A CRUSTAL SPREADING/MANTLE PLUME MODEL FOR THE TECTONICS OF VENUS; James W. Head and Larry S. Crumpler, Department of Geological Sciences, Brown University, Providence, RI 02912

On the basis of recent regional analyses there is evidence for a variety of characteristics and processes operating on the surface of Venus including crustal spreading, zones of convergence and possible crustal loss, latitudinal variation in styles of tectonism and volcanism, major horizontal movement and deformation of the crust, a relatively young age for the surface, and large-scale mantle upwelling, or mantle plumes (1-13; reviewed in 18). On the basis of these characteristics and interpretations, we propose that a model in which crustal spreading and superposed Icelandic-like mantle plumes associated with the crustal spreading process (1) (Fig. 1) dominate much of the Equatorial Highlands and can account for many of the regional and global characteristics outlined above.

Crustal Spreading: Crustal spreading at Aphrodite Terra is interpreted from linear cross-strike discontinuities (CSDs) thought to represent fracture zones, which segment Aphrodite into domains characterized by bilateral symmetry parallel to the linear discontinuities. The centers of symmetry of the domains have central depressions and form linear rises that are oriented normal to the CSD's, terminate against them, and are offset at them in an en echelon manner (1), in patterns comparable to spreading centers in the Earth's ocean basins. On the basis of these data and analysis of topographic profiles, Eastern Aphrodite Terra appears to be the site of spreading at the present time at rates of the order of 1.5-3 cm/yr (1,3). Analysis of the nature of the process of crustal spreading in the Venus environment indicates that the enhanced upper mantle temperature (about 1500°C) caused by high surface temperature should result in a crustal thickness of about 15 km, a factor of 2-3 greater than that for the Earth (2). Material formed at the rise crest and moved laterally would become lower topographically as it cooled and would be modified by subsequent volcanism and tectonism (Fig. 1).

Mantle Plumes and the Formation of 'Plume Plateaus': Localized plateaus along the Equatorial Highlands, such as Ovda and Thetis Regiones, are interpreted to be the site of elevated upper mantle temperatures, enhanced melting, and greater crustal thicknesses (2) (Fig. 1). Specifically, these Iceland-like plateaus could be formed by increased upper mantle temperatures of about 100°C, which would produce a 30 km thick crust characterized by an increase in isostatically supported elevations of about 1.5 km (2). Models of Ovda Regio that are consistent with both topography and gravity data suggest that such a process is plausible, with upper mantle temperatures of about 1600°C and spreading rates of about 1 cm/yr (2). The most likely mechanism for the enhanced upper mantle temperature is a localized upwelling of the mantle, and the geometry of the plateaus suggests that it may be a mantle plume or 'hot spot' similar to the one thought to underlie the Icelandic plateau (14).

Evolution of 'Plume Plateaus': Cessation of the enhancement of upper mantle temperature at the site of a mantle upwelling or hot-spot would return the spreading environment to a more normal condition of spreading (if nominal, to a crustal thickness of about 15 km, and isostatically compensated topography of 1-1.5 km less than previously). In this case continued spreading would split the 'plume plateau', separate it, and move it laterally off the thermal rise into the adjacent lowlands at rates comparable to the spreading rates (Fig. 1) (15). Although the split and separated plateau would become topographically lower as it evolved thermally, its enhanced crustal thickness and its correspondingly increased isostatic topography, would result in the plateau remaining elevated above the adjacent surrounding plains by an amount related to crustal thickness variations. The plateaus in the northern high latitudes characterized by the sea-floor-like trough-and-ridge tessera (such as Laima Tessera) (16) are interpreted to be remnants of thick crust originally created at rise crests ('plume plateaus') and transported laterally to their present positions.

Relationship to Observed Gravity Data: Variations in the apparent depth of compensation (ADC) along the Equatorial Highlands are observed and there are correlations between characteristic gravity values and style of geologic structure (16) in the Equatorial Highlands. Most workers conclude that the characteristics and magnitude of the gravity anomalies require dynamic support mechanisms and mantle upwelling or hot-spots are common interpretations of these data (13). In a specific analysis of the Ovda Regio portion of Aphrodite Terra, where an Iceland-like plateau is superposed on the linear rise crest interpreted to represent a spreading center (1), it was shown that the apparent depth of compensation can be interpreted as a consequence of both a thicker crust and elevated upper mantle temperatures beneath the plateau in a crustal spreading environment (2) (Fig. 1).

Our model proposes to account for the observed gravity data through a combination of crustal spreading and mantle upwelling (Fig. 1). Normal crustal spreading on Venus would be characterized by buoyant rise of mantle material, and correlation of gravity and thermal topography at relatively short wavelengths. From time to time, plumes rise from mantle depths below the spreading center. In general, the buoyant diapirs ascend as blobs which decelerate, collapse, and flow out laterally as they approach the viscous lid. The ascending plumes begin to influence the crustal spreading environment through thermal uplift and increased melting to produced thickened crust. As the plume impinges on the viscous lid and flows out laterally, an Iceland-like 'plume plateau' of thickened crust forms with part of its altitude resulting from thermal uplift. As the plume collapses, the plateau continues to grow and move laterally through crustal spreading processes until the sub-spreading center region returns to normal upper mantle temperatures. Subsequent to this, thin crust is again produced at the spreading center, and the 'plume plateau' of thickened crust is split and moved laterally away. These various stages would be characterized by different apparent depths of compensation, contributions to which include dynamic factors (depth, temperature, and geometry of the mantle plume), and static factors (variations in crustal thickness), among other things. Outside of the Equatorial Highlands the correlation of gravity and topography and the magnitude of the gravity anomalies is often not as great (12). For example, some of the plateaus of tessera terrain (e.g., Tellus, Laima, Alpha) appear to be characterized by small anomalies and relatively shallow depths of compensation (12). We interpret these examples to be consistent with the shallow compensation expected from Icelandic-like 'plume plateaus' of thickened crust that have been formed at rise crests and moved laterally off the rise to adjacent lowlands.

Summary: In summary, a crustal spreading/mantle plume model for the tectonics of the Equatorial Highlands (Fig. 1), in which crustal spreading is accompanied by waxing and waning of a number of mantle plumes of varying magnitude and age along the rise crest, appears to be consistent with the major features of geology, topography, and gravity. Terrestrial spreading processes extrapolated to Venus predict that the nominal crust would be about 15 km thick (2), and that enhancement of upper mantle temperatures by about 100°C at hot spots would produce a doubling of crustal thickness to about 30 km, and an isostatically compensated plateau of thicker crust standing about 1.5 km above the surrounding plains.

Thus, crust formed and moved laterally away from the spreading centers should be relatively constant in thickness except where 'plume plateaus' are formed at hot spots. This relatively constant crustal thickness may help to explain the general unimodal nature of the Venus hypsometry. Spreading rates in the range of 1-3 cm/yr predict a relatively young average age for the surface, well within the range of that observed (10,11). Processes of crustal loss must be occurring if crust is being formed and moved laterally at these rates. Regions of compressional deformation (6) and orogenic belts (5) with adjacent foredeeps of possible flexural origin (6) may be sites of crustal underthrusting, possible subduction, and crustal loss. Plateaus of trough-and-ridge tessera terrain are interpreted to be 'plume plateaus' which represent crust of enhanced thickness created at hot spots and moved laterally away from active spreading centers. Larger accumulations of complex tessera (such as Fortuna Tessera) may represent accretion and deformation of several smaller plateaus of thicker crust which undergo crustal shortening and loss less readily than thinner crust (8). Lack of information about the detailed nature of tectonic zones over the whole of Venus precludes the determination of the global distribution of different types of boundaries associated with crustal spreading and crustal loss and the total length and significance of this process, although Aphrodite Terra alone is about one-third the total length of crustal spreading centers observed on Earth at present. Simple geometric considerations as well as consideration of poles of rotation for Aphrodite Terra (3) indicate that spreading must be more complex than simple equatorial extension and poleward spreading. Nonetheless, the fundamental geologic, topographic, and gravity characteristics of the Equatorial Highlands strongly suggests that they represent a rather basic pattern of mantle upwelling and circulation.

The presence of the Equatorial Highlands, their dominance of the global topography (17), the gravity data, and the relatively larger number of apparent mantle plumes and hot-spot plateaus in the Equatorial Highlands relative to the Earth, are all factors which suggest that crustal spreading processes on Venus may be more closely linked to large-scale mantle convection than on the Earth.

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Fig. 1. Schematic block diagram illustrating the structure and topography associated with the crustal spreading/mantle plume model.