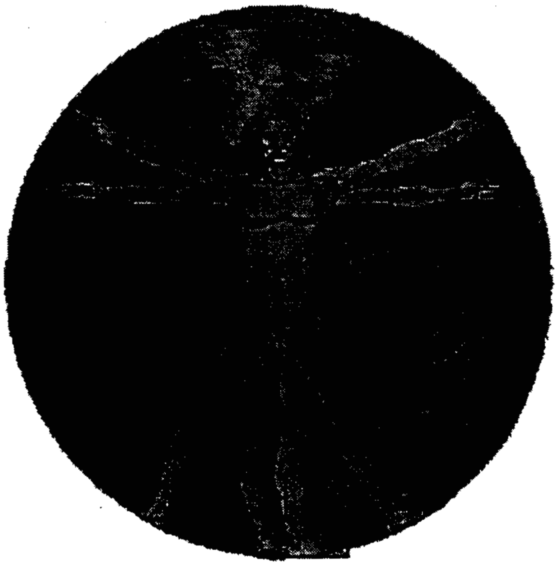

Proxemy Research
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Closeout Report

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1. Introduction

Proxemy Research had a grant from NASA to perform science research on upwelling and volcanism on Venus. This was a 3 year Planetary Geology and Geophysics grant to E. Stofan, entitled "Coronae and Large volcanoes on Venus." This grant NAG5-11535 closes on 12/31/05. Here we summarize the scientific progress and accomplishments of this grant. Scientific publications and abstracts of presentations are indicated in the final section. This was a very productive grant and the progress that was made is summarized below. Attention is drawn to the publications and abstracts published in each year.

Volcanism and tectonism are the dominant geological processes that have shaped the surface of Venus, as revealed by the Magellan data. Coronae and large volcanoes are of particular significance, as they provide constraints on both models of surface and interior evolution. Coronae are volcano-tectonic features believed to form over small-scale mantle upwellings [Basilevsky *et al.*, 1986; Pronin and Stofan, 1990; Stofan *et al.*, 1991; Squyres *et al.*, 1992; Janes *et al.*, 1992]. A continued exploration of their great variations in morphology (e.g., Stofan *et al.*, 1997; Jurdy and Stefanick, 1999; Stofan *et al.*, 2001a) and complex histories (e.g., Copp *et al.*, 1998; Smrekar and Stofan, 1999) will provide further constraints on the geologic history of Venus, the planet's overall thermal evolution, and variations in such parameters as crustal and lithospheric thickness. Large volcanoes with basal diameters greater than 100 km are a typical form of volcanism on Venus. Venusian large volcanoes tend to have heights of 2-3 km, and complex summit regions [Head *et al.* 1992; Crumpler *et al.* 1997; Stofan *et al.*, 2001b]. The volumes of large volcanoes at venusian hotspot rises are comparable to volcanic volumes produced at terrestrial hotspot island chains [Stofan *et al.*, 1995]. To understand further the implications of large volcanoes for the overall geologic history of Venus, there is a need to investigate more the morphology of these volcanoes, define their magma storage systems and how they may have changed with time, and their overall evolution. We have recently demonstrated that, while large volcanoes have many similarities, their differences can be used to define variations in their plumbing systems over time [Stofan *et al.*, 2001b].

The proposal consisted of two tasks, one examining coronae and one studying large volcanoes. The corona task (Task 1) consisted of three parts: 1) a statistical study of the updated corona population, with Sue Smrekar, Lori Glaze, Paula Martin and Steve Baloga; 2) geologic analysis of several specific groups of coronae, with Sue Smrekar and others; and 3) determining the histories and significance of a number of coronae with extreme amounts of volcanism, with Sue Smrekar. Task 2, studies of large volcanoes, consisted of two subtasks. In the first, we studied the geologic history of several volcanoes, with John Guest, Peter Grindrod, Antony Brian and Steve Anderson. In the second subtask, I analyzed a number of venusian volcanoes with evidence of summit diking along with Peter Grindrod and Francis Nimmo.

Task 1. *Studies of Coronae on Venus*
Task 1a. *A new statistical analysis of the updated population of coronae on Venus*
Participants: E.R. Stofan, S.E. Smrekar, L.S. Glaze, P.M. Martin, S.M. Baloga
Under Task 1a, we utilized statistical analysis to study the new, expanded corona population [Stofan et a., 2001a]. Applying these sophisticated analysis tools to specific types of coronae, such as topographic coronae, has helped to constrain the particular causes for the great variations observed in corona morphology and provided new insights into corona formation [Glaze et al., 2002; Stofan et al., in prep.]. Our statistical analysis of corona topography has produced strong results [Stofan et al., 2003; Stofan et al., in prep.], suggesting that the heights and basal altitudes of coronae differ between some corona topographic groups, which we are comparing to current models of corona formation and evolution. We compared the maximum height of the corona rim and interior to corona type (Type 1 vs. Type 2), topographic form, width, rim width, and geologic setting using statistical analysis. Our analysis of the rim heights, widths and basal altitudes of topographic groups 4 and 7 for Type 1 and 2 coronae indicate that the lack of a fracture annulus coincident with the topographic rim at Type 2 coronae could be caused by several factors: 1) a weak lithosphere due to high heat flux; 2) a very strong lithosphere, such that there is a small curvature and thus low stress at the surface; and 3) slow viscous bending (low strain rate) [Stofan et al., 2001; Glaze et al.,

2002]. We favor option (3). Our results suggest that many Type 2 coronae have rims that are higher and broader. We interpret this to be consistent with the rims of Type 2 coronae forming from isostatic rebound, a process likely to be slower than plume-related processes, producing less strain and rims with a lower moment of curvature. The higher rims of the Type 2 coronae are indicative of the amount of crustal thickening [Stofan et al., in prep.].

We also expected this analysis to yield results for coronae in particular regions, such as along Parga Chasma. Under previous proposals, we have studied Parga coronae, and have been unable to relate the observed variations in morphology to model predictions. Utilizing the full data sets described above, in particular the topography, volcanic characteristics and gravity data, we were able to demonstrate that the coronae in Parga Chasma do not differ from the entire population in a statistical sense [Martin et al., 2004; Martin et al., 2005]. We also determined that their distribution was random, illustrating that their formation is not controlled by the Parga rift [Martin et al., 2005; Martin et al., in prep.].

Task 1b. *Regional Studies of Coronae: Clusters of Topographic Coronae*
Participants: E.R. Stofan, S.E. Smrekar, A.W. Brian, J.E. Guest

We performed regional studies of coronae to constrain the amount of resurfacing associated with groups of coronae [Stofan et al., 2004; Stofan et al., 2005]. We found that coronae contribute approximately 20% to the resurfacing of Venus, as compared to about 22% from small edifices and 35% for volcanic plains with no apparent source. In chasmata regions, coronae contribute up to 38% of resurfacing [Stofan et al., 2005]. The results of our survey indicate that the majority of units that have resurfaced Venus can be tied to a specific source, whose stratigraphic relationship with surrounding units can be determined. Plains with no identifiable sources cover an average of 35% of the surface. This is contrary to previous work, which has suggested that Venus resurfacing is dominated by extensive, sheet-like plains units (e.g., Basilevsky *et al.* 1997).

In association with this study, we documented the previously unrecognized fact that small edifices fields resurface a significant (22%) portion of the surface. Previous workers, focusing on large clusters of shields, had estimated that shield plains make up about 10% of the surface (Basilevsky and Head, 1998; Addington, 2001). The small edifices do not appear to be the source of extensive flows, but are so ubiquitous on the surface that they add up to be a major source type [Stofan et al., 2005]. Small edifices either appear in clusters within plains units (i.e., 'mottled lineated plains material' unit, quadrangle V43 (Bender *et al.* 2000)) or as mappable units with associated deposits (i.e., 'shield field flow material' unit of quadrangle V37 (Hansen and deShon 2002)).

Coronae and small shields together resurface about 43% of the regions we surveyed. These two categories of features are operating at two very different scales, with coronae (mean diameter 253 km (Glaze *et al.* 2002)) resurfacing on scales of at least 10^4 km^2 and small edifices (diameters <10 km) resurfacing on scales of $<10^2$ km^2. For example, the corona Atete in quadrangle V40 (Chapman 1999) resurfaced an area greater than 630,000 km^2. Thicknesses of the units is, in most cases, not determinable, although many coronae have multiple, overlapping flow units (e.g., Stofan and Guest 2003).

Eruption durations required to produce volcanic units on Venus are unknown, but terrestrial durations can provide a benchmark given the overall similarities between venusian and terrestrial flows and edifices (e.g., Stofan *et al.*, 2001). Based on terrestrial experience, edifices can either be monogenetic and constructed in <10 years, or they can be built up over on the order of 10^6 years by numerous eruptions. Large-scale flows that are typical of corona resurfacing and possibly the plains no source regions may be emplaced rapidly (days to weeks) (e.g., Shaw and Swanson 1970) or slowly (years) (e.g., Self *et al.* 1996). Without a reliable way to date flows on Venus, we can only constrain the observed activity to have occurred within approximately the last 750 my, assuming that the crater data has been accurately interpreted [Stofan et al., 2005].

Task 1c. *Investigation of the Factors Determining the Amount of Volcanism at Coronae*
Participants: E.R. Stofan, S.E. Smrekar

We combined the results of studies under this task with our previous PGG proposal results to better understand volcanism at coronae and propose an integrated hypothesis of upwelling and volcanism on Venus [Stofan and Smrekar, 2005]. We base this framework on the model developed for Earth by Courtillot et al. [2003], who described three types of upwelling: primary plumes from the core-mantle boundary; secondary plumes originating from shallower depths on the domes of superswells; and tertiary hotspots likely related to lithospheric tensile stresses and decompression melting. Despite the fundamental differences in tectonic style, Venus has ten Earth-like hotspot rises [Stofan et al., 1995; Brian et al., 2004].

As described above, they are very similar to terrestrial hotspot rises, in that they have extensional rifts, large shield volcanoes, broad topographic swells, and gravity anomalies suggesting deep compensation. These are the primary hotspots, formed by plumes rising from the core mantle boundary. Unfortunately, we cannot apply the five criteria of Courtillot et al. [2003] to fully test this hypotheses: (1) long-lived tracks; (2) traps at initiation; (3) flux in excess of 10^3 kg s^{-1}; (4) high He or Ne ratio; and (5) anomalously low shear velocities indicating elevated temperatures. Given the lack of plate motion on Venus, tracks are not predicted and traps would be superposed by subsequent geologic activity at rises. However, Stofan et al. [1995] noted that volumes of venusian swells are comparable to those of terrestrial swells, suggesting that time-integrated plume strengths are similar. Modeling of Venusian hotspots also supports this hypothesis [Nimmo and McKenzie, 1996; Smrekar and Parmentier, 1996].

Secondary plumes are generated as when a superplume impinges on the upper mantle-lower mantle boundary spawning smaller thermal instabilities [Jellinek et al., 2002; 2003; Courtillot et al., 2003]. Coronae are likely to be products of secondary plumes, originating from the shallow mantle. Small-scale plumes are unlikely to be able to rise through the mantle without either cooling or being swept up in large-scale flow patterns (e.g. Richards and Griffiths, 1988). Thus they may spawn off of larger scale convective upwellings (e.g., Johnson and Richards, 2003), off of convective upwellings responsible for the stresses inducing chasma formation, or from an upper mantle boundary resulting from mantle stratification [Phillips and Hansen, 1994; Smrekar and Stofan, 1997; Gonnermann et al. 2002]. Large volcanoes may be related to primary or secondary plumes, or, like large flow fields, can be classified as tertiary hotspots related to melting associated with lithospheric stress [Stofan and Smrekar, 2005].

Task 2. Studies of Large Volcanoes on Venus

Task 2a. *Evolution of Large Volcanoes on Venus: Case Studies*

Participants: E.R. Stofan, J.E. Guest, A.W. Brian, P.M. Grindrod, S.W. Anderson,

We studied the detailed eruptive histories of volcanoes in Laufey Regio [Brian et al., 2004a], and a volcano-corona hybrid, Atai Mons [Grindrod et al., 2004; 2005]. We also performed a study of all large volcanoes, including an analysis of their gravity [Brian et al., 2004b; Brian et al., in prep.]. Previous studies mapped 168 volcanoes on Venus [Crumpler et al., 1997], while recent work by Brian et al. [2004b] identified135 large volcanoes. Of these, only 14 are located on topographic rises. The others are distributed across the surface, with a noted concentration in the region bounded by Beta Regio, Atla Regio and Themis Regiones [Crumpler et al., 1997]. Most of the venusian volcanoes are larger than their terrestrial counterparts, with relatively low summits but extensive flow aprons [Crumpler et al., 1997]. The volcanoes have average heights of about 1.5 km and flow aprons that extend 100's of kilometers from the summit. A decline in SO_2over time observed by the Pioneer Venus spacecraft has been interpreted to possibly indicate a relatively recent eruption [Esposito, 1984; Glaze, 1999], and volcanism within the last 10-50 my is supported by climate models [Bullock and Grinspoon, 2001]. Preliminary studies of the gravity signatures of 33 large volcanoes by Brian et al. [2004b] find that a number of volcanoes have bottom-loading signatures suggesting that they may be dynamically supported, and thus still active. Kiefer and Potter [2000] modeled the gravity anomalies for 8 large volcanoes, calculating elastic thickness values from 8-22 km. Brian et al. [2004b] calculate a wide range in elastic lithospheric thickness, contrary to previous studies that suggested that venusian volcanoes form preferentially on thick lithosphere [McGovern and Solomon, 1998].

At Laufey Regio, volcanic material dominates the majority of the Laufey rise and is centred at three large volcanic edifices, Var, Tuli and Atanua Montes. Tuli Mons (13.3°N, 314.6°E) is a 300 km diameter volcano that lies 600 km north of the centre of the plateau. It has little relief, reaching a maximum height of only 0.6 km above the surrounding plains It is constructed of many small edifices which are well defined and display variable radar backscatters. Many display radar bright pits which are interpreted to be calderas. The extensive flow apron surrounding Tuli clearly overlies the surrounding plains and is composed of many individual flow units showing a wide range of radar backscatters, well defined margins and varying morphologies. Some of the longer lava flow lobes reach a maximum of 400 km from the centre of the volcano. Atanua Mons (9.5°N, 309°E) is located in the northern end of the plateau. Its flows, along with those from Var Mons, dominate the region, extending over 350 km from the summit. The apron of flows has been divided into eight units which may indicate distinct episodes of eruptions over the history of the volcano. The summit region is characterised by a steep sided cone that appears to have been built up by flows that extend radially around it. It is capped by a circular caldera almost 10 km across. The caldera has a radar bright rim, which has been breached by a fan of lava flows on the northern side. The floor of the caldera is covered by radar dark material, and a 2.5 km arcuate area within the centre has collapsed. A second vent marked by two bright pits lies 130 km to the west of the main cone. Var Mons is a 1000km diameter volcano centred at 1.2°N 316°E. It consists of three main cones with maximum heights, west to east, of 1.5 km, 0.7 km and 1.7 km above its base. The middle edifice is offset to the north by approximately 30 km from a line connecting the other two. As observed at other volcanoes, the main edifices are made up of shorter more numerous flows while the outer apron consists of longer, more extensive flows [Guest and Stofan 1999; Stofan et al., 2001]. The three summits of Var display different styles of eruptive centres. At the western end, a 25 km diameter steep-sided dome sits at the summit of the cone. Low radar backscatter lava flows, with ill-defined flow fronts surround the dome, radiating out approximately 50 km from the centre. Chains of pits, associated with through going fractures that trend along the axis of the summits, are visible around the dome. The summit of the central cone consists of a partially filled 30 km diameter caldera. The eastern summit region reaches the highest altitude of the three cones. Lavas with a range of radar backscatter characteristics have been erupted radially from the centre of what may once have been a steep-sided volcanic dome. These lavas have flowed down and embayed a second steep-sided dome (22 km across) which lies 45 km to the north. This second dome has an 8 km wide central depression which is partially filled with radar dark lavas. The southern part of the rim has been breached by flows from the dome to the south. Small shields and pits are scattered over the summit and some are superposed on radial faults, which are likely to be the surface manifestation of dykes. A radar bright feature with scalloped sides that appears to have been highly eroded lies midway between the western and central centres. It does not show any associated lava flows and has been embayed by material from the western summit [Brian et al., 2004a].

Numerous other small and intermediate sized (<50 km in diameter) edifices are also found on the rise and in the surrounding plains. The Laufey area is dominated by the flows of Var and Atanua Montes, which are superposed on the regional and mottled plains. There is no visible contact between flows from the two centres and therefore relative timing cannot be determined. Materials associated with Hulda Coronae at the north end of the Laufey rise overlap with flow units from Atanua, indicating the protracted and overlapping histories of each. Undivided corona materials in the centre of the rise are generally superposed on the regional plains but overlain by deposits from the two large volcanoes. The local set of wrinkle ridges that surround the rise deforms the outer flows of Var and Atanua along with the regional and mottled plains. This indicates they were formed after the initiation of centralised volcanism [Brian et al., 2004a].

Detailed analysis of superposition relationships at Atai Mons area suggests the following general sequence of events: formation of original plains material; emplacement of sheet and digitate lava flows; uplift and associated radial fracturing at Atai Mons; gravitational relaxation of the topographic high causing a broad summit depression and exterior concentric fracturing; some lava flows from flank eruption sites; formation of extensional tectonic features associated with Pinga Chasma; volcanic flooding of the broad summit depression; further Pinga Chasma-related extension; localised summit collapse causing caldera-like interior concentric fracturing; continued summit volcanism giving rise to a small volcano and associated lava flows [Grindrod et al., 2004; 2005]. This history points to processes typical of both large volcanoes and coronae occurring contemporaneously, and does not necessarily seem to suggest evolution from one feature into another. Features typical of both coronae (radially-fractured annulus, concentric fractures, central depression and topographic rim) and large volcanoes (radial lava flow apron and summit calderas) on Venus are observed to occur at the same location. We observe tectonic and volcanic processes occurring simultaneously and repeatedly, indicating a complex history at this hybrid feature. This history includes three different periods and scale of collapse indicating possible resurgent activity. Differing lava flow morphologies indicate different eruption conditions both locally and/or temporally. More recent volcanism has been confined to the summit region, both in large and small volumes. We observe large volcano processes occurring in a region of relatively thick lithosphere, which may still be ongoing at present [Grindrod et al., 2004, 2005]. Continued detailed mapping and gravity studies of other hybrid features at different geological settings is required to further understand the intimate relationship between coronae and large volcanoes on Venus. We plan to continue this analysis, analyzing other large volcanoes and volcano-corona hybrids.

Task 2b. *Histories of intrusion and extrusion at large volcanoes on Venus: An investigation of summit diking*

Participants: E.R. Stofan, P. Grindrod, F. Nimmo

Radially fractured centers on Venus (sometimes termed 'novae') are distinctive radiating systems of graben and fractures arranged around some central topography. In this task, we used Magellan data to constrain some subsurface parameter at four radially fractured centers, Dhorani Corona, Lengdin Corona, Mbokomu Mons and Pavlova Corona. At each o f the features, the fractures radiate from a central volcano, some located within coronae. Radially fractures may have originated from uplift (e.g., Squyres et al., 1992) or from diking (e.g., Grosfils and Head, 1994).

We determined the hoop strain at large radial graben by measuring the amount of extension that has occurred [Grindrod et al., 2005; Grindrod et al., in press, 2005b]. We have measured the depths and wall dip angles of several large radial graben using two different methods. We find depths of < 0.1 to > 1 km, with most within the range of about 0.3 to 0.9 km. We found the dip angles of the graben walls to be about 36°, consistent with primary talus slopes from collapsed fault scarps. By assuming an original fault dip angle of 60° we determined the extension at individual graben to be of the order of 0.5 to 1 km for graben typically between 5 and 10 km wide. We used the extension to estimate the hoop strain, and found varying levels of strain at each feature, but strain levels are generally high and concentrated within a narrow region. The observed strain is too large to be explained by previous plume models of uplift and also by magma chamber inflation. We therefore conclude that subsurface dikes must have made a significant contribution to the formation of the large radial graben at the RFCs, as well as being responsible for the numerous smaller fractures present. Our results suggest that measurement of strain at radial graben is a successful way to determine the relative amount of construction and uplift at radially-fractured centers [Grindrod et al., in press, 2005b].

Summary

The research on coronae and large volcanoes described above has permitted us to better constrain the formation of these features [Brian et al., 2004; Grindrod et al., 2005a; Grindrod et al., 2005b; Martin et al., in prep.], contributing to our overall understanding of how volcanotectonic features evolve on the surfaces of terrestrial planets. In addition, we synthesized these data to propose an overall model of plume-related feature on Venus and how this compares to Earth [Stofan and Smrekar, 2005]. We also integrated our understanding of the formation of these features to better constrain the geologic history of resurfacing on Venus [Stofan et al., 2005], providing new constraints on a controversial subject in Venus research.

3. Manuscripts, Abstracts and Outreach

Manuscripts

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Public Outreach

In addition to talks and poster presentation at scientific conferences such as the American Geophysical Union meetings and the Lunar and Planetary Science Conference, publication in popular books and journals and media work, I participated in various educational activities. I have lectured to primary school children on both space science, studying the Earth from space, and terrestrial volcanoes. I worked with undergraduate and graduate students at several institutions, including students at University College London and at Black Hills State University, SD. I have mentored local high school student senior research projects. Paula Martin and I also published an article (Martin, P. and E.R. Stofan, Planet in a Bottle, *Physics Education*, 39, 228-232, 2004), updating and adapting an astrobiology lesson for late elementary/early middle school children that we have extensively tested at various schools.

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