Large volcanoes on Venus:
volume, geometry and depth of magma chambers

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INTRODUCTION

Venus, because of its striking similarity in mass, density and size to Earth, provides a unique opportunity to test our understanding of fundamental volcanic processes. It is assumed that on Venus, as on Earth, a volcanic edifice forms only after an initial magma chamber is established. Predictions based on neutral buoyancy theory state that there is a point at which a rising magma body reaches equilibrium with the surrounding country rocks such that their respective densities are equal (Ryan, 1987). It is at this neutral buoyancy zone (NBZ) that the rising magma collects and grows laterally to form the magma chamber that feeds the volcano (Head and Wilson, 1992).

Because of the extreme atmospheric surface pressure exerted on the lowlands of Venus, volatiles do not exsolve from rising magma bodies as readily as they would on Earth. In addition, because erupted lava has a density that is about equal to the surrounding substrate on Venus, a layer of low density material does not form, and the rising magma body does not stall in the Venusian crust. However, as altitude on Venus increases, the atmospheric pressure decreases significantly (Head and Wilson, 1992). At higher altitudes, volatiles are exsolved more readily and the density of the resulting rock is relatively low due to the higher amount of vesiculation. Unlike at the lower altitudes, these conditions allow a NBZ within the crust and, hence, the formation of a magma chamber. Head and Wilson (1992) conclude that magma reservoirs on Venus grow larger than they do on Earth because they linger in the substrate, and do not migrate rapidly upwards into the edifice as the volcano gets taller. This slow migration is also a consequence of the enormous atmospheric pressure on Venus.

Using Magellan data, we examined 15 of 18 known large volcanoes with calderas to determine if a relationship exists between altitude and magma chamber volume and geometry, and if a uniform geometry exists between magma chambers, or if several shapes are needed to explain the observed surface features. The presence of a magma chamber is assumed from features such as volcanic edifices, lava flows and calderas. The measurements from the latter two features can be used to constrain a model for describing the magma chamber volume and depth (Blake, 1981; Wood, 1984). The three-dimensional geometry of the magma chamber can be estimated from the surface geometry of the caldera, assuming that the chamber is an ellipsoid, and the volumes of the surface flows erupted from the chamber. Therefore, three volcanoes, Shiwanokia Corona (Fig. 1), an unnamed volcano located at 9N029 (Fig. 2), and Hatshepsut Patera (Fig. 3), and their associated lava flows and calderas were mapped to gain insight into the associated reservoir geometries. These volumes were then used to approximate the total volume of the magma chamber for each of the volcanoes. Finally, we determined the basal altitude, caldera diameter, and height of all 15 volcanoes (Table 1). These type of data provide a way to test predictions based on neutral buoyancy theory and its application to Venus, and may help to identify fundamental differences between volcanic processes operating on Earth and Venus.

DISCUSSION

Basal height, caldera diameter, and basal altitude. The caldera diameter of a shield volcano is approximately equal to the map view diameter of the associated magma chamber (Wood, 1984). Therefore, the caldera diameter can be used as an indicator of the relative size of the magma chamber. The magma chamber volume calculations of the three mapped volcanoes were based on lava flow volume in relation to eruptive percentage of the magma chamber (Blake, 1981); they did not consider the caldera diameter. Hatshepsut Patera, which has the largest caldera, also has the largest magma chamber, while Shiwanokia Corona, which has the smallest caldera, also has the smallest magma chamber (Table 1 & Fig. 4). These two independent approximations confirm that a larger caldera corresponds to a greater magma chamber volume. The basal altitudes of Shiwanokia Corona, the unnamed volcano, and Hatshepsut Patera are 6051.9 km, 6051.5 km, and 6051.1 km respectively. Thus, for these three volcanoes, magma chamber volume does not appear to be dependent on basal altitude.

they measured caldera diameter for each of the 15 large volcanoes on Venus which exhibit this structure, then plotted these data as a function of altitude to constrain the plan view diameter of the underlying reservoirs [*Wood, 1984*]. In the second part of the study, Dave and Nick selected three of the large volcanoes and evaluated the three dimensional magma reservoir geometry for each by determining the average volume of each volcano's individual lava flows.

ACKNOWLEDGMENTS

I will begin by thanking the Keck Foundation and the NSF for providing the support which made this project possible; it is my hope that the results from this project justify the faith these institutions have in the Keck Geology Consortium's ability to involve undergraduate students in significant and exciting geologic research. I would next like to offer my sincerest thanks to the faculty and staff of the Geology Department at Washington and Lee and to *Mata Mcguire* and *Anne Davis*: the support and selfless efforts of all these individuals contributed significantly and directly to the success of the Planets project during the challenging summer weeks. I would also like to offer special thanks to *Dr. Ed Spencer* for teaching us about Appalachian geology and for taking us out into the field to see some of the wonders of Virginia first-hand! Finally, in addition to again thanking all of our visiting speakers, I wish to thank *Dr. Tracy Gregg* of the Woods Hole Oceanographic Institute for her assistance formulating the Arrhenius dome field project on Mars, *Dr. Ken Tanaka* of the United States Geological Survey's Branch of Astrogeology for his generous donation of a set of martian geologic maps, *Dr. Barbara Bruno* from the Hawaii Institute of Geophysics and Planetology for her advice during the fractal project, and *Dr. Jim Zimbelman* for graciously hosting our visit to the Center for Earth and Planetary Studies.

REFERENCES CITED

Baker, V.R., M.H. Carr, V.C. Gulick, C.R. Williams, and M.S. Marley, Channels and valley networks on Mars, in *Mars*, edited by H.H. Kiefer, B.M. Jakosky, C.W. Snyder and M.S. Matthews. Tucson: University of Arizona Press, 1992.

Bruno, B.C., and G.J. Taylor, Morphologic identification of venusian lavas, *Geophysical Research Letters*, *22*, 1897-1900, 1995.

Craddock, R., Geologic history of Isidis Planitia and Syrtis Major Planum, Mars, *Lunar and Planetary Science Conference*, *XXV*, 291-292, 1994.

Grosfils, E.B., and J.W. Head, Radiating dike swarms on Venus: Evidence for emplacement at zones of neutral buoyancy, *Planetary and Space Science*, *43*, 1555-1560, 1995.

Head, J.W., L.S. Crumpler, and J.C. Aubele, Venus volcanism: Classification of volcanic features and structures, association and global distribution from Magellan data, *Journal of Geophysical Research*, *97*, 13153-13197, 1992.

Head, J.W., and L. Wilson, Magma reservoirs and neutral buoyancy on Venus: Implications for the formation and evolution of volcanic landforms, *Journal of Geophysical Research*, *97*, 3877-3903, 1992.

Keddie, S.T., and J.W. Head, Height and altitude distribution of large volcanoes on Venus, *Planetary and Space Science*, *42*, 455-462, 1994.

Strom, R.G., G.G. Schaber, and D.D. Dawson, The global resurfacing of Venus, *Journal of Geophysical Research*, *99*, 10899-10926, 1994.

Tibaldi, A., Morphology of pyroclastic cones and tectonics, *Journal of Geophysical Research*, *100*, 24521-24535, 1995.

Wood, C.A., Calderas: A planetary perspective, *Journal of Geophysical Research*, *89*, 8391-8406, 1984.

Of these 15 large volcanoes with calderas, 8 lie below the mean planetary radius (MPR) of 6051.8, one occurs at the MPR, and 6 lie above the MPR (Table 1). Work done by Head and Wilson (1992) predicts that neither a NBZ, nor a magma chamber is likely to form below the MPR and, if a magma chamber does form, it will be small and poorly developed. The presence of 9 calderas, each >10 km in diameter, at or below the MPR (Table 1), indicates that magma chamber formation has occurred at these elevations, suggesting that formation of magma chambers is not strongly dependent on basal altitude. The results from this study indicate that there is no correlation between volcano height and caldera diameter (Table 1). However, a larger caldera does correspond to a large magma chamber volume, but no relationship exists between the height of the edifice and the volume of the magma chamber. Hence, caldera diameter appears to be a useful tool for approximating magma chamber volume. Based on these conclusions, we have determined that basal altitude cannot be used to predict caldera diameter (and, therefore, magma chamber volume) or volcano height on Venus.

Magma chamber geometry. The geometry of the magma chambers was determined by measuring the volume of individual eruptive episodes assuming a flow thickness of 15 m (derived from terrestrial analogs (Williams and McBirney, 1979) and Keddie and Head (1994)). Then, assuming the erupted volume of an individual flow is proportional to the size of the associated magma chamber (Blake, 1981), we extrapolated the volume of each volcano's magma chamber. As illustrated in figure 4, It appears that Shiwanokia Corona and the unnamed volcano have maximum magma chamber diameters 4.8 and 4.3 times greater than their vertical dimensions, respectively. However, Hatshepsut Patera has a magma chamber with a maximum diameter 56.7 times greater than its vertical dimension. Hatshepsut Patera has numerous lineaments extending radially from its caldera (Fig. 3), some for hundreds of kilometers. Head and Wilson (1992) suggest that lateral growth is common for extremely large magma chambers deep within the substrate. They suggest this is because the stress state in the country rock is such that lateral intrusion will occur before fracturing of the chamber roof when new magma enters the chamber. Following the work of previous authors (Grosfils and Head, 1994), we assert that these lineaments are the surface expression of intrusive dikes. The presence of these dikes indicates that Hatshepsut Patera has undergone extensive intrusive episodes, which could explain its flattened magma chamber geometry. Although there appears to be a common three-dimensional geometry among the magma chambers, the variation in ratios indicates that more than one shape exists.

Depth to the neutral buoyancy zone and magma chamber. The calderas associated with the volcanoes mapped in this study are relatively circular with aspect ratios that range from 0.833 to 1.0 (major axis of the caldera divided by the minor axis). According to Ryan et al. (1983), if the caldera aspect ratio is greater than 0.31, then the associated magma chamber is circular in plan view and is located deep within the crust. If the magma chamber is close to the surface the caldera will be elliptical in plan view with an aspect ratio less than 0.31. Head and Wilson (1992) point out that as a volcanic edifice is built up on Earth, there is little noticeable change in atmospheric pressure. Therefore, extruded lava will experience the same surface pressure over the entire height of the volcano. Upon eruption the resulting rock will have the same density as the previous lava flows because it has a similar amount of vesiculation. This causes the NBZ to remain at a constant depth from the surface and to migrate with the rising terrestrial edifice. The depth to the magma chamber can be roughly approximated as the diameter of the caldera (Wood, 1984). The depth to the NBZ and the magma chamber of the three volcanoes using Wood's method (1984), as shown in figure 4, is greater than the depth based on predictions made by Head and Wilson (1992). Several possible explanations could account for these discrepancies including 1) magma chambers on Venus form at depths that do not coincide with a NBZ, 2) NBZs on Venus are much deeper than predicted by Head and Wilson (1992), and 3) caldera diameter on Venus does not accurately reflect the depth to the magma chamber; that is, if the formation of a magma chamber on Venus is not intimately linked to a NBZ, then magma chamber depth based on our model may be erroneous.

CONCLUSIONS

Magma chambers associated with the three volcanoes from this study lie deep within the crust. Although each of the three magma chambers appears to be an oblate ellipsoid, the observed variation indicates that more than one geometry exists. Furthermore, magma chambers may form at depths that do not coincide with a NBZ, implying that they may be forming in response to other mechanisms (e.g. planes of weakness within the crust or underplating of extremely thin crust). On the other hand, if magma chambers form only at NBZs, then these zones may occur at depths greater than previously predicted. Additionally, caldera diameter may be a poor indicator of magma chamber depth on Venus. This, in turn, may indicate that terrestrial analogs do not apply to Venus when addressing the question of internal volcanic processes.

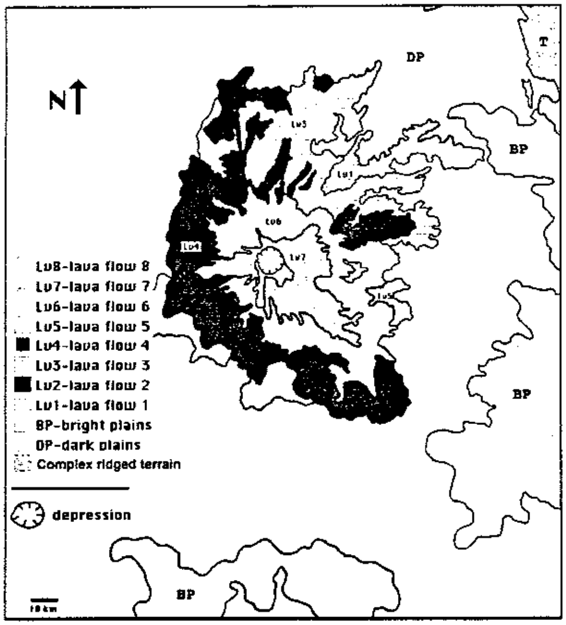

Figure 1. Map of Shiwanokia Corona located at 43S028.

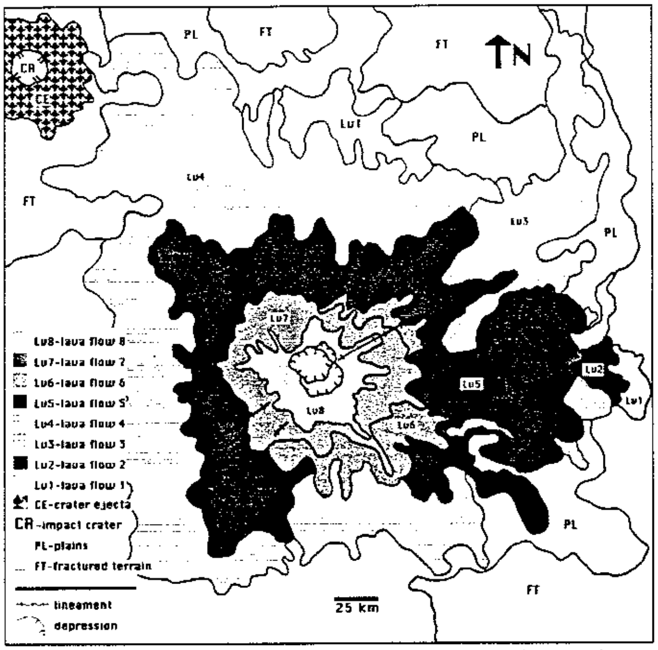

Figure 2. Map of the unnamed volcano located at 9N029.

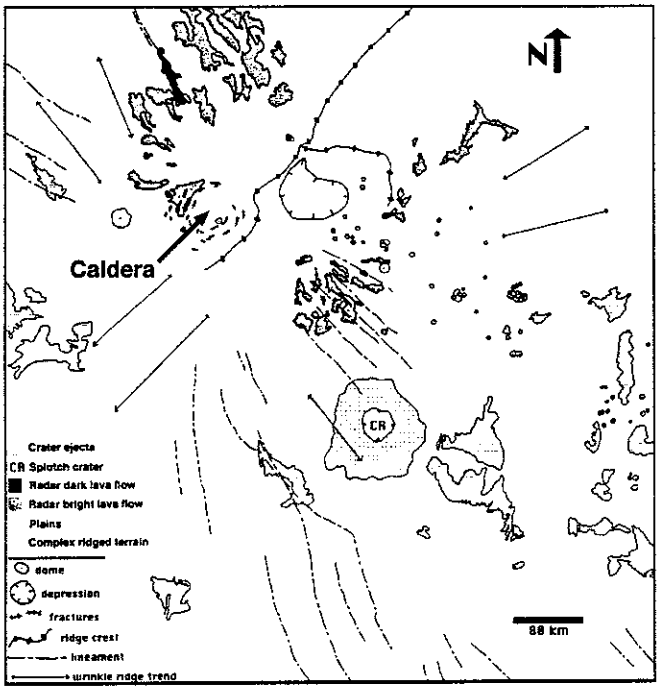

Figure 3. Map of Hatshepsut Patera located at 9N029. Current caldera is indicated by a ring of circular fractures to the west of the depression.

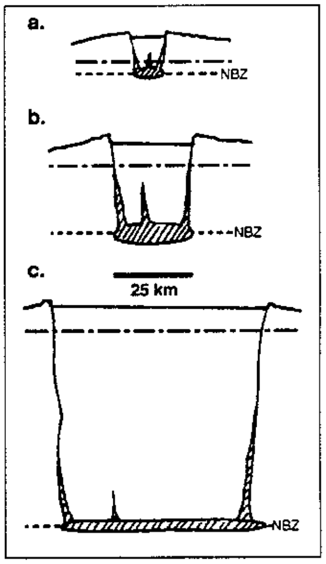

Figure 4. A cartoon depicting the locations of the NBZs and magma chambers associated with a) Shiwanokia Corona (Fig. 1), b) the unnamed volcano (Fig. 2), and c) Hatshepsut Patera (Fig. 3). Also shown are the locations of the NBZ based on Head and Wilson (1992) (dot-dashed line). Note the large difference in the location of our NBZ and Head and Wilson's much shallower NBZ. Vertical scale is the same as the horizontal scale.

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.)

References.

Blake, S., 1981, Volcanism and the dynamics of open magma chambers: Nature, v. 289, p. 783-785.

Grosfils, E. B., and Head, J. W., 1994, The global distribution of giant radiating dike swarms on Venus: implications for the global stress state: Geophysical Research Letters, v. 21, p. 701-704.

Head, J. W., and Wilson, L., 1992, Magma reservoirs and neutral buoyancy zones on Venus: implications for the formation and evolution of volcanic landforms: Journal of Geophysical Research, v. 97, p. 3877-3903.

Keddie, S. T., and J. W. Head, 1994, Height and altitude distribution of large volcanoes on Venus: Planetary and Space Science, v. 42, p. 455-462.

Ryan, M. P., 1987, Neutral buoyancy and the mechanical evolution of magmatic systems, *in* Mysen, B.O., editor, Magmatic Processes: Physicochemical Principles, Geochemical Society, Special Publication No. 1., p. 259-287.

Ryan, M. P., J. Y. K. Blevins, A. T. Okamura, and R. Y. Koyanagi, 1983, Magma reservoir subsidence mechanics: theoretical summary and application to Kilauea volcano, Hawaii: Journal of Geophysical Research, v.88, p. 4147-4181.

Williams, H., and A.R. McBirney, 1979, Volcanology: San Francisco, Freeman, Cooper and Co., p. 379.

Wood, C. A., 1984, Calderas: a planetary perspective: Journal of Geophysical Research, v. 89, p. 8391-8406.

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