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GLOBAL CORRELATION OF VOLCANIC CENTERS ON VENUS WITH UPLANDS AND WITH EXTENSION: INFLUENCE OF MANTLE CONVECTION AND ALTITUDE.

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Introduction: In this paper the observed distribution of volcanism on Venus and its associations with geologic and tectonic characteristics are examined for significant global-scale tectonic, mantle, and volcanic influences. We find that volcanic centers are correlated geologically with zones of extension, infrequent in lowland regions, and infrequent in regions with evidence for tectonic shortening. In addition, volcanic centers are significantly concentrated in a broad region at least 10,000 km in diameter between Beta, Atla, and Themis Regiones. This area is nearly hemispheric in scale and coincides spatially with the area of greatest concentration of extensional characteristics. Our analysis suggests that the observed distribution patterns of volcanic centers reflect the regional patterns of extension, the origin of the extension and volcanism are closely related, and the hemispheric scale of both patterns implies a deep-seated origin such as large-scale interior mantle dynamic patterns. However, altitude-dependent effects on both the formation and preservation of volcanic centers could also strongly influence the observed distribution pattern.

Identification/Classification: The global survey of volcanism includes the area available for analysis from the first and second mission cycles [17], more than 90% of the surface area. The final volcanic catalog [4] identifies, describes, and locates to the nearest half-degree 1548 individual volcanic features larger than ~20 km in diameter. Volcanic features identified include large volcanos, intermediate volcanos, calderas, coronae, arachnoids, novae, shield fields, large lava channels, large lava flows and lava floods, and several other unusual volcanic features. Criteria for identification and classification of volcanic features on Venus [6,4] were carefully outlined and consistently used throughout the survey in order to reduce drift and biases in the classification systematics. The identification criteria selected are dependent on observed image characteristics of a large precursor dataset, were chosen to follow previous usages, and have been supplemented for additional rigor and reproducibility with the use of three size divisions of radial structure, five size divisions of concentric structure, and a concisely-organized identification flowchart. Details of the classification and related observations and reduction procedures are presented elsewhere [4]. In the following, the distribution characteristics and several models for the origin of the observed distribution are discussed in further detail.

Analysis of Distribution: The global distribution of volcanic centers on Venus is nonrandom both visually (Fig. 1) and from several spatial statistical measures. Areas of significant overabundance and underabundance correlate with several specific regional and global geologic characteristics.

Areal Distribution: The global distribution map (Fig. 1) shows that anomalous concentrations of volcanic centers occur at two scales; "global," with dimensions in excess of 10,000 km, and "regional," with dimensions in excess of a few thousand kilometers. Volcanic centers are prominently clustered in a circular region 10,000 to 12,000 km in diameter and centered near longitude 250° and encompassing the areas of Beta Regio, Atla Regio, and Themis Regio. Hereafter this anomaly is referred to as Beta-Atla-Themis, or BAT. A more diffuse clustering of moderate- to high-density areas may be present in the opposite hemisphere (Fig. 1), but in this discussion we focus on BAT in order to further assess some of the primary characteristics of areas bearing concentrated volcanic centers.

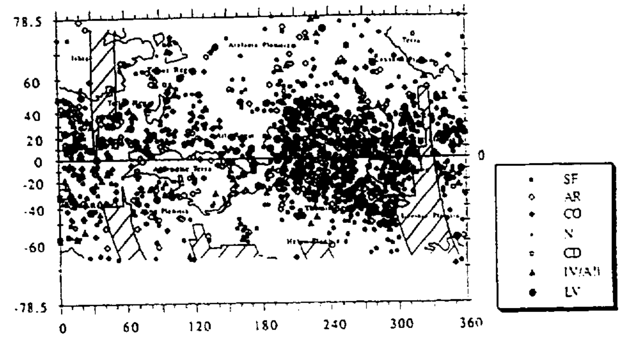

Fig. 1. Global map of the distribution of volcanic centers relative to significant highlands and prominent named surface areas. The highland outlines are represented by the 1.5-km contour. Mercator projection. Ruled areas are cycle 1 and 2 mission gaps.

The average global areal abundance of volcanic centers (>20 km in diameter) is 3.5 ± 2.9 per 10^6 km^2, based on a sample of 361 equal areas 1000 km × 1000 km. The areal number density is contoured in Fig. 2 in order to show where significant departures (>1 std.dev.) occur relative to the global average density. Areas of moderate volcanic center abundance (>3 to 7 centers/10^6 km^2) attain their greatest contiguous areal extent in the Beta-Atla-Themis area. Several smaller areas (<3000 km across) of greater density (>10 centers /10^6 km^2) also occur locally within this cluster. Large areas of moderate (>3 to 7 centers/10^6 km^2) density also occur elsewhere in the equatorials regions, notably in the hemisphere centered about longitude ~70° trending from Alpha Regio northeast to Tethus Regio. Estimates of the relative areas over which significantly different densities occur show that moderate densities of >3 to 7 centers/10^6 km^2 occur over ~40% of the surface area. Approxi-

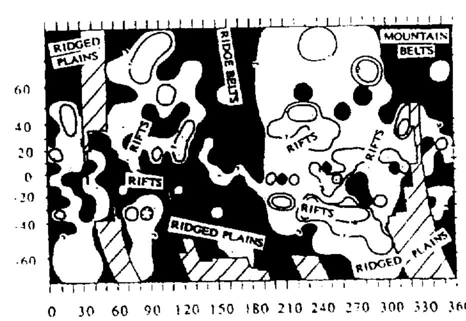

Fig. 2. Contour map of the observed global abundance of cataloged volcanic features on Venus. Contours (3, 7, and 10 volcanic centers per 10^6 km^2) selected to show the mean, mean +-1 s.d., and mean +-2 s.d. intervals. Background dots are volcanic center locations for reference. Areas with lower than nominal abundances occur primarily in association with tessera (for example, Aphrodite Terra) and in areas of lowland plains (for example, Atalanta and Helen Planitiae). The areas of higher abundance are generally associated with geological characteristics of extensional strain (for example, Beta-Atla-Themis Regiones).

mately 60% of the 40% of the surface area covered by moderate volcanic center abundance is accounted for by BAT; the other 40% lies in the broad region noted above just noted in the opposite hemisphere. Higher densities, between 7 and 10 centers/10^6 km^2, occur over ~10% of the surface area. Areas with the greatest densities (>15 centers/10^6 km^2) occur over less than 1% of the surface, mostly within BAT. The abundances over the remaining ~50% of the surface are less than the global mean.

Volcanic centers are primarily associated with regions lying at intermediate altitudes between MPR and 1 to 2 km above MPR. This includes primarily the areas known as uplands, and generally excludes most of the highlands and lowlands. Extreme high or low altitudes are underepresented in the population. In the following, some of the significant geological associations that this distribution implies are discussed further.

Geological Relationships/Correlations: Areas of low density (fewer than 3 centers/10^6 km^2) occur mostly in lowlands and volcanic centers are strongly excluded from highlands. These areas include primarily extensive ridged lava plains and tesserae respectively. The distribution of tesserae have been mapped from Magellan data [9], appear widely distributed, and are frequently associated with prominent highlands. Where tesserae occur within broader areas of high regional volcanic center concentrations, the tesserae areas are manifest as anomalously vacant areas. Prominent "holes" in the concentration of volcanic centers occur in association with the tessera areas of Ovda, Thetis, Beta, and Phoebe regions.

Extreme high or low altitudes are underrepresented in the population. Areas with lowland characteristics are widespread but occur over relatively well-defined regions with either east-west orientation (Sedna, Niobe, Aino, and Helen) in midlatitudes or as north-south swaths ~30° wide along meridians centered at the longitudes of Eastern Aphrodite (Atalanta, Rusalka, Helen) (165°) and Eistla Regio (Guinevere, Lavinia) (345°).

Although volcanic centers are less abundant in areas of tessera, where there are through-going rifts and zones of extension, volcanic centers are relatively more abundant in tessera settings. In fact, many volcanic centers are clearly associated with regional riftlike patterns of extension. The greatest concentration of volcanic centers, BAT, is characterized by a variety of structural settings, but is mostly situated in a region characterized tectonically by uplift and extension, including that associated with magma emplacement and flank rifting [7,20]. Detailed maps of the location of fracture locations and trends [13], and the sites of several major intersecting rifts [21], show that graben, fractures, fracture belts, and riftlike patterns of extension occur primarily in the Beta-Atla-Themis Regiones and the Alpha-Tellus-Tethys region. We note that these areas of observed high fracture abundance correspond to the areas of greater volcanic center abundance reported here. Major rifts connect the larger volcanic centers within Eistla and Sappho Regiones [20,5], and a network of interlaced fractures connect local concentrations of volcanism to the north and south of Aphrodite Terra.

Geologically, most of the lowland plains appear to be the site of extensive lavas characterized by frequent large lava channels and a mosaic of linear mare-type ridge structural patterns generally interpreted to be the result of tectonic shortening of a few percent over large regions [23]. Ridges of this type are particularly abundant in the extensive lowland plains of eastern Aino and Helen Planitiae, and occur throughout the lowlands of Guinevere, Lavinia, Rusalka, Atalanta, and Snegurochka Planitae. Volcanic centers are also underabundant within the regions of mountain belts where there is evidence of intense shortening and regional compression [3,8,25]. Models for the origin of regional shortening associated with mountain belts include both upwelling and downwelling [16,17,5,1,12,11], but the lowland plains, particularly where ridge belts are common, are most consistent with the characteristics of broad mantle downwelling [27,15]. Therefore, in contrast to areas of high volcanic center density where extension is pervasive, evidence for the sign of the strain in the extreme upper and lower altitudes frequently implies tectonic shortening, and may be associated with regional mantle downwelling.

Coronae, which are thought to represent the sites of intense mantle upwelling [23,24,10,22], are abundant throughout the region of abundant rifting associated with BAT, particularly in Themis Regio. In addition, the area of BAT includes several areas of large positive gravity anomalies thought to represent regions of significant dynamic mantle support and possibly associated with local mantle upwelling [11]. Overall the distribution pattern of coronae and related features may be interpreted as general maps of the global regions of mantle upwelling and surface extension.

Significance of Geologic Correlations: Interior Dynamics, Environment of Formation, or Age? Initial study of these relationships suggests that spatial variations in volcanic center density and global geological and geophysical characteristics are correlated with global structural patterns and styles of tectonism.

On the basis of (1) the observed correlation between areas of high volcanic center abundance and areas with geological evidence for extension and (2) the correlation of areas of low volcanic center abundance and areas with geological evidence for compression, we outline in the following a series of hypotheses for the observed distribution that may be tested.

1. The distribution is governed by the predicted influence of the high gradient in surface pressure with altitude on the occurrence and style of volcanic centers and intrusions on Venus [26]. This suggests that the absence of volcanic centers in lowlands could also be a primary result of the absence of shallow-depth magma reservoirs in lowlands. Shallow magma emplacement is a necessary characteristic of volcanic centers as it regulates the volume and rate of individual magma eruptions in a manner conducive to building local edifices. In the absence of shallow magma reservoirs, eruptions, when they do occur, would be from great depths, and large lava flood events, rather than local volcanic edifices, would be formed. Under this hypothesis, volcanic centers are underabundant in lowlands because the environment of formation does not favor their formation there.

2. Low volcanic center abundance occurs in the plains because these are areas of mantle downwelling. Volcanic centers are excluded from areas associated with mantle downwelling because these are areas of net regional compressional strain and locally cooler mantle. Areas of high volcanic center abundances might be primarily associated with characteristics of mantle upwelling, regional extensional strain, and relatively warmer mantle and associated increased regional partial melt production. The abundance of rifting and coronae in these areas supports this interpretation, but does not address the origin of the observed range in morphology of centers between the plains and uplands.

3. Because the regions of high volcanic center abundance are elevated areas, they are preserved as islands from surrounding lava plains-type flooding events. This hypothesis predicts that the surface where volcanic centers are most abundant should be older on average relative to areas of low volcanic center abundance. Initial correlation of volcanic center frequency with reported impact crater distribution [19,14] suggests that if such a correlation is present it is relatively weak.

Conclusions: On the basis of our initial analysis, we conclude that the observed pattern of volcanic features may be correlated with the distribution pattern of global physiographic and geologic characteristics. The distribution of volcanic centers and regional tectonic patterns suggests that volcanic features are generally excluded from lowlands and regions of tectonic shortening, and occur predominantly in upland regions characterized by geologic evidence for extension. Three hypotheses that may account for the observed distribution and geologic association may be categorized as (1) environment/elevation-related, (2) mantle dynamics-related, and (3) age-related. It is likely that all three influences occur, but on the basis of the global association of areas of high volcanic center abundance with tectonic characteristics of extension and the probable association of many individual volcanic centers with local mantle upwelling and plumes, we believe that the regional concentrations of volcanic centers may be primarily associated with regions of broad mantle upwelling phenomena. Although the broad-scale characteristics and association of the distribution of volcanic centers may be accounted for by the first hypothesis, details of the distribution and local associations may be strongly influenced by altitude and age-dependent effects.

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THE SPIN VECTOR OF VENUS DETERMINED FROM MAGELLAN DATA.

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A control network of the north polar region of Venus has been established by selecting and measuring control points on full-resolution radar strips. The measurements were incorporated into a least-squares adjustment program that improved initial estimates of the coordinates of the control points, pole direction, and rotation rate of Venus. The current dataset contains 4206 measurements of 606 points on 619 radar strips. The accuracy of the determination is driven by spacecraft ephemeris errors. One method used to remove ephemeris errors is to adjust the averaged orbital inclination and argument of periapsis for each orbit. A more accurate method that has been used with selected blocks of orbits incorporates optimally fitting measurements of additional points at all latitudes of the radar strips together with Earth-based spacecraft radiometric tracking measurements to compute new spacecraft ephemerides. The root-mean-space (RMS) of the point measurement residuals in these improved ephemeris solutions is typically about 20 m in slant range, and 40 m in the along-track direction. Both the control network computations and the improved ephemeris solutions incorporate radii at the measured points derived from the Magellan altimetry dataset [1]. The radii of points north of 85° are computed in the least-squares adjustments.

An accurate estimate of the rotation period of Venus was obtained by applying the ephemeris improvement technique to the second cycle closure orbits 2166–2171 that overlaid the first cycle initial orbits 376–384. Sixty-four common points were measured on both orbit groups and improved ephemeris solutions computed over both blocks simultaneously, along with the rotation rate. A similar analysis was made using orbits 874–878 from cycle 1 and 4456–4458 from cycle 3. Fifty-two common points were measured on both orbit groups and the rotation period of 243.0185 ± 0.0001 was computed. This latter solution confirmed the initial solution, and was an improvement over the first closure solution because of the longer period between overlapping orbits.

The geodetic control network uses measurements of points on overlapping radar strips that cover the north polar region; these are only the even-numbered orbits. These strips were taken in the first cycle and encircle the pole except for three gaps due to the superior conjunction data loss, the reduced data due to occultation, and the area of ongoing work. Improved ephemeris solutions for 40 orbits (376–384, 520–528, 588–592, 658–668, 1002–1010, 1408–1412, 1746–1764, and 2166–2170) are included and fixed in the geodetic control computations, thus tying the network to the J2000 coordinate system. The argument of periapsis and orbital inclination of all remaining orbits were allowed to vary as part of the least-squares adjustment. The RMS of the point measurements is typically on the order of 75 m in both along-track and cross-track. The rotation period was fixed at 243.0185 days. The coordinates of the 606 measured points were determined and the solution for the direction of the north pole was $\alpha = 272.76° \pm 0.02°$, $\delta = 67.16° \pm 0.01°$ (J2000).

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MONTE CARLO COMPUTER SIMULATIONS OF VENUS EQUILIBRIUM AND GLOBAL RESURFACING MODELS.

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Two models have been proposed for the resurfacing history of Venus: (1) equilibrium resurfacing and (2) global resurfacing. The equilibrium model [1] consists of two cases: In case 1 areas ≤0.03% of the planet are spatially randomly resurfaced at intervals of ≤150,000 yr to produce the observed spatially random distribution of impact craters and average surface age of about 500 m.y., and in case 2 areas ≥10% of the planet are resurfaced at intervals of ≥50 m.y. The global resurfacing model [2] proposes that the entire planet was resurfaced about 500 m.y. ago, destroying the preexisting crater population and followed by significantly reduced volcanism and tectonism. The present crater population has accumulated since then, with only 4% of the observed craters having been embayed by more recent lavas.

To test the equilibrium resurfacing model we have run several Monte Carlo computer simulations for the two proposed cases. For case 1 we used a constant resurfacing area of 0.03% of the planet with a constant thickness and a constant 150,000-yr time interval