Buoyant Subduction on Venus: Implications for Subduction Around Coronae

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Potentially low lithospheric densities, caused by high Venus surface and perhaps mantle temperatures [1], could inhibit the development of negative buoyancy-driven subduction and a global system of plate tectonics/crustal recycling on that planet [2]. No evidence for a global plate tectonic system has been found so far, however, specific features strongly resembling terrestrial subduction zones in planform and topographic cross-section have been described, including trenches around large coronae and chasmata in eastern Aphrodite Terra [3,4,5]. The cause for the absence, or an altered expression, of plate tectonics on Venus remains to be found. Slab buoyancy may play a role in this difference, with higher lithospheric temperatures and a tendency toward positive buoyancy acting to oppose the descent of slabs and favoring underthrusting instead. This study seeks to explore the effect of slab buoyancy on subduction and to define the conditions which would lead to underthrusting versus those allowing the formation of trenches and self-perpetuating subduction. Applying a finite element code to assess the effects of buoyant forces on slabs subducting into a viscous mantle, we find that mantle flow induced by horizontal motion of the convergent lithosphere greatly influences subduction angle, while buoyancy forces produce a lesser effect. Induced mantle flow tends to decrease subduction angle to near an underthrusting position when the subducting lithosphere converges on a stationary overriding lithosphere. When the overriding lithosphere is in motion, as in the case of an expanding corona, subduction angles are expected to increase.

An initial stage of this work [6] involved estimating the changes in slab buoyancy due to slab heating and pressurization over the course of subduction. Modelling a slab, descending at a fixed angle and heated by conduction, radioactivity, and the heat released in phase changes, slab material density changes due to changing temperature, phase, and pressure were derived. In brief, slabs were found to remain positively buoyant until they had penetrated to a depth of 250 to 300 km. Thus, during the early stages of subduction, slabs must overcome positive buoyancy forces to achieve net negative buoyancy and promote self-sustained subduction. The rate at which buoyancy forces can force a slab to rise through a viscous mantle may be important in determining the slab fate.

To understand better the effects of buoyancy on slab descent a finite element code was applied to a simplified model of a slab subducting into a viscous mantle. The model consists of a lithospheric slab descending at an initial 45 degree angle into the mantle. The density structure includes a basaltic crust and peridotite mantle, with the basalt-eclogite phase change applied at a depth of 100 km. The complexities of density variation due to pressure and temperature were ignored. The depleted mantle layer, the mantle residue remaining after crustal material was removed by partial melting, was also not included. Its low density relative to the undepleted mantle would add somewhat to the positive buoyancy of the slab. Buoyancy forces appropriate to the crustal thickness were applied, using basaltic densities above the basalt-eclogite phase change, and eclogite densities below. The mantle and slab materials differ in viscosity by a factor of 100. The convergence velocity was imposed where the slab enters the mantle and horizontally along the surface of the model as a surface boundary velocity. Meanwhile, horizontal velocities were set to zero beneath the stationary overriding lithosphere. Side boundary conditions were imposed to allow passage of material into and out of the model region, while a zero shear stress condition was used at the bottom boundary. Changes in the subduction angle were then estimated as the slab lengthened according to the convergence rate.

Figure 1 illustrates the mantle flow pattern resulting from this model. Generally, the flow shown proceeds from right to left in concert with the convergent lithospheric motion at the surface. Horizontal lithospheric motion appears to cause this mantle flow. The slab partially deflects the mantle flow, but, impinging on the slab base, the flow causes the subduction angle to decrease. While positive slab buoyancy also has the effect of decreasing the subduction angle, the mantle flow induced by the horizontal motion of the lithosphere at the surface dominates.

Figure 2, plotting slab length against subduction angle, shows the effect over time of the mantle flow on the subduction angle. Starting with a 50 km slab initially dipping 45 degrees, the graph shows the angle decreases rapidly, reaching a minimal value near 15 degrees within 15 to 20 million years. This result appears consistent for a range of subduction rates and crustal thicknesses. The significance of the minimum angle is uncertain, but it may represent the diminishing influence of mantle flow as the slab profile shrinks. Slab buoyancy alone has a lesser effect, yielding a similar decrease in the subduction angle, but over a longer time span. Thus, it appears that mantle flow induced by the horizontal motion of the converging lithosphere at the surface dominates in governing the changing angle of subduction.

Two consequences derive from this result. First, a slab must subduct much further, to lengths near 1000 km, over a much longer time, before negative buoyancy is attained. Second, mantle flow induced by the convergent motion of the slab will reduce the subduction angle and force the slab into a nearly underthrusting position. In order for subduction to become self-sustained through the negative buoyancy of the slab, other means may be necessary to mitigate or eliminate the effects of the induced mantle flow. These means might include the attachment of a slab to a deepening crustal root which, upon becoming negatively buoyant itself, delaminates and sinks taking the slab with it. Another alternative is presented by the case of subduction on the periphery of a corona.

In the model of Sandwell and Schubert [3], a radially expanding corona may override the lithosphere on its border and cause that lithosphere to subduct. In this scenario the overriding lithosphere of the corona is moving horizontally while the subducting material sinks vertically. This contrasts with the situation given in the model where the overriding lithosphere remains stationary and the subducting material first converges horizontally before descending. This would lead to a reversal of the induced flow in the mantle and cause it to impinge on the upper side of the slab. Due to the apparent dominance of the effects of mantle flow over buoyancy forces, increasing subduction angles may be favored despite positive buoyancy in the subducting slab. This enhances the tendency of the slab to reach negative buoyancy. Thus, in the case of subduction resulting from corona growth, self-perpetuating subduction may be possible leading to further corona expansion.

In the case of overturn initiated by a growing negatively buoyant lithosphere [7] or depleted mantle layer [8], the negative buoyancy of the slab guarantees continued subduction. If, in these cases, appreciable horizontal movement and convergence of lithosphere were to develop, then induced mantle flow may affect the subduction angle, but it could not prevent or slow further recycling.

References: [1] Phillips R.J. and Malin M.C. (1982) in Venus, Hunten D.M. et al. eds., U. AZ Press, Tucson, p.159-214. [2] Anderson D.L. (1981) Geophys. Res. Lett., 8, 309-311. [3] Sandwell D.T. and Schubert G. (1992) J. Geophys. Res., 97, 16069-16084. [4] Schubert G., Sandwell D.T., and Johnson C.L (1992) Eos, 329. [5] McKenzie D., Ford P.G., Johnson C., Parsons B., Sandwell D., Saunders S., and Solomon S.C. (1992) J. Geophys. Res., 97, 13533-13544. [6] Burt J.D. and Head J.W. (1992) Geophys. Res. Lett., 19, 1707-1710. [7] Turcotte D.L. (1992) International Colloquium on Venus, 127. [8] Parmentier E.M. and Hess P.C. (1992) Geophys. Res. Lett., 19, 2015-2018.

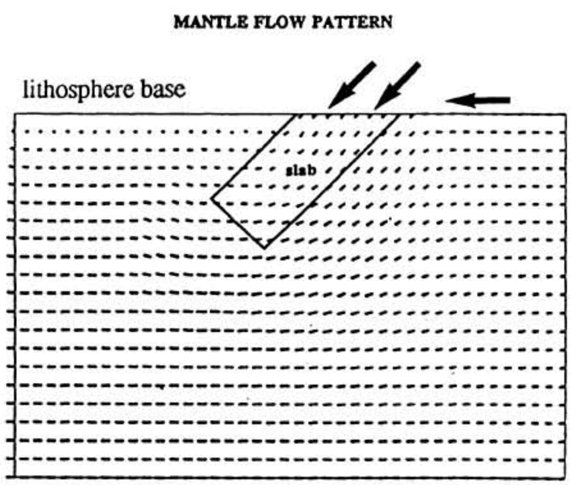

Figure 1: Mantle flow pattern. Flow trends right to left. Base of lithosphere is at top.

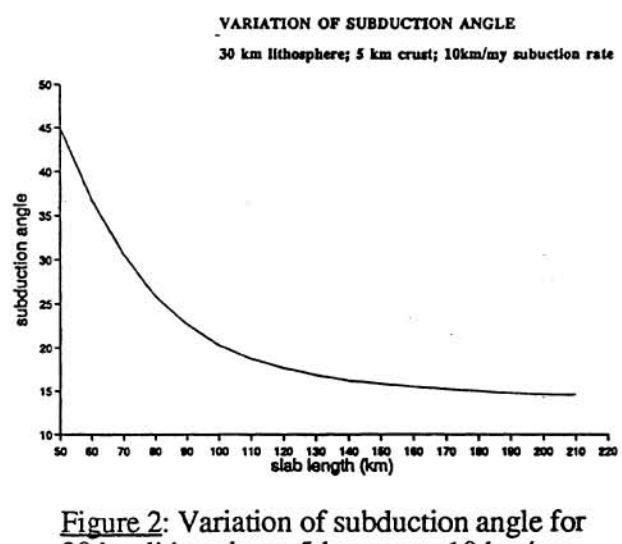

Figure 2: Variation of subduction angle for 30 km lithosphere, 5 km crust, 10 km/my subduction rate.