

Geotherms, Lithosphere Thickness and Sedimentary Basins

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ABSTRACT

A relation between the thickness of the lithosphere and geothermal gradients in the mantle can be extracted from two independent sets of observations. One set is the relation between lithosphere thickness determined from magnetotelluric measurements and surface heat flow. The other set of observations is the temperature-depth array that can be extracted from xenoliths in kimberlites. Both sets lead to the conclusion that an increase in the temperature at the Moho is accompanied by thinning of the lithosphere when the lithosphere is thinner than 180 km, but is accompanied by thickening of the lithosphere when the lithosphere is thicker than 200 km. The corollary of this conclusion is that the same high Moho temperature can be associated with very thin or very thick lithosphere. Switching from very thin to very thick lithosphere can initiate the formation of a sedimentary basin. Continued increase in Moho temperature results in further thickening of the lithosphere and growth of the sedimentary basin.

Key words: heat flow, geodynamics

INTRODUCTION

A guiding principle of diamond exploration is Clifford's Rule. Clifford (1966) showed that diamonds were associated with the continental cores where crustal ages are in excess of 1.5 Ga. Subsequent workers observed that diamondiferous kimberlites were invariably associated with lithosphere older than 2.5 Ga so the modified Clifford's rule directs exploration for diamondiferous kimberlite toward Archaean lithosphere (Janse, 1991). An apparent exception to Clifford's rule is the richly diamondiferous Argyle lamproite which intrudes Proterozoic crust. However Lugué et al. (2008) discerned late Archaean ages in the diamondiferous peridotites from this locality, re-affirming the modified Clifford's rule. Archean cratons are usually considered to have a low surface heat flow, with a value of 40 mW/m² regarded as typical for the Kaapvaal craton (Boyd and Gurney, 1986). The richly diamondiferous Slave craton, however, has a surface heat flow of 54 mW/m². Russell and Kopylova (1999) showed that the geothermal gradient in the mantle was relatively low, 4.3°C/km, and that the high heat flow was the result of high radioactive heat production in the crust. McKenzie et al. (2005) estimated an even higher surface heat flow of 58 mW/m² in the lithosphere below the richly diamondiferous Udachnaya kimberlite. The lithosphere below the Udachnaya kimberlite is thicker than that below the Slave craton, suggesting that as lithosphere thickness increases, surface heat flow increases. This is not one would expect from the model geotherms of Pollack and Chapman (1977). These indicate the

opposite behaviour; as lithosphere thickness increases, surface heat flow would be expected to decrease.

Here I show that previous determinations of the relation between surface heat flow and lithosphere thickness determined from magnetotelluric observation (Artemieva, 2006), and the determinations of lithospheric thickness and geothermal gradients derived from xenoliths in kimberlite both lead to the same conclusions.

- As lithosphere thickens from 100 to 180 km the temperature at the base of the crust decreases, resulting in the decrease in surface heat flow that is portrayed in the model geotherms of Pollack and Chapman (1977).
- As lithosphere thickness increases above 200 km the temperature at the base of the crust increases, leading to the high surface heat flow that McKenzie et al. (2005) find in association with very thick lithosphere.

An important implication is that a high temperature at the Moho may be associated either with very thick lithosphere or with very thin lithosphere. Switching between these two states provides the basis for a new hypothesis for the development of continental sedimentary basins.

LITHOSPHERE THICKNESS

In the lithosphere heat is transferred by conduction while heat transfer in the asthenosphere is by

convection. The lithosphere-asthenosphere boundary is therefore defined by the temperature at which the mantle becomes soft enough to convect. There is a general consensus that at surface this temperature lies in the range 1280°C (1553 K) to 1327°C (1600 K) (McKenzie and Bickle, 1988; Turcotte and Schubert, 2002).

For a steady-state temperature profile the temperature at the lithosphere-asthenosphere boundary increases along an adiabatic gradient of 0.5 K/km (Turcotte and Schubert, 2002). The steady-state can only be maintained by heat input which is provided by mantle plumes or by small-scale convection below the lithosphere-asthenosphere boundary (Turcotte and Schubert, 2002; Schubert et al., 2001).

Xenolith geotherms

Garnet lherzolite xenoliths in kimberlites and related rocks allow temperature-depth arrays to be determined from geothermobarometers. The intersection of the temperature depth array with the temperature-depth curve of the lithosphere-asthenosphere boundary determines lithosphere thickness. A consistent set of thicknesses and thermal gradients determined from xenolith data compiled from the literature is shown in Figure 1. The geothermobarometer of Brey and Kohler (1991) was used to determine the temperature-depth array from the xenoliths. The mantle adiabat of McKenzie and Bickle (1988) was used for the temperature at the base of the lithosphere, T_L ;

$$T_L = 1280^\circ\text{C} + 0.5^\circ\text{C}/\text{km} \quad (1)$$

Magnetotelluric measurements

Artemieva (2006) compiled results of determinations of the thickness of the electrically resistive lithosphere for lithosphere thicknesses and found a power law relation between surface heat flow, q_{surface} , and lithosphere thickness, z_L ;

$$z_L = 418 \exp(-0.023 q_{\text{surface}}), \quad (2)$$

where lithosphere thickness is in km and q_{surface} is in mW/m^2 .

On average mantle heat flow contributes 60% of the surface heat flow (Pollack and Chapman, 1977; Stein, 1995) so lithosphere thickness can be related to Moho heat flow by

$$z_L = 418 \exp(-0.023 q_{\text{Moho}}/0.6). \quad (3)$$

According to Fourier's law, heat flow is the product of the thermal conductivity and the geothermal gradient. Heat flow into the Moho is determined by thermal gradient in the lithosphere, $(dT/dz)_L$ so

$$q_{\text{Moho}} = k (dT/dz)_L \quad (4)$$

Assuming a constant thermal conductivity in the lithosphere of $3.2 \text{ W m}^{-1} \text{ K}^{-1}$ (Stein, 1995; Russell and Kopylova, 1999) equations 3 and 4 can be combined and rearranged to give the geothermal gradient in the lithosphere, $(dT/dz)_L$, as a function of lithosphere thickness

$$(dT/dz)_L = -8.15 \ln(z_{\text{LAB}}/418), \quad (5)$$

where $(dT/dz)_L$ is in $^\circ\text{C}/\text{km}$.

The relation between lithosphere thickness and thermal gradient derived from magnetotelluric measurements is in good agreement with those values measured in xenoliths (Figure 1).

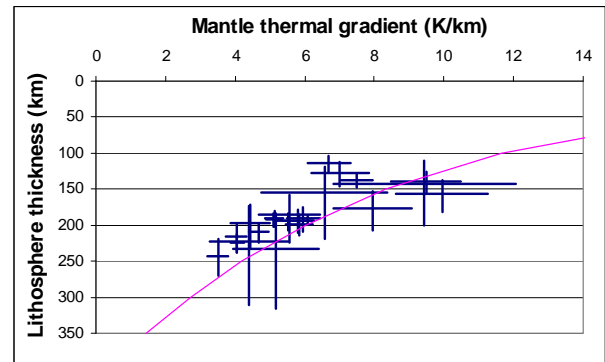


Figure 1. Variation of thermal gradient in the mantle with lithosphere thickness. The crosses show estimates derived from xenoliths in kimberlites. The line is an entirely independent estimate derived from magnetotelluric measurements.

MOHO TEMPERATURE

The thermal gradient in the lithosphere determines the temperature drop from the base of the lithosphere to the Moho. Moho temperature, T_{Moho} , is determined from

$$T_{\text{Moho}} = T_L - (z_L - 40)(dT/dz)_L \quad (6)$$

where the Moho depth is taken as 40 km.

Substituting equation (1) into equation (6), the Moho temperature for a particular lithosphere thickness can then be determined (Figure 2). The results demonstrate that a particular Moho temperature may be associated with either thin lithosphere or thick lithosphere. Only for lithosphere near 180 km thickness is Moho temperature associated with a single value for lithosphere thickness. Another result is that when the lithosphere thickness exceeds 200 km, the lithosphere will thicken as the Moho temperature increases. Both these results have implications for the formation of sedimentary basins.

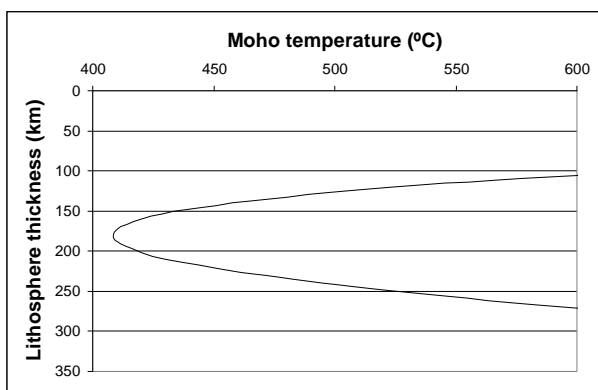


Figure 2. Moho temperature as a function of lithosphere thickness.

INITIATION OF A SEDIMENTARY BASIN

Consider thin lithosphere that is about 110 km thick and has a Moho temperature of 600°C. One possible scenario for the evolution of such lithosphere is that of incipient rifting as it migrates over a hot asthenospheric upwelling associated with the small scale convection layer below the asthenosphere. Asthenosphere then rises toward the Moho. As the lithosphere migrates over the cold down-welling limb of the small scale convection layer, hot asthenosphere is replaced by cold. The stable state for lithosphere associated with a Moho temperature of 600°C now switches to a lithosphere thickness of 270 km (Figure 3). Attachment of this thick cold lithosphere to the crust would act as a gravitational anchor, dragging the crust downward and creating accommodation space for sediments.

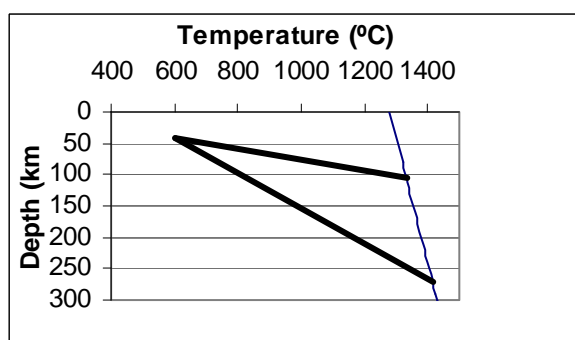


Figure 3. Two possible geothermal gradients for lithosphere with a Moho temperature of 600°C (thick lines). The thin line is the temperature at the base of the lithosphere for the McKenzie and Bickle (1988) adiabatic gradient.

GROWTH OF A SEDIMENTARY BASIN

Once initiated the sedimentary basin would thicken by lateral displacement of hot lower crust. McKenzie et al. (2005) showed earthquakes do not occur in crust that is hotter than 600°C, suggesting that the crust loses its strength above this temperature.

For crust with an initial temperature of 550°C and thickness of 120 km, replacement of relatively cold lower crust by hotter crust would act in concert with cooling and thickening of the lithosphere to switch the lithosphere thickness toward 270 km. This process would lead to broadening of the basin.

As the sedimentary basin is filled with radioactive upper crust, the Moho temperature would increase. Ultimately the lower crust would melt at temperatures above 700°C. This rise in temperature above 600°C would produce a final thickening of the lithosphere and a last increase in accommodation space prior to the onset of magmatism.

Many aspects in the development of the Karoo basin are compatible with the scenario outlined above.

CONCLUSIONS

For the same Moho temperature two stable geothermal gradients are possible. The switch from the thermal gradient associated with thin lithosphere to the thermal gradient associated with thick lithosphere can initiate the formation of a sedimentary basin.

A surprising result is that the response of thick lithosphere to an increase in Moho temperature is further thickening. This leads to continued deepening of the sedimentary basin.

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