**	**100**	**100**
20	-500	500
24	-300	2300
***b.* 25**	**-1000**	**200**
25	-500	1100
31	1000	1100
35	0	200
35	100	200
50	-300	300
50	200	0
***c.* 68**	**-700**	**0**
70	400	700
90	-300	0
150	-700	400
150	200	1700

Table 1. Caldera diameter, basal altitude and volcano height for all 15 volcanoes. Also shown are the three mapped volcanoes: a) Shiwanokia Corona (Fig. 1), b) the unnamed volcano (Fig. 2), and c) Hatshepsut Patera (Fig. 3).
*(Basal altitude is given as the distance from the mean planetary radius (MPR) of 6051.8 km; a negative value indicates meters below the MPR.)

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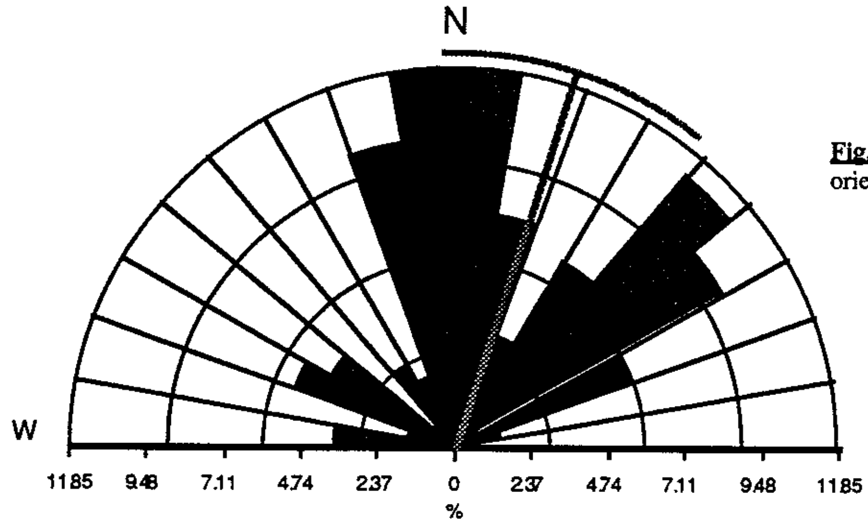

Fig. 1: Rose diagram of ridge orientation, northern Ovda Regio.
N = 135
Vector Mean = 17.8
Class Interval = 10 degrees
Standard Deviation = 3.72

features: it is angled away from the Magellan SAR, and does not reflect radar back. The second half of the pattern is bright because it is angled towards the radar, and hence reflects the energy back. These are also prevalent throughout the Magellan data, in varying scale.

These morphological interpretations have certain geological implications. Ridge systems on Venus are often characterized as compressional features [*Bindschadler et al.*, 1992; *Ivanov and Head*, 1996]. These are most commonly found within the tessera regions of our map area and, to a much lesser extent, within the plains. Surface depressions are manifested in a wider range of morphologies. Some depressions contain a radar-dark area between the dark and bright lineaments, while others have no such division. The radar-dark area is interpreted as a floor, and such features are interpreted to be graben. Those without a floor we interpret to be fractures. Floors may be present in these smaller features, but if they are smaller than the Magellan resolution of seventy-five meters per pixel, they are not detectable. Also present within our map area are features that present a bright lineament similar to those of graben, but lack a matching dark lineament. These are commonly found in association with depressions and ridges, and we describe these as scarps. Some of these are most likely individual lineaments, while in others, it was not possible to confirm if there was a dark lineament to pair to the bright one. In cases where there was doubt as to whether there was a matching dark lineament for a graben-like bright lineament, it was mapped as a scarp rather than a graben or fracture. These criteria were the basis for our structural mapping.

Structural analysis. In order to determine if there is a preferred direction of stress within our mapped structural units, we have prepared rose diagrams of graben and ridge orientations. We have placed graben and ridge orientation within ten degree bins in a half-rose format. Our goal from this analysis was to ascertain whether the deformational history of the area followed specific orientations, as one would expect from directed stress, or if the deformation was randomly orientated, and was not the result of a specific stress field. To further this analysis, we have also determined the relative density of number of ridges per kilometer of tessera/plains boundary. To differentiate between possible stress directions, we have divided the edge of the tessera in our map area into sections, each of which has a general strike. The number of ridges aligned with the strike of a particular section was then divided by the length in kilometers of the section. This unit of ridges/km gives us insight into whether there was a preferred direction of stress creating ridges, or if the number of ridges simply reflects the percentage of tessera/plains boundary with a given orientation.

RESULTS

Sequence of events. We have inferred a sequence of events based upon our map of the region. The first event was the formation of a dense ridge system which constitutes the highland proper. These ridges are generally sub-parallel to the tessera/plains boundary and are not aligned preferentially with a specific azimuth. The development of the volcanic plains to the north follows this event. These plains

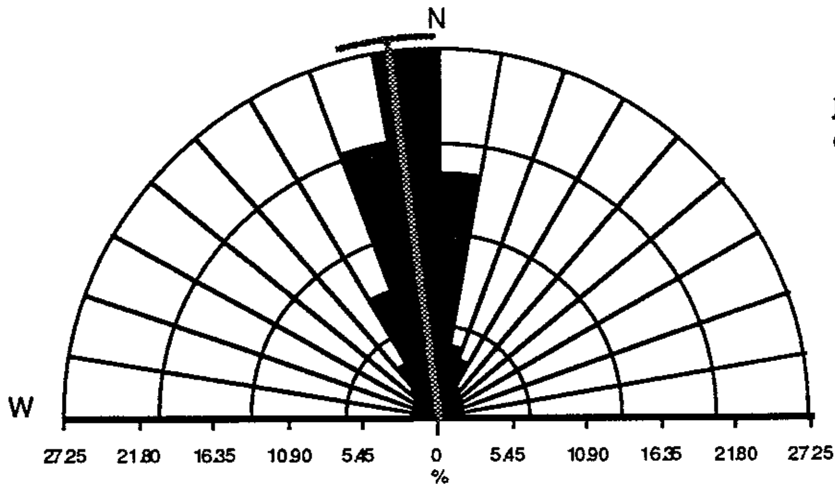

Fig. 2: Rose diagram of graben orientation, northern Ovda Regio.

N = 110

Vector Mean = 352.4

Class Interval = 10 degrees

Standard Deviation = 8.69

extend to and embay the edges of the tessera, dating these plains as a younger unit. Extensional deformation, manifested as fractures and graben, has also occurred in the region. The interaction of the extensional features in the deformational fabric of the region makes the relative age of this deformation unclear. Similar fractures are both embayed by and cut across the volcanic plains, and in addition to this fractures are present that cross-cut other fractures. This seems to indicate the possibilities of one sequence of deformation over a long period of time or several, shorter deformational events.

Structural analysis. Ridge orientation does not fall along a dominant azimuth, and ridges preferentially form sub-parallel to the tessera/plains boundary [Fig. 1]. Likewise, the number of ridges per kilometer of tessera/plains boundary does not indicate a preferred direction of compressive stress for this area. The values for each section are roughly similar and range from 0.102 r/km to 0.146 r/km. The sub-parallel nature of the ridges and the similar values for ridges per kilometer suggests the possibility that the compressive stress responsible for creating the ridges in this region was radially oriented and relatively even in magnitude. In contrast to the ridges in the region, the extensional features we have mapped preferentially form with a N30W-N10E alignment [Fig. 2]. Some of these features cut across the boundary from tessera to plains, and are not restricted to one type of unit. As these features are aligned in a general direction, and have formed in both highland and lowland terrains, it appears that there was an E-W extensional stress operating in the region which created these features.

DISCUSSION

We have considered three different models for the development of northern Ovda Regio. Given our interpretation of the structural history of this region, we can now compare this analysis to the predicted sequence of structure given by each model.

Spreading Center. This model suggests that many features present in Ovda Regio are similar to those found in terrestrial spreading centers. Specifically, these features include fracture zone-like lineaments, plus bilateral topographic and morphologic symmetry on either side of a postulated ridge crest [*Head and Crumpler*, 1987]. This study was corroborated by another in which a strong correlation was found between the bilateral topography cited in [*Head and Crumpler*, 1987] and Pioneer gravity data [*Sotin et al.*, 1989]. The predicted structures of this model, however, are not observed in our study area, and thus we conclude that this mechanism did not operate within our map area.

Hotspot/Mantle Plume. This model theorizes that hot, upwelling mantle creates the high topography and morphology of a plateau-shaped highland [*Kiefer and Hager*, 1991; *Phillips et al.*, 1991]. This sequence of events begins with uplift and radial fracturing, crustal thickening and flood-basalt volcanism, followed by subsidence of the dome and concentric compression due to an end of dynamic support [*Kiefer and Hager*, 1991]. This sequence of structure does not appear in our study area. Many of the components are reflected in the regional geology, but our order of events does not correlate well with this theory.

Mantle Downwelling. A plateau-shaped highland is produced in this model by crustal shortening over a region of mantle downwelling [*Bindschadler et al.*, 1992]. Here, ridges form sub-parallel to the highland boundary due to radial compression, which also causes an overall increase in elevation [*Bindschadler et al.*, 1992]. As this process eventually begins to slow and end, it is also predicted that extension and an overall decrease in elevation will occur as the highland begins to spread under its own weight [*Bindschadler et al.*, 1992]. *Parmentier and Hess* [1992] and *Head et al.* [1994] have proposed a depleted mantle layer overturn mechanism to begin such a downwelling event. The basic operating premise is that an accumulated depleted mantle layer from basaltic volcanism will eventually become negatively buoyant and founder, creating a mantle downwelling site [*Parmentier and Hess*, 1992; *Head et al.*, 1994]. There is good agreement between the structure predicted by this model and what we have observed in northern Ovda Regio. The prediction of sub-parallel ridges as the formative unit of the highland, and the subsequent sequence of structure, all agree with our observations, indicating that this region could have formed during such an event.

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Morphology and possible volcanic origin of sub-kilometer domes in the Arrhenius Region, Mars

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OVERVIEW

Mapping part of an extensive field of sub-kilometer domes in the Arrhenius Region of Mars has revealed characteristics similar to some terrestrial volcanic fields. Important for this recognition is the identification of a veneer of sediments whose erosion by aeolian deflation has exposed the domes. There is compelling evidence to support a fracture control for emplacement of the domes because elongate dome long-diameter orientations are nearly identical to those of fractures and a trough in the region. In a volcanic context the two most plausible models for this dome field are cinder cones and table mountains; the choice is dependent upon identifying the time of dome emplacement relative to deposition of the sediments.

INTRODUCTION

The 36,000 km^2 Arrhenius Region is located in the southern hemisphere of Mars east of Hellas Planitia between 235° and 240° east longitude and 40° to 45° south latitude. Several terrestrial analogs previously have been proposed to explain the origin of the sub-kilometer domes in this region. These include: diatremes (Hodges, 1994), cinder cones (Hodges, 1979; Plescia 1980; Wood, 1979), table mountains (Hodges, 1979), pingos (Judson and Rossenbacher, 1979) and pseudocraters (Hodges, 1979; Allen, 1979; Frey, et al, 1979; Frey and Jarosewich, 1981). The domes likely formed during the Amazonian Era (Hodges and Moore, 1994), which began approximately 1.8 billion years ago. Since then, a variety of processes may have dramatically altered the appearance of this region. For example, extensive aeolian erosion and deposition occurred during the Noachian and Early Hesperian periods in the southern hemisphere (Tanaka and Leonard, 1995).

In this study, we rigorously test the volcanic origin hypothesis by comparing statistical and morphological data from domes in the Arrhenius Region with several terrestrial volcanic dome fields (Tibaldi, 1995). The data utilized in this study were obtained from digital images of Mars acquired by the Viking Orbiter missions. The images have resolutions ranging from 173 meters per pixel to 32 meters per pixel. To make the most accurate measurements we elected to focus our study on two frames, 586B34 and 586B36 (34 and 36, Figures 1a and 1b), comprising an area where a greater concentration of the individual domes is more visible above the surrounding sediments.

METHODS

Frames 34 and 36 were mapped in order to develop an understanding of the regional geomorphology and stratigraphy. Understanding the regional geology is important for constraining the types of factors that might affect interpretation of dome morphology. It is particularly important to determine whether or not the domes are partially buried by surrounding sediments.

In our study area, 649 domes, comprising numerous dome clusters, were identified as either elliptical or circular in shape. For those that appeared circular one diameter was measured. Those that appeared elliptical were