ISSUES IN VENUS TECTONICS: RETROSPECT AND PROSPECT. Sean C. Solomon, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

Introduction. Although Venus, of all the planets, is most similar to the Earth in terms of mass, radius, and bulk composition, data of ever increasing resolution and detail collected over the last decade from Venus have continued to challenge our understanding of how large silicate planets evolve. As Magellan speeds toward its August rendezvous with our sister planet, it is timely to attempt to synthesize what is known about the geophysical workings of Venus, highlight the most important unresolved issues, and discuss how Magellan data may help to resolve these issues.

Heat Budget. Cosmochemical considerations [1] and surface measurements of U, Th, and K [2] suggest that radiogenic heat production in Venus is broadly similar to the Earth. The atmospheric ^{40}Ar is about a factor of 3 less than that of the Earth [3], though whether the lower amount is attributable to differences in outgassing or in the bulk K abundance is uncertain. If Venus loses heat at the same rate per mass as the Earth, the mean heat flux is 74 mW/m^2 [4], with an uncertainty of perhaps 30% contributed by possible differences in the K abundance and in the fraction of heat loss contributed by secular cooling of the planet [1] and by possible non-monotonic variations in terrestrial heat loss [5]. This heat flux is sufficient to fuel vigorous mantle convection and is equivalent to an average conductive thermal gradient in the lithosphere of 20-30 K/km, depending on the crustal thickness and thermal conductivity structure. While the prospects for direct measurement of surface heat flow on Venus are remote, the thermal gradient may be inferred indirectly from the thickness of the elastic lithosphere estimated from the flexural response to lithospheric loads [6]. At present, topography provides the only resolvable signature of flexure, and other contributors to topographic relief may mimic flexure [7]. The most likely case of flexure yet identified is where the North Polar Plains underthrust Freyja Montes [8]; the flexural length scale indicates an elastic lithosphere 12-17 km thick, consistent with a thermal gradient of 15-25 K/km [9]. Because the North Polar Plains are near the modal elevation for the planet, this gradient is consistent with the expectation that scaling global heat loss from the Earth is reasonable and that regions on Venus at an elevation near the modal value have heat flow near the global average. The Magellan mission, through altimetry and high-resolution images of regions near lithospheric loads, should permit the estimation of elastic lithosphere thickness more widely on the planet.

Lithospheric Heat Transport Mechanisms. For about a decade it has been clear that among the solid planets and satellites one of three distinct mechanisms has dominated heat loss across the outer 100 km or so of the interior: plate recycling (as on Earth), hot spot volcanism (as on Io), and lithospheric conduction (as on the smaller terrestrial planets); see Fig. 1. While the dominant lithospheric heat transport mechanism on Venus was a matter for debate in the immediate aftermath of the Pioneer Venus mission [4, 10], results from the Venera and Vega missions and from Earth-based radar imaging have restricted the possibilities.

Heat transport by volcanism, also known as the heat pipe model [11], can acount for the global heat loss if the surface volcanic flux is 200 km^3/y [4,11]. Two separate lines of argument, however, suggest that the actual flux is lower than this figure by two orders of magnitude. Both the rate of volcanic replenishment of SO_2 necessary to maintain the global H_2SO_4 clouds [12] and the surface density of impact craters imaged by Venera 15-16 [13] limit the volcanic flux to about 2 km^3/y. Thus extrusive magmatism contributes negligibly (~ 1%) to global heat loss (Fig. 1).

While Venus lacks plate recycling on the terrestrial scale, the issue remains as to the contribution of creation and destruction of lithosphere to the global heat loss. The equatorial highlands appear to be regions of crustal divergence, although whether they are more analogous to continental rifts [14] or to oceanic spreading centers [15] will not be clear until imaging of Aphrodite Terra and other equatorial highlands is forthcoming from Magellan. Under the assumption that all of the terrestrial highlands are analogues to oceanic spreading centers, the rate of creation of new lithosphere indicated by the fall-off of topography with distance from the spreading axis is 0.7 km^2/y and the contribution to global heat loss is less than 15% [16], a result consistent with the impact crater density in the well-imaged portions of the planet [13]. While sites of horizontal convergence and underthrusting have been identified [8,17], whether these and other

sites accommodate 0.7 km^2/y of lithospheric removal is questionable, so even this modest contribution to global heat loss must be regarded as an upper bound (Fig. 1).

It is thus evident that most of the interior heat loss is transported conductively through the Venus lithosphere, a result that leads to the prediction of a lithosphere on average no more than a few tens of kilometers thick [4]. In response to strong coupling of the lithosphere to mantle convection [18], much of the topographic relief and tectonic deformation of the surface may be in response to mantle dynamic stresses.

Crustal Thickness. The thickness and average surface residence time of the crust are closely tied to the thermal and dynamical evolution of the Venus mantle. Several have suggested, largely on theoretical grounds, that the Venus crust may be as thick as 100 km, limited only by the depth of the basalt-eclogite transition [19,20]. Such a thick crust would have profound effects on the interior dynamics. If the surface radioactivity at the Vega 1-2 and Venera 9-10 sites [2] is representative of the underlying crustal column, then the heat produced in the crust would provide half of the mean heat flux. Most of the crust would be easily deformable and convectively unstable [20]. Two lines of evidence suggest that the Venus crust is typically only 10-20 km thick: the measured depths of Venus impact craters require a layer comparable in strength to the mantle at shallow depth [21], and multiple scales of deformation are most plausibly interpreted as controlled by the thickness of a strong upper crust and the depth to and thickness of a strong upper mantle layer [22]. Further data of both sorts will be provided by Magellan. Whether the present crustal volume, comparable to that of the Earth [21], indicates a much lower rate of crustal formation on Venus than the Earth (by a factor of up to 10), or a history of crustal recycling, is open.

Mantle Dynamics. A major challenge in unravelling the evolution of Venus is to understand the interaction between mantle convection and the lithosphere. The strong correlation between long-wavelength gravity and topography [23] and the large (100-400 km) apparent depth of compensation of relief for many upland regions suggests both that such uplands are sites of mantle upwelling and that mantle dynamic stresses couple strongly to the lithosphere [18,24]. The several thousand kilometer separation between inferred centers of upwelling suggest that the plumes originate deep in the Venus mantle. Magellan measurements of topography and gravity and delineation of large-scale patterns of volcanism and tectonics will provide important constraints, but new models linking magmatism and surface deformation to interior flow will also be needed.

References. [1] BVSP, *Basaltic Volcanism on the Terrestrial Planets*, Pergamon, 1981; [2] Yu. A. Surkov et al., *JGR, 92*, E537, 1987; [3] J.H. Hoffman et al., *JGR, 85*, 7882, 1980; [4] S.C. Solomon and J.W. Head, *JGR, 87*, 9236, 1982; [5] D.L. Turcotte and K. Burke, *EPSL, 41*, 341, 1978; [6] M.K. McNutt, *JGR, 89*, 11180, 1984; [7] S.C. Solomon and J.W. Head, *LPS, 21*, this vol., 1990; [8] J.W. Head, *Geology*, in press, 1990; [9] S.C. Solomon and J.W. Head, *LPS, 20*, 1032, 1989; [10] R.J. Phillips et al., *Science, 212*, 879, 1981; [11] D.L. Turcotte, *JGR, 94*, 2779, 1989; [12] B. Fegley and R.G. Prinn, *Nature, 337*, 55, 1989; [13] R.E. Grimm and S.C. Solomon, *GRL, 15*, 1455, 1987; [14] G.E. McGill et al., *GRL, 8*, 737, 1981; [15] J.W. Head and L.S. Crumpler, *Science, 238*, 1380, 1987; [16] W.M. Kaula and R.J. Phillips, *GRL, 8*, 1187, 1981; [17] L.S. Crumpler et al., *Geology, 14*, 1031, 1986; [18] R.J. Phillips, *GRL, 13*, 1141, 1986; [19] D.L. Anderson, *GRL, 7*, 101, 1980; [20] W.M. Kaula, *Science*, in press, 1990; [21] R.E. Grimm and S.C. Solomon, *JGR*, 93, 11911, 1988; [22] M.T. Zuber, *JGR, 92*, E541, 1987; [23] B.G. Bills et al., *JGR, 92*, 10335, 1987; [24] W.S. Kiefer et al., *GRL, 13*, 14, 1986.

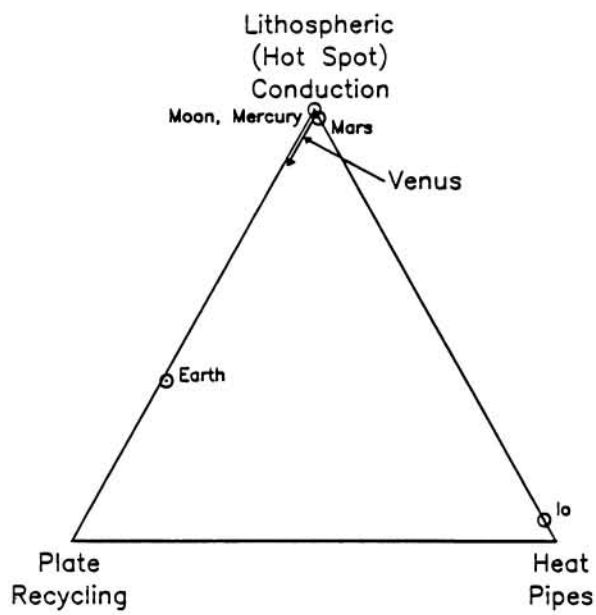

Fig. 1. Schematic ternary diagram showing the relative contributions of lithospheric heat transport toward global heat loss on solid planets and satellites [4]. The range of possible positions for Venus is indicated.