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# Mechanisms for Lithospheric Heat Transport on Venus: Implications for Tectonic Style and Volcanism

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The tectonic and volcanic characteristics of the surface of Venus are poorly known, but these characteristics must be closely related to the mechanism by which Venus rids itself of internal heat. On the other solid planets and satellites of the solar system, lithospheric heat transport is dominated by one of three mechanisms: (1) plate recycling, (2) lithospheric conduction, and (3) hot spot volcanism. We evaluate each mechanism as a candidate for the dominant mode of lithospheric heat transfer on Venus, and we explore the implications of each mechanism for the interpretation of Venus surface features. Despite claims made to the contrary in the literature, plate recycling on Venus cannot be excluded on the basis of either theoretical arguments or present observations on topography and radar backscatter. Landforms resulting from plate convergence and divergence on Venus would differ substantially from those on the earth because of the high surface temperature and the absence of oceans on Venus, the lack of free or hydrated water in subducted material, the possibility that subduction would more commonly be accompanied by lithospheric delamination, and the rapid spreading rates that would be required if plate recycling removes a significant fraction of the internal heat. If plate recycling occurs on Venus, the rolling plains and lowlands provinces would be approximate analogs to terrestrial ocean basins in terms of age, igneous rock type, and formative process; highlands on Venus would be roughly analogous to terrestrial continents. The hypothesis that lithospheric conduction dominates shallow heat transfer on Venus leads to the prediction that the lithosphere is thin. If Venus has a global heat loss per mass equal to that for earth, then temperatures marking the base of the thermal lithosphere on earth would be reached on Venus at an average depth of about 40 km. Unless the mantle convective planform can maintain lithospheric regions of persistently low heat flow or unless the present atmospheric greenhouse on Venus is geologically recent, then such a lithospheric thickness leads to the conclusion that the topographic features contributing to the 13 km of relief on the planet must be geologically young. The hypothesis that hot spot volcanism dominates lithospheric heat transfer on Venus leads to the prediction that the surface must be covered with numerous active volcanic sources. In particular, if a typical Venus hot spot has a volcanic flux equal to the average flux for the Hawaiian hot spot for the last 40 m.y., then $10^4$ such hot spots are necessary to remove the Venus internal heat by volcanism. Such a number would produce enough volcanic material to resurface the entire planet to a depth of 1 km every 2 m.y.; few areas of the planet would escape resurfacing for geologically long periods of time. We find that none of the mechanisms for lithospheric heat transfer on Venus can be excluded as unimportant at present; it is likely that, as on earth, a combination of mechanisms operates on Venus. The strongest conclusion to emerge from this evaluation is that most of the major topographic features and probably many of the surface geological units on Venus are young by comparison with the surfaces of the smaller terrestrial planets.

## INTRODUCTION

The mechanism by which a solid planet transports heat across the outer 100 km of its interior plays a pivotal role in determining the styles and magnitudes of tectonic and volcanic activity at the planet's surface. Among the planets can be found examples of bodies in which one of three distinct mechanisms has dominated heat loss (Figure 1), and the resulting geological histories for these bodies differ profoundly. For the earth, the majority of mantle-derived heat is delivered to the surface through plate recycling: the processes of creation, cooling, and subduction of oceanic lithosphere [*Sclater et al.*, 1980]. For the smaller terrestrial bodies, including Mars, Mercury, and the earth's moon, heat transport has occurred principally by conduction through a globally continuous lithospheric shell [*Solomon*, 1978], and the levels of both tectonic and volcanic activity have been much more limited than on earth [*Head and Solomon*, 1981]. For Jupiter's moon Io, eruptions at individual volcanic centers, or 'hot spots,' dominate the lithospheric heat flux [*Matson et al.*, 1981; *Reynolds et al.*, 1980; *O'Reilly and Davies*, 1981] and result in geologically rapid rates of global resurfacing [*Johnson et al.*, 1979].

For Venus, the available radar imaging and altimetry data [*Goldstein et al.*, 1976, 1978; *Campbell et al.*, 1976, 1979; *Campbell and Burns*, 1980; *Pettengill et al.*, 1980; *Masursky et al.*, 1980] are at too coarse a horizontal resolution to allow the tectonic and volcanic features diagnostic of one or more of these mechanisms of lithospheric heat transfer to be discerned unequivocally. As a result, debates have ensued over such issues as whether the surface of Venus displays features indicative of lithospheric recycling analogous to terrestrial plate tectonics [*Masursky et al.*, 1980; *Phillips et al.*, 1981; *Arvidson and Davies*, 1981; *Head et al.*, 1981; *Kaula and Phillips*, 1981; *Arvidson and Guinness*, 1982; *Brass and Harrison*, 1982; *Phillips and Malin*, 1982]. Rather than simply continuing such a debate, we take in this paper a different approach to the coupled questions of lithospheric heat transport and volcanic and tectonic activity on Venus.



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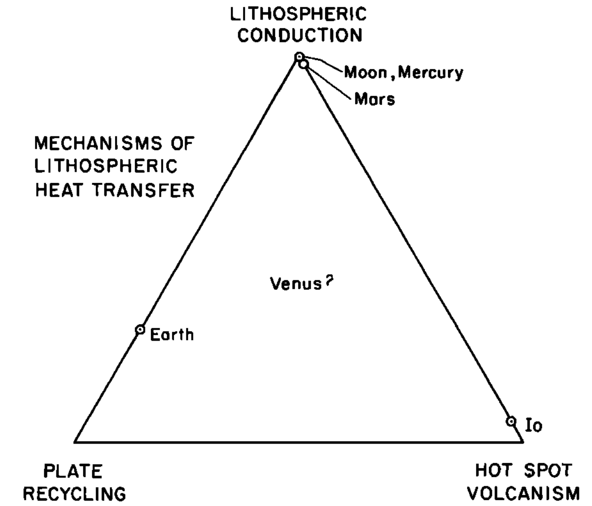


Fig. 1. Schematic ternary diagram showing the relative contributions of each mechanism of lithospheric heat transfer toward global heat loss on solid planets and satellites. For the moon, Mercury, and Mars, thermal conduction carries all of the lithospheric heat flow. The position of the earth, on which the majority of lithospheric heat transport occurs by plate recycling, is from *Sclater et al.* [1980] and does not include the contribution to global heat loss from crustal radioactivity. Hot spot volcanism dominates heat loss on Io, but the relative fraction contributed by conduction is not known precisely [*Reynolds et al.*, 1980; *O'Reilly and Davies*, 1981]; at the position shown on the diagram, the conductive heat flow on Io is equal to the earth's average heat flux.

We pose three hypotheses for lithospheric heat transfer on Venus, each based on one of the mechanisms known to dominate heat flux on other planetary bodies: (1) that lithospheric heat transport occurs primarily through plate recycling, (2) that lithospheric conduction dominates the heat loss, and (3) that heat is transported through the lithosphere principally by hot spot volcanism. These three hypotheses should be regarded as end-members; clearly, combinations of mechanisms may also serve to deliver internal heat to the planetary surface. We test each hypothesis against the known properties of Venus, and we explore the implications of each for the character of tectonic and volcanic activity at the Venus surface. We find that none of the individual hypotheses can currently be excluded. Although specific predictions of the three hypotheses for surface geological evolution differ substantially, each hypothesis leads to the conclusion that many, if not most, of the physiographic features of the Venus surface are geologically young.

## VENUS HEAT FLOW

To quantify discussions of specific mechanisms for lithospheric heat transport on Venus, it is necessary to adopt a value for the rate of global heat loss from the planet. Since the surface heat flux on Venus has not been measured, we assume as a basis for an estimate that the heat loss per mass on Venus is identical to that on earth. The present heat loss from the solid earth is $4.2 \times 10^{13}$ W, for a globally averaged heat flow of 82 mW/m$^2$ [*Sclater et al.*, 1980]. The mass of Venus is 0.815 earth masses [e.g., *Ash et al.*, 1971], and the surface area of Venus is 4.60 $\times 10^8$ km$^2$ [*Pettengill et al.*, 1980]. The earth-scaled values for global heat loss and surface heat flux for Venus are therefore $3.4 \times 10^{13}$ W and 74 mW/m$^2$, respectively.

The heat flux from the earth consists of two parts: heat generated by currently operative internal processes and heat remaining from such ancient processes as planetary accretion and core-mantle differentiation. A recent review of these aspects of the thermal history problem is given by *Solomon et al.* [1981]. Of the currently operative processes, radioactive decay contributes the vast majority of the heat generation, with minor increments contributed from the motion of phase boundaries (e.g., inner core freezing) and tidal dissipation. To determine the partitioning of global heat loss between presently generated and ancient heat, it is necessary to solve for the earth's thermal evolution, including particularly the effect of solid state convection on mantle heat transfer. A number of such calculations have recently been performed using one of several parameterization schemes for heat transport by mantle convection [*Sharpe and Peltier*, 1978, 1979; *Schubert et al.*, 1979*a*, *b*, 1980; *Schubert*, 1979; *Sleep*, 1979; *Stevenson and Turner*, 1979; *Turcotte et al.*, 1979; *Daly*, 1980; *Davies*, 1980; *McKenzie and Weiss*, 1980; *Stacey*, 1980; *Turcotte*, 1980; *Cook and Turcotte*, 1981; *McKenzie and Richter*, 1981]. These calculations indicate that some fraction between 50 and 90% of the earth's heat loss is contributed by presently operative heat generation processes, with the specific value dependent on the type of parameterization adopted and the assumptions made about heat sources, the temperature dependence of viscosity, and radial zoning in the mantle. The remainder of the earth's heat loss is a consequence of the secular cooling of the planet.

There are several observational and theoretical arguments that provide some support for the assumption of equal rates of heat loss per mass for Venus and earth. Several independent cosmochemical models for the formation of the terrestrial planets yield roughly comparable bulk abundances by mass for heat-generating elements in the two bodies [see *Wood et al.*, 1981]. The measured abundances of U, Th, and K at the Venera 8, 9, and 10 landing sites [*Vinogradov et al.*, 1973; *Surkov et al.*, 1977; *Surkov*, 1977] and the measured $K_2O$ abundances at the Venera 13 and 14 landing sites [*Barsukov*, 1982] are generally comparable to values in terrestrial tholeiites and alkali basalts. The total amount of radiogenic $^{40}$Ar in the Venus atmosphere is within a factor of 3 of that in the earth's atmosphere [*Hoffman et al.*, 1980], though whether the lower amount on Venus is attributable to differences in outgassing history or in the bulk K abundance is not known.

Parameterized-convection models of the thermal history of Venus [*Sharpe and Peltier*, 1979; *Turcotte et al.*, 1979; *Solomon et al.*, 1981; *Phillips and Malin*, 1982] indicate that for the same assumptions as those used in models of the thermal history of the earth, the evolution of the two planets has been broadly similar. In particular, secular cooling of Venus contributes to the predicted present heat loss of Venus by an amount comparable to that for the earth.

We conclude that a scaling of heat loss by mass from the earth to Venus is a reasonable working hypothesis. The value of the Venus heat loss, however, even under such a hypothesis, has considerable uncertainty. The earth's heat flux may have been 25 to 50% greater at times of enhanced rates of seafloor spreading in the Phanerozoic [*Hays and Pitman*, 1973; *Pitman*, 1978; *Turcotte and Burke*, 1978; *Sleep*, 1979; *Harrison*, 1980; *Sprague and Pollack*, 1980], so that the terrestrial heat loss determined for the present earth [*Sclater et al.*, 1980] may be less than the average global heat loss on time scales of $10^8$ years. If the difference in the amount of $^{40}$Ar between the atmospheres of Venus and earth represents a difference in the planetary abundance of potassium, the Venus heat loss would be less than the value assumed here. The difference, however, would probably be small. The present contribution of $^{40}K$ to the heat production in terrestrial material with K/U = $10^4$ and Th/U = 3.7 by weight [*Wasserburg et al.*, 1964] is 15%; thus if the abundances by weight of refractory elements such as U and Th are comparable on Venus and earth but the abundance of the more volatile element K is lower by a factor of 3, the overall heat production per mass would be only 10% less for Venus than for the earth.

## PLATE RECYCLING

The recycling of lithosphere into the underlying mantle is the major governor of terrestrial volcanic and tectonic activity and of the formation of the large-scale physiographic features of the earth's surface. Creation of new lithosphere at mid-ocean ridges is the dominant volcanic process on the planet. Spreading and cooling of the oceanic lithosphere, the thermal boundary layer of mantle convection, produces the characteristic relationship between ocean depth and seafloor age [e.g., *Parsons and Sclater*, 1977] as well as the distinctive pattern of ridge axis and fracture zone physiography. Trenches, great thrust faults, and volcanic island arcs mark the loci of subduction of oceanic lithosphere beneath another oceanic plate. Island chains and many oceanic aseismic ridges are products of the motion of surface plates over mantle sites of persistent hot spot volcanism [e.g., *Wilson*, 1965]. Passive margins of continents mark the sites of former intracontinental rifting where new oceans were created. Tectonically active mountain belts form where subduction occurs beneath overriding continental lithosphere, as in the Andes, or where two continental masses collide after closure of an intervening ocean, as in the Himalayas [e.g., *Dewey and Bird*, 1970].

Plate recycling is also the dominant mechanism for heat transfer across the outermost 100 km of the solid earth. The most careful analysis of the partitioning of terrestrial heat flow among the contributiong processes is that of *Sclater et al.* [1980]. These workers estimate that about 65% of the present heat loss of the earth is associated with the plate recycling process, including the creation and cooling of oceanic lithosphere and continental orogeny associated with plate interactions. Another 20% of the heat loss occurs by conduction through oceanic and continental lithosphere, and 15% is generated by radioactive decay within the continental crust. As noted earlier, there have been extended periods during the Phanerozoic when the volumes of mid-ocean ridges, and by inference the global rates of plate creation, have been substantially greater than they are at present [*Hays and Pitman*, 1973; *Pitman*, 1978; *Turcotte and Burke*, 1978]. During such times both the total rate of global heat loss and the fraction of that heat loss contributed by the plate recycling process were greater than their present values [*Turcotte and Burke*, 1978; *Sleep*, 1979; *Harrison*, 1980; *Sprague and Pollack*, 1980].

Because such a large fraction of the earth's heat is lost by plate recycling, the typical thermal gradients in old oceanic and continental lithosphere are much less than they would be in the absence of plate tectonics [e.g., *Sclater et al.*, 1980]. That conduction through the continental lithosphere has contributed only modestly to the earth's global heat loss as far back as the Archean is strongly suggested by the observation of *Burke and Kidd* [1978] that products of crustal remelting are not observed on a regionally extensive basis in exposed sections of lower continental crust in the Archean terrain of the Superior Province. A clear implication of the process of lithospheric heat transport on earth is that terrestrial continental and oceanic geotherms cannot be extrapolated to Venus without making internally consistent assumptions about both the global heat loss and the fraction of that heat loss delivered by lithospheric conduction. This point has not been addressed in several discussions of the thermal structure of the Venus interior [e.g., *Warner*, 1979; *McGill*, 1979; *Kaula and Phillips*, 1981].

Because Venus and the earth have similar masses, bulk densities, and positions in the solar system, and on the basis of the assumed similarities in global heat loss, a reasonable hypothesis is that Venus, like the earth, loses much of its heat by lithospheric recycling. We shall evaluate this hypothesis and its implications for the evolution of the Venus surface in this section.

The hypothesis that plate recycling presently occurs on Venus has been challenged in the literature on several grounds: (1) that topographic features indicative of terrestrial plate tectonics cannot be 'seen' on Venus [*Masursky et al.*, 1980; *Phillips et al.*, 1981; *Arvidson and Davies*, 1981; *Kaula and Phillips*, 1981; *Arvidson and Guinness*, 1982; *Schaber*, 1982], (2) that most of the Venus surface is 'ancient,' as indicated by the distribution of inferred impact craters and basins [*Schaber and Boyce*, 1977; *Masursky et al.*, 1980; *Phillips et al.*, 1981], (3) that because of the high surface temperature on Venus, the lithosphere is less likely to subduct than oceanic lithosphere on earth [*Anderson*, 1981; *Phillips and Malin*, 1982], and (4) that because of the high surface temperature and from the observed characteristics of 'ridges' on Venus, plate recycling is a less 'significant' process for removing heat than on earth [*Kaula and Phillips*, 1981]. As we discuss below, however, none of these arguments is sufficiently strong to rule out plate recycling on Venus on the basis of present evidence.

### *On Topographic Features Diagnostic of Plate Recycling*

The global topography of Venus as measured by the Pioneer Venus orbiter [*Pettengill et al.*, 1980] stimulated considerable interest in the question of whether the nature of tectonic and volcanic activity on that planet can be discerned from the large-scale physiography. In particular, the statement has been made repeatedly in the literature that Venus lacks topographic features indicative of terrestrial-style plate tectonics [*Masursky et al.*, 1980; *Phillips et al.*, 1981; *Arvidson and Davies*, 1981; *Arvidson and Guinness*, 1982; *Schaber*, 1982].

There are several reasons why a search for features indicative of lithospheric recycling on Venus may be more difficult than has been generally appreciated. The horizontal resolution of the Pioneer Venus topographic data is about 100–200 km [*Pettengill et al.*, 1980], so that features of lesser horizontal dimensions than these values are not resolvable. A topographic map of the earth at comparable resolution would not resolve such features, for instance, as many oceanic trenches and the axial valleys on slowly spreading mid-ocean ridges [*Head et al.*, 1981]. Further, oceanic topography on earth is capable of approximately 50% greater relative relief because of the presence of the water layer. In addition, the rate of deepening of the terrestrial oceanic lithosphere, or thermal boundary layer, with age is proportional to the difference in temperature between the bottom and top of the layer [*Parsons and Sclater*, 1977]; on Venus, with its higher surface temperature, the rate of deepening of the surface of any analog to oceanic lithosphere should be correspondingly less. Both of these effects would thus act to reduce the relief of Venus analogs to spreading ridges, trenches, and submarine hot spot traces compared with their terrestrial counterparts [*Phillips et al.*, 1981; *Head et al.*, 1981; *Arvidson* and Davies, 1981; *Kaula and Phillips*, 1981]. While this reduced relief would still permit the identification of large-scale plate tectonic features (such as mid-ocean ridges, mountain belts, and hot spot traces) on earth using only altimetry at Pioneer Venus resolution, at issue is whether such features could be correctly interpreted if no other information were available [*Head et al.*, 1981; *Arvidson and Davies*, 1981].

Any tectonic comparison of the topography of Venus and earth should also be made in recognition of the fact that many of the physiographic characteristics of terrestrial features of plate tectonic origin are a direct result of the present distribution of continents and ocean basins, the present range of ridge spreading rates, and the presence of surface water. On a planet with a higher surface temperature and negligible surface water, many of these characteristics might be expected to differ. For example, the orthogonal pattern of mid-ocean ridge segments and transform faults is held to be a diagnostic feature of terrestrial plate tectonics that is visible in the topographic data for some oceanic regions even at Pioneer Venus resolution [*Arvidson and Davies*, 1981]. On the basis of laboratory experiments, however, it appears that this pattern may be a function of material properties. *Oldenburg and Brune* [1975] found that in wax analogs of spreading center systems, establishment and maintenance of an orthogonal ridge-transform pattern occurred only if the resistive stresses along transform faults are less than the shear strength of the lithosphere. If, compared with the earth, the shear strength at the elevated surface temperature of Venus is reduced relative to transform-fault resistance, then Venus might display lithospheric recycling without the familiar orthogonal pattern at spreading centers.

Convergence zones on a Venus with lithospheric recycling may also differ substantially from analogous zones on the earth. Island arc volcanism, though incompletely understood, is thought to result from partial melting initiated by the dehydration at depth of subducted oceanic crust [e.g., *Lofgren et al.*, 1981]. If subduction occurred on Venus without the entrainment of water or hydrous phases in the subducted material, then dehydration at depth would not occur and the Venus equivalent of island arc volcanism need not be present. The deep-sea trenches marking the locus of subduction of oceanic lithosphere are known to owe their physiographic characteristics, such as relative depth and width, to the thickness of the elastic or viscoelastic portion of the subducted plate, the velocity of convergence, and the nature of any adjacent sources of sediment [e.g., *Grellet and Dubois*, 1982]; these parameters would be expected to differ for Venus. Because of the high surface temperature of Venus, a better model for some convergence zones on that planet might be based on the notion of lithospheric delamination as proposed for zones of terrestrial continental collision [*Bird*, 1978, 1979; *Reutter et al.*, 1980; *Bird and Baumgardner*, 1981; *Fleitout and Froidevaux*, 1982]. According to this model, a low-strength zone at the base of the crust permits delamination of the lithosphere, subduction of the mantle portion, and deformation without subduction of the more buoyant crustal material. Such a model, applied to some subduction zones on Venus, would lead to the prediction of regions of intense surface deformation surrounding convergence zones but little recycling of surficial or crustal material back into the underlying mantle.

It is worth noting that there are topographic features on the Venus surface which differ from any seen on the smaller terrestrial planets and which resemble features on earth of plate tectonic origin. These features include linear mountain belts such as Akna and Freyja montes, continental size plateaus such as Lakshmi Planum, and arcuate ridges and troughs such as in the Ut and Vesta Rupes region on the southwest margin of Ishtar Terra [*Masursky et al.*, 1980; *Head et al.*, 1981; *McGill et al.*, 1981, 1982; *Campbell et al.*, 1982; *Phillips and Malin*, 1982].

We therefore regard the tectonic interpretation of the topographic features of the Venus surface as uncertain at the resolution of our current information. Both an improvement in the resolution of surface features on Venus and detailed investigations of the effects of Venus surface conditions on the characteristic landforms produced by various geological processes are needed to improve our understanding in this area.

### *On the Age of the Venus Surface*

A number of approximately circular features on the Venus surface, ranging in diameter from 20 to over 1000 km, have been identified on the basis of variations in radar reflectivity or topography [*Goldstein et al.*, 1976, 1978; *Schaber and Boyce*, 1977; *Campbell et al.*, 1979; *Campbell and Burns*, 1980]. The hypothesis that many or all of these features originated by impact has led to the inference that much of the surface of Venus is geologically ancient. In particular, if the quasi-circular regions of low radar backscatter 200 km or greater in diameter have been correctly identified as impact basins dating from the heavy bombardment of the inner solar system, then Venus contains major geologic units with surface ages approaching 4 b.y. [*Schaber and Boyce*, 1977; *Masursky et al.*, 1980].

Because of the high surface temperature, topographic features on Venus are subjected to viscous relaxation at rates much higher than for the other terrestrial planets [e.g., *Weertman*, 1979]. In particular, if the surface temperature of Venus has been comparable to its present value for much of the planet's history, then a 4-b.y.-old impact basin on Venus should have negligible topographic relief [*Solomon et al.*, 1982]. Large circular depressions on Venus, such as Atalanta Planitia, are substantially younger than 4 b.y. and are unlikely to be impact basins. Such topographic depressions may owe their origin to one of the tectonic mechanisms proposed for intracontinental basins on earth, i.e., cooling and subsidence following lithospheric extension or thermal uplift and erosion [*Sleep and Snell*, 1976; *McKenzie*, 1978]. The large quasi-circular, radar-dark features on the Venus surface may still be impact basins, degraded by essentially complete relaxation of long-wavelength topography. Such features may also be older versions of circular lowland regions of Venus, however, and by implication also of tectonic origin.

The question of the age of the Venus surface should be regarded as open. There are alternative tectonic interpretations of the large circular features visible in radar images. Even the population of smaller 'craters' 20–200 km in diameter may contain features of volcanic as well as impact origin [*Saunders and Malin*, 1976; *Campbell and Burns*, 1980; *McGill et al.*, 1982]. These uncertainties do not preclude the possibility that portions of the Venusian surface are billions of years old, nor do they permit the rejection of the hypothesis that much of the Venusian surface, as with the solid surface of the earth, is geologically young.

### *On Lithospheric Buoyancy on Venus*

A necessary condition for subduction is that the subducted material be of greater density than the surrounding mantle. The negative buoyancy of the subducted slab of lithosphere on earth is a consequence of its relatively cooler temperature and also a result of phase changes which occur at shallower than normal depth in the cooler slab [*Toksöz et al.*, 1971; *Turcotte and Schubert*, 1971]. The argument has been advanced that a Venus lithosphere similar in crustal thickness and other physical properties to oceanic lithosphere on earth would have less negative buoyancy because of the higher surface temperature and smaller lithospheric thickness on Venus [*Anderson*, 1981; *Phillips and Malin*, 1982]. *Anderson* [1981] has argued further that an additional factor which might make the Venus lithosphere positively buoyant is the enhanced depth range of the basalt stability field on Venus compared with that on earth, thereby opening the possibility for crustal thicknesses substantially greater than in terrestrial ocean basins.

These buoyancy calculations are sensitive to the assumptions made about parameters which are at best poorly known for Venus, including the thickness of a crustal layer, the location of the mantle residuum remaining after extraction of partial melt to produce the crust, and the partitioning of planetary heat loss among plate recycling and conduction. Thus the uncertainty attached to an individual result is large, and both positive and negative values for net lithospheric buoyancy are possible results at our present stage of understanding [*Phillips and Malin*, 1982].

That the Venusian lithosphere is less negatively buoyant than old oceanic lithosphere on earth is likely, yet even this conclusion is not a strong argument against some form of subduction on Venus. On the earth, oceanic lithosphere with seafloor as young as 10 m.y. is subducted [*Menard*, 1978], yet such lithosphere is certainly less negatively buoyant than unsubducted oceanic lithosphere 150 m.y. old. *Parsons* [1982], in fact, has demonstrated that the distribution of ocean floor area versus age on the earth is consistent with the hypothesis that plate consumption is uniformly distributed with age except for seafloor younger than 10 m.y. old. Subduction of young seafloor may, of course, be sustained by a finite-amplitude instability; i.e., 10 m.y. old oceanic lithosphere may be only marginally unstable or even stable gravitationally yet continue to subduct if attached to a negatively buoyant slab. Such a finite-amplitude instability might equally well be invoked to sustain subduction on Venus. Once subduction of an aging piece of Venusian lithosphere is initiated, by this argument, the subduction process may be sustained by thermal anomalies and elevated phase transitions in the subducted slab, and the characteristic age of subducted material may be substantially younger than that initially subducted. If, as suggested earlier, lithospheric delamination occurs on Venus, then the mantle portion of the lithosphere would be negatively buoyant even if the crustal portion is not. Thus a thicker crust on Venus compared with terrestrial ocean basins [*Anderson*, 1981] need not restrict subduction of the mantle portion of the lithosphere where such delamination occurs. To the extent that the mantle residuum complementary to a basaltic crust resides in the lithosphere, in fact, the net lithospheric buoyancy may be largely insensitive to crustal thickness.

### *On the Kaula-Phillips Arguments on Heat Removal by Lithospheric Recycling on Venus*

*Kaula and Phillips* [1981] estimated an upper bound on the fraction of the global heat loss on Venus contributed by plate tectonics. While not an argument against plate recycling on Venus per se, their conclusion that the heat transported by plate tectonics is 15% or less of the global heat flux on Venus compared with 65% on earth [*Sclater et al.*, 1980] would, if true, provide an important contrast between the two planets.

We do not regard the 15% result of *Kaula and Phillips* [1981], however, as necessarily valid. Their calculation was based on an identification of candidate spreading ridges on Venus, a measurement of the rate of decrease in elevation with distance from each segment of the ridge, an application of thermal boundary layer theory to scale the physical parameters of mantle convection in the earth to those of Venus, and a conversion of the measured rates of change in elevation to estimates for the heat delivered along each spreading ridge segment. Further elaboration of the boundary layer scaling arguments is given by *Phillips and Malin* [1982].

The candidates for ridges chosen by *Kaula and Phillips* [1981] include Beta Regio and Aphrodite Terra. Both of these features contain large regions which, together with Ishtar Terra, compose the highlands province of Venus [*Masursky et al.*, 1980]; terrestrial continents rather than ocean ridges may provide a preferable analog to much of the Venus highland terrain [e.g., *Head et al.*, 1981]. Having made this selection of ridges, Kaula and Phillips then note that the Venus ridge heights do not show a narrow distribution about a mode as do terrestrial ocean ridges well removed from hot spots [*Parsons and Sclater*, 1977] and that these ridges do not form an interconnected global system. While these observations may be sufficient to rule out either Beta Regio or Aphrodite Terra as Venusian analogs to terrestrial mid-ocean ridges [cf. *Schaber*, 1982], neither observation is a compelling argument against lithospheric recycling on Venus in general.

Having posed the hypothesis that plate recycling dominates lithospheric heat transport on Venus, we should consider the expected form of Venusian spreading centers. A reasonable guide to the rate of heat loss per length of spreading ridge follows from the spreading-plate model of oceanic lithosphere [*Williams and von Herzen*, 1974; *Kaula and Phillips*, 1981]:

$$q_r = \rho C_p L v \, \Delta T \qquad (1)$$

where $\rho$ and $C_p$ are the density and specific heat of the lithospheric plate, $L$ is the lithospheric thickness, $v$ is the average half spreading rate, and $\Delta T$ is the difference in temperature between the bottom and top of the lithosphere. Subduction of the lithosphere before it has reached thermal equilibrium will reduce $q_r$ from that given by (1). Because of the higher surface temperature on Venus, $\Delta T$ will be less for Venus than for the earth's ocean basins, though boundary layer scaling arguments suggest that the difference in $\Delta T$ between Venus and earth may be somewhat less than the difference in surface temperatures [*Kaula and Phillips*, 1981; *Phillips and Malin*, 1982]. For a spreading ridge system on Venus to deliver to the surface an amount of heat comparable to that delivered by ridges on earth, either the characteristic spreading rate or the total length of ridges (or both) must be greater on Venus than on earth. Because either possibility would likely be accompanied by a lesser characteristic age of subducted lithosphere on Venus than on earth, the product of ridge length and mean spreading rate would exceed that quantity for the earth by a ratio greater than simply the ratio of the values of $\Delta T$ for the two bodies.

These considerations suggest that the most likely candidates for spreading ridges on Venus should be characterized by rapid rates of spreading and correspondingly small rates of change in topographic height with distance from the ridge axis. *Phillips and Malin* [1982] have shown that a fast spreading ridge, such as the East Pacific Rise, would have only modest topographic

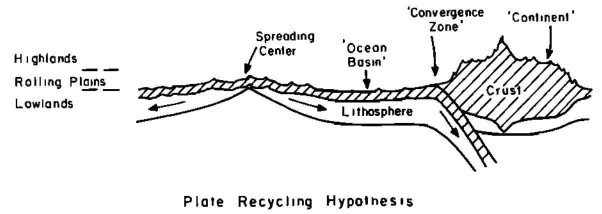


Fig. 2. A schematic illustration of the plate recycling hypothesis for lithospheric heat transport on Venus. The rolling plains (0 to 2 km elevation with respect to the planetary modal radius) and lowlands (0 to −2 km) are analogous to terrestrial ocean basins and include spreading centers and convergence zones not currently resolvable from altimetry or imaging data. The highlands (2 to 11 km elevation) are analogous to terrestrial continents.

relief at Venus conditions and that such a ridge on Venus could not be detected from Pioneer Venus altimetry given the 200-m standard error for these data [*Pettengill et al.*, 1980]. By the plate recycling hypothesis for Venus, the rolling plains and lowlands provinces (as defined by *Masursky et al.* [1980]) should be the Venusian analogs to terrestrial ocean basins. Altimetric and imaging data from rolling plains and lowlands areas must be obtained at resolutions superior to those of data currently available in order to search for the predicted extensive system of fast spreading ridges and thereby to provide a rigorous test of the plate recycling hypothesis for Venus.

### *Assessment and Implications of the Hypothesis*

We find no convincing argument to reject at present the hypothesis that some form of plate recycling dominates lithospheric heat transfer on Venus. This conclusion does not mean that plate tectonics can presently be demonstrated on Venus or that we may not at some future date obtain improved information on the Venusian surface or interior that will allow the question to be firmly resolved. Rather, the conclusion demands that at our present level of understanding, the hypothesis that plate recycling is important for heat flow on Venus should continue to be rigorously tested against available geological information.

The lithospheric recycling hypothesis for Venus is illustrated schematically in Figure 2, and some of the implications of the hypothesis for the surface characteristics of the planet are listed in Table 1. As on earth, volcanic activity on Venus should be extensive by this hypothesis and should be concentrated at divergent plate boundaries. Intraplate volcanic activity may also be present. Volcanism at subduction zones may be minor at present if no free water or hydrous phases are subducted. Tectonic activity should be widespread and dominated by the large-scale horizontal motions and mutual interactions of the plates. As noted above, however, the specific physiographic characteristics of many tectonic features at plate boundaries may differ from those on earth because of the greater surface temperature and negligible surface water on Venus. Theoretical models are needed for the expected form of such features at Venus-surface conditions.

By the plate recycling hypothesis, the rolling plains and lowlands provinces are analogs to terrestrial ocean basins in terms of formative process, crustal composition, and geologically youthful age. The spreading centers are expected to be characterized by rapid spreading rates and modest relief in comparison to earth. The Venus highlands may be analogs to terrestrial continents, though whether the analogy extends to composition or simply to crustal thickness is uncertain. The surface ages of highland geologic units on Venus may be considerably greater than the ages of units in the plains and lowlands. As with terrestrial continents, highland lithosphere should have greater buoyancy than the lithosphere beneath plains and lowlands and should therefore be more difficult to subduct. Mountainous terrain should, by this hypothesis, form by the collision of highland blocks (Himalayan analog) or at the locus of subduction beneath highland lithosphere (Andean analog). Both highland regions in general and mountain belts in particular will be modified as they age. Because of the high surface temperature and negligible water on Venus, viscous relaxation may be a more rapid process than weathering and erosion for reducing highland relief, in contrast to earth.

## LITHOSPHERIC CONDUCTION

The dominant mechanism for lithospheric heat transport on the smaller terrestrial planets is conduction through the single global lithospheric shell. That lithospheric conduction dominates the planetary heat loss on Venus has been an implicit or explicit element of a number of recent discussions of the internal and surface evolution of Venus [*Schaber and Boyce*, 1977; *Warner*, 1979; *Anderson*, 1981; *Phillips et al.*, 1981; *Arvidson and Davies*, 1981].

If the global heat loss on Venus is delivered to the surface

TABLE 1. Implications of End-Member Hypotheses for Lithospheric Heat Transport on Venus

| Surface Characteristics | Plate Recycling | Lithospheric Conduction | Hot Spot Volcanism |
|---|---|---|---|
| Volcanic activity | extensive; activity dominantly at divergent boundaries | minor | extensive; active centers nearly cover surface |
| Tectonic features | widespread; dominated by plate interactions | possibly extensive deformation of thin lithosphere | primarily vertical tectonics |
| Ages of surface units | rolling plains and lowlands geologically young ($<10^8$ years) | unconstrained; ancient impact features may be preserved | much of surface young ($\lesssim 10^7$ years) |
| Nature of mountain belts | products of plate convergence | anomalously thick crust and lithosphere | volcanic constructs |
| Nature of highlands | analogs to terrestrial continents | thickened crust and lithosphere | thickened volcanic crust |
| Nature of rolling plains and lowlands | analogs to terrestrial ocean basins | thinned crust and lithosphere | 'normal'-thickness volcanic crust |

entirely by lithospheric conduction, then the conductive geotherm may be estimated from the average surface heat flow of 74 mW/m$^2$ derived earlier. This heat flow is very close to twice the heat flux in old oceanic lithosphere near thermal equilibrium, given as $38 \pm 4$ mW/m$^2$ by *Sclater et al.* [1980]. Thus if the Venus lithosphere has a thermal conductivity similar to the average value of 3.1 W/m K adopted for the terrestrial oceanic lithosphere [*Parsons and Sclater*, 1977], then the thermal gradient in the Venus lithosphere is 24 K/km, or approximately twice that in old ocean basins. Geotherms for oceanic lithosphere at equilibrium [*Sclater et al.*, 1980] and for average lithosphere on Venus, assuming that heat transfer occurs solely by lithospheric conduction, are shown in Figure 3.

A consequence of the Venus geotherms shown in Figure 3 is that the lithosphere would be substantially thinner than on earth for comparable material properties of the mantle. The base of the thermal lithosphere in ocean basins is $1350 \pm 275$°C [*Parsons and Sclater*, 1977]. A temperature of 1350°C would be reached at a depth of about 40 km on Venus according to the geotherms shown in Figure 3. The base of the elastic lithosphere in oceanic regions is well approximated by the position of the $500 \pm 150$°C isotherm [*Watts et al.*, 1980]. An elastic lithosphere on Venus limited by this same temperature, a value governed by the ductile flow law for dry olivine [*Goetze and Evans*, 1979], would be at most 10 km in average thickness for a purely conductive Venus.

On both of these grounds, it is difficult to envision mechanisms for supporting the 13 km of relief on Venus [*Pettengill et al.*, 1980] for geologically long periods of time except perhaps through shear tractions associated with mantle convective flow. A likely implication, therefore, of the hypothesis that conduction dominates heat transfer on Venus is that all surface topographic relief on scales smaller than the characteristic horizontal scales of mantle convection is geologically young. Preservation of topographic relief for extended periods of time might occur more readily if elevated regions on Venus are

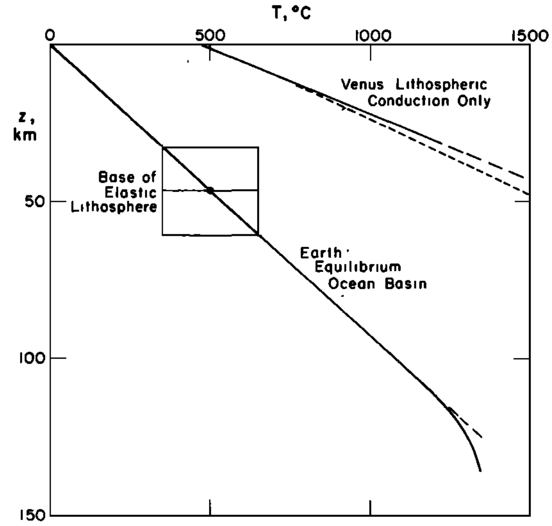


Fig. 3. Average lithospheric geotherms on Venus assuming that conduction is the only mode of lithospheric heat transfer. The solid line shows the case when all of the heat loss from Venus is generated below the lithosphere; the short-dashed curve indicates the case when 15% of the Venus heat loss is generated by radioactivity distributed uniformly in a crust 30 km thick. Also shown are the terrestrial geotherm for an old ocean basin in thermal equilibrium [*Parsons and Sclater*, 1977; *Sclater et al.*, 1980] and the range of isotherms inferred to define the base of the elastic lithosphere in ocean basins [*Watts et al.*, 1980].

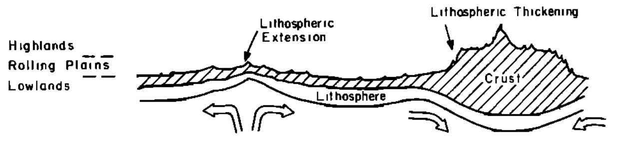


Fig. 4. A schematic illustration of the conduction hypothesis for lithospheric heat transport on Venus. On average, the lithosphere is only about 40 km thick and may be readily deformed by tractions associated with convection in the underlying asthenosphere. Modestly elevated regions in the rolling plains may be areas of recently extended and thinned crust and lithosphere, areas which will subside to lowland elevations during lithospheric cooling and thickening [e.g., *McKenzie*, 1978]. The more elevated highlands may be areas of thickened crust and lithosphere resulting from lithospheric compression.

characterized by a mantle heat flux that is lower than average. That such regionally low values of mantle heat flux could persist for hundreds of millions to billions of years for a planet with lithospheric heat transfer dominated by conduction, however, is unlikely. Alternatively, since the history of the surface temperature is uncertain [*Pollack*, 1971, 1979], topographic relief may have persisted for geologically long periods if the characteristic time for viscous relaxation is comparable to or less than the time since formation of the present atmospheric 'greenhouse.' The viscous relaxation time is unlikely to exceed a few hundred million years [*Solomon et al.*, 1982], however, so this possibility would require a geologically recent greenhouse.

The Venus geotherm shown as a solid line in Figure 3 is based on the simplification that all of the heat lost by the planet is generated beneath the lithosphere. The lithospheric thermal gradient would be lessened if concentration of radioactive heat sources in the Venus crust has occurred, thereby reducing the heat flux from the mantle [e.g., *Phillips and Malin*, 1982]. Since, by the conduction hypothesis, plate recycling and attendant remelting of basaltic crust at subduction zones would not have progressed on Venus to the current stage of concentration of heat sources in continental crust on the earth, a reasonable upper bound to the fraction of Venus heat flux contributed by crustal radioactivity is the terrestrial value of about 15% [*Sclater et al.*, 1980]. A greater concentration of radioactive heat sources into the crust on Venus than on the earth would also be difficult to reconcile with the lower $^{40}$Ar abundance in the Venus atmosphere [*Hoffman et al.*, 1980]. With the 15% value assumed for the fraction of global heat loss generated in the crust, the mantle heat flux on a Venus with the same heat loss per mass as the earth would be $29 \times 10^{12}$ W, and the temperature gradient in the Venus lithosphere would, as shown by the dashed curve in Figure 3, be only slightly modified from that discussed above.

The hypothesis that lithospheric heat flux on Venus occurs principally by conduction cannot be rejected on the basis of presently available information. A schematic illustration of this hypothesis is given in Figure 4, and a summary of the implications for the surface geology of Venus is given in Table 1. The average lithospheric thermal gradients are predicted to be substantially greater, and the lithospheric thickness correspondingly less, than for volcanic mechanisms of heat transport, including both plate recycling and hot spot volcanism. The lithospheric strength and resistance to deformation should generally be less for this hypothesis than for the hypothesis that either plate recycling or hot spot volcanism dominates lithospheric heat transport on Venus. As a result, lithospheric and crustal thinning and thickening may occur in response to tractions exerted on the base of the lithosphere by mantle convective flow (see Figure 4). The ages of surface geological units are not constrained by the conduction hypothesis and may span a great range. Because of the expected high rate of viscous relaxation, however, topographic relief on Venus should be either geologically young or dynamically maintained. Since the planform of mantle dynamics is not likely to be steady on time scales approaching the age of the planet, it would be reasonable to conclude by this hypothesis that none of the topographic features of Venus is likely to date from the first half of the planet's history.

## HOT SPOT VOLCANISM

Individual volcanic hot spots transport heat from a planetary interior by the ascent and cooling of magma and by conduction through a locally thinned lithosphere. *Phillips and Malin* [1982] have proposed that hot spot activity on Venus may provide the dominant mechanism of lithospheric heat transfer.

The implications of such a hypothesis may be quantified by considering first the archetypical terrestrial hot spot, the source of the Hawaiian-Emperor island-seamount chain [*Wilson*, 1965; *Morgan*, 1971]. The rate of heat loss $Q_v$ due to volcanism at a hot spot is given approximately by

$$Q_v = \rho(C_p \, \Delta T + \Delta H_f) \frac{dV}{dt} \tag{2}$$

where $\rho$ and $C_p$ are the density and specific heat, respectively, of the volcanic material, $\Delta H_f$ is the heat of fusion of the magma, $\Delta T$ is the difference between the eruption temperature of the magma and the ambient surface temperature, and $dV/dt$ is the volumetric flux of magma with time. *Shaw* [1973] has estimated that the Hawaiian hot spot has produced $8.5 \times 10^5$ km$^3$ of lava between the time of formation of the bend in the Hawaiian-Emperor chain and the present. Adopting the figure 42 m.y. for the age of the bend [*Dalrymple and Clague*, 1976] gives an average for $dV/dt$ of $2 \times 10^{-2}$ km$^3$/yr, though values larger by up to a factor of 5 have been appropriate for time intervals of a few million years [*Shaw*, 1973]. To estimate the average volcanic heat loss contributed by the Hawaiian hot spot for the last 42 m.y., we assume $\rho = 2.8$ g/cm$^3$, $C_p = 1.2$ J/g K, $\Delta H_f =$ 400 J/g, and $\Delta T = 1300$ K [*Solomon et al.*, 1981]. Then from (2), $Q_v = 3.5 \times 10^9$ W, or 0.008% of the earth's global heat loss.

The total contribution of hot spot volcanism to the overall heat loss of the earth is minor [*Sclater et al.*, 1980]. Of all the proposed hot spots [e.g., *Morgan*, 1971; *Burke and Wilson*, 1976], Hawaii has had probably the greatest volumetric flux of magma in recent geologic history. Thus whether the important terrestrial hot spots number 20 [*Morgan*, 1971] or closer to 100 [*Burke and Wilson*, 1976], the summed contribution of volcanically delivered heat from such hot spots to global heat flow is less than 1%.

If a hot spot with the same magmatic flux as Hawaii were on Venus, the rate of heat loss due to volcanism would be somewhat less than on earth because of the higher surface temperature and therefore the lesser extent of cooling. For an eruption temperature and other parameters equal to those assumed for the earth, equation (2) gives $Q_v = 2.5 \times 10^9$ W, or 0.007% of the global Venus heat loss if the heat loss per mass of Venus and the earth are equal. Thus to remove the total heat flux from Venus by volcanism at hot spots with rates of volcanic activity similar to that of Hawaii, a total of $10^4$ such hot spots would be needed. This figure amounts to an average of one 'Hawaii' on every 200-km square of the Venus surface. Whether the mantle convection system on Venus could supply magma to this number of volcanic centers essentially simultaneously on geological time scales is an open question.

Two effects may increase somewhat the contribution of volcanism at a Hawaiian-type hot spot to the total heat flux of Venus. The eruption temperature of typical hot spot magmas on Venus may be greater than on earth, due either to a lower FeO/(MgO + FeO) ratio [*Goettel et al.*, 1981; *Phillips and Malin*, 1982] or to lower volatile abundances [*McGill*, 1979; *Anderson*, 1980] in the Venus mantle compared with that of the earth. The rate of heat loss $Q_v$ for a Venus 'Hawaii' increases by $0.2 \times 10^9$ W for every 100 K increase in $\Delta T$ in equation (2), so that even a 500 K difference in eruption temperature between Venus and earth would raise $Q_v$ by no more than 40%. A second effect, also noted in the last section, is that concentration of radioactive heat sources in the Venus crust may reduce the heat flux from the mantle and thus the number of individual hot spots needed to remove that heat. Adopting, as above, the 15% value [*Sclater et al.*, 1980] as an upper bound to the fraction of Venus heat loss generated by crustal radioactivity, the contribution of volcanism at a Hawaiian-type hot spot to the total heat loss would still be about 1 part in $10^4$.

A planet with $10^4$ hot spots as active as Hawaii would have a total volcanic flux sufficient to affect the planetary surface profoundly on geologically short time scales. If the global rate of heat loss $Q$ is contributed entirely by hot spot volcanism, the planetary volcanic flux is

$$\frac{dV^*}{dt} = \frac{Q}{\rho(C_p \, \Delta T + \Delta H_f)} \tag{3}$$

For $Q = 34 \times 10^{12}$ W and other parameters as adopted above, $dV^*/dt = 280$ km$^3$/yr. Averaged over the surface of Venus, this flux amounts to a rate of surface burial of $6 \times 10^{-7}$ km/yr, or an additional 1-km thickness of new volcanic material over the entire planet every 2 m.y. This global burial rate is comparable to the estimated lower bound on the burial rate for Io [*Johnson et al.*, 1979].

Terrestrial hot spots contribute heat to the lithosphere by mechanisms other than extrusive volcanism. Lithospheric thinning beneath hot spots leads both to an enhanced conductive heat flux and to modest elevations in surface topography, such as the Hawaiian swell associated with the hot spot beneath Hawaii [*Detrick and Crough*, 1978]. This lithospheric thinning occurs on time scales short compared with the characteristic time for lithospheric heating or cooling by conduction [*Detrick and Crough*, 1978]; asthenospheric stoping, or in situ delamination and sinking of the lower lithosphere, may be involved in the rapid thinning process [*Turcotte*, 1982]. The lithosphere is apparently thinned by about a factor of 2 to 3 beneath the Hawaiian hot spot [*Detrick and Crough*, 1978; *Crough*, 1978; *Detrick et al.*, 1981; *Sandwell*, 1982; *von Herzen et al.*, 1982]. If a large number of hot spots are operative on Venus, then the conductive gradient would be lessened and the effective lithospheric thickness increased in those areas distant from hot spots compared with the global averages calculated in the last section.

These ideas may be quantified as follows. Let $\bar{q}$ be the globally averaged heat flux, let $q_0$ be the average heat flux in areas distant from hot spots, let $f$ be the fractional area of planetary surface occupied by hot spots, and let $\eta q_0$ be the conducted heat flux in the vicinity of a typical hot spot. The quantity $\eta$ may be regarded as the factor by which the lithosphere is characteristically thinned by some unspecified process at a hot spot. Clearly,

$$\bar{q} = f\eta q_0 + (1 - f)q_0 + q_v \tag{4}$$

where $q_v$ is the contribution to the global heat flux delivered by volcanism.

If volcanically delivered heat is small compared with conducted heat at hot spots and elsewhere (i.e., $q_v \ll \bar{q}$), then $q_0$ is given by

$$q_0 = \frac{\bar{q}}{1 - f + f\eta} \tag{5}$$

Under the assumption that the Hawaiian hot spot is a guide to the characteristics of possible hot spots on Venus, we take $\eta \simeq 2$–3 [*Detrick and Crough*, 1978; *Crough*, 1978; *Detrick et al.*, 1981; *Sandwell*, 1982; *von Herzen et al.*, 1982]. For $\eta = 2$, $q_0 \gtrsim \bar{q}/2$. That is, the lithospheric thickness far from hot spots can be increased by a factor only as large as 2 compared with the global average derived in the last section, with the factor of 2 approached only for the case where hot spots cover most of the surface of Venus ($f \simeq 1$). For $\eta = 3$, $q_0 \gtrsim \bar{q}/3$, again with near equality only if $f \simeq 1$. Lithospheric thicknesses approaching typical terrestrial values would be possible, but only in a few areas of very limited spatial extent.

If, in contrast, lithospheric heat transfer on Venus occurs dominantly by magma transport at individual hot spots (i.e., $q_v \simeq \bar{q}$ in equation (3)), the average lithospheric thickness is not constrained by global heat flow [cf. *O'Reilly and Davies*, 1981] and can be considerably greater than estimates obtained in the last section. In particular, the average lithospheric thickness can be greater than the 100-km depth of isostatic compensation inferred from the gravity anomalies over a number of topographically distinct features on the planet [*Phillips et al.*, 1979, 1981; *Reasenberg et al.*, 1981]. Thus large topographic relief could be supported passively and on nearly a global basis either by local isostatic compensation or by regional compensation and lithospheric strength.

The hypothesis that hot spot volcanism dominates lithospheric heat transfer on Venus (Figure 5) cannot be excluded on the basis of our present knowledge of the surface. The hypothesis carries important implications for the interpretaton of surface physiographic features (Table 1). The Venus surface, if most of the heat loss occurs by volcanism, should be densely covered with thousands of distinct centers of current or recent volcanic activity. Most of the physiographic features would have surfaces less than 10 m.y. old, though a few areas of older terrain may have escaped recent resurfacing. If the majority of the heat delivered at hot spots is due to lithospheric thinning, then hot spots would nearly have to cover the surface of Venus for the lithospheric thickness far from hot spots to be substantially greater than the globally averaged value. Much of the surface material should, in either case, consist of volcanic deposits. In particular, the Venus highlands would most likely have been formed by volcanic construction. Tectonic activity in the absence of large-scale horizontal motions should be principally restricted to that associated with vertical motions of the lithosphere.

The *Phillips and Malin* [1982] model for hot spot tectonics on Venus includes both volcanic transport of heat and lithospheric thinning beneath major volcanic centers, with the latter process making a greater contribution to the global heat loss. This model may be viewed as a combination of the mechanisms of lithospheric conduction and hot spot volcanism as considered in this paper, and the implications of their model involve a combination of aspects of the scenarios depicted in Figures 4 and 5.

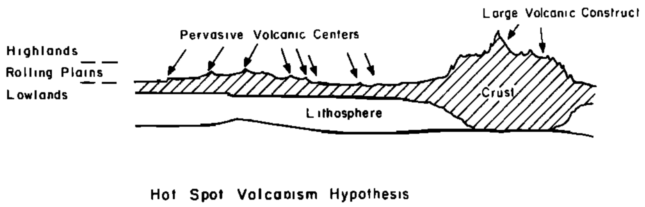


Fig. 5. A schematic illustration of the hot spot volcanism hypothesis for lithospheric heat transport on Venus. Volcanism carries the majority of the heat through the lithosphere, and active volcanic centers on the surface of Venus should be widespread. The highland terrain consists of large volumes of volcanic deposits and probably thickened crust. The surface material is generally volcanic and geologically young.

## CONCLUSIONS

Without more detailed information on the Venus surface, all of the mechanisms for lithospheric heat transfer considered here (lithospheric recycling, conduction, and hot-spot volcanism) should be regarded as potentially important for Venus. Though each of these mechanisms has been treated individually in this paper, weighted combinations of mechanisms must, of course, also be considered [e.g., *Phillips and Malin*, 1982]. The possibility that the dominant mechanism early in the history of the planet was different from that at present [e.g., *Phillips et al.*, 1981] should be recognized as well.

Each of the possible end-member models for lithospheric heat transfer on Venus carries different implications for the detailed characteristics of Venus landforms. The predicted characteristics (Table 1) should serve as a guide to the interpretation of existing and future imaging and topographic data on the Venus surface. For each of the hypothetical models for heat transfer, however, there is a clear implication that either many of the surface geological units or much of the surface topography is geologically youthful.

A common presumption in discussions of comparative planetary evolution has been that planetary size plays a crucial role in controlling the internal heat budget and the volcanic and tectonic responses to global heat loss. The comparison of Venus and earth holds a key spot in the test of this presumption [*Phillips et al.*, 1981; *Head and Solomon*, 1981]. Establishing the nature of the tectonic and volcanic history of the Venus surface and inferring the dominant mechanisms for lithospheric heat transfer on that body remain elusive goals of the highest priority for our understanding of the evolution of the terrestrial planets, including our earth.

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