TWO GLOBAL CONCENTRATIONS OF VOLCANISM ON VENUS: GEOLOGIC ASSOCIATIONS AND IMPLICATIONS FOR GLOBAL PATTERN OF UPWELLING AND DOWNWELLING; L.S.CRUMPLER and J.C.AUBELE, Department of Geological Sciences, Brown University, Providence, RI 02912

INTRODUCTION. The global patterns of volcanism on Venus derived from a global survey and cataloging of volcanic features from Magellan data indicate that the distribution of large volcanoes, coronae, arachnoids, shield fields, calderas, intermediate volcanoes, novae, lava floods, and lava channels is non-random [1]. Volcanic centers are significantly concentrated in two broad clusters occurring in low latitudes. In this paper we examine the observed distribution and concentration of volcanic centers and related volcanic features and assess their correlations with other global geological and geophysical characteristics. We conclude that the observed pattern of volcanic features are reflected in the global distribution of geologic and geophysical characteristics. The observed arrangement between volcanic features and tectonic features may reflect global-scale patterns of mantle upwelling and downwelling.

ANALYSIS OF DISTRIBUTION. Global maps of the location of volcanic features of all types [2] reveal a large concentration of volcanic centers in the broad region between Beta, Atla, and Themis Regions and smaller areas of similar concentration scattered between Alpha, Tellus, and Tethus Regions. Volcanic centers are also infrequent relative to the global average over large areas in the lowland plains [3].

Between 70 and 80 % of the observed total population of large volcanoes, coronae, and shield fields each occur within less than one-half of the surface area. For each type, chi-square analysis shows the probability that the observed patterns are the results of a random distribution is vanishingly small. Together the areal number density of large volcanoes, coronae, arachnoids, shield fields, calderas, intermediate volcanoes, and novae is greatest near the equator and attains moderate spatial densities (>5 centers /10^6 km^2) in a concentrated region at least 12,000 km in diameter centered near longitude 250° ["BAT";3]. Smaller areas <3000 km across of greater density (>10 centers /10^6 km^2) occur within this cluster. Areas of moderate to low density occur elsewhere in the equatorial regions, notably in the opposite hemisphere centered near longitude 70°. Initial global assessments of the relative areas over which differing densities are attained show that volcanic centers occur at low densities of <2 centers /10^6 km^2 over approximately 30% of the surface area. Moderate densities of >2 to 5 centers/10^6 km^2 occur over 38% of the surface area, and high densities between 5 to 10 centers /10^6 km^2 occur over 32% of the surface area. Areas with greater densities occur over less than 3% of the surface.

A general equatorial-concentrated arrangement of volcanic centers is also supported by analysis of the inertial tensor in which each of the 1500 volcanic features is treated as a point mass, the corresponding inertia matrix diagonalized, and solved for the principal axes of the observed distribution (similar to that used previously for hot spots on Earth [4]): on the basis of this type of analysis, volcanic centers are concentrated in at least one and possibly two areas centered on the equator and their principal axis is near the current rotational pole. The significance and potential origins of a relationship between the location of areas of greatest volcanic feature density and the rotational inertial axes is being further investigated.

Areas of low density (fewer than 2 centers/10^6 km^2) occur in two characteristic areas: (1) tessera and (2) along the meridians centered at longitudes 165° and 345° in a north-south swath 20 to 30 degrees wide (where it crosses the equator) (southern latitudes covered by Arecibo [5]). The volcanic features are rare within tessera, and where tessera occur within areas of high regional volcanic center concentrations, the tessera areas are manifest as vacant areas within the distribution. The low frequency occurrence along the 160° and 340° meridians defines a north-south oriented swath (between the two hemispheres centered at -70° and -250°) along which there are relatively few volcanic centers. Volcanic centers occur in this region mainly where it intersects the equatorial highland trend in the area between Beta and Eistla Regiones and in the area of eastern Aphrodite Terra (Dali Chasma). Assuming an arc width of 30°, the area of this swath is ≤30% of the global area, or more than sufficient to account for most of the observed global area (29%) where densities are low. On the basis of the observed characteristics of cluster distribution, number density, spatial patterns of areas of differing density, and the intervening, meridional characteristic of the area of low number density, we identify two fundamental global groupings of volcanic centers on Venus each approximately 120° to 140° across: (1) a large moderate-density concentration (Beta-Atla-Themis, "BAT") is centered at longitude -250° and (2) a patchwork region of moderate number density (Alpha-Tellus-Tethus, "ATT") centered at longitude -70°. These are divided along a great circle swath along which volcanic centers are infrequent.

GEOLOGICAL/GEOPHYSICAL ASSOCIATIONS. Initial study of these relationship between the global spatial variations in volcanic center density and global geological and geophysical characteristics suggest that variations in intensity of volcanism may be correlated with global structural patterns and styles of tectonism. Combined the observed correlations between the density of volcanic centers and the observed tectonic and geophysical characteristics may provide some insights into global interior processes.

Areas with large concentrations of volcanism occur in a variety of detailed structural settings, but are generally associated with regional characteristics of tectonic extension. Many large volcanoes, intermediate volcanoes, calderas, arachnoids, coronae, novae, and shield fields are clearly associated with regional rift-like patterns of extension in
addition to local uplift and extension associated with magma emplacement and rifting [6]. The Beta-Arla-Themis concentration [3] is characterized by one of the largest identified concentrations of graben, fractures, and rift-like patterns of extension, including the site of several major intersecting rifts [6]. Large positive gravity anomalies are characteristic throughout this region and may be related to a more buoyant local mantle [7], corresponding regional uplift, and intense crustal extension. Many of the volcanic features, such as coronae, are thought to represent the sites of intense mantle upwelling [8], and overall the distribution pattern of coronae and related features may be interpreted as general maps of the global regions of mantle upwelling [1]. Individual concentrations within the Alpha-Tellus-Tethus grouping, in the opposite hemisphere are also the site of predominantly extensional fractures and rifts. Major rifts connect the larger volcanic centers within Eistla and Sappho Regiones [9,10], and a network of interlaced fractures connects local concentrations of volcanism to the north and south of Aphrodite Terra. The areas of greatest density of volcanic centers are also areas of greater fracturing and faulting.

Based on global distribution maps of all volcanic features, areas of low volcanic center density include, in addition to tessera and highlands, areas of lowland plains [1,2] and ridge belts. Geologically, most of the lowland plains appear to be the site of extensive lavas and frequent large lava channels, and a mosaic of linear structural patterns indicative of minor tectonic strain over broad regions. Evidence for the sign of the strain frequently implies shortening, in contrast to areas of high volcanic center density where extension is more pervasive. This includes abundant ridges analogous to mare ridges which are interpreted to be the result of tectonic shortening of a few percent over large regions. Mare-type ridges of this type are particularly abundant in eastern Aino and Helen Planitiae, but occur throughout the lowlands of Guinevere, Lavinia, and Rusalika, and Snegurochka Planitiae. Volcanic centers are also generally absent from the regions of mountain belts where there is evidence of intense shortening and regional compression [11]. Models for the origin of regional shortening associated with mountain belts include both upwelling and downwelling [12], but the lowland plains, particularly where ridge belts are common, are generally thought to represent regions of broad mantle downwelling [12].

**IMPLICATIONS OF ASSOCIATION.** The observed distribution pattern of volcanic centers and regional tectonic patterns suggest that volcanic features are generally excluded from lowlands and regions of tectonic shortening, and occur predominantly in upland regions characterized by geologic evidence for tectonic extension. Two fundamental geologic associations may be defined: (1) the areas of shortening tend to follow the global distribution of regions of low volcanic density within a meridional swath along longitudes 340° and 160° and equidistant from two regions of high volcanic center density (BAT and ATT), and (2) the areas of extension tend to occur within these two hemispheric regions of high volcanic center density. The abundance of geologic and geophysical characteristics associated with mantle upwelling within the areas of the two global concentrations implies that these are regions of broad mantle upwelling. Similarly, the evidence for mantle downwelling in a great circle swath corresponding to areas of low volcanic densities implies that the regions equidistant from the global concentrations are regions of broad mantle downwelling.

A simple large-scale pattern of broad mantle upwelling may characterize the two hemispheres of Venus in which downwelling occurs in the great circle swath between the two hemispheres. Although local upwelling and downwelling may be distributed widely and occur in association with local and regional mantle instabilities, at a global scale and to first order the general tectonic patterns of Venus may be influenced by two fundamental areas of broad mantle upwelling and associated peripheral downwelling.


**Figure 1.** Global map showing observed areal number density of all cataloged volcanic features on Venus. Areas with < 2 volcanic centers/10⁶km² are shaded. 90% of all volcanic centers are encompassed within the two outlined areas. Contours: 2.5, 5, and 10/10⁶km².