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MAGMA TRANSPORT OF HEAT ON IO: A MECHANISM ALLOWING A THICK LITHOSPHERE

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Abstract. Models indicate that the high heat flow from Io would result in a very thin (approximately 5 km) silicate lithosphere overlying a molten interior, if all heat was transported through the lithosphere via conduction. However, the presence of mountains with relief in excess of 10 km would seem to demand a thick lithosphere, at least locally. A significant fraction of Io's heat flow may be transported via advection through volcanoes. Advective heat transfer permits a thicker lithosphere than does pure conduction, possibly reconciling Io's high heat flow with the rugged topography.

Infrared (IR) observations, the Voyager spacecraft observations of volcanic plumes and flows, and the prediction of large tidal energy dissipation in Io all indicate that Io has a large surface heat flux, such that a conductive lithosphere would be only on the order of 10 km thick. On the other hand, the Voyager images show relief of the order of 10 km in polar regions, which seems to demand a thick lithosphere. Here we present a model that allows both high heat flow and theoretically unlimited lithosphere thickness.

In addition to active plumes, the Voyager spacecraft observed over 100 calderas on Io's surface, many of them surrounded by radiating flow patterns hundreds of kilometers long [Smith, et al., 1979, Carr, et al., 1979]. Analysis of Voyager IR spectrometer data has revealed a hot spot within a caldera at a temperature of approximately 300 K, and another in the vicinity of an active plume at 650-700 K [Hanel, 1979, Sinton, 1980]. Earthbased IR observations of a transient 5 micron outburst are consistent with a blackbody at 600 K and covering 2×10^{-4} of the total surface [Witteborn, et al., 1979]. Based on anomalously high IR fluxes emitted by Io while in eclipse by Jupiter, Matson et al. [1981] constructed a thermal model consisting of hotspots laterally distributed within a cooler regolith. Their data are consistent with hotspots comprising 2 ± 1% of the Ionian surface and a total average heat flow of 2 ± 1 watts per square meter (W/m^2), or nearly 30 times the terrestrial value!

This high value has recently been corroborated by two independent heat flow determinations from eclipse data; Sinton [1981] obtained a value of 1.8 ± 0.6 W/m^2, and Morrison and Telesco [1981] derived a value of 1.5 ± 0.3 W/m^2.

In a report published a week before the Voyager 1 encounter, Peale et al. 1979 predicted a largely melted interior and consequent surface volcanism due to "runaway" melting caused by tidal flexing from Jupiter and Europa. Assuming tidal flexing is the only heat source, and that heating occurs only in an outer solid silicate lithosphere, Peale et al. calculate a total surface heat flow of 0.4 W/m^2 and a conduction-limited lithospheric thickness of 18 km. The heat flow value of Matson et al. would lead to an even smaller (4.5 km) conduction-limited thickness.

Rugged mountains having relief in excess of 10 km, and apparently of silicate composition, have been observed by Voyager [Carr et al., 1979]. This observation poses an interesting question; how can the thin lithosphere implied by Io's high heat flow support 10 km of silicate topography? Calculation of the maximum bending stress in a floating elastic lithosphere (see McNutt, 1980) yields an estimate of 6 kbar for the case of a 5 km-thick lithosphere supporting a mountain 10 km high and 10 km wide. This is much greater than estimates of the strength of the Earth's lithosphere at low pressure (maximum is 1-2 kbar). Thus it seems unlikely that a 5 km lithosphere could support such a load without failure, causing the mountains to "founder." There are at least three possibilities;

a) Dynamic support, i.e. convection within Io is holding up the mountains. The localized nature of the topography would seem to demand some special pleading to maintain this hypothesis.
b) The mountains are compensated by a thick lower density root. Conductive warming would probably limit the age of a static root to 10^6-10^7 years, which implies that both mountain and root are dynamic features. Perhaps analogy can be made with terrestrial plate tectonics, but no evidence for this on Io has been recognized.
c) The lithosphere is thick under the mountains, and perhaps globally, and conductive warming is suppressed by subsidence of lithospheric material. A thicker lithosphere could support uncompensated topography. It is this possibility that is addressed by our model, although it is not claimed that alternative models can be definitely excluded at this stage.

In our model, illustrated in Figure 1, part of the heat is removed by advection, i.e., magma from depth rises to the surface through isolated vents, spreads out, and cools. The solid lithosphere subsides under the weight of flows and is heated by conduction. Solid material at the base of the lithosphere melts, beginning the cycle again.

The heat flow q_a due to advection is given by

$$q_a = v\rho\ [\Delta H_f + C_p\ (T_m - T_o)] \qquad (1)$$

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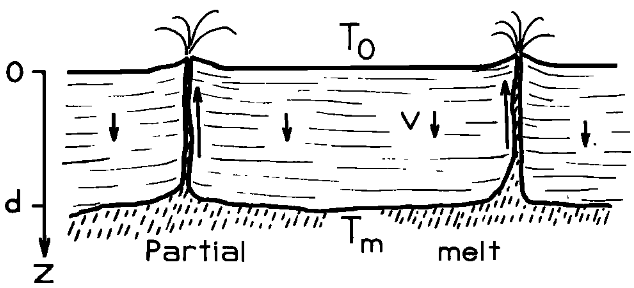

Fig. 1. Model of Ionian lithosphere. Magma at temperature T_m rises through vents and spreads across surface, cooling to surface temperature T_o. Weight of flows depresses lithosphere at subsidence velocity v, which equals resurfacing rate.

where v is the subsidence rate (equal to the resurfacing rate in our model), ρ is the magma density, ΔH_f is the heat of fusion, C_p is the specific heat, T_m is the melting temperature, and T_o is the surface temperature. Heat will also be conducted through the subsiding solid material. For sufficiently wide spacing of the vents, conduction will be vertical, and the equation of interest is (for z positive downwards);

$$\alpha \frac{\partial^2 T}{\partial z^2} = v \frac{\partial T}{\partial z} - \frac{A}{\rho C_p} \qquad (2)$$

where α is thermal diffusivity, $\frac{\partial T}{\partial z}$ is the vertical temperature gradient, and A is the heating rate per unit volume in the solid layer.

We can consider two extreme cases. One extreme case is "bottom heating;" all heat is supplied from below and none is produced in the solid layer (A=0). If Io's heat is indeed produced by tidal flexing, bottom heating may be a valid approximation, as some studies suggest that strain heating is greatest in regions of partial melt [Mavko and Nur, 1975, O'Connell and Budiansky, 1975]. The other extreme case is "internal heating," in which all heat production is confined to and uniformly distributed within the solid layer.

The expressions for temperature and corresponding upwards conductive heat flow q_{cs} that satisfy equation 2 are, for the bottom heating case (A=0);

$$T = \frac{\Delta T (e^{z/\ell} - 1)}{e^{d/\ell} - 1} + T_o \qquad (3a)$$

$$q_{cs} = K(\partial T/\partial z)_{z=0} = \frac{K \Delta T}{\ell (e^{d/\ell} - 1)} \qquad (3b)$$

where $\Delta T = T_m - T_o$, $\ell = \alpha/v$, d is the solid lithosphere thickness, $K = \rho C_p$ is the thermal conductivity, and the boundary conditions are $T = T_o$ at z=0 and $T = T_m$ at z=d. For the internally heated case the solutions are;

$$T = \left[\frac{\Delta T - q_t/v\rho C_p}{e^{d/\ell} - 1}\right] (e^{z/\ell} - 1) + \frac{\alpha q_t}{vd} z + T_o \qquad (4a)$$

$$q_{cs} = \frac{K}{\ell} \left[\frac{\Delta T - q_t/v\rho C_p}{e^{d/\ell} - 1}\right] + \frac{\alpha q_t}{vd} \qquad (4b)$$

where q_t is the total heat flow (advected plus conducted), and, as a consequence of all heat being produced in a layer of thickness d, the additional condition $A = q_t/d$ is applied. [For details of solutions of equations of this type, see, e.g., Oxburgh and Turcotte, 1971].

If all other parameters are fixed, a given value of subsidence velocity v uniquely constrains advected heat flow q_a (equation 1) and lithosphere thickness d. In Figure 2 we show d as a function of v and q_a/q_t for internal and bottom heating, assuming a total heat flow of 1 W/m^2. As the measured heat flow values have large uncertainties attached to them, our values should be regarded as very preliminary and mainly illustrative. It can be seen that d increases without limit in both cases as v and q_a increase, but that d increases faster in the internally heated case. In both cases, as v approaches zero, q_a becomes negligible and simple conduction predominates. For large v, conducted heat flow q_{cs} becomes negligible and heat is transported mostly by advection. If the magma can find its way efficiently through the lithosphere, it can carry most of the heat and the lithosphere can be arbitrarily thick. Thus the high heat flow and rugged topography of Io may be reconciled.

The rate of resurfacing necessary to transport most of the heat by advection can be

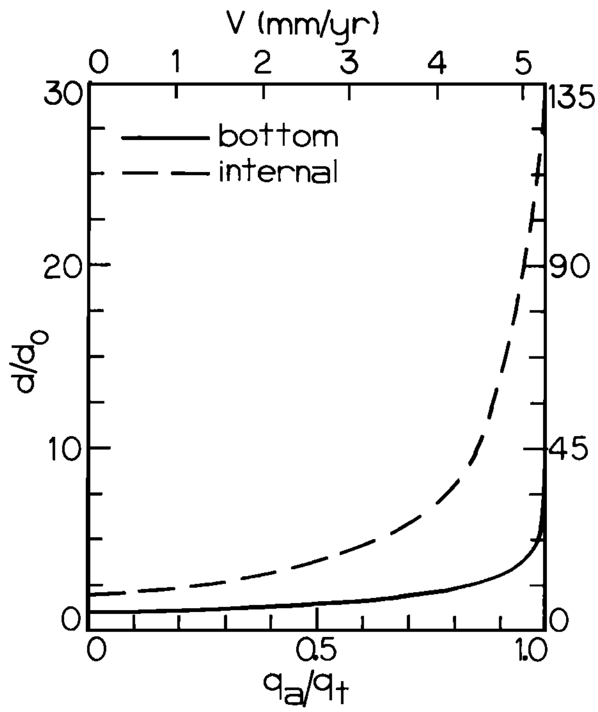

Fig. 2. Normalized silicate lithosphere thickness d/d_o as a function of advected heat flow fraction q_a/q_t and subsidence velocity (=resurfacing rate) v, for bottom heating (solid curve) and internal heating (dashed curve). Thickness normalization factor d_o is 4.5km (the thickness of a purely conductive bottom-heated lithosphere), and total heat flow q_t is assumed to be 1 W/m^2. Silicate magma parameters are K=3W/mK, ρ=3000 kg/m^3, C_p =1000J/kgK, ΔH_f=4.5x10^{5}J/kg, ΔT=1500K.

TABLE 1

RESURFACING RATES NEEDED TO ADVECT 0.5 W/m^2 HEAT FLUX

	$\rho (kg/m^3)$	$\Delta H_f (J/kg)$	$C_p (J/kg°K)$	$\Delta T (°K)$	v(mm/yr)
Sulfur[1]	1810	$3.7x10^4$	730	290	35
Silicate[2]	3000	$4.5x10^5$	1000	1500	3

1. Physico-chemical data for sulfur is from the International Critical Tables.

2. Order-of-magnitude values from various sources, e.g. Yoder, 1976.

obtained from equation 1. For silicate magma, a resurfacing rate of 3 mm/yr transports 50% of the heat by advection; for sulfur magma the necessary rate is 35 mm/yr (Table 1). The rate for sulfur is an order of magnitude higher than that for silicate mainly because of the lower melting point and heat of fusion of sulfur. Both resurfacing rates are compatible with the minimum resurfacing rate of 0.1 to 10 mm/yr as inferred from the lack of impact craters in the Voyager images [Johnson, et al., 1979].

Most of Io's surface may be covered by sulfur or a mixture of sulfur and SO_2 ice, and both the sulfur/SO_2 and underlying silicates may be resurfaced and recycled [Smith, et al., 1979]. In that case, both the silicate and sulfur/SO_2 would have to transport the total heat flux, and both the above rates would apply, except that the observed resurfacing would be identified with that of the sulfur/SO_2 layer. Of course, if SO_2 plays a significant role, the values of the physical parameters used in calculating the "sulfur" rate will not be accurate, but will still be indicative of the behavior of volatiles relative to silicates.

Although our model allows an arbitrarily thick, cool lithosphere, other factors, such as lateral conduction and the dynamics of magma ascent may limit the thickness in reality. Some magmas certainly penetrate through 100 km or more of the terrestrial lithosphere; the process may be poorly understood, but occurs nonetheless. Perhaps the tides raised on Io could enhance the effectiveness of magma transport. Apart from the rugged topography coexisting with high heat flow, there are at least two independent observations that suggest the importance of advective heat transport on Io. First, the model of Matson, et al. [1981] indicates that most of the heat flow comes from localized sources covering approximately 2% of the surface. Calderas, active and dormant, are estimated to comprise about 5% of the surface [Carr, et al., 1979]. Second, the estimated high resurfacing rate [Johnson, et al., 1979] suggests that considerable amounts of material may be coming up from below the surface. Reynolds and Cassen [1979] considered the possibility of magma heat transport, but assumed that because such transport must be episodic it could not account for more than about 10% of the total heat flow.

The high heat flow first reported by Matson et al. has been substantiated. More accurate measurements of the height and extent of the topography, together with the relevant calculations, may yield a minimum value for the lithospheric thickness. Also needed are more accurate (if possible) determinations of the resurfacing rate, which could help constrain the nature and properties of Ionian eruptive materials. If the results of this paper are sustained, then one more characteristic of Io may be added to its list of unique features; a new kind of lithosphere with an unusual heat transport mechanism.

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