Appendix H

On The Increase of The Thermal Gradient Caused By Erosion

by

L. M. Cathles
2-24-97

It has been known for some time that rapid erosion can cause the thermal gradient can be increased by rapid erosion (e.g., Koons, 1987; Royden, 1993). We present a series of calculations and a summary diagram which show how much the geothermal gradient can be elevated by a specified amount of erosion over a specified time period.

The graphs presented in Figure 2a-j were calculated by solving the one dimensional heat flow equation:

$$\rho_m c_m \frac{\partial T}{\partial t} = K \nabla^2 T \quad , \tag{1}$$

where $\rho_m c_m$ = 0.55 cal/cm^3-°C, K=4x10^{-3} cal/cm-sec-°C, T is temperature in °C, and t is time in seconds. The solution method was implicit finite difference. It was verified by comparison to Carslaw and Jager (1976, p101) solutions for a cooling bar. Erosion was simulated by removing nodes at the erosion rate for the period of time specified. The results were validated by comparison to Koons(1987) one dimensional solution for 1 Ma of erosion at 10 km/Ma.

Figure 1 sumarizes the results of the simulation in terms of a simple formula. To first approximation we can consider the effects of erosion as a two step process: (1) Erosion suddenly excavates to some depth (isotherm), and then (2) the top surface is set to ambient temperature and the excavated terrain cooled for the period of time taken to accomplish the erosion. Since the depth of conductive cooling, z, in a time t can be approximated:

$$z = 2\sqrt{\kappa t} \quad , \tag{2}$$

and the excavation thermal anomaly is given by the expression below for a depth of excavation E:

$$\Delta T = E \left(\frac{\partial T}{\partial Z}\right)_o \quad , \tag{3}$$

where the expression in parentheses is the geothermal gradient before erosion. Estimating the near surface heat flow gradient by z/2 yeilds a simple expression for the percent increase in the geothermal gradient as a function of the amount of and time-duration of erosion:

$$\text{Increase in Geothermal Gradient } [\%] = \frac{100\,E}{\sqrt{\kappa t}} \quad (4)$$

Figure 1 uses this expression to estimate the increase in heat flow caused by specified amounts and durations of erosion. Estimates of the increase in heat flow for the cases explicitly calculated and presented in Figure 2 are shown as circles.

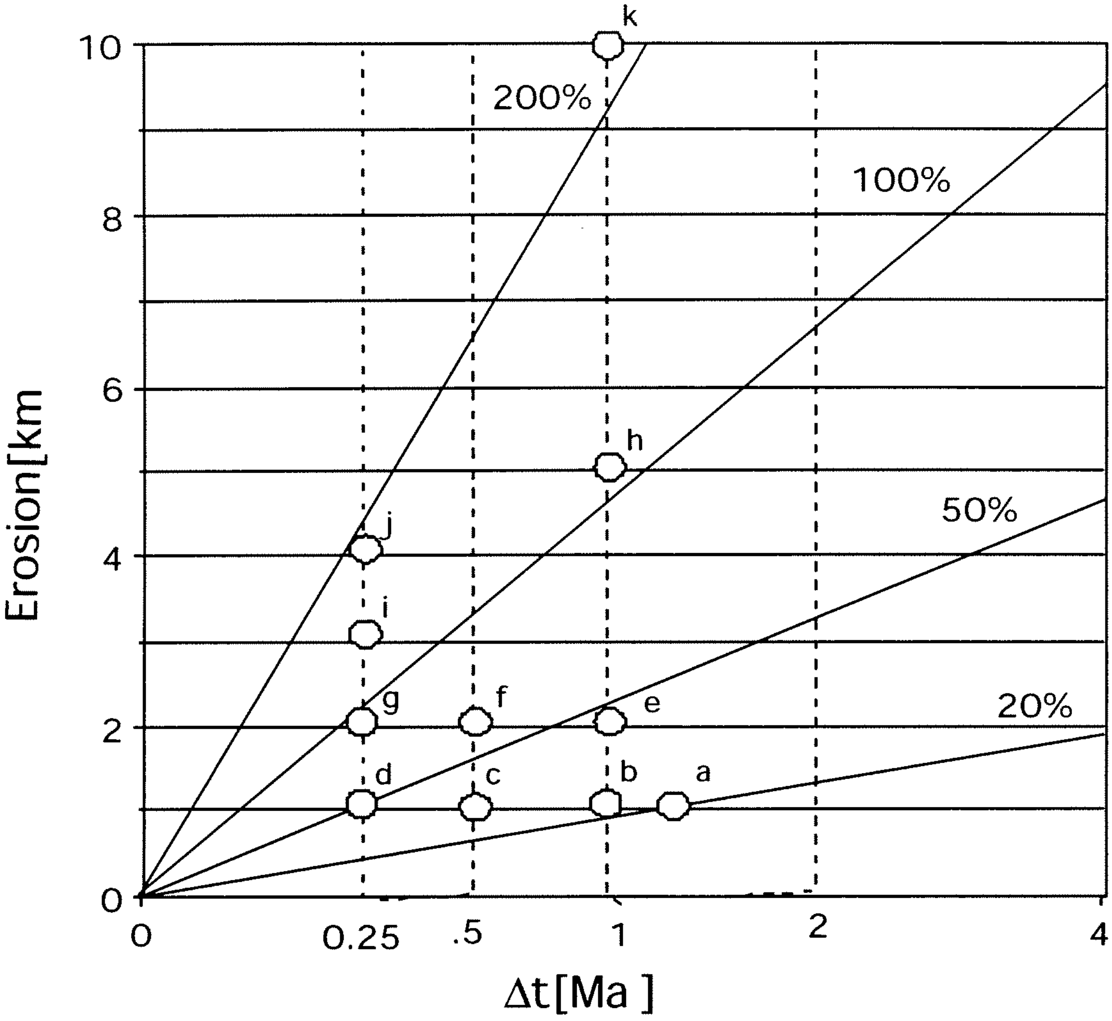


Figure 1. Estimates of the percent increase in the geothermal gradient caused by specified amounts and durations of erosion. Erosion is assumed steady over the time period of erosion and the percent increase in geothermal gradient is relative to the geothermal gradient prior to erosion. The percent increase contours were calculated with equation (4) in the text. The increased thermal gradients predicted for the specific cases simulated with a 1D finite difference model that are shown in Figure 2 are indicated by circles labeled with the figure letters. For example Figure 2a shows the elevation in geothermal gradient caused by 1km of erosion over 1 Ma. Formula (4) suggests that this magnitude and durationof erosion will cause a ~20% increase in heat flow. The case is marked with a circle and labeled with the letter a.

In Sumatra the present geothermal gradient is generally about 3.5°F/100 ft or 64°C/km. Figure 1 shows that if the heat flow were to be increased to this level from a pre-erosion value of ~30°C/km (a 100% increase) by erosion in the last 0.5 to 2 Ma, between 4 and 7 km of erosion would be required.

Erosion probably was less than 2 km over the last 1.6 Ma, and was not uniform spatially. Non-uniform erosion will decrease the change in thermal gradient (see Koons, 1987). Particularly taking this into account, Figure 1 shows that 2 km of erosion could elevate the geothermal gradient by at most ~50%. This is not sufficient to produce the gradient observed today from a normal geothermal gradient of 25°C/km such as would be produced by a base-of-basin heat flow of ~1 HFU. However, if the base-of-basin heat flow were already high (~2.8 HFU), 1 to 2 km of rapid erosion could produce the elevated heat flows in the upper 1 km very similar to those observed.

Schoellkopf has plotted Carvalho's heat flow data as a function of depth and shown that this data indicated a constant heat flow of 2.6 to 2.8 HFU below 4000 ft depth. Above 4000 ft the heat flow data is more scattered but clearly increases. Near-surface heat flows are ~4 HFU, about 42% greater than the deeper heat flow. Figure 1 shows that this magnitude of increase can be produced by ~ 1km of erosion over ~1 Ma. Figure 2c-g show that the increased thermal gradients (apparent heat flow) occur mainly in the uppermost kilometer, as is observed in Sumatra.

The average heat flow in Central Sumatra appears to be about 2.8 HFU, with apparent heat flows variably increased to ~4 HFU by the ~1+ km of erosion that has taken place in the last 1 to 2 Ma As a whole, all temperatrue data are quite consistent with this interpretation.

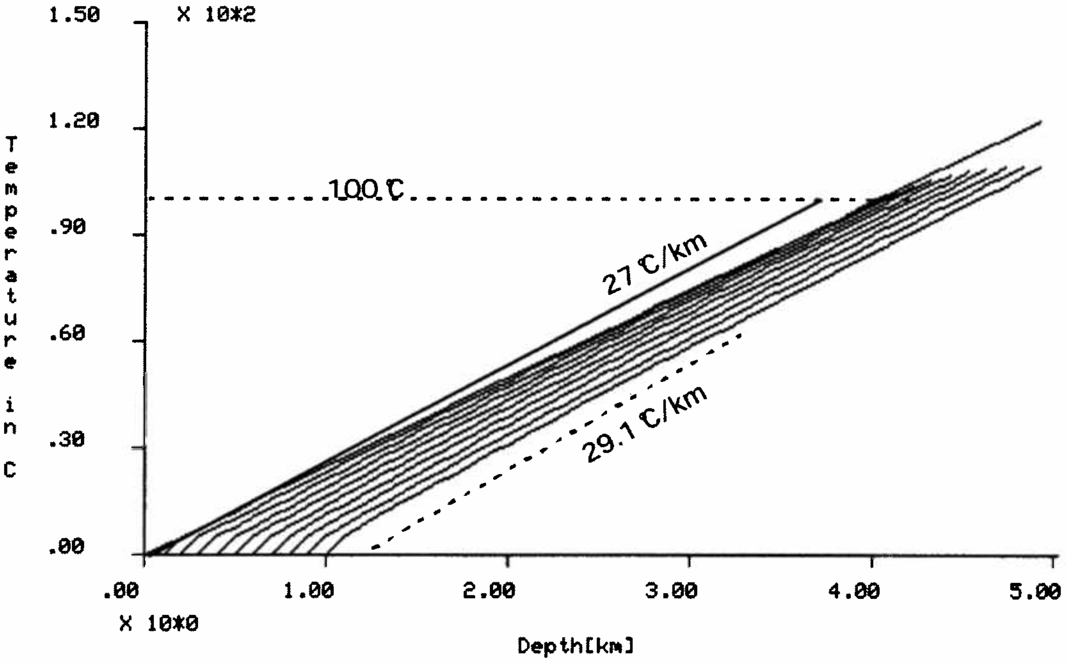


Figure 2a. One kilometer of erosion in 1.6 ma elevates the original 25°C/km thermal gradient about 8%. Temperature vs depth curves are plotted every 0.1 ma. The labeled solid line to the left of the curve cluster indicates the best visual average thermal gradient at the present day. The dashed curve to the right of the cluster indicates the present day gradient increase estimated from equation (4). In this case equation (4) suggests a gradient increase of 17% to 29.1°C/km

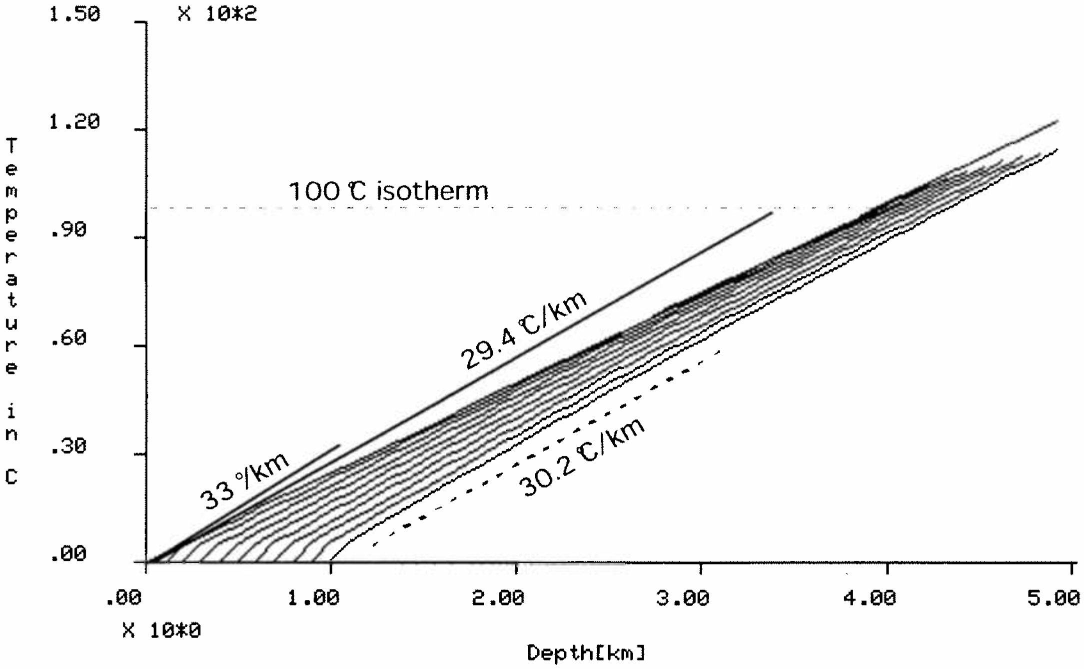


Figure 2b. One kilometer of erosion in 1 ma elevates the original 25°C/km thermal gradient about 18% to 29.4°C/km. Equation 4 would suggest a 21% increase to 30.2°C/km. Within 1 km of the surface, erosion heatflow is 33°C/km (a 32% increase).

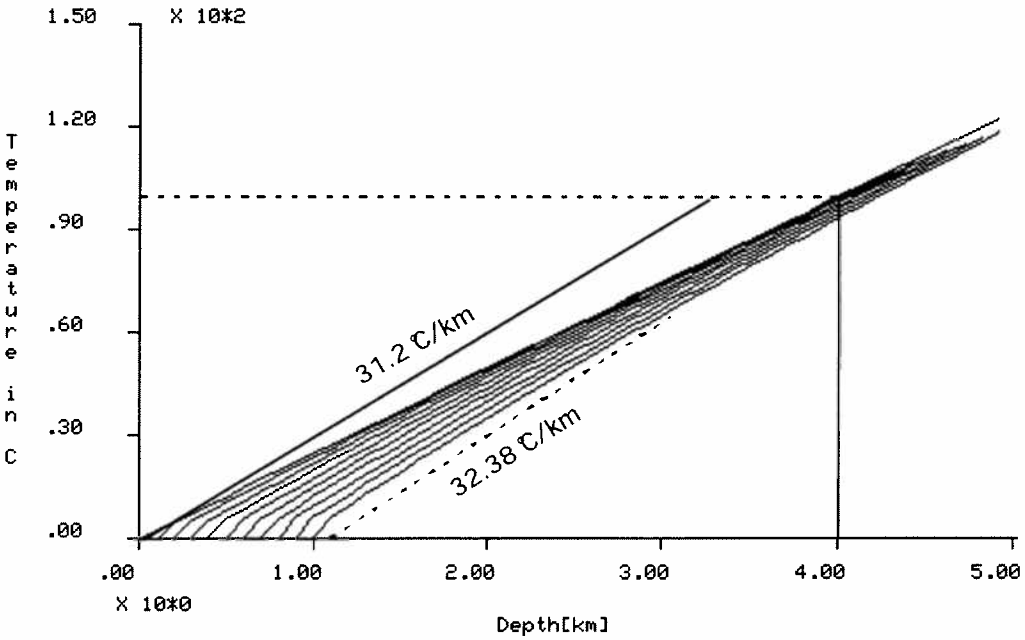


Figure 2c. One kilometer of erosion in 0.5 ma elevates temperature gradient about 25% to 31.2°C/km compared to an equation (4) estimate of 29% (to 32.25°C/km).

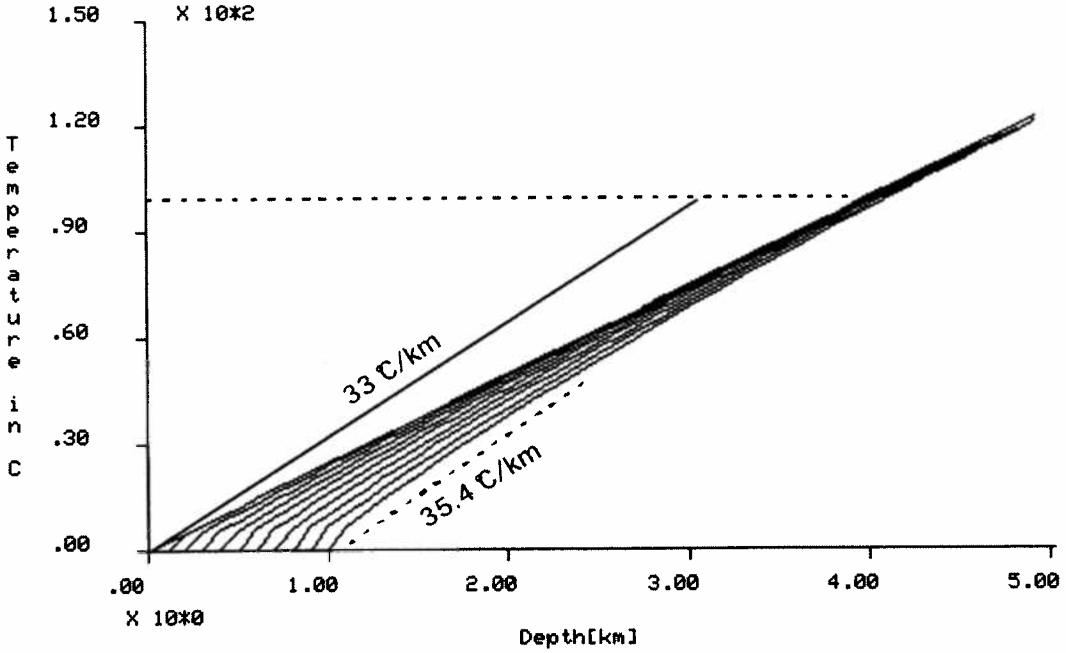


Figure 2d. One kilometer of erosion in 0.25 ma elevates temperature gradient about 33% to 33°C/km compared to 42% by equation (4) to 35.4°C/km.

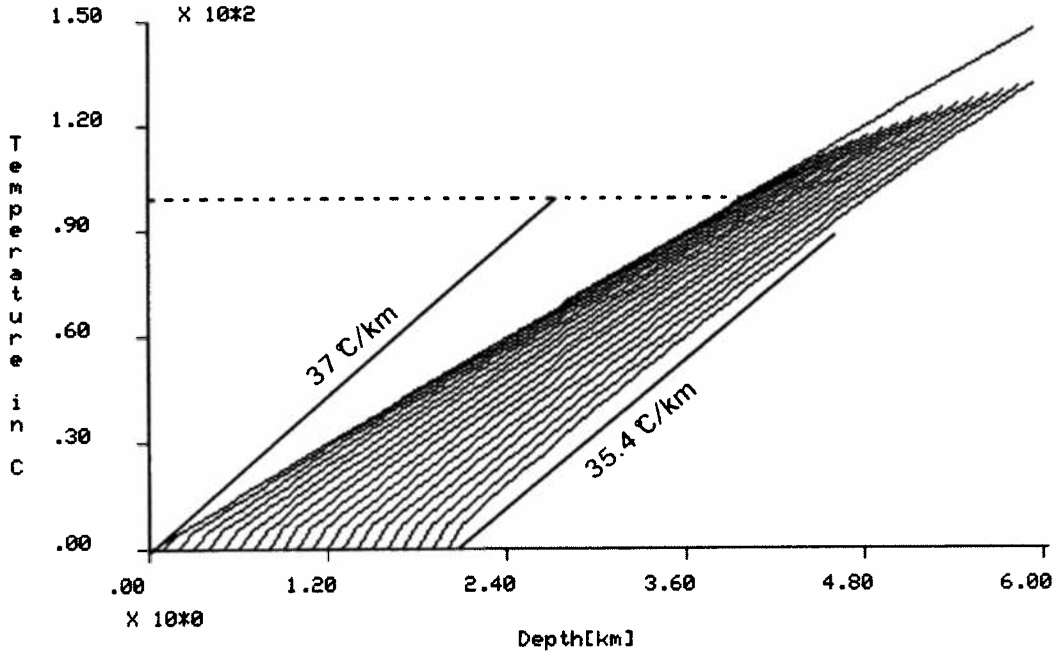


Figure 2e. Two kilometers of erosion in 1 ma elevates thermal gradient about 48% to 37°C/km whereas equation (4) estimates a 42% increase to 35.4°C/km.

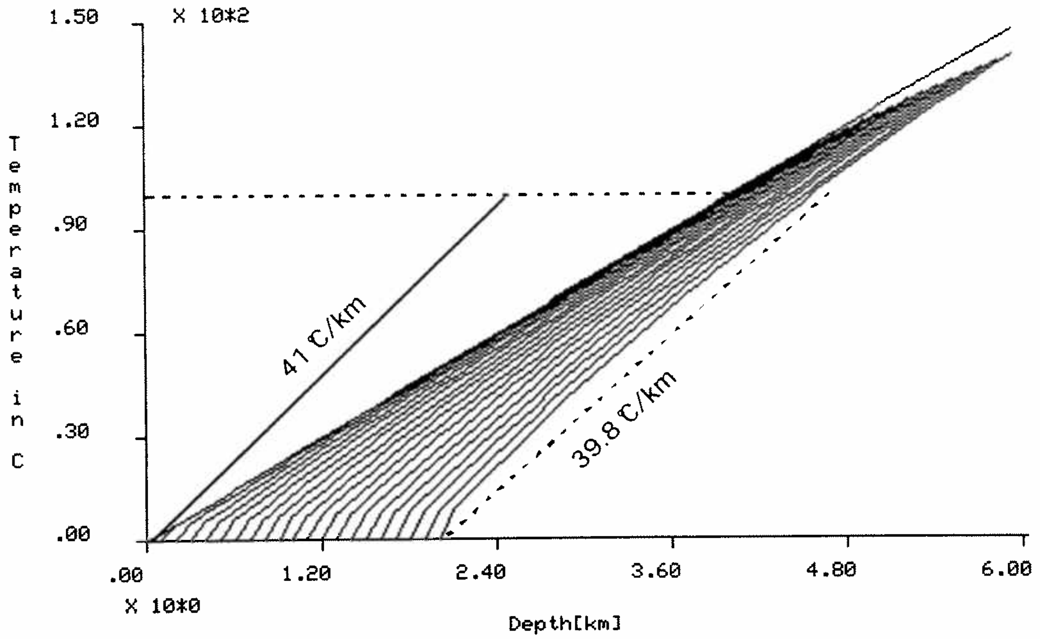


Figure 2f. Two kilometers of erosion in 0.5 ma increases temperature gradient ~64% to 41°C/km whereas equation (4) estimates an increase of 59% to 39.8°C/km.

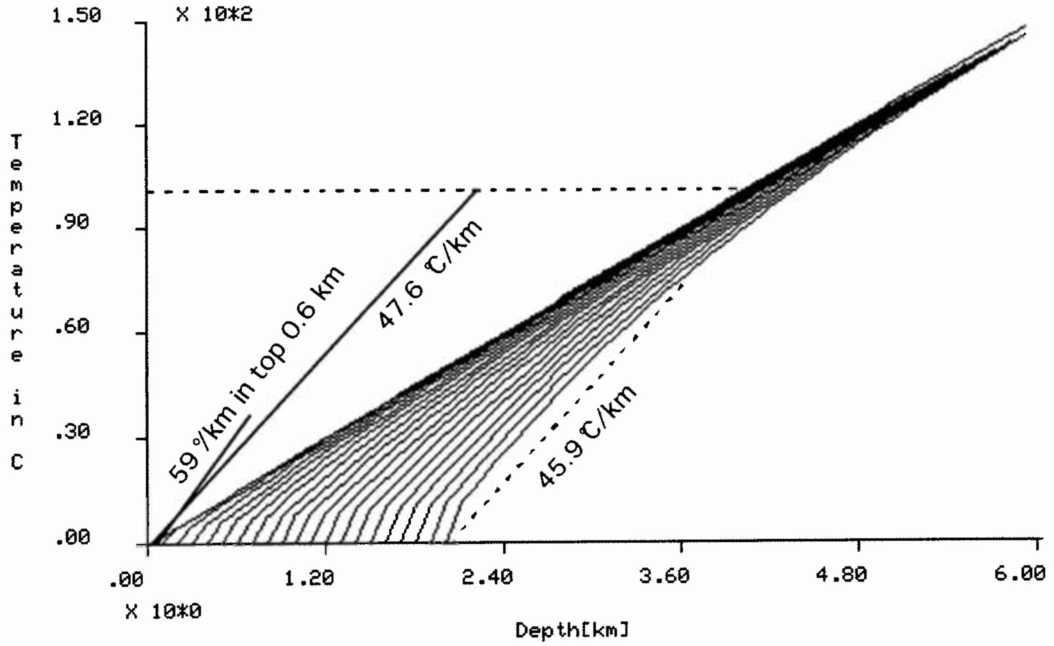


Figure 2g. Two kilometers of erosion in 0.25 ma elevates temperature gradient ~90% to 47.6°C/km (135% in top 0.6 km), whereas equation (4) estimates an 83% increase to 45.9°C/km.

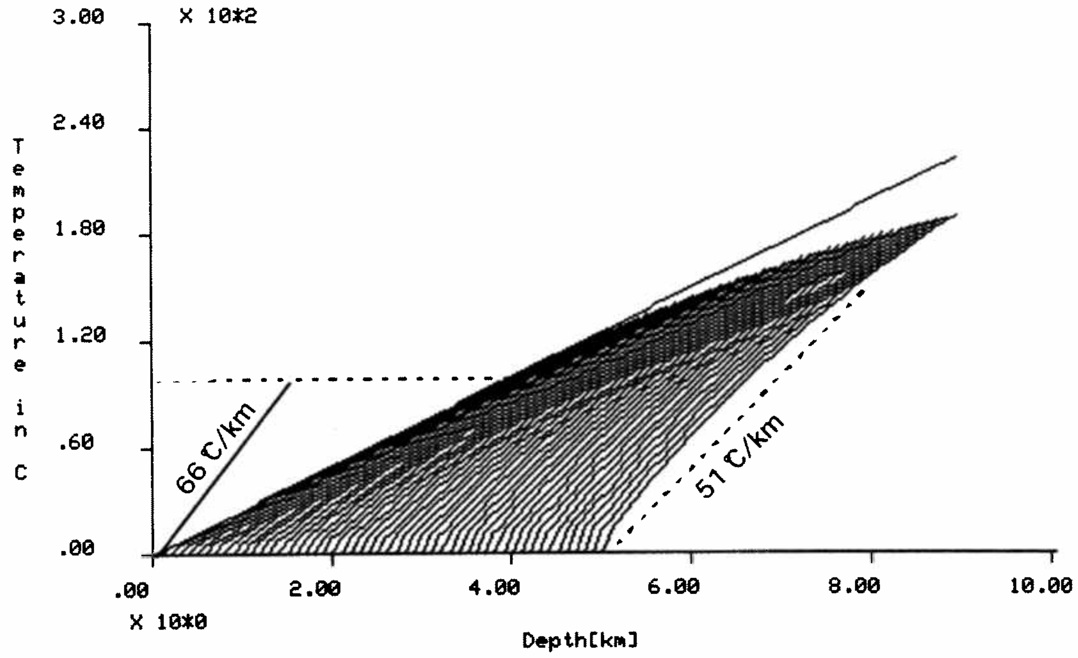


Figure 2h. Five kilometers erosion in 1 ma increases thermal gradient about 166% to 66°C/km within the top 1 km (less over a greater depth interval). Equation (4) estimates 104% to 51°C/km over ~3 km depth interval.

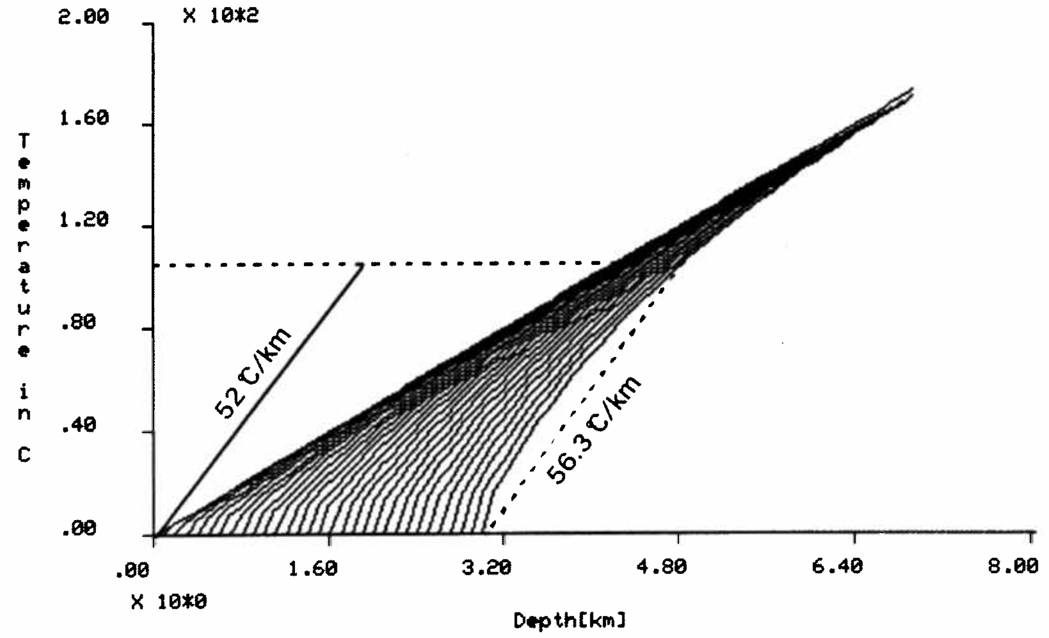
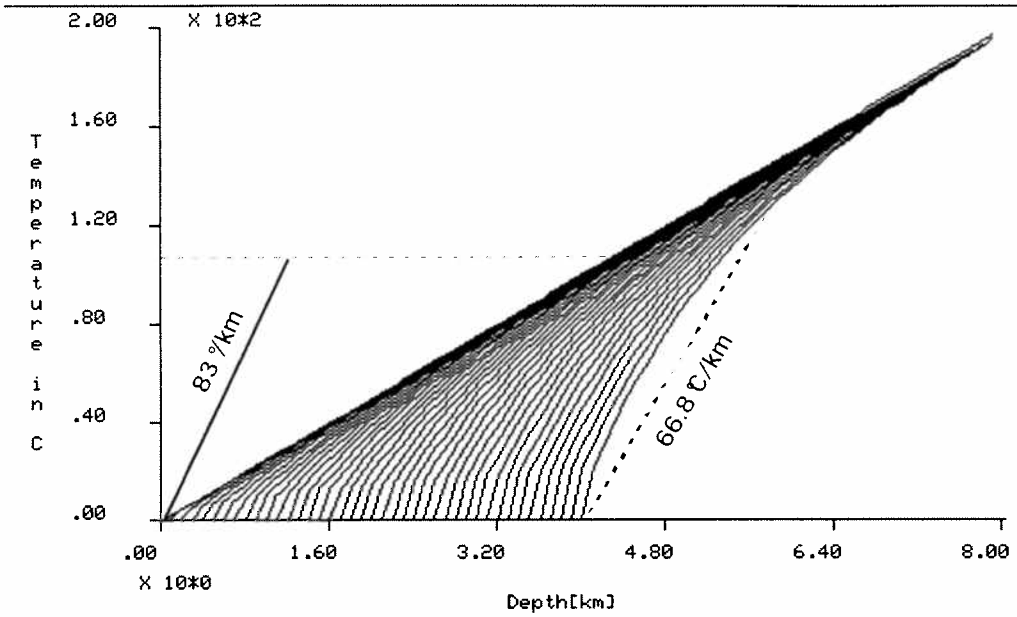


Figure 2i. Three kilometers of erosion in 0.25 ma increase thermal gradient 110% to 52°C/km compared to an equation (4) estimate of 125% to 56.3°C/km.



Figreu 2j. Four kilometers of erosion in 0.25 ma increases thermal gradient 233% to 83°C/km over the first km of depth compared to an equation (4) estimate of 167% (to 66.8°C/km) for a broader depth range.

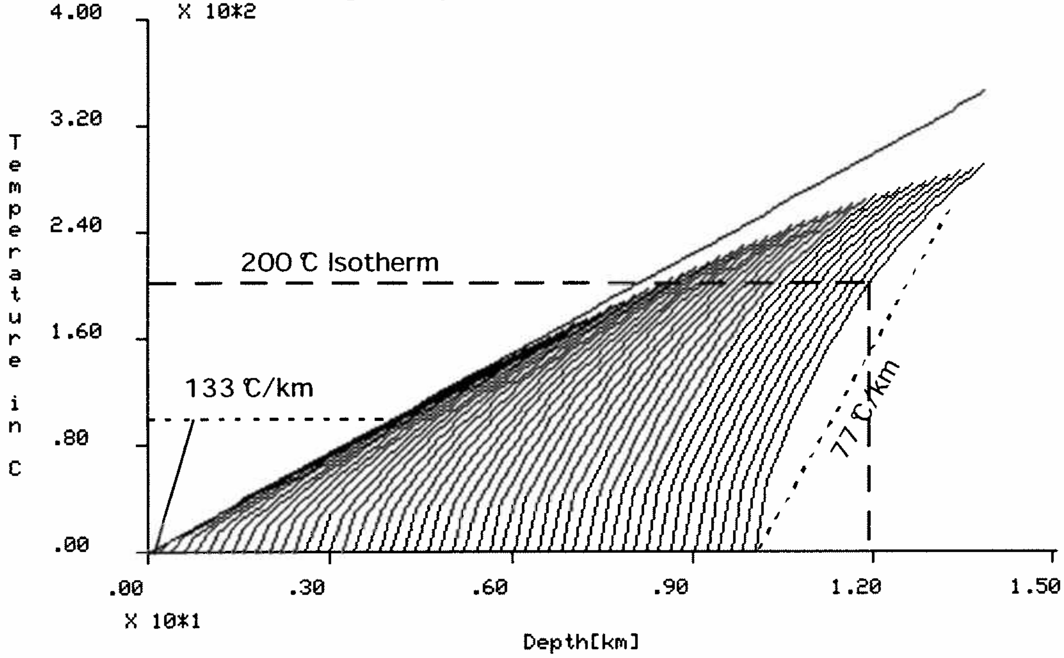


Figure 2k. Ten kilometers of erosion in 1 ma elevates thermal gradient in upper 1 km about 433% (to 133°C/km) compared to an equation (4) estimate of 208% (to 77°C/km) for a broader depth interval. Two hundred degree isotherm is about 2 km below surface which agrees with 1D solutions of Koons(1987)

References:

Carslaw, H. S. and Jaeger, J. C., 1976, Conduction of Heat in Solids, Oxford, Clarendon Press, 2d Edition, 497p.

Koons, P. O., 1987, Some thermal and mechanical consequences of rapid uplift: an example from the Southern Alps, New Zealand; Earth Planet. Sci. Let., 86, 307-319.

Royden, L. H., 1993, The steady state thermal structure of eroding orogenic belts and accretionary prisms, Jour. Geophys. Res., 98, 4487-4507.