Determining Venusian Lithospheric Thickness using Frequency-Length Statistics of Fractures

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ABSTRACT

Frequency-length statistics were applied to the north-west trending set of irregularly spaced curvilinear radar-bright fractures on Venus’ Guinevere Planitia, located at 30º N latitude between 330º E and 333º E longitudes, to determine the thickness of the elastic lithosphere in this region. These fractures are interpreted as shear fractures in the lithosphere which have propagated up through the surface basalt flow. According to Scholz & Shaw (2002) cracks that penetrate through the entire thickness of a brittle layer have a surface length of twice their height. A log-log plot of the length distribution of this set of shear cracks has a sharp bend at a length of about 80 km. This reflects the transition from 2-dimensional growth of a penny-shaped crack in the lithosphere to the 1-dimensional elongation of a crack which has penetrated the elastic lithosphere. This interpretation implies that the lithosphere is roughly 40 km thick, in agreement with other recent estimates based on flexure and analyses of gravity and topography. This interpretation also implies that the 500 Ma resurfacing event suggested by crater statistics was accompanied by the emplacement of extensive flood basalts in the plains regions, and that the global resurfacing event may have been accomplished by global destruction of an older preexisting lithosphere.

INTRODUCTION

In this study, frequency-length statistics were applied to the Guinevere Planitia to determine the elastic lithospheric thickness of this region. The Guinevere Planitia, located 30º N latitude between 330º E and 333º E longitudes, is comprised of a north-east trending set of radar-faint equally spaced linear fractures and a north-west trending radar-bright curvilinear set of fractures which are irregular in spacing and length (Banerdt & Sammis, 1992). According to Scholz & Shaw (2002) cracks that penetrate through the entire thickness of a brittle layer have a surface length of twice their height. Here, we propose by measuring a sufficient quantity of fracture lengths from the brighter set of shear cracks observed in Magellan SAR images, a log-log plot of the length distribution of this set will exhibit a sharp bend at some length. This bend reflects the transition from 2-dimensional (2-D) growth of a penny-shaped crack in the lithosphere to the 1-Dimensional (1-D) elongation of a crack which has penetrated the elastic lithosphere. Using the length of these transition cracks we can calculate their total depth which in turn equals the thickness of the elastic lithosphere.
BACKGROUND

Between September 1990 and October 1994 the Magellan mapping mission scanned portions of the surface of Venus to produce high-resolution (>300m) Synthetic Aperture Radar (SAR) images (Ford and others, 1993). The “gridded plains” of the Guinevere Planitia is one such area imaged using this technique. The fainter NE set of fractures have been interpreted as cooling cracks in a thin but widespread basalt flow layer in frictional contact with its substrate. Banerdt & Sammis (1992) propose that the shear lag model can explain the formation of the smaller set of lineations. This model describes the formation of tensile cracks in the top brittle layer of a layered composite under conditions of tensile loading. Material scientists have used the shear lag model to explain similar Earth-based patterns of regularly spaced tensile cracks. The brighter NW trending set of fractures are interpreted as shear fractures in the lithosphere which have propagated up through the surface basalt flow after the more regular set of cooling cracks had formed. These fractures have no significant amount of displacement visible in the radar images and so represent true crack-like behavior. (Figure 1)

Globally, Venus can be divided into three basic groups of terrains: highlands, uplands (or rift-volcano-coronae regions), and lowlands (or plains). The uplands are stratigraphically the oldest terrain known on the surface of Venus. Over 85% of Venus’ surface is made up of plains of volcanic origin located at a nearly uniform altitude close to the average radius of the planet. The Guinevere Planitia contains both lowland and upland terrains and so is representative of both the oldest as well as the majority of the Venusian surface. (Mursky, 1996)

Two main, but very different models exist that explain evolution of geologic conditions on Venus. One model calls for a thin crust due to episodic global subduction or crustal inversion tectonics. This model stems from results collected from the Magellan mission which indicated that the surface of Venus is nearly uniform and is neither very old (< 4.6 Ba) nor very young (> 500 Ma). Venus does not appear to have plate tectonics like Earth. Turcotte (1993, 1995) and Turcotte et al (1998) used pair-correlation statistics for Venusian craters to show that the spatial distribution of craters is indistinguishable from a random distribution. This confirms their previous proposition that episodic global subduction events have occurred on Venus resulting in catastrophic resurfacing. It is believed the last event occurred approximately 500 ± 200 Ma and was possibly due to chemical instability of the lithosphere. However, Turcotte et al (1998) also concluded this type of resurfacing is not continuing at a significant rate today. The second model uses a thick crust, in which Venus during its early evolution had active plate tectonics like Earth. Subsequently, the global lithosphere stabilized and Venus altered into a transient state between plate tectonics and lithospheric conduction similar to the current state of Mars. (Arkani_Hamed and Toksoz 1984, Arkani-Hamed et al. 1993, Arkani-Hamed 1994)

PREVIOUS STUDIES

Smrekar and Anderson (2005) used Global Admittance to estimate the elastic and crustal thickness of Venus. Their study covered about 89% of the planet and found a range of values for both elastic (Te) and crustal (Zc) lithospheric thicknesses. For Te, values of 0-80 km and for Zc values of 40-70 km with a few 90 km locations were found for both top (highland terrains) and bottom-loading (upland terrains) models. Isostatic compensation is equal to either top or bottom-loading models where small values resulted (lowland terrains). They compare these results with that of previous studies using local admittance models with values of 20-50 km for crustal thickness. They conclude this variation may indicate that Venus remains a geologically active and complex planet.
Barnett, Nimmo, and McKenzie (2002) modeled flexure of Venusian lithosphere using residual topography for various locations. A range of elastic thicknesses was found from approximately 10 to 40 km or greater. The elastic thickness at seven volcano-like structures yielded estimates between approximately 20 and 60 km. Results from modeling the gravity found an average global elastic thickness of 29 ± 6 km.

METHODS

In this study, high-resolution SAR images produced by the Magellan mapping mission were used to customize a large mosaic of the Guinevere Planitia (Figure 1). The mosaic dimensions (approximately 840 x 540 kilometers) were decided on in order to accumulate a sufficient quantity of fracture length data. This resulted in the measurement of 6937 fracture lengths from the NW trending brighter set.

A common method for characterizing distributed fracture sets is to analyze their frequency-length statistics. Two types of length distributions have recently been observed by geologists. One is a power-law frequency-size distribution seen in continental faults. The second is an exponential frequency-size distribution seen in mid-ocean ridge faults. According to Scholz & Shaw (2002), the two distributions reflect different stages of crack evolution. They argue that exponential distributions are characteristic of very low strain regions where crack nucleation dominates the deformation. Power law distributions indicate low to intermediate strain regions where crack propagation dominates. Additionally, Scholz & Shaw showed that exponential distributions may also be found of the largest cracks in regions of high strain where coalescence occurs.

For the purpose of this study, two crack populations are identified. Population I contains cracks that developed during the first two stages of crack evolution, where crack nucleation and propagation dominate in 2-D. When plotted logarithmically, Population I has a slope >1 (Figure 2). This slope illustrates the relationship between the density of cracks per length interval and a greater rate of crack nucleation than the rate of crack propagation per length interval. Population II corresponds to cracks that have penetrated the entire thickness of the lithosphere and are actively coalescing and propagating in 1-D. When plotted logarithmically, population II has a slope < 1. This slope illustrates the relationship between the density of cracks per length interval and the increasing rate of propagation in 1-D per length interval. Therefore, the point at the transition from the slope > 1 and the slope < 1 reflects the cracks in transition from Population I to Population II that have just penetrated the elastic lithosphere. (Figure 3)

Scholz & Shaw (2002) considered the evolution of fractures that are contained entirely within a brittle layer (the lithosphere) coupled to a ductile substrate (the mantle). Initially, a fracture must extend itself both laterally and vertically, in 2-D, as it propagates. However, once the crack has penetrated the entire thickness of the brittle layer, its vertical movement ceases and it will only extend laterally in 1-D, increasing the rate of propagation along the strike. (Figure 3) In a log-log plot of the frequency-length statistics for a mature, well developed fracture set this will appear as an increase in the frequency of the largest fractures (Figure 2). Scholz & Shaw (2002) applied this idea to the Guinevere Planitia. However, Scholz & Shaw choose a study region too small such that they did not observe the Population II fractures. Therefore they did not see the transition from 2-D to 1-D propagation and could not make an accurate conclusion.

According to Scholz & Shaw (2002) the total vertical extent of a fracture (D) within a homogeneous brittle layer is equal to twice its greatest horizontal length at the surface (L). Therefore, by finding the length of the fractures that are transitioning from Population I to Population II, which
extend the entire thickness of the brittle layer, we can calculate their total vertical height which equals the total thickness of the elastic lithosphere ($T_e$) beneath the Guinevere Planitia.

Equation 1. $T_e = D = 2L$

DATA

Using the methodology described above a total of 6937 fracture lengths was measured. Initially, it was determined that large fractures extending beyond the study region were to be measured (from tip to mosaic boundary or boundary to boundary) and plotted as they would undeniably fall into Population II. Furthermore, fractures with lengths greater than 115 km either extended beyond the study region or were so curvilinear such that they were difficult to measure. Also, the high density of very short fractures and limits of the mosaic at high resolution prevented a sufficient amount of accurate measurements of fractures with lengths less than 10 km. Therefore, cracks with fracture lengths less than 10 km and greater than 115 km were excluded from the slope calculations, due to insufficient quantities of data in these ranges, in order to obtain the most accurate slope values. Lastly, a region (approximately 300-square km) located in the northeast quadrant of the mosaic, containing a high density of fractures that morphologically appear to have been significantly influenced by shear deformation, was not included in this study.

The log-log plot of the 6937 measured fracture lengths against the cumulative number of fractures longer than $L$ clearly shows the two crack populations as hypothesized (Figure 1). According to the data, we identify Population I as cracks with fracture lengths between 10 and approximately 80 kilometers, characterized by a slope $> 1$. Population II cracks have fracture lengths between approximately 80 and 115 km, with a slope $< 1$. Thus, the point at which the slope changes from Population I to Population II represents the transitional cracks with fracture lengths of approximately 80 kilometers (Figure 2). Using Scholz & Shaw’s equation (Equation 1) we calculated the Venusian lithosphere in the study area to be approximately 40 km thick.

CONCLUSION

There are two conclusions regarding the implications of frequency-length statistics of the Guinevere Planitia. The first and main focus of this study is that the length distribution of the brighter set of shear cracks exhibits the sharp bend at a length of about 80 km. This interpretation implies that the lithosphere is roughly 40 km thick, in agreement with other recent estimates based on flexure and analyses of gravity and topography (Smrekar and Anderson, 2005; Barnett et al, 2002). Secondly, this interpretation also implies not only that the 500 Ma resurfacing event suggested by crater statistics was accompanied by the emplacement of extensive flood basalts in the plains regions, and that the global resurfacing event may have been accomplished by global destruction of an older preexisting lithosphere as well.

Conversely, the model has two significant limitations. First, the above conclusions are based on the assumption that the Guinevere Planitia fractures form as circular cracks due to a decreasing strength of the lithospheric material as a function of depth. However, it is possible that the lithosphere actually become stronger with depth, consequently, the fractures are more elliptical in geometry. Thus, our model’s implied thickness of 40 km is more accurately described as the maximum thickness for the Venusian elastic lithosphere. Secondly, in order to see the sharp bend in the log-log plot the study region must be pervasively fractured and large enough to see the “run-away” fractures. Furthermore,
this region must consist of a low overall deformation rate and a history of no significant erosion. Since both populations were seen, the chosen dimensions of the study region and overall tectonic regime has provided the necessary quantity and quality of data in order to see the transitional fracture lengths required to calculate the lithospheric thickness.
References

Johnson, C. L., and Sandwell, D. T., Flexure on Venus: Implications for Lithospheric Elastic Thickness and Strength, Scripps Institution of Oceanography, La Jolla, CA.
Figure 1. The “gridded plains” of Guinevere Planitia. Note that the image is dominated by short fractures; very few fractures span the entire width of the region. The width of the image is ~490km. (Portion of Magellan image C1-30N333)
Figure 2. Fracture length distribution for the gridded plains region of Guinevere Planitia. The points labeled I in the plot are fractures that have not yet broken through the lithosphere. The points labeled II are through-going fractures that have begun to "run-away" relative to the population I fractures. The sharp decrease in the number of population II fractures which occurs at a length of 300 km is a result of the limited spatial extent of the gridded plains.
Figure 3. Hypothesized model of lithospheric fracture propagation. Ductile creep in the substrate increases the stress intensity factor at the shallower levels of the advancing crack front, causing the fracture to rapidly increase in length.