HOT SPOT HEAT LOSS AND TECTONIC STYLE ON VENUS AND IN THE EARTH 3 ARCHAEAN

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Studies of the earth's thermal history, Archaean tectonic style and magmatism, isotopic evidence for continental growth, and rare earth element data, have suggested to many authors that conventional plate tectonic processes do not appear to have operated in the Archaean (e.g., 1-6). It has been speculated that some form of hot spot tectonics was the dominant heat loss mechanism in the earth's early history (e.g., 3, 5), but these models lack a modern-day analogue in which the processes and their implications can be studied. Recent radar altimetry and other data from Venus have been interpreted to indicate that hot spot heat loss is the dominant modern heat loss process on Venus (e.g., 7, 8), a planet very similar to Earth in mass and size, and presumably in its thermal history. Venus topographic data has been used to constrain a model of lithospheric thickness and heat loss variations on Venus (8), and this model is now used as a possible analogue of hot spot tectonics in the earth's Archaean.

The Venus hot spot/topography model is based on the principle of "thermal isostasy" in which elevation differences are explained primarily by thermally induced lateral density variations in the lithosphere/asthenosphere system. The model is similar to the boundary layer cooling model of the terrestrial oceanic lithosphere (e.g., 9), except that steady state heat flow through the lithosphere is assumed, and lateral variations in surface heat flow and elevation are related to a laterally varying heat flux into the base of the lithosphere rather than plate age. As a first approximation, it is assumed that all heat loss is by conduction. The relationships among surface elevation, heat flow, and lithospheric thickness derived for Venus are summarized in Figure 1. To explain elevations above 6053 km (approx. 7% of the mapped surface area of Venus) a variable thickness, low density (sialic?) crustal component is required by the model in the high elevation areas (8).

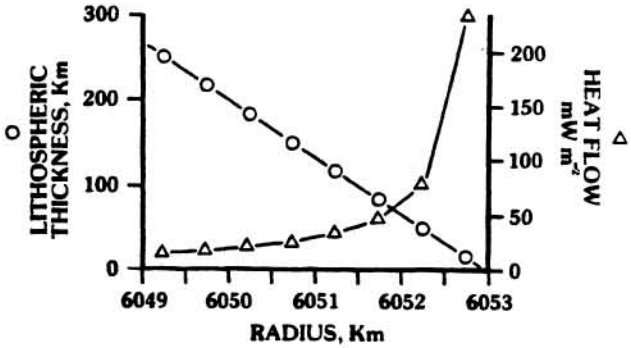

Figure 1. Relationships among surface elevation, heat flow and lithospheric thickness derived for Venus hot spot/ topography model. Elevation is given in terms of planetary radius. [Adapted from (8)].

Several conclusions about the nature of hot spot systems can be made if it is accepted that the hot spot/topography model is valid and applicable to modern Venus. Conclusions potentially significant to Archaean hot spot tectonics are as follows: (a) hot spot heat loss and sea floor spreading are equally viable mechanisms for modern heat loss from a planet the size of the Earth; (b) a large area of lithosphere (on the order of 1000 km diameter) is very thin (on the order of 20 km) over each hotspot, although there is likely to be a range in strength and size of the hot spots, and the spacing between the centres of hot spots is on the order of 5000 km (based on the mapped topography of Venus and the modelled relationship between elevation and lithospheric thickness); (c) the hot spots are fixed relative to each other and the lithosphere for time periods on the order of 700 m.y. or greater (the time required to develop the thick lithosphere modelled to underlie the areas of lowest elevation on Venus by cooling from the surface); and (d) some low density (sialic?) crust (or crustal thickening) is localized over the hot spots (as indicated by elevations above 6053 km with gravity signatures interpreted to require dominantly deep isostatic compensation). These conclusions are discussed in greater detail in (8): Their significance to Archaean hot spot tectonics is discussed below.

The present mean heat flux of the earth is estimated to be 82 mW/m^2 (10). Heat flow was higher in the Archaean by a factor of 2 to 4 (11, 12). The modern Venus hot spot model was based on a mean heat flux of 50 mW/m^2 (13), although for present arguments the exact value is unimportant. The modelled Venus heat loss must be increased by a factor of 3 to 6 to match the earth's Archaean heat loss. It is a simple exercise to show that the modelled heat loss can be increased to fall within this range by any combination of the following mechanisms: (a) increasing the number of hot spots; (b) increasing the mean diameter of the hot spots; (c) thinning the lithosphere even further, hence increasing the heat loss from each hot spot; and (d) decreasing the mean and/or maximum thickness of the lithosphere, as would be expected for a planet with higher mean heat flux and less time for a thick lithosphere to develop. The important result of this exercise is that a significant range in lithospheric thickness is predicted even in the high mean heat flux hot spot model, and large areas with relative thick lithosphere (on the order of 50-100 km) with correspondingly low geothermal gradients and heat flow (see e.g., Figure 1) would develop if the the hot spots remained fixed relative to the lithosphere for a few hundred m.y. or longer.

From the size and spacing of the hot spots in the Venus model, and assuming the lithospheric thickness range for an equivalent Archaean model to be on the order of 10-100 km, slopes on the flanks of the Archaean model hot spots are similar to those on the flanks of modern slow to medium

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spreading rate (2.5 to 5.0 cm/yr) mid-ocean ridges. "Ridge push" has been suggested to be a significant force in plate tectonics (e.g., 14, 15), and presumably a similar force would be generated by the elevation and lateral density variations associated with similar slopes on the flanks of a hot spots. Large lateral motions (1000's km) are not consistent with the concept of the hot spot heat loss model, but more modest lateral movements (10's to 100's km) are not strictly precluded by hot spot tectonics, and could be driven by a "hot spot push" force, analagous to "ridge push." These lateral movements on the flanks of the hot spots could cause tectonic thickening of the Archaean crust in which Archaean granulites, now exposed at the surface of normal thickness continental crust, could have been formed.

It is unlikely that hot spots lose heat by conduction alone, and some convective heat loss by volcanism seems probable. It has been estimated that on the order of 10% of the heat loss from the Hawaiian Swell results from the Hawaii volcanic flux (8). In a hot spot system in which the lithosphere is fixed relative to the hot spot positions, large volumes of volcanics and their associated erosional products would accumulate over and adjacent to the hot spots. If the rate of addition to the volcanic pile exceeds the rate of removal of material by erosion, the depth of the base of the pile and its temperature will increase until melting occurs. The original volcanics will probably be differentiated by partial remelting (e.g. 16), and the magmatic products will be more viscous than the primary basaltic activity, and are likely to be dominantly volumetrically represented by plutonic activity. Additional episodes of hot spot volcanism are likely to be associated with periods of maximum strength of the upwelling convection system, and with the associated uplift and stresses, continental rift-like volcanic systems are likely to develop. High shallow mantle temperatures associated with these events are compatible with the generation of high temperature magmas, such as komatiites, with the basaltic volcanism. Repetition of this volcanism-plutonism-volcanism cycle is proposed as mechanism for the generation of Archaean "granite-greenstone" terrains.

The efficiency of generation or recycling of differentiated crust by the hot spot burial mechanism must be less than that of a sea floor spreading system: Much of the primary basaltic crust in the hot spot system will not be buried sufficiently deeply for remelting to occur, whereas all oceanic crust is recycled by subduction in plate tectonics every few hundred m.y. However, the relative lateral stability of the hot spot system should allow a thick, heavily sedimented basaltic crust to develop, and the transition from hot spot tectonics to plate tectonics (Late Archaean?), would include the subduction of the undifferentiated hot spot crust, with perhaps much greater crustal generation and recycling associated with this subduction than with the subduction of normal oceanic crust. This hypothesis is consistent with evidence for an increase in the rate of evolution of continental crust towards the end of the Archaean (e.g., 17).

The study of Venus tectonics is in its infancy. However, if new data and further studies continue to suggest that heat loss on Venus is dominantly by hot spot tectonics, it will serve as a valuable analogue for other proposed hot spot tectonics systems. The hypotheses presented above suggest that, using the Venus analogue, hot spot tectonics could have been reponsible for many of the basic features of the Archaean, including: (a) absence of ophiolites and blueschist terrains (lack of subduction); (b) dominance of greenschist-granite and high-grade terrains (hot spot crustal generation and limited lateral tectonics on the flanks of the hot spots); (c) presence of komatiites which are rare in the Proterozoic and Phanerozoic (vigorous hot spot volcanism); and (d) indications from geology, isotopic and rare earth element studies that major amounts of sialic crust were produced only post 2.5 m.y. (transition from hot spot tectonics to plate tectonics).

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