CRUSTAL CONVERGENCE AND MANTLE DOWNWELLING IN THE ISHTAR TERRA REGION OF VENUS, Walter S. Kiefer (Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena CA, 91125) and Bradford H. Hager (Dept. Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge MA, 02139)

Ishtar Terra is one of the major highland structures on Venus and therefore plays an important role in our understanding of the global geology of Venus. Based on the observed density of impact craters, Ishtar is probably at least several hundred million years old [1]. Ishtar is centered on Lakshmi Planum, a flat, 1500 km wide plateau which is about 3.5 km above mean planetary radius (MPR). Lakshmi is surrounded on the west, north, and east by the mountain belts Akna, Freyja, and Maxwell Montes, which reach elevations of 6 to 10 km above MPR. Maxwell Montes contains the highest topography known on Venus [2]. The mountain belts contain a pronounced banded structure which parallels the contact between the mountains and Lakshmi and is presumably of tectonic origin [3-5].

In principle, the banded terrain in the mountain belts could have either an extensional origin, as in the terrestrial Basin and Range, or a compressional origin, as in the Himalaya mountains. In the case of mountains formed by extension of a pre-existing high plateau, the mountains should be no higher than the adjacent plateau, whereas in the case of mountains formed by compression, the mountains may be much higher than any adjacent plateau. The Montes units in Ishtar Terra are observed to be much higher than Lakshmi Planum, favoring a compressive origin for the mountains. This conclusion is consistent with the conclusions which other workers have reached on morphological grounds [3-5].

Although a mantle upwelling model has been proposed for Ishtar [6], such a model predicts extensional tectonism in the region of elevated topography, in contrast with the observed compression. A second thermal mechanism for supporting the topography, lithospheric delamination, can account for at most 1.5 km of topography [7]. It therefore seems likely that much of Ishtar's topography is due to thick crust. Both the compressive deformation and the high topography may be the result of crustal convergence over a region of mantle downwelling [7-10]. Lithospheric delamination may nevertheless play some role in supporting the observed topography. Houseman et al. [11] have argued that the time-scale for lithospheric delamination in crustal convergence zones is of order 10 million years, which would suggest that Ishtar has undergone numerous delamination epsiodes over its lifetime. If most or all of the mantle lithosphere delaminates, then the crust will be suddenly exposed to temperatures of order 1300° C, which would cause melting and volcanism. A number of probable volcanic structures, such as Colette, Sacajawea, and and Cleopatra Patera, are located in Ishtar [4,12]. This volcanic activity may be at least partially related to delamination events.

As a test of the crustal convergence model, we have previously developed a simple model for the forces which support Ishtar's high topography, in which the extensional normal stress associated with the high topography was balanced by shear stresses applied on the crust by convective flow in the mantle [9]. Based on a likely upper bound on the magnitude of the mantle shear stress, we argued that Ishtar's high topography could only be supported if the crustal thickness in the plains surrounding Ishtar is no more than 20 to 30 km. This force balance model treated the crust as a set of rigid blocks, although in reality the high surface temperature of Venus may allow the crust to deform viscously [13,14]. We therefore consider a model in which the crust is modeled using a stress- and temperature-dependent viscous rheology and can flow in response both to a basal velocity imposed by the mantle and to shear stresses created by topographic gradients.

In the absence of an imposed basal velocity, crustal material will flow down slope, but if a sufficiently large basal velocity is imposed, the crustal flow can be reversed so that there is a net movement of material up slope. Although we do not know whether there is currently a net inflow or outflow of crustal material at Ishtar, the crustal convergence model requires that

there was a net inflow of material at some time, either now or in the past. We therefore calculate the minimum basal velocity required to create a net inflow of crust as a function of other parameters such as topographic slope, crustal thickness, flow law, and thermal gradient. By considering a reasonable upper bound of 20 cm/yr for the basal velocity, we can set bounds on the allowed values of other parameters which must be satisfied in order to allow a net inflow into Ishtar.

We consider in particular a region in Fortuna Tessera, to the east of Maxwell Montes, where the topographic slope averages 0.4 degrees. Because we are interested in a region of mantle downwelling, we consider a nominal thermal model in which the heat flow from the mantle into the crust is equivalent to a thermal gradient of 10 K/km, plus a heat flow contribution from crustal radioactivity based on measurements by Soviet landers in other regions [15]. Using the diabase flow law of Shelton and Tullis [16], we find that the reference crustal thickness at MPR can not exceed 25 km. Even if we arbitrarily stiffen the flow law by decreasing the pre-exponential constant by an order of magnitude, the allowed crustal thickness is still only 33 km. If the crust is thicker than this, there is a net outflow of material and Ishtar could not have formed. If we use the much softer diabase flow law of Caristan [17], the crustal thickness must be less than 14 km. The only way to substantially increase the allowed crustal thickness is to assume a flow law activation energy which is significantly larger than observed in lab experiments, or equivalently, to assume a much colder thermal model. These estimates of crustal thickness are in good agreement both with our previous work [9] and with several independent estimates [18-20]. Anderson [21] and Kaula [22] have argued that Venus's crust must be at least 70 km thick on the grounds that it will grow in thickness until it reaches the basalt-eclogite phase boundary, after which the dense eclogite will be recycled into the mantle. However, this argument neglects the possibility that positively buoyant basalt can be recycled into the mantle, provided that it is attached to a sufficient quantity of cold, negatively buoyant mantle. In this way, it is possible for Venus to maintain an equilibrium crustal thickness of only a few tens of kilometers.

Vorder Bruegge and Head [23] have described the so-called Chevron Tessera unit within Fortuna Tessera and proposed that the Chevron Tessera formed by compressive buckling and disruption of normal tessera on a length scale of about 100 km. While this idea may well be correct, we note that our flow modeling shows that under some circumstances, there can be down-slope flow of the near-surface layer at the same time as up-slope flow of crustal material at deeper depths. Thus, even though Ishtar Terra as a whole may be a crustal convergence zone, it is still possible for some extensional deformation associated with down-slope flow to occur. We speculate that some of the structures observed in the Chevron Tessera, such as several graben-like features, may be the result of such down-slope flow. Sukhanov [24] has argued that much of Fortuna Tessera may be the result of down-slope flow.

References

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