THE ANCIENT AGE OF MAXWELL MONTES, VENUS: PRESERVATION OF HIGH TOPOGRAPHY UNDER HIGH-SURFACE-TEMPERATURE CONDITIONS. J.D. Burt, J.W. Head, and E.M. Parmentier, Brown University (Dept. of Geological Sciences, Brown University, Providence, RI 02912 jburt@eos.hitc.com).

ABSTRACT: Maxwell Montes has the highest terrain and surface slopes of Venus, but displays little gravitational relaxation except on its northern and southern flanks [1]. Evidence that Maxwell is as old as the surrounding plains [2] leads to the challenge of explaining the preservation of high topography under conditions of surface temperature that would quickly cause the collapse of terrestrial mountain belts [3]. The dry diabase flow laws of Mackwell et al. [4] may provide the key to understanding this problem. Model results indicate that gravitational relaxation should not be important in changing the topography of Maxwell, if the mantle and crust of Venus are very dry.

BACKGROUND: Vorder Bruegge and Head [5] examine the implications of Airy support for Maxwell under conditions of low thermal gradients created by compressional deformation. At low strain rates thermal equilibration would permit volcanism to occur at the same time as mountain belt growth. Low viscosity of a deep crustal root would also promote gravitational collapse. At higher strain rates the thermal gradient would be depressed, preserving the strength of crustal root and delaying igneous activity. Therefore, they favor rapid construction of Maxwell because the mountain belt lacks evidence of simultaneous deformation and volcanism. Additionally, at low temperatures the gabbro-eclogite phase change occurs slowly, but the transformation of deep crustal material would eventually reduce topography.

Namiki and Solomon [6] investigate further the role of the gabbro-eclogite phase change in determining the mountain belt topography. The possible low water abundance on Venus may mean the gabbro-eclogite phase change occurs there by solid state (volume) diffusion rather than grain boundary diffusion, inhibiting the rate of the transition and preserving metastably basaltic crustal material within the stability zone of eclogite in mountain roots. They conclude that rapid mountain belt formation, resulting in low thermal gradients, favors metastable gabbro in the crustal root and preserves high topography, implying that Maxwell must be young relative to the surrounding plains. The lower elevations of volcanically active Danu may illustrate the effects of the temperature-enhanced phase change limiting elevations. Also, a young Maxwell would be consistent with the undeformed appearance of Cleopatra crater.

In contrast, Basilevsky [2] finds stratigraphic evidence that Maxwell is at least as old as neighboring ridged plains. He interprets this as evidence that Maxwell is as old as the estimated surface age of 0.3 to 0.5 Ga [7, 8] and that low water abundance allows high topography and steep slopes to last for geologically long periods. Meanwhile, Herzog et al.[9] point out that the high surface atmospheric pressure would prevent exsolution of H_2O for abundances below about one weight percent. The dry atmosphere could thus be consistent with hydrous minerals existing in the venusian mantle. This represents a volatile source capable of expediting the gabbro-eclogite phase change. If so, high topography may be dynamic, limited by the balance between rate of elevation increase and the rate of eclogite formation.

Smrekar and Solomon [1] have investigated the evidence for gravitational relaxation in Maxwell. While extensional features can be found on the northern and southern flanks of the belt, the western slopes, where the steepest slopes occur, bear no recognizable evidence of relaxation. They model viscous relaxation of topography, invoking the flow law of Caristan [10] for Maryland diabase. They predict that gravitational spreading is likely to occur on a time scale shorter than the mean surface age indicated by the crater statistics. They conclude that dynamic tectonic support may be necessary to preserve the high topography and slopes of the mountain belts.

Freed and Melosh [11] modelled the gravitational collapse of Ishtar Terra. Building on the work of Smrekar and Solomon [1], they find that the dry flow law of Mackwell [4] permits the crust to be sufficiently viscous to support Ishtar's topography for periods on the order of 500 million years.

We have formulated two simple models to explore the role of the dry mantle viscosities in the support of Maxwell. Assuming Maxwell topography is supported by thickness variations in a basaltic crust we calculate the stress distribution for periodic topography having a wavelength similar to that of Maxwell. A steady-state thermal gradient should apply if Maxwell is old. This allows for estimation of the crustal viscosities beneath the belt and estimation of the rate of collapse of the topography.

THEORETICAL MODEL: A simple assessment of the age of Maxwell can be obtained using a model for viscous flow in response to a surface load [12]. Assuming a periodic surface load of the form

$$\omega = \omega_o \, \rho \, g \cos \frac{2\pi x}{\lambda}$$

where ω_o is the amplitude of the surface load or topography, and λ is the wavelength, the characteristic relaxation time is given by

$$\tau = \frac{4\mu\pi}{\rho g \lambda} \quad .$$

If the wavelength of Maxwell is assumed to be λ = 1000 km, ρ = 3 gm/cm^2 and μ to be 10^{21} Pa s, the relaxation time is 1.2 x 10^4 years. For Maxwell to have a relaxation time on the order of 10^9 years the viscosity would be 8 x 10^{25} Pa s.

Mackwell et al. [4] provide flow laws appropriate to materials subject to the dry conditions of Venus. Their flow law for Maryland Diabase is

$$\varepsilon = 4.2 \, \sigma^{5.1} \exp - \left(\frac{505}{RT} \right) ,$$

where ε is the strain rate, σ the differential stress in MPa, R the gas constant, and T the temperature. This can be rewritten, for this model, and using the second invariant of the stress tensor, as

$$\varepsilon = 4.2\left[\rho g\ \omega_o\ y\ \frac{2\pi}{\lambda}\ \exp-\left(\frac{2\pi y}{\lambda}\right)\sqrt{2}\ \right]^{4.2}$$
$$\left(\rho g\ \omega_o\ y\ \frac{2\pi}{\lambda}\ \cos\frac{2\pi x}{\lambda}\ \exp-\left(\frac{2\pi y}{\lambda}\right)\right)\exp-\left(\frac{505}{RT}\right)$$

From this relation μ can be derived

Using viscosities for a thermal gradient governed by basaltic crustal radioactivity, a surface temperature of 750 K, and a uniform mantle temperature of 1321 K below 200 km depth, the relaxation rate for Maxwell can be evaluated. A mid-crustal viscosity can provide an estimate of the relaxation time. Assuming Maxwell to be in isostatic equilibrium a maximum crustal thickness is about 120 km. The viscosity for the 60 km depth is $\mu = 10^{25.6}$Pa s, yielding a characteristic relaxation time of about 5×10^8 years. This is close to the value that is required to maintain the topography of Maxwell for 10^9 years.

If gravitational collapse may happen slowly enough to permit Maxwell to retain its high elevations, the transformation of gabbro to eclogite may become more important. A characteristic reaction time for the conversion from one phase to the other can take the form

$$\tau = \frac{\delta^2}{D}$$

where τ is the characteristic reaction time, δ is the grain size, and D is the diffusion coefficient. Taking $D_{Al, Opx}$ as given in Namiki and Solomon [6] as a lower bound,

$$D_{Al, Opx} = 1.1 \times 10^{-5} \exp\left(\frac{-400\ kJ}{RT}\right)$$

an estimate can be made of the reaction time for a given temperature. At the base of the crust the temperature is about 925 K. At this temperature, the reaction time is on the order of 10^{14} years. Clearly this indicates that the phase change happens too slowly to significantly affect the isostasy over periods as short as a billion years.

This simple modeling is based on a formulation assuming uniform, not variable, viscosity. To more accurately determine rates of relaxation for a model in which the viscosity varies with temperature, numerical models are necessary.

NUMERICAL MODEL: In a model region measuring 1000 km wide and 1000 km deep, and having an imposed surface load of the form

$$\omega_o\ \rho\ g \cos\frac{2\pi x}{\lambda}\ ,$$

we solve for fluid flow using a Lagrangian finite element method. A free surface and free-slip vertical and basal boundaries comprise the boundary conditions. The imposed depth-dependent viscosity is derived from the flow law of Mackwell et al. [4]. Flow calculations result in estimates of the surface vertical velocity component.

To evaluate the rate of collapse we again appeal to the simple theory. Since the rate of change of the vertical displacement (the vertical velocity) is given by

$$\frac{\delta\omega}{\delta t} = \frac{\rho g\lambda}{4\pi\mu}\ \omega_o\ \exp-\left(\frac{\rho g\lambda}{4\pi\mu}\right)\ ,$$

then

$$v = -\frac{1}{\tau}\ \omega_o\ \exp\left(\frac{-t}{\tau}\right)\ .$$

At t = 0 this simplifies to

$$v = -\frac{\omega_o}{\tau}\ .$$

The model calculates the amplitude of the vertical component of the surface velocity to be 1.2×10^{-15} m/s. This produces a characteristic relaxation time of 2.7×10^{11} years.

CONCLUSIONS: While these models are not complicated, they do provide an estimation of the rate of collapse of Maxwell Montes. These results indicate that gravitational relaxation should not be important in changing the topography of Maxwell, if the mantle and crust of Venus are very dry. If significant water does not exist within the interior of Venus, then the mantle and crust are strong and the rate of the gabbro-eclogite phase change is very low. Both of these factors would contribute to the preservation of high topography despite the high temperatures of the venusian surface. If hydrous minerals exist [9] within the mantle, however, dynamic mechanisms may be required to explain the existence of old high topography.

REFERENCES

[1] Smrekar, S.E. and S.C. Solomon, (1992) JGR, 97: 16121; [2] Basilevsky, A.T., (1995) LPSC 26; [3] Weertman, 1979; [4] Mackwell, S.J. et al., (1994) LPSC 25: 817; [5] Vorder Bruegge, R.W., and J.W. Head, III, (1991) Geology 19: 885; [6] Namiki, N., and S.C. Solomon, (1993) JGR 98, E8: 15025; [7] Schaber, G.G. et al., (1992) JGR 97, E8: 13257; [8] Strom, R.G. et al., (1994) JGR, 99, E5: 10899; [9] Herzog, S.G. et al., (1995) LPSC 26: 591; [10] Caristan, Y., (1982) JGR 87: 6781 ; [11] Freed, A.M., and H.J. Melosh, (1995) LPSC 26: 421; [12] Turcotte, D.L. and G. Schubert, (1982) Geodynamics Applications of Continuum Physics to Geological Problems, John Wiley & Sons, New York, 1982;