Mantle Flow Tectonics and a Weak Lower Crust: Implications for Formation of Large-scale Features on Venus. D.L. Bindschadler and E.M. Parmentier, Brown University Dept. of Geological Sciences, Providence, RI 02912

One model for Venus tectonics is the formation of large-scale topographic uplands such as Beta Regio, Ishtar Terra, and Aphrodite Terra as a consequence of convective flow in the interior [1-3]. Such models do not consider the presence of a weak lower crustal layer, although experimental flow laws predict that the crust of Venus is likely to be ductile at depths of more than a few km. A model for mantle flow tectonics which includes such a crustal layer demonstrates that significant horizontal deformation can occur within the crust, and allows us to predict topography, crustal thinning or thickening, and timescales of deformation [4]. Here we briefly describe the model, then consider potential implications for the evolution of large-scale features on Venus

Model: We treat the crust and mantle as a layered linear viscous halfspace containing a density discontinuity (the crust-mantle boundary). Elastic layers can be included to represent brittle portions of the crust and mantle. Effective linear viscosities are based on diabase and olivine flow laws for the crust and mantle and vary as functions of depth-dependent temperature. Flow is driven by a harmonic mass sheet at a prescribed depth within the halfspace. For time-invariant flow, we calculate surface relief and crustal thickness changes as functions of time (Fig. 1).

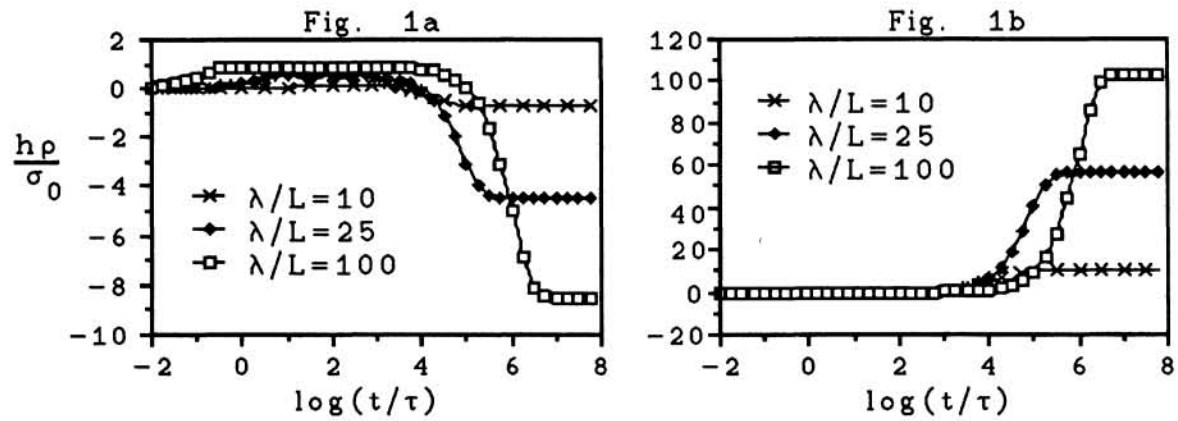

Fig. 1) (a) Surface height and (b) crustal thinning as functions of time for three wavelengths of flow (λ) at depth. Height and thinning are scaled to σ_0, the amplitude of the driving force at depth. This model consists of crustal thickness L=30km and thermal gradient = 10°C/km. At strain rate=10^{-15}sec^{-1}, mantle and lower crust viscosities are ~10^{20} and ~10^{21} Pa-sec. One unit of time is ~1000 years, so ~10^7 years are needed before crustal thinning begins at λ=25L. Larger crustal thicknesses and higher thermal gradients significantly reduce times required for crustal thinning.

The above plots are for mantle upwelling but apply to downwelling if the sign is changed on the vertical axes. Times are scaled to $\tau = 2\mu/\rho gL$, where μ is mantle viscosity. Upwelling first causes crustal uplift (Fig. 1a), without significant change in thickness (Fig. 1b), while downwelling causes crustal subsidence. If upwelling continues, however, crustal thickness decreases (Fig. 1b) and the surface begins to subside (Fig. 1a). Thinning is driven by (1) body forces and the tilted geometry of the surface and crust-mantle boundary [4,5], and (2) by shear coupling of mantle flow into the crust, forcing surface subsidence [4]. In a complementary fashion, downwelling results in crustal thickening and uplift of the surface. Thinning or thickening proceeds until a steady state is reached. The degree of steady-state crustal attenuation or thickening depends on the characteristic size and depth of the source of mantle flow, variations in viscosity within the crust and upper mantle, and the presence and extent of brittle layers in the upper crust and upper mantle [4].

Application to Features on Venus: The most direct application of this mantle flow tectonics model is to domelike uplift regions [6] such as Beta and Bell Regiones. In addition to topographic effects, a long-lived upwelling should result in surface deformation beginning with flexural graben due

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to uplift and proceeding with either localized (rifting) or distributed surface manifestations of crustal thinning. Crustal attenuation may also result in pressure-release melting of mantle material, and subsequent intrusion and volcanism. Beta Regio has long been suggested to be related to dynamic effects in the mantle, as evidenced by its extreme depth of Airy compensation (~300 km [7,2]). The presence of Devana Chasma is consistent with the beginnings of extension [8,9] and crustal thinning. The lack of a large rift zone in Bell may reflect a younger age for this feature. Both regions are characterized by large volcanic constructs and plains volcanism.

Compressional deformation is manifested in western Ishtar Terra in the banded terrains of Akna, Freyja, and Maxwell Montes and Vesta Rupes [6,10] which encircle the volcanic plains of Lakshmi Planum. Long-term mantle downwelling causes initial subsidence, but continued downwelling would be expected to result in compression and high topography as shown below.

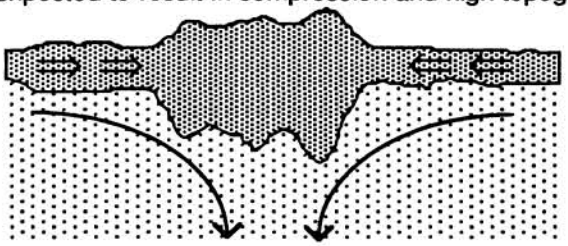

Fig. 2) Sketch representing possible long-term effects of mantle downwelling. High topography is prevented from relaxing by shear stresses imposed at the base of the crust.

An interesting possibility is that warming of an initially cool, thickened crust could result in basal melting and volcanism. Finally, the cessation of downwelling should lead to relaxation of the thickened crust, lowering of surface topography, and extensional deformation [11,12]. If the topography and deformation in western Ishtar are due to mantle flow and basal melting has created the Planum surface, this region is older than Beta or Bell since more crustal strain has occurred (Fig. 1). Regions of tessera bound all of the banded terrain [6], and we note that one implicit prediction of this model is that crustal deformation increases with time. Increasing deformation may result in transformation of banded terrain to particular subtypes of tessera [13]. Mantle downwelling thus represents a useful working hypothesis for the formation of the banded terrains that surround Lakshmi Planum and related tessera, and is one of several currently being evaluated for the tessera [14].

Models for Aphrodite Terra include crustal divergence [15] and mantle hotspots [16]. In the context of this model, it may represent an evolved Beta Regio. Consider the case in which crustal attenuation due to upwelling ceases at a finite crustal thickness. If partial melting occurs, intrusion of melts then tends to underplate and thicken the crust, forcing further extension and additional intrusion. The subsurface nature of such a "spreading" center may have significant consequences for its basic morphology in comparison to terrestrial spreading centers. An additional possibility is raised by the steep topographic slopes and the unusual small-scale surface roughness properties of Ovda and Thetis Regiones [17], characteristics more similar to tessera than to Beta-like regions [9]. Like tesserae, Aphrodite might be a relaxational remnant of mantle downwelling, with the large chasmata explained as features of relaxation. Further modeling to delineate the conditions under which each of these various processes could occur, as well as additional observations may help to more closely constrain the range of probable hypotheses.

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