MANTLE DIFFERENTIATION AND WATER BENEATH VENUS CRATERS

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Empirical flow laws for peridotite and diabase were used to model the viscous relaxation of large impact craters on Venus. The approach was to calculate the rate of viscous relaxation of a model crater and then reject hypotheses about the water or diabase content of the upper mantle that led to significant viscous relaxation in less than 0.5 Ga. Simple layer and composite layer models of the Venus lithosphere were examined (Figure 1). In the simple layer models the lithosphere consisted of a homogeneous peridotite upper mantle beneath a diabase crust. In composite layer models the upper mantle was comprised of diabase inclusions in a peridotite matrix. Several three layer models were also examined in which the diabase was assumed to undergo a phase transition to eclogite or partial melting at a depth of 50-100 km. Every viscous relaxation model was run under the alternative hypotheses that peridotite viscosity was determined by the dry or wet peridotite steady state creep laws [1]. A minimum temperature gradient (10°/km) and crust thickness (5 km) were used in the calculations. Over the interval of crater diameters from 60 to 140 km, the viscous relaxation time increased with increased crater diameter in dry peridotite models and decreased with increased crater diameter in wet peridotite models. The maximum crater retention time for craters <60 km in diameter was independent of whether the wet or dry peridotite flow law was used. Therefore the Venus impact craters suitable for comparison with the model were the three largest craters with depths measured by Venera 15/16 radar altimetry [2] and diameters ≥60 km: Klenova, Cochran, and Zhilova. Models assuming ≥ 0.03% wt. water in the upper mantle predicted more viscous relaxation than was consistent with the observed depths of these craters and an age for any crater ≥0.5 Ga. Models that assumed an upper mantle water content of ≤ 0.003% wt. however were consistent with the measured crater depths and crater ages of 1.0 Ga. This result was insensitive to the presence of up to 60% by volume diabase mixed into the upper mantle as inclusions at the several kilometer scale and to the presence of a diabase-eclogite or melting transition at a depth of 100 km.

Viscous models have been previously used to simulate the gravity-driven relaxation of impact crater topography [3]. Prior studies have examined the influence of elastic properties and non-Newtonian behavior on viscous relaxation models [4,5] ; however, the potential effects of water and petrologic heterogeneity in the upper mantle upon crater relaxation rates have not been explicitely modeled. Accordingly an algorithm described by Grimm and Solomon [6] was used to investigate these variables. Empirical steady state creep laws for Anita Bay Dunite, containing 0.03% and 0.003% wt. H_2O [1,7], were used to compute the effective viscosity of peridotite under wet and dry mantle conditions. The flow law for Maryland Diabase [8] was used to calculate the effective viscosity of diabase in the crust and mantle. Mantle viscosity in the composite layer models was calculated by computing the effective viscosities for diabase and peridotite and then using a self-consistent spheres (SCS) method to calculate the average viscosity of the peridotite-diabase composite [9]. The use of SCS averaging added no new assumptions about flow beyond those already introduced by using the computational algorithm [6]. Although the SCS average is formally independent of the inclusion size, inclusions are restricted to be sufficiently small to be uniformly distributed through the volume beneath the crater. Therefore for craters ~100 km in diameter, the hypothetical inclusions could be no larger than ~1-3 km in diameter. Effective viscosity of the partially melted peridotite layer was calculated using the flow law for olivine-basalt partial melts [10].

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Models that assumed a wet upper mantle predicted more viscous relaxation in 0.5 Ga than was observed for the three largest Venus craters and therefore suggest that the upper mantle beneath these craters is dry to at least 50 km depth. These craters would have to be <100 Ma old and the weathering rates of radar-bright eject haloes would have to have been much greater than 1 km/Ga [11,12] to make the wet peridotite models consistent with measured crater profiles. Because water would be partitioned into the liquid during partial melting, the migration of basalt melt into the crust or into intrusions in the upper mantle would efficiently remove water and leave behind dry peridotite. This means that a large volume of mantle differentiation products could exist as inclusions of diabase or gabbro in the lithosphere without significantly increasing the viscous relaxation rate of large impact craters. If the upper 100 km of the Venus mantle contained the maximum 60% of diabase inclusions, then an amount of mantle differentiation products could be present in the lithosphere equivalent to a continuous 60 km thick crust.

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Figure 1.The three Venus lithosphere models used in the viscous relaxation calculations