MANTLE VISCOSITY AND FLOW GEOMETRY: IMPLICATIONS FOR SURFACE MOTIONS ON VENUS, Walter S. Kiefer (Code 921, Goddard Space Flight Center, Greenbelt, Md 20771; 301-286-6412; kiefer@ltpsun.gsfc.nasa.gov)

Mantle convection is an important process on both Earth and Venus. One type of convective motion, upwelling plumes with approximately axisymmetric planforms, produces at least some terrestrial hotspots and is also the most likely mechanism for producing the Equatorial Highlands on Venus [1,2]. In addition to plumes, other types of convective flow may also be important. On Earth, plumes carry only a small fraction of the total mantle heat flow [3,4], with heat flow being dominated by plate-scale flow. On Venus, convective modes other than plumes probably also occur but have not yet been explicitly identified. Modeling of the geoid anomalies and topographic uplifts produced by mantle convection has demonstrated that Venus and Earth have significantly different viscosity structures as a function of depth in the mantle, with Venus lacking an Earth-like low viscosity asthenosphere [1,2,5-7]. Here, I examine how variations in mantle viscosity structure and flow geometry may affect the possible existence of surface motions driven by convective flow on Venus.

Effect of Asthenospheric Viscosity on Surface Velocities

It has sometimes been suggested that the surface of Venus behaves as a rigid or nearly rigid boundary, with a surface velocity that is essentially zero [8,9]. The presence of a low viscosity asthenosphere has been proposed to be important in maintaining plate tectonics on Earth [10] and the apparent absence of an asthenosphere on Venus has been suggested as a mechanism for preventing significant surface motions on Venus [11,12]. Although the presence of a low-viscosity asthenosphere will tend to partially decouple the flow in the top boundary layer from flow in the deeper mantle, some coupling will nevertheless occur. Thus, it is inappropriate to simply balance the driving force due to boundary layer thickening against a resisting shear stress in the asthenosphere; the full viscosity structure must be explicitly considered.

In order to quantitatively assess the effect that varying the asthenosphere's viscosity has on surface velocities, I have begun a series of finite element calculations using a two-dimensional, Cartesian geometry convection code [13]. These models use a high viscosity near-surface layer to simulate the effect of temperature-dependent rheology in the thermal boundary layer. Low viscosity "weak zones" are imposed at the ends of the convection cell to simulate weakening at plate margins by non-viscous effects such as faulting and partial melt formation. Such weak zones have been commonly used in prior studies of plate-like convective flow [14-16]. If some type of weakening at plate boundaries is not included in the model, so that the high viscosity lid is laterally continuous across the entire convection cell, then the surface velocity will be quite low [14-16]. The observed plate motions on Earth demonstrate that faulting at plate boundaries can produce weak zones on a planet with a moderately thick elastic lithosphere. Numerical modeling of convection with a non-Newtonian rheology has demonstrated that weak zones can form also in a self-consistent manner in a purely viscous rheology [16]. With a high surface temperature, Venus must have a thin elastic lithosphere and should therefore be intermediate in behavior between the Earth and purely viscous models. It is therefore plausible that weak zones may also form on Venus.

Initial results indicate that if a low viscosity layer extends throughout the entire upper mantle, then for a fixed lower mantle viscosity, varying the the upper mantle viscosity between 0.01 and 1 times the lower mantle viscosity changes the peak surface velocity by only a factor of about 4. This change in velocity is due at least in part to changes in the effective Rayleigh number as the upper mantle viscosity is varied. If the average viscosity of the convecting layer is held fixed, then varying the upper mantle-lower mantle viscosity ratio should have a smaller effect on the surface velocity. More detailed modeling is presently underway to assess this. Based on presently available results, it appears that the likely differences in viscosity structure in the upper mantles of Venus and Earth should not prevent the occurrence of geologically significant (> 1 cm/yr) surface motions on Venus.

Effect of Mantle Flow Geometry on Surface Velocities

In order to assess the effects of convective planform on the surface velocity, a companion series of calculations has been run using a cylindrical axisymmetric finite element convection code [17]. For isoviscous models, Cartesian and axisymmetric geometries give similar peak surface velocities. However, for models with high viscosity surface layers, the two geometries behave quite differently. In cylindrical geometry, if a high viscosity lid is imposed, then the radial velocity within the lid region is always much less than for the isoviscous case, regardless of the size or viscosity of the weak zones. For cylindrical axisymmetric geometry, the azimuthal strain-rate is given by $\dot{\varepsilon}_{\phi\phi} = \frac{v_r}{r}$, where v_r is the radial velocity and r is the distance from the axis of the cylinder. High viscosity implies that the strain-rate must be small, which in turn implies that the radial velocity must also be small. Thus, an isolated plume is unable to drive significant surface motions. $\dot{\varepsilon}_{\phi\phi}$ takes a similar form in spherical axisymmetric geometry, so similar arguments should apply in that case as well. On the other hand, the strain-rate tensor for Cartesian geometry depends only on velocity derivatives rather than directly on the velocity, so this argument does not apply in Cartesian geometry. Although individual plumes can not drive substantial surface motions, if several plumes are closely spaced along a single line, then the overall flow geometry will depart significantly from axisymmetry, which should allow substantial surface motions to occur.

Discussion

The convective velocity at the surface of Venus is not strongly controlled by the depth-stratification of viscosity within its mantle. Instead, the possible existence of non-zero surface velocities hinges on the existence of convection cells with the appropriate planform and of weak zones at the boundaries between convection cells. Magellan observations of tectonic and volcanic provinces may be useful in outlining convective planforms and in looking for evidence of weak zones at cell boundaries. If significant convective flow velocities do occur at the surface of Venus, because of its thin elastic lithosphere, Venus may still lack the rigid plate motions that characterize terrestrial plate tectonics. Instead, it may exhibit "diffuse deformation" [18] in a style that more nearly resembles continental tectonics on Earth [19]. Indeed, features such as the Ishtar Terra mountain belts, the Atalanta Planitia ridge belts, and the various tessera are all consistent with the existence of diffuse deformation.

If significant convective velocities extend to the surface, one way to look for them is to look for hotspot tracks [20]. Although no clear-cut hotspot tracks are evident in pre-Magellan data, some possibilities can at least be suggested. One is the apparent north to south age progression in volcanic activity from Rhea Mons to Theia Mons in Beta Regio [21]. A more speculative possibility is that the northwest trending topographic high from Ozza Mons to Nokomis Montes in Atla Regio [22] is a hotspot track, although Magellan imagery will be needed to ascertain the true nature of this feature.

References

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