GRAVITATIONAL SPREADING OF DANU, FREYJA AND MAXWELL MONTES, VENUS; Suzanne E. Smrekar, and Sean C. Solomon, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

Introduction. The potential energy of elevated terrain tends to drive the collapse of the topography. This process of gravitational spreading is likely to be more important on Venus than on Earth because the higher surface temperature weakens the crust [1]. The highest topography on Venus occurs in Ishtar Terra. The high plateau of Lakshmi Planum has an average elevation of 3 km above mean planetary radius, and is surrounded by mountain belts. Freyja, Danu, and Maxwell Montes rise, on average, an additional 3, 0.5, and 5 km above the plateau, respectively. Recent, high resolution Magellan radar images of this area, east of ~330°E, reveal widespread evidence for gravity spreading [2]. This paper describes observational evidence for gravity spreading and dicusses the implications in terms of simple mechanical models.

On Earth, gravitational potential energy is known to drive extensional normal faulting near the crest of high topography, where the vertical stress is greater than the horizontal stress, and thrust faulting on the flanks, where the horizontal normal stress exceeds the vertical normal stress [3, 4]. Strike-slip faulting occurs when additional regional stresses interact with gravitational stresses. Gravity can also be an important force for reducing topographic slope through the formation of detachments [5], which result in normal faulting at the surface [6].

Models. Several simple models predict that gravity spreading should be an important process on Venus. Most of the potential energy of crustally compensated mountains is a result of the mantle pushing on the root [4]. However, given an apparent depth of compensation of 130 km at Ishtar Terra [7], Airy isostasy is unlikely to be the dominant compensation mechanism. An estimate of the deviatoric stress resulting from the topographic relief alone, without a crustal root, is simply $\rho gh/2$, where ρ is density, g is gravitational acceleration, and h is height [1]. Using $\rho = 3000\ kg/m^3$, $g = 8.87\ m/s^2$, this equation gives 13 MPa/km of relief. For average elevations of 3.5, 6, and 8 km for Danu, Freyja, and Maxwell Montes, this gives respectively 50, 80, and 100 MPa. If some component of crustal compensation is present, actual stresses due to gravitational potential will be greater. Whatever the degree of crustal compensation, it is clear that gravity produces considerable tectonic stress in these mountain ranges.

The formation of ductile detachments is predicted for surface slopes such as those found in these mountains. Smrekar and Phillips [5] developed a model for detachment in a viscous layer inclined at an angle, using a diabase flow law for the crust. As the model is highly dependent on temperature, both higher thermal gradients and thicker crustal layers, which are hotter at the base, produce greater rates of deformation. The rate of deformation also increases with surface slope. Even for a modest surface slope of 1°, a diabase crust 20 km thick with a thermal gradient of 15 K/km will flow at a rate of 10 mm/year. Locally, surface slopes in the mountains are much greater. The western flank of Maxwell Montes has a slope of ~30°; a slope of ~20° is found along Vesta Rupes. For a slope of 30°, a deformation rate of 10 mm/year is expected for a thermal gradient of 5 K/km, given a crustal thickness of only 10 km. These results predict that detachments are very likely in the mountains.

Observations. Danu Montes has the least relief of the mountain ranges. The highest topography in Danu Montes is centered near 59°N, 336°E. A large graben-like structure (10 x 50 km) occurs parallel to the crest in this region, suggesting that extension occurred along preexisting weaknesses resulting from the formation of the range. The southwestern end of this graben is cross-cut by faults with the same NE-SW trend that is defined by the folds and thrusts that make up the mountains. The implication is that the extension occurred while regional compressional stresses were still active. Several long (~100 km) normal faults strike approximately parallel to the trend of Vesta Rupes. It is possible that these faults are the surface expressions of thrust faults, as the toes of thrust faults are frequently cut by normal faults. Although conclusive evidence in the form of the vergence of these faults is impossible to obtain, faults parallelling topographic strike are expected on the flanks of extending mountains. Numerous, narrow (~1 km) graben, with lengths of tens of kilometers and a spacing of 0.5-2 km, parallel the large NW-SE trending faults, providing further evidence of extension. These narrow, closely spaced faults may represent the surface expression of deformation above a detachment.

Freyja Montes appears to have undergone intense deformation, as evidenced by high roughness and complex tectonic patterns. The north slope of Freyja Montes between 330°E and 335°E is cut by numerous graben with widths of 1-3 km and spacings of 3-10 km. These graben trend NW-SE to N-S; however their truncation at long lineations and their curved patterns suggest that they have been shortened and probably sheared. As at Danu Montes, we interpret these small-scale graben to indicate detachment at depth, and the deformation of the graben to mean that extension occurred while regional compression was still active.

NW-SE trending graben are also found on the southern front of Freyja Montes, but are less numerous and larger, up to 5 km across, and more widely spaced. This set continues tens of kilometers onto the plains of Lakshmi Planum, where the spacing is ~5 km and the width is ~1 km. A large (~100 x 150 km) dome-like structure occurs on the eastern flank of Freyja Montes, which in addition to displaying the same NW-SE trending graben set, is dissected by a N-S to NE-SW graben set with an irregular spacing of 1-10 km and widths of 1-2 km. This set appears to be older than the NW-SE set. We interpret these graben sets as normal faulting above a detachment. On the eastern side of the dome, the blocks that form where the two graben sets intersect are absent, possibly because they spread downslope. Compressional features farther downslope support this interpretation. A similar pattern occurs on the SW flank of the dome, also suggesting that material has moved downslope. This feature may be analogous to terrestrial metamorphic core complexes.

Maxwell Montes contain the highest topography and steepest regional slopes observed to date on Venus. Several pairs of long, nearly linear faults occur between Cleopatra Patera and the crest of Maxwell Montes. These features are 10-20 km wide and ~100 km long. The slight undulations in these faults may indicate that they are originally straight normal faults that have been subsequently deformed. Alternatively, they may be compressional ridges that happen to be paired. Given the remarkably steep slopes (up to 30°) found on the western front of Maxwell Montes, the observed lineations are most easily interpreted as thrust faults. These features are consistent with gravitational spreading, but do not provide conclusive evidence.

Two additional, perpendicular sets of graben occur on the southern slope of Maxwell Montes. One set is perpendicular to topographic strike and has a spacing of 5-10 km and widths of 2-5 km. The other set is parallel to topographic strike and curves with the border of the southern flank of Maxwell Montes, giving the two sets a radial and concentric pattern. The concentric graben have widths of ~5 km and a spacing of ~5 km. This set of graben is cut by the radial set. Similar, narrow graben sets also occur on the northern flank of Maxwell Montes. The set perpendicular to topographic strike also appears to be the youngest in this region. Although the graben set which is parallel to topographic strike might be interpreted as faulting above a detachment, the perpendicular set is difficult to explain.

Discussion. One difficulty in using remote observations to infer interior properties is that the observed features may not have formed in response to stresses which are still active. However, the observation that gravity spreading has apparently occurred in some areas but not others suggests there is a difference between regions that have very high surface slope but do not appear to have not spread, and those which have already spread. The implication is that the thermal gradients are relatively low in the high-slope regions that lack evidence for spreading. Among possible explanations are that regions that have spread simply had higher heat flow, or that regions of steep slopes which have not spread may represent stacks of recently emplaced and relatively cold thrust sheets that have not reached thermal equilibrium. We favor the latter interpretation for the western slope of Maxwell Montes. There is evidence for volcanism at Danu Montes, favoring high heat flux, but not in the vicinity of the graben sets at Freyja and Maxwell Montes. A further implication is that these mountains probably do not have large crustal roots as they would then have to be able to resist a much greater amount of gravitationally induced stress.

References. [1] J. Weertman, *Phys. Earth Planet. Int., 19*, 197, 1979; [2] S.C. Solomon et al., *Science*, in press, 1991; [3] B.C. Burchfiel and L.H. Royden, *Geology, 13*, 679, 1985; [4] P. Molnar and H. Lyon-Caen, *Geol. Soc. Am., Spec. Paper 218*, 179, 1988; [5] S.E. Smrekar and R.J. Phillips, *Geophys. Res. Lett., 15*, 693, 1988; [6] B.C. Burchfiel et al., *Geology, 17*, 448, 1989; [7] R.E.Grimm and R.J. Phillips, *LPSC XXI*, 437, 1990.