
Introduction. The mechanism of heat transport across the outer 100 km of a planetary interior plays a pivotal role in determining the styles and magnitudes of tectonic and volcanic activity at the planet's surface. For the Earth, heat transport is dominated by the processes of plate creation, cooling and subduction [1]. For the smaller terrestrial planets, heat transport is principally by conduction through a globally continuous lithospheric shell [2]. For Io, volcanic activity at individual eruptive centers dominates the planetary heat flux [3-5]. For the planet Venus, the evidence on the dominant lithospheric heat transfer process is equivocal [6-9]. In this paper we evaluate in turn the hypotheses that one of these processes is the most important mechanism for lithospheric heat transport on Venus: (1) plate recycling, (2) lithospheric conduction, and (3) hot spot volcanism. The hypotheses carry very different implications for the character of tectonic and volcanic activity at the Venus surface.

Plate Recycling. The creation of new lithosphere, its cooling during seafloor spreading, and its subsequent subduction account for about 65% of the current heat loss of the earth, estimated at 4.2x10^{13} W [1]; the remainder of the heat loss is contributed by lithospheric conduction (20%) and radioactive decay in the continental crust (15%). Plate tectonics, in addition to its dominant role in heat transfer in the outer portions of the earth, accounts for most of the characteristics of the large scale topography of this planet, including the mid-ocean ridges, the systems of trenches and island arcs, the linear mountain belts at Andean-type subduction zones or at Himalayan-type continental collisions, and ultimately the formation, growth and distribution of continents. Venus, similar in mass and radius to the earth, is likely to have a roughly similar heat budget, an assumption consistent with the Venera measurements of surface radioactivity and the Pioneer measurements of atmospheric 40Ar. Scaling by volume from the earth gives the Venus heat loss at 3.6x10^{12} W. A reasonable hypothesis is that Venus, like the earth, loses much of this heat by plate recycling.

This hypothesis has been challenged in the literature on the basis of several arguments: (1) that topographic features indicative of plate tectonics can't be "seen" on Venus [6, 7, 9, 10]; (2) that most of the Venus surface is "ancient" on the basis of the distribution of inferred impact craters and basins [10]; (3) that because of the high surface temperature, the Venus lithosphere is less likely to subduct than oceanic lithosphere on earth [9, 11]; and (4) that because of the high surface temperature, plate recycling is a less "efficient" process for removing heat than on earth [12]. None of these arguments, however, is sufficiently compelling to warrant the conclusion that plate recycling does not occur on Venus.

The search for topographic analogs on Venus to plate tectonic features on earth is made difficult by the coarse horizontal resolution of Pioneer Venus altimetry and, for oceanic-type features, by the lack of an ocean and by the likely lesser temperature drop across the lithospheric thermal boundary layer on Venus [8]. Further, many terrestrial tectonic features may owe their principal characteristics to the abundance of surface water or to the low temperature rheology of rocks. Island arc volcanism, for instance, may require the subduction of material containing free water or hydrated minerals and the release of that water at depth to initiate melting [13]. Finally, of course, there are topographic features, such as linear mountain belts, continental-sized plateaus and arcuate ridges and troughs, which resemble terrestrial features of plate-tectonic origin [8, 10].
LITHOSPHERIC HEAT TRANSFER ON VENUS

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The inference that much of the Venus surface is "ancient" is based on the identification of a number of large quasi-circular features in radar images [14] as impact basins [10]. As discussed elsewhere in this volume [15], a 4 b.y. old basin on Venus subjected to viscous relaxation at rates governed by the high surface temperature should have negligible topographic relief. Thus large circular depressions on Venus are substantially younger than 4 b.y. in age, and are unlikely to be impact basins. The implication that there is more than one mechanism for forming large circular depressions on Venus opens to question the identification as impact basins of circular features discerned on the basis of radar reflectivity.

While the conclusion that the Venus lithosphere is less unstable gravitationally than terrestrial oceanic lithosphere [9, 11] is generally correct, this result is not an argument against subduction on Venus. On earth, seafloor as young as 10 m.y. old is subducted [15], yet such lithosphere is certainly less unstable than unsubducted oceanic lithosphere 150 m.y. old. Further, even if the Venus lithosphere were marginally stable, subduction could be sustained by a finite-amplitude instability once initiated. The argument [12] that plate recycling would be less efficient on Venus is sensitive to the assumptions made for the tectonic models and would apply as well to other heat transfer mechanisms in which magma transport to the surface plays a central role.

We conclude that plate recycling on Venus, while certainly not proven, remains a viable mechanism for lithospheric heat transfer.

Conduction. If all of the heat from Venus were transported by conduction, the lithospheric thermal gradient would be roughly twice that in terrestrial ocean basins [16], or about 20°C/km. Thus temperatures corresponding to the base of the thermal lithosphere in oceanic regions on earth [16] would be reached at about 40-45 km depth. It is difficult to envision mechanisms for supporting the 13 km of relief on Venus if the thermal lithosphere is this thin. Certainly one immediate implication of the hypothesis that conduction dominates heat transfer on Venus is that all surface topographic relief on scales smaller than characteristic horizontal scales of mantle convection must be geologically young.

Hot Spot Volcanism. If on Venus, as on Io, the dominant mechanism of lithospheric heat transfer is volcanic activity at individual vents [9], then there are profound implications for volcanic flux and rates of resurfacing. The most prominent hot spot on earth, Hawaii, has an average volcanic flux for the past 45 m.y. of 2x10^-7 km^2/yr [17]; at this rate Hawaiian volcanism contributes less than 0.1% of the earth's heat loss. Whether the number of important hot spots on earth is 20 [18] or closer to 100 [19], the total contribution of hot spots to terrestrial heat loss is minor. If all of the Venus heat were lost by hot spot volcanism, a total of 10^6 "Hawaii's" would be needed, or one "Hawaii" for each 200-km square of Venus surface. Every 2 m.y. these hot spots would add enough volcanic material to cover the entire Venus surface to a depth of 1 km.

Conclusion. Without more detailed information on the Venus surface, all of the mechanisms for lithospheric heat transfer considered here should be considered as potentially important for Venus. Although the specific implications of these mechanisms for tectonic and volcanic features on the Venus surface are quite different, each of the hypotheses that one of these mechanisms dominates leads to the prediction that many if not most of the topographic features of the Venus surface are geologically young.