GENERATION AND EVOLUTION OF CRUST ON VENUS: IMPLICATIONS OF VISCOUS RELAXATION MODELS. Robert E. Grimm and Sean C. Solomon, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

Introduction. Because of the high surface temperature and the strong temperature dependence of strain rate in silicates, solid state creep may be an important mechanism for the reduction of topographic relief on Venus [1,2]. We have developed a general formulation for the gravity-driven flow of a linearly viscous fluid [3]; the densities and temperature-dependent effective viscosities of the crust and mantle are taken to be those of diabase and olivine, respectively. The viscous relaxation of a specified geological feature is constrained by its age t, initial topography h(0), final topography h(t), initial degree of local isostatic compensation c, and by the local crustal thickness H and mean lithospheric thermal gradient dT/dz. Allowable combinations of H and dT/dz are of particular interest. Since viscosity decreases with increasing temperature, relaxation will occur more rapidly at a higher value of dT/dz for fixed a surface temperature. Because the crust is less viscous than the mantle at a comparable temperature, topographic decay will be more rapid for larger H. We can therefore anticipate that a trade-off exists between dT/dz and H when other parameters are fixed, and that greater topographic support may be achieved through a lower thermal gradient or a thinner crust. Topographic relaxation will also be inhibited by initial isostatic compensation of relief, which minimizes the stresses that drive viscous flow. In this paper we discuss the effects of these parameters on the evolution of the relief of impact craters in the lowlands and rolling plains of Venus, and we derive an upper bound to H in these regions. From this limit we estimate the volume of crustal material and speculate on rates of crustal formation.

Relaxation of impact crater relief. Venera 15-16 altimetric measurements [4,5] have provided h(t) for a number of impact craters (15 are used here), and h(0) may be estimated by scaling from fresh lunar craters [6]. The age t may be taken approximately equal to half the mean crater retention age of the surface; a minimum estimate of this latter quantity must be used to derive upper bounds on dT/dz and H, so we adopt t = 50 m.y. [7]. The parameter c is taken to be 0 or 1, corresponding to zero or complete initial compensation of topography. From the mean and variance of h(0) and h(t) at fixed crater diameter D, we use a *t*-test to determine when the predicted depth of craters following viscous relaxation becomes inconsistent with the observations. Combinations of dT/dz and H that result in such a shallow depth may be rejected. A more complete description of the method is given in [3]. We find that smaller craters (D ~ 30 km) do not directly provide useful constraints on H and dT/dz, because the short wavelengths dominating their topographic profiles are sensitive only to stronger, near-surface material. The largest observed craters (D > 100 km), however, are sensitive to deep variations in viscosity and provide important constraints on the structure of the crust and upper mantle. Because there are only two such craters, however, extrapolation to regional or global conditions warrants caution.

If the mean lithospheric thermal gradient for Venus lies in the range of 10 - 30 K/km, as may be expected from heat loss arguments [8,9], then the crustal thickness beneath the largest craters is only 10 - 20 km, so that viscous relaxation does not reduce the depths of these craters significantly more than is observed. There are two alternatives to this conclusion, but both are unlikely. First, the largest craters on Venus with measured relief could be very young, i.e., considerably younger than 50 m.y., so that viscous relaxation would be minimal for any plausible model. The ages of 40 - 2000 m.y. for the largest (D = 100 - 140 km) terrestrial craters [10] do not support this view. Further, the largest craters with measured relief have intermediate states of preservation [5], and therefore are inferred not to be substantially younger than the overall crater population. In a second scenario, the topographic relief of large impact craters could be completely compensated by variations in crustal thickness; a crustal thickness of 30 km or greater would then be compatible with the observed relief and inferred surface age even in the presence of a lithospheric gradient in excess of 20 K/km. Variations in the Bouguer gravity anomaly across large (D ~ 100 km) terrestrial impact structures in continental crust, however, are modest (~10 mgal) and do not indicate significant Moho relief. It is doubtful that in crust of comparable

thickness on Venus that craters in this size range should be completely compensated.

Implications for the crust. The impact craters used in this study are typical in terms of morphology, underlying geologic unit (largely plains), and planetary elevation [5], so is not unreasonable to infer a crustal thickness of 10 - 20 km beneath geologically similar plains units at comparable elevations, at least over the northern quarter of the planet imaged by Venera 15-16.

These values may be compared with other estimates of crustal thickness on Venus. Upper bounds of one hundred to several hundred kilometers have been suggested on the basis of the projected depth of the basalt-eclogite stability field [11] or the apparent depth of isostatic compensation of long-wavelength topography [9,12]. These bounds may greatly exceed the actual crustal thickness if the crust does not fill the volume of the interior lying within the basalt stability field or if mantle dynamical effects contribute significantly to the support of long-wavelength topography. Much lower values of maximum crustal thickness have been derived [13] from the observation that there are often two characteristic wavelengths of tectonic features in extensional and compressive terrains on Venus. This observation is taken as evidence for a layered lithosphere: strong upper crustal and mantle layers separated by a weak lower crust. The observed scales of deformation can be quantitatively related to crustal thickness and lithospheric thermal gradient. The implied crustal thickness is less than about 15 km if $dT/dz = 25$ K/km and less than about 30 km if $dT/dz = 10$ K/km [13]. These values are quite similar to those obtained in this study.

If this result is globally valid, we may obtain a simple estimate of the total crustal volume from the hypsometry of the Venus surface by assuming that long-wavelength topographic variations are locally compensated by crustal thickness variations. Measured gravity anomalies indicate that other compensation mechanisms also operate [9,12], so that the crustal volume V estimated under this assumption is an upper bound. Let H_0 be the crustal thickness beneath plains units of elevation z_0. If the Pioneer Venus hypsometry curve [14] is representative of the planet and if z_0 corresponds to a planetary radius of 6051.5 km (the elevation of one of the large craters studied), then V is $0.5 - 1.2 \times 10^{10}$ km^3 for $H_0 = 10 - 20$ km. This range includes the present crustal volume of Earth.

Whether this represents the total volume of crustal material produced on Venus is uncertain. Assuming that the present terrestrial rate of plate creation is approximately representative of the past 4 b.y., the total volume of crust generated on Earth is $\sim 10^{11}$ km^3. If Venus has produced a comparable crustal volume over geologic time, then recycling of older crust, by subduction, foundering or remelting, must have occurred. If 10^{10} km^3 is the full time-integrated volume of crustal material, then the average rate of crustal generation over the last 4 b.y. would be 2 km^3/y. This value coincides with the upper bound on the global rate of volcanic resurfacing obtained from the density of preserved impact craters [15]. It should be noted that the latter calculation is insensitive to the contribution to crustal generation by igneous intrusions. Since the rate of intrusion of new crustal volume may be several times the rate of extrusion of new material, the average volcanic flux on Venus in the absence of crustal recycling could be considerably less than 2 km^3/y.

Conclusion. A thin crust (10-20 km) is required to support the topographic relief of large impact craters in the rolling plains and lowlands of Venus for plausible values of mean thermal gradient. The total volume of the crust on Venus, by extrapolation, is less than 10^{10}km^3, an order of magnitude less than the probable time-integrated volume of crust produced on Earth. Either the rate of crustal generation on Venus has not exceeded 2 km^3/y over the history of the planet or some form of crustal recycling has occurred.

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