THE OLYMPUS MONS PARADOX: WHY HASN'T THE MARTIAN LITHOSPHERE FAILED
UNDER THE LOAD? Robert P. Comer and Sean C. Solomon, Department of Earth and
Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

Introduction. By a substantial margin, Olympus Mons is the largest super-
isostatic load on the surface of Mars [1]. Other large loads, such as the
three large Tharsis shield volcanoes, Elysium Mons, and the Isidis Planitia
mascon have associated systems of concentric fractures [2] but Olympus Mons
has none. This is very remarkable, because while models of the flexure of the
Martian elastic lithosphere by the Isidis mascon indicate that tensional
stresses of about 20 bars are sufficient to fracture the surface of the
lithosphere, Thurber and Toksöz [3] found that tensional stresses due to the
Olympus Mons load should be 1 kilobar or more, for elastic lithosphere thick-
ness up to 200 km. The puzzle is accentuated when Olympus Mons is contrasted
with the three large Tharsis volcanoes: volume and gravity measurements indi-
cate that Olympus Mons is almost totally uncompensated [4] but that the
Tharsis volcanoes are locally compensated to a large extent [5]. We have con-
sidered five possible explanations of the "Olympus Mons paradox:" (1) visco-
elastic relaxation of stresses during the growth of Olympus Mons, (2) burial
of fractures by later geologic activity, (3) superposition of global horizon-
tal compressive stresses due to thermal contraction of Mars, (4) dynamic sup-
port by flow in the Martian mantle, and (5) a very great thickness for the
elastic lithosphere in the vicinity of Olympus Mons.

(1) Viscous relaxation. To investigate the possibility of viscous
relaxation in the lithosphere we used a method developed to calculate the
vertical deflection and horizontal stresses associated with the loading
of a flat visco-elastic plate overlying an inviscid fluid by an axisymmetric
load [6]. We approximated Olympus Mons as a cone of 375 km radius, 23 km
height, and 2.9 g/cm³ density, based on a topographic study by Blassius
and Cutts [4]. The viscoelastic plate which represented the lithosphere was as-
signed elastic parameters E (Young's modulus) = 10¹² dynes/cm² and ν (Poisson's
ratio) = 1/2. A visco-elastic plate must also be characterized by a relaxa-
tion time $\tau = \eta / 3E$ where $\eta$ is the viscosity, but because it is impossible at
present to obtain a reasonable estimate of the viscosity of the Martian litho-
sphere we have had to leave $\tau$ arbitrary; so that the units of time in all our
calculations are proportional to $\tau$. To estimate the effect of viscous relaxa-
tion on the flexure and stresses of the lithosphere under Olympus Mons, we
applied our Olympus Mons model to the plate at time $t=0$ and calculated ver-
tical deflection $w$ and horizontal stresses at times $t=0,1,4,16$, where $t$ is in
units of $\tau$. (An assumption made at this point is that Olympus Mons grew to
its present size in a period of time not too long in comparison with $\tau$, how-
ever in the opposite case one would expect Olympus Mons to be locally com-
pensated to a large degree, contrary to the observations cited above.) Some
results of our calculations are illustrated in Figure 1, and they indicate
that visco-elastic relaxation is not an adequate explanation of our paradox.
For lithospheric thicknesses $T$ of 100 to 150 km the vertical deflection under
the load is already too high at $t=0$ for the observed lack of local compensa-
tion. Topographic data for Olympus Mons [4] also indicate lack of the sur-
rounding depression or moat such as that observed at Hawaii [7] which would
be expected for such large vertical subsidence. For larger values of thick-
ness ($T=200$ to 250 km), considerable subsidence occurs without significant relax-
ation of stresses and similar contradictions to the observed topography are
encountered. We should note also that the calculated vertical deflection is
actually a slight under-estimate. For example, for $T=100$ km and $t=0$ we have
a volcano height of 23 km and a subsidence of 6.6 km, but if we correct the
height for subsidence we find 16.4 km, which does not match the observations; rather we should have a volcano of height 32 km subsiding 9 km (23 and 6.6 are in the same proportion as 32 and 9) to give an apparent height of 32-9=23 km. Of course this simply compounds the misfit of large calculated vertical deformations to the observations.

Fault Burial. Burial of fractures by more recent geologic activity is a slight possibility, but since Olympus Mons is considerably younger than many features which have not had their fracture systems buried [8], it seems remote.

Global Compression. Mars has probably been in a state of thermal contraction in the geologically recent [9], and the consequential global compressive horizontal stresses may have been significant enough to suppress extensional failure of the lithosphere during the formation of Olympus Mons but not during the formation of the other, older super-isostatic loads cited previously.

Dynamic support. Upward flowing mantle material would exert a vertical force on the lower surface of the lithosphere; such a mantle "plume" would exert a force of roughly $\rho v^2$ where $\rho$ is the mantle density and $v$ is the velocity of flow. However, to wholly support a load of the order of $10^8$ or $10^9$ dynes/cm$^2$, such as Olympus Mons, would require a velocity of roughly $10^4$ cm/sec, so that it is clear that dynamic processes cannot provide a significant fraction of the support of Olympus Mons.

Thick Lithosphere. The last of our five explanations is a very thick lithosphere beneath Olympus Mons. In their study of Olympus Mons, Thurber and Toksöz [3] concluded that the lithosphere was very thick in order to explain the lack of a fracture system and the lack of a moat. It is clear from Fig. 1. that as the lithosphere thickness is increased both stresses and vertical deflection decrease. Decreasing the amount of vertical deflection also means decreasing the degree of local isostatic compensation, so a thick lithosphere tends to satisfy three basic observations concerning Olympus Mons: no fracture system, no moat, and very little local compensation. However, an elastic thickness of 200-250 km still implies tensional stresses of about 500 bars for a load the size of Olympus Mons. An additional factor (barring extraordinary thickness) seems to be required to decrease the extensional stresses, and global, thermal, compressive stress is the most likely possibility.

Conclusions. We therefore feel that a thick ($T \approx 200$ km) Martian elastic lithosphere and global thermal contraction resulting in compressive horizontal stresses are the two factors which most likely combine to resolve the Olympus Mons paradox. It is still remarkable that the lithosphere is so much thinner under the neighboring Tharsis volcanoes [2], but this is at least consistent with their relative heights, if one considers lithostatic pressure to be important for magma ascent [10]. It is difficult to say anything quantitative about the thickness of a very thick Martian lithosphere because our calculations and those of Thurber and Toksöz [3], although in close agreement, are based on thin plate and thin shell approximations, respectively; however we have recently developed a solution to the thick plate flexure problem which may be applied advantageously to the case of Olympus Mons.

REFERENCES:
OLYMPUS MONS PARADOX

Comer, R.P. and Solomon, S. C.

volcanoes, Icarus, in press.


Figure 1. Visco-elastic relaxation of the Martian lithosphere under the load of Olympus Mons. For four values of thickness T the vertical subsidence w at the center of the load is plotted against the maximum radial tensional stress, at four times t. Each time is in multiples of the unknown characteristic relaxation time of the lithosphere T and the figure is intended to show relative increases in subsidence and stress relaxation. For t=0 the visco-elastic solution reduces to a purely elastic case and our results are comparable to those which Thurber and Toksöz [3] obtained using an elastic shell model.