highest basal elevation, Maat Mons, should have a well-developed, large, and relatively deeper NBZ and that the volcano at the lowest altitude, an unnamed volcano located southwest of Beta Regio at 10°, 273°, should have either a poorly developed magma chamber or none at all [2]. Preliminary mapping of Maat Mons [3] identified at least six flow units that exhibit greater variations in morphology and radar properties than the flows of Sapas Mons. These units are also spatially and temporally distinct and suggest the eruption of a continuously evolving magma. Although smaller in diameter, the summit caldera is much better defined than the depression at Sapas. The inferred young age of Maat (Klose et al. [4] suggest that it may even be "active") may mean that the chamber has not yet grown to "full size," explaining the relatively smaller caldera. There is no evidence of radial fractures at Maat Mons, suggesting that if lateral dike propagation occurred, it was sufficiently deep that there was no surface expression. In contrast, the unnamed volcano has no summit features, no radial dikes, and only three flow units that exhibit considerable morphologic variations within units [3]. These observations suggest that either the NBZ is very poorly developed or it does not exist and the magma erupts directly at the surface. Thus the character of three large volcanos on Venus supports the suggestion that basal altitude can play a critical role in the development of a NBZ. Examination of other volcanos at a greater range of altitudes will help to further test this hypothesis.

In addition to studying the detailed evolution of three large volcanos, the altitude and height distribution of all volcanos was determined. Although in general there is a broad distribution of large volcanos as a function of altitude, there is somewhat of a paucity of large volcanos at elevations below 6051 km (Fig. 2). Between 6051 and 6053 km the number of volcanos is slightly greater than expected and above this an absence of volcanos is again observed. This absence at the highest elevations is probably due in large part to the predominance of tessera terrain at these elevations. Those volcanos that do occur in this area are associated with regions of uplift and rifting probably caused by mantle upwelling. Head and Wilson [2] suggested that below an elevation of 6051 km it is unlikely that a NBZ would develop, due largely to the high atmospheric pressure, and thus edifice growth would be inhibited. They also found that the first few kilometers above 6051 km would be most favorable for edifice growth as NBZs develop early at relatively shallow depths beneath the surface. A survey of 110 large volcanos found that this altitude distribution appears to be observed on Venus.

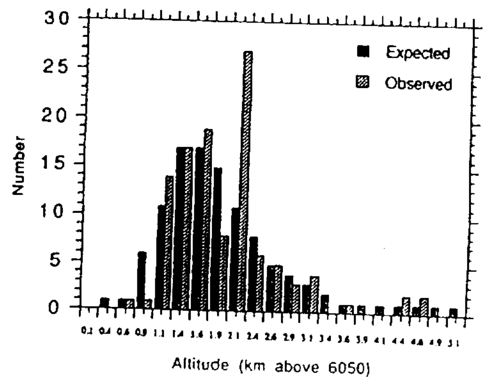


Fig. 2. Location of large volcanos as a function of basal altitude. The dark-shaded columns indicate where volcanos would be located if they were randomly distributed on the surface as a function of the percentage of area at a given altitude. The striped columns show where the volcanos actually occur. See text for a discussion of the implications of this distribution.

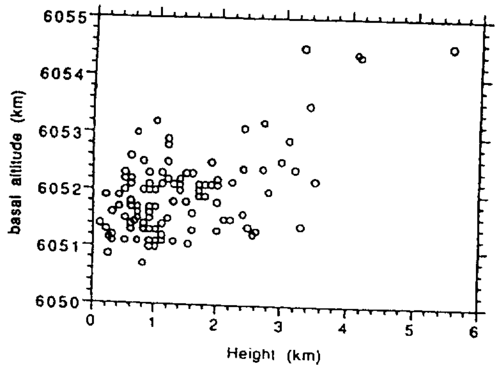


Fig. 3. Graph showing the heights of 110 large volcanos as a function of basal altitude. The majority of volcanos cluster between 6051 and 6053 km and there is a weak positive correlation between height and basal altitude. The majority of volcanos that occur above 6052.8 km and are taller than 2.6 km are located in zones of mantle upwelling and/or rifting.

The height of volcanos is also related to basal altitude and the development of zones of neutral buoyancy. There is a weak correlation of volcano height with basal elevation (Fig. 3). Although many factors need to be considered to explain this correlation, in a general sense NBZ development is responsible. As magma chambers become larger, and thus the "life" of the volcano is lengthened, there is an opportunity for a greater number of repeated, relatively small volume eruptions. This type of eruption enhances edifice growth. Head and Wilson [2] suggested that NBZs will grow to relatively larger sizes at greater altitudes. Therefore this correlation of height with altitude is expected.

Although a good deal more work needs to be done to test the idea that basal altitude plays a significant role in the development and evolution of neutral buoyancy zones on Venus, studies of the altitude distribution and heights of many large volcanos, as well as the evolution of individual volcanos, indicates that NBZ development is occurring, that it is varying, apparently as a function of altitude, and that the morphology and history of large edifices is being strongly influenced.

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N93-14334

**MANTLE PLUMES ON VENUS REVISITED.** Walter S. Kiefer, Code 921, Goddard Space Flight Center, Greenbelt MD 20771, USA.

The Equatorial Highlands of Venus consist of a series of quasicircular regions of high topography, rising up to about 5 km above the mean planetary radius [1]. These highlands are strongly correlated with positive geoid anomalies, with a peak amplitude of 120 m at Atla Regio [2,3]. Shield volcanism is observed at Beta, Eistla, Bell, and Atla Regiones and in the Hathor Mons-Innini Mons-Ushas Mons region of the southern hemisphere [4–10].

Volcanos have also been mapped in Phoebe Regio [11], and flood volcanism is observed in Ovda and Thetis Regiones [10,12]. Extensional tectonism is also observed in many of these regions [5,10,12,14–16].

It is now widely accepted that at least Beta, Atla, Eistla, and Bell Regiones are the surface expressions of hot, rising mantle plumes [e.g., 5,9,10,12,14–16]. Upwelling plumes are consistent with both the volcanism and the extensional tectonism observed in these regions. The geoid anomalies and topography of these four regions show considerable variation. Peak geoid anomalies exceed 90 m at Beta and Atla, but are only 40 m at Eistla and 24 m at Bell [2]. Similarly, the peak topography is greater at Beta and Atla than at Eistla and Bell [1]. Such a range of values is not surprising because terrestrial hotspot swells also have a wide range of geoid anomalies and topographic uplifts [17]. Kiefer and Hager used cylindrical axisymmetric, steady-state convection calculations to show that mantle plumes can quantitatively account for both the amplitude and the shape of the long-wavelength geoid and topography at Beta and Atla [15,18]. In these models, most of the topography of these highlands is due to uplift by the vertical normal stress associated with the rising plume. Additional topography may also be present due to crustal thickening by volcanism and crustal thinning by rifting. Smrekar and Phillips [19] have also considered the geoid and topography of plumes on Venus, but they restricted themselves to considering only the geoid-topography ratio and did not examine either the geoid and topography amplitudes separately or the shapes of anomalies.

Several factors could contribute to the smaller geoid and topography amplitudes at Eistla and Bell Regiones. Comparison of models in axisymmetric and two-dimensional Cartesian geometries shows that elongated upwellings produce smaller geoid anomalies and topographic uplifts [18]. Eistla is an elongated topographic feature [1], suggesting the possibility of an elongated upwelling. Recent modeling of gravity anomalies in this region also indicates a component of elongated upwelling, although there is also evidence for plume-like upwellings with more circular planforms beneath western Eistla (Sif Mons and Gula Mons) and to a lesser extent beneath central Eistla (Sappho Patera) [14]. The elongated nature of the Eistla upwelling could contribute to the relatively small geoid and topography in this area. The geoid and topography of a plume are also increasing functions of the aspect ratio of the upwelling [18]. The plumes inferred to exist beneath western and central Eistla are each about 1000 km across [14], much less than the 2000 to 2500 km dimensions of Beta and Atla. The narrowness of the Eistla plumes could be another factor that contributes to the relatively small geoid and topography in this region. Bell Regio is also smaller than Beta and Atla, which might contribute to its smaller geoid and topography. In the southern hemisphere, the cluster of shield volcanos Hathor Mons, Innini Mons, and Ushas Mons [7] are separated by a maximum distance of about 1500 km. If these features are plume related [15], their moderate amplitude geoid (15 m) and regional topography (1 km) may be due to a relatively narrow underlying plume. Another factor that may contribute to variations in the geoid and topographic uplift associated with different plumes is the temperature contrast between plumes and the adjacent mantle. Both the geoid anomaly and the topographic uplift are linearly proportional to the magnitude of the temperature contrast. On Earth, the temperature contrasts between various plumes and the surrounding mantle are estimated to vary by about a factor of 2 [20]. Time-dependent changes in the thermal structure of a plume, due to the formation of boundary layer instabilities, can also cause the geoid and topography of a plume to vary by up to about 50% relative to their time-averaged values [21].

Both mantle plumes and cold downwellings have been proposed as possible models for Ovda and Thetis Regiones. Plume models have been proposed by Kiefer and Hager [15,22] and by Herrick and Phillips [16,23]. These models all invoke some form of time-dependent plume behavior, but the details of this behavior were not quantified in these works. Kiefer and Kellogg have begun quantifying the effects of time-dependent convection in spherical axisymmetric geometry on the geoid anomalies and dynamic topography of plumes [21]. An important difference between the plume models for Ovda and Thetis is in the geometry of the plume. In the Herrick and Phillips model [23], a plume is visualized as a discrete blob of hot material that detaches from the lower thermal boundary layer and rises to the surface. This produces an episode of tectonic uplift and extensive magmatism, followed by topographic subsidence and deformation of the thickened crust once the blob collapses at the base of the lithosphere. In the Kiefer and Hager model [15], plumes are assumed to be continuous between the upper and lower thermal boundary layers, although boundary layer instabilities may be superimposed on the basic structure. Continuous plumes are consistent both with the results of numerical modeling [e.g., 15,18] and with the record of nearly continuous volcanism at terrestrial hotspots such as Hawaii [24]. In this model, the ascent of a boundary layer instability up a plume will alter both the geoid anomaly and the topographic uplift of the plume. In models that do not include temperature-dependent viscosity, the increased volume of buoyant material increases both the geoid anomaly and the dynamic topography of the plume [21].

The rising thermal anomaly will heat the upper mantle and should cause a temporary decrease in the regional viscosity. This will alter the expected geoid and topography signatures but has not yet been quantified. At a minimum, the creation of a temporary low-viscosity zone should decrease the apparent compensation depth of these features [25]. This is consistent with the observation that the apparent compensation depths of Ovda and Thetis are shallower than for Beta, Atla, Bell, and Eistla [14,19]. The rising thermal anomaly should also cause an episode of increased volcanic activity; efforts are underway to quantify this effect. An increased volcanism rate should lead to an increased resurfacing rate and a young cratering age, consistent with the observation that Ovda and Thetis have some of the lowest impact crater densities observed on the planet [26]. The increased volcanism rate should also thicken the crust. Thick crust in an area of high heat flow should have a very low vertically integrated strength [27], and should therefore be quite susceptible to tectonic disruption. Sources of stress that could contribute to this disruption include the flow driven by the rising plume (which will vary with time as the plume's thermal structure evolves), viscous flow of the crust down topographic gradients, and other regional stresses that may exist. This may account for the observed high level of tectonic deformation in Ovda, Thetis, and Phoebe [10].

Eventually, the thermal anomaly beneath the highland will dissipate by a combination of lateral advection and conductive cooling and the topography and geoid anomaly of the plume will return to their normal levels. Continuing volcanism at normal rates will gradually cover the surface of the highland, obscuring evidence for earlier episodes of tectonic disruption. This cycle of boundary layer instability formation followed by a period of enhanced volcanism and tectonism may be repeated episodically [21]. The tessera observed on the flanks of Beta and Bell Regiones [6,10,28] may be remnants of deformation from earlier plume instability cycles that have so far escaped resurfacing since the most recent boundary layer instability events at these plumes. If so, this would essentially invert the sequence proposed by Herrick and Phillips [23], who suggested that Beta Regio represents an early stage of their blob model and that Thetis and Ovda represent later stages.

As an alternative to the mantle plume model, Bindschadler and colleagues [12,29] proposed that Ovda, Thetis, and Phoebe Regiones formed by crustal convergence over downwelling mantle "coldspots." As arguments against a plume model, coldspot advocates [12] point to the absence of evidence for early volcanism, prior to the formation of tessera, in these areas. This could be due to plumes rising beneath preexisting tessera, as suggested for Beta Regio by Senske et al. [28]. Alternatively, tessera formation may be an intrinsic part of the plume instability evolutionary sequence, but the tectonic disruption involved in forming the tessera may be sufficiently severe to destroy any evidence for earlier volcanism. A second argument that has been used against the plume model is the observation that the tessera is embayed by later flood volcanism, which is asserted [12] to be contrary to the plume model. This assertion is based on the detached blob model of a plume [23]. If a vertically continuous plume exists [15,18], then adiabatic decompression provides a continuing source of magma. In this case, volcanism and tectonic deformation can go on simultaneously, leading to possible complex superposition relationships.

Several observations have been asserted to favor the coldspot model, including the existence of steep topographic slopes on the margins of some highlands, margin-parallel compression at high elevations, and extensional deformation superimposed on compressional features [12]. However, a combination of dynamic uplift and crustal thickening by volcanism might be able to produce the observed marginal slopes. Margin-parallel compression might be the result of viscous flow of volcanically thickened crust down the topographic gradient. In such a model, one would expect extension on the topographic highs and compression on the lower flanks of the highland. However, as boundary layer instabilities move laterally through the upper thermal boundary layer, the margin of the highland can migrate laterally outward [21]. Thus, compressional features that originally formed at low elevations can be uplifted to high elevations. As these features are uplifted, they may be overprinted by extensional features. An additional argument that has been asserted to favor the coldspot model is the observation that the apparent compensation depths of Ovda, Thetis, and Phoebe are shallower than for Beta and Atla, and the correlation between gravity anomalies and topography is not as strong [12]. However, as noted above, a decrease in the apparent compensation depth is expected in the plume model because of the effect of the hot thermal anomaly on the mantle's viscosity. The increased volcanism associated with a rising thermal instability should lead to local crustal thickening, which will create topographic highs whose gravity anomalies will be small due to shallow compensation. This should decrease the overall correlation between gravity and topography. Thus, it appears that the time-dependent plume model is at least qualitatively consistent with observations of Ovda, Thetis, and Phoebe. Contrary to some assertions [12], qualitative geological and geophysical arguments cannot rule out the mantle plume model for these regions. Quantitative modeling of both the time-dependent plume model and the coldspot model are needed to assess their relevance to highlands on Venus.

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## PIONEER VENUS POLARIMETRY AND HAZE OPTICAL THICKNESS.

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The Pioneer Venus mission provided us with high-resolution measurements at four wavelengths of the linear polarization of sunlight reflected by the Venus atmosphere. These measurements span the complete phase angle range and cover a period of more than a decade. A first analysis of these data by Kawabata et al. [1] confirmed earlier suggestions of a haze layer above and partially mixed with the cloud layer. They found that the haze exhibits large spatial and temporal variations. The haze optical thickness at a wavelength of 365 nm was about 0.06 at low latitudes, but approximately 0.8 at latitudes from 55° poleward. Differences between morning and evening terminator have also been reported by the same authors.

Using an existing cloud/haze model of Venus, we study the relationship between the haze optical thickness and the degree of linear polarization. Variations over the visible disk and phase angle dependence are investigated. For that purpose, exact multiple scattering computations are compared with Pioneer Venus measurements.

To get an impression of the variations over the visible disk, we have first studied scans of the polarization parallel to the intensity equator. After investigating a small subset of the available data we have the following results. Adopting the haze particle characteristics given by Kawabata et al. [1], we find a thickening of the haze at increasing latitudes. Further, we see a difference in haze optical thickness between the northern and southern hemispheres that is of the same order of magnitude as the longitudinal variation of haze thickness along a scan line. These effects are most pronounced at a wavelength of 935 nm.

We must emphasize the tentative nature of the results, because there is still an enormous amount of data to be analyzed. We intend to combine further polarimetric research of Venus with constraints on the haze parameters imposed by physical and chemical processes in the atmosphere.

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