Revista Brasileira de Geofísica; 1987, Vol. 5, 111-115

doi: 10.22564/brjg.v5i2.2231

GEOTHERMAL HEAT FLOW ANOMALIES CAUSED BY THERMAL CONDUCTIVITY CONTRAST

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Heat flow measurements are usually made in boreholes considering that the heat flow field is homogeneous and the flux vector is vertical. This is not true in regions where thermal conductivity anomalies exist. In this paper we study configurations which may disturb heat flow density distribution. A numerical method is used to investigate the two-dimensional character of heat flow field which could be associated with three situations: a layer almost vertical, an inclined layer and a layer situated between two media of different conductivities. Vertical and horizontal heat flow components are calculated along the surface of the earth and through the region on study. The results indicate that the heat flow is greatly disturbed by thermal conductivity anomalies.

As medidas de fluxo de calor são usualmente feitas em furos considerando-se que o campo de fluxo térmico é homogêneo e o vetor fluxo é vertical. Isto não é verdade em regiões onde anomalias de fluxo térmico existe. Neste trabalho estudamos as configurações que podem perturbar a distribuição de densidade de fluxo térmico. Um método numérico é usado para investigar o caráter bidimensional do campo de fluxo térmico que pode estar associado com tres situações: uma camada quase vertical, uma camada inclinada e uma camada situada entre dois meios com diferentes condutividades. As componentes de fluxo térmico vertical e horizontal são calculadas sobre a superfície da Terra e através da região em estudo. Os resultados indicam que o fluxo térmico é fortemente perturbado por anomalias de condutividade térmica.

INTRODUCTION

Generally the determinations of terrestrial heat flow are made on the assumption that heat transfer only takes place by conduction, in the vertical direction and in a steady — state regime. In these conditions the horizontal flux will be zero.

The existence of geological inhomogeneities of the crust results in local heat flow variations due to contrast in thermal conductivities. In these cases, although steady — state temperature is continuous everywhere, there are discontinuities in the thermal conductivity, and so the heat flow is no longer a continuous function and the horizontal component of the heat flux can take considerable values. In these cases we say that heat flow is refracted.

To obtain the value of the heat flow in these regions we can't use the mean of the vertical heat flow values obtained in the region. It is necessary to make a correction for the effect of refraction. This effect depends on the thermal conductivities contrast, on the configuration of the anomalous medium and on the distance to the region of contact of materials with different conductivities.

Lachenbruch & Marshall (1966) presented an analytic study of the heat flow refraction associated with some simple geometrical configurations. From then on several studies have been presented focusing on different aspects of this problem (Geertsma, 1971; Lee & Henyey, 1974; Lee, 1975; Jones & Oxburgh, 1979; Jones & Sydora, 1980). In the present piece of work we study the effect on the heat flow of a sloping layer with a thermal conductivity inferior to the one of the surrounding medium. We shall evaluate the heat flow on the surface and through the whole medium under study.

THE NUMERICAL METHOD AND PARAMETERS USED

If we consider a two — dimensional region in the X — Z plane, and if we assume there are constant heat sources and that steady — state conditions exist, the heat conduction equation is

$$\mathrm{div}\,(K\ \mathrm{grad}\ T) = A \qquad (1)$$

where A is the heat production by sources, K is the thermal conductivity and T is the temperature.

This equation is solved by Finite Differences Method; the domain where the equation is solved is covered by a "mesh point" and the Relaxation Method is employed to solve finite difference equations used to represent (1). The dimensions of the models were established on the assumption that heat flux in the vertical and bottom boundaries is only vertical (Fig. 1). The size of the mesh changes with the inclination of the layer. We have 1085 points for the layer almost vertical, 1240 points for a layer with an inclination 60° and 1395 points for a layer with a inclination 45°. The mesh points are separated 100m. The grid is square.

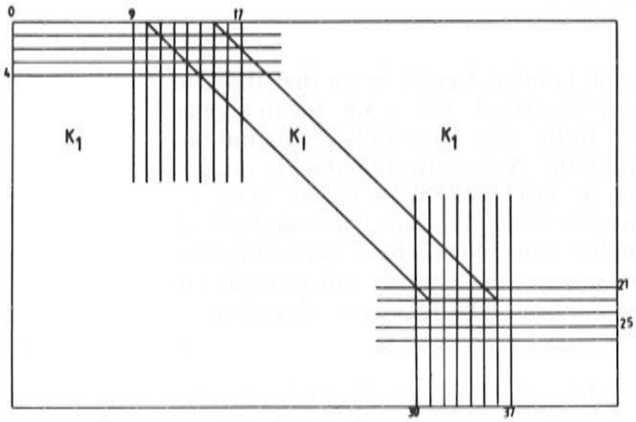

Figure 1 — Geometrical model for the calculation of heat refraction effects. The grid dimension is 100 meters.

To obtain the temperature at vertical boundaries we make an analytical integration of the heat conduction equation in O — Z direction, assuming that surface heat flow is 90 mWm^{-2} and the heat production by the radioactive sources is 2.07 μWm^{-3}. As an initial condition we consider that the temperatures in the interior of the mesh are equal to the tempearture in vertical boundaries. The surface of the earth (top of the mesh) is mantained at a constant temperature and a uniform heat flux into the bottom of the mesh is assumed. Furthermore, it is assumed that there is no heat flux across the side boundaries of the mesh (heat flux exclusively vertical).

MODELS

In the model used we considered an intrusion of a sloping layer with thermal conductivity inferior to the surrounding medium. The heat flow at the surface was calculated for layers with different inclinations (table 1). In Fig. 2 we show the configuration of the heat flow at the surface considering a layer with an inclination 45°. The contrast of thermal conductivities is 1.25 (Fig. 2a) and 1.58 (Fig. 2b). Then a layer with an inclination 60° was considered. In model 3 we considered a layer with an inclination of about 60° located between two media of different conductivities. The contrast 1.25 and 1.58 appear together in the same model.

RESULTS

The values of the vertical component of the heat flux were evaluated for all models. The value of the heat flow at one point is obtained by making the multiplication of the thermal conductivity by the difference between the temperatures evaluated above and under the point in question. The heat flow values are normalized to the value that would be obtained at the same depth if there were no contrasts of thermal conductivity.

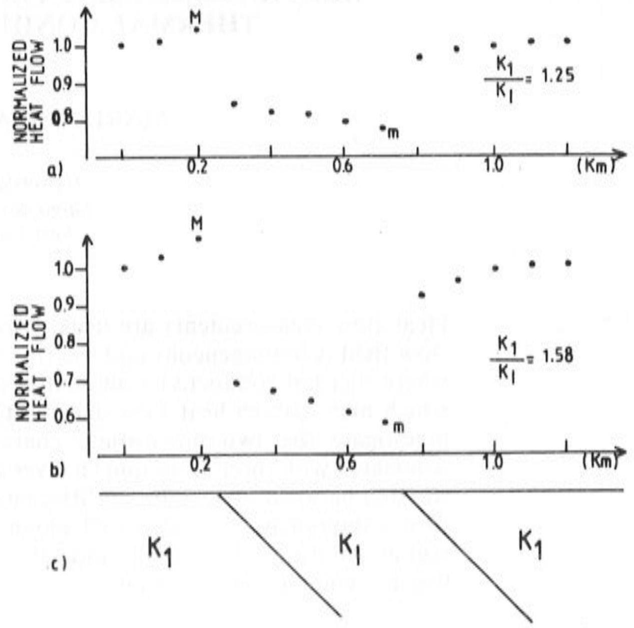

Figure 2 — Layer with thermal conductivity lower than the surrounding medium.
a) Vertical heat flow at the surfacxe for a medium with thermal conductivity K_1 times superior to the thermal conductivity of the layer K_I.
b) The same as above, but the thermal conductivity of the medium is 1.58 times superior to the thermal conductivity of the laver, K_I.
c) Model

In Fig. 2 we show the vertical heat flow at the surface for a layer with an inclination 45°. We notice an increase of the heat flow as we approach the anomalous medium by the left side, and we reach the maximum M. We find the minimum m inside the inclined layer but near the boundary, at the right side.

If the thermal conductivity contrast is 1.25 (Fig. 2a) the maximum heat flow value is 1.03 (M) and the minimum 0,78 (m). If the contrast is 1.58 (Fig. 2b) then the maximum will be 1.05 (M) and the minimum 0.59 (m). This configuration of the vertical heat flow at the surface remains when we change the inclination of the layer, but the values obtained may be different (Table 1).

In Fig. 3 we show isolines of the vertical heat flow, considering a layer with an inclination 60°. The thermal conductivity contrast is 1.25. In the left side we see a region of high values (maximum 1.04) and one region of lower values at the right side (minimum 0.76), in the first 250 meters. At greater depths we notice a reduction of the heat flow in all the anomalous region. At a distance of 400 meters (horizontally) from the inclined layer we do not obtain any heat flow anomaly.

Table 1 — Maximum and minimum values of the vertical heat flow at surface considering a layer with an inclination.

Θ	K_1/K_I	M	m
45	1.25	1.03	0.78
45	1.58	1.05	0.59
60	1.25	1.02	0.78
60	1.58	1.04	0.60
83	1.25	1.01	0.78
83	1.58	1.03	0.60

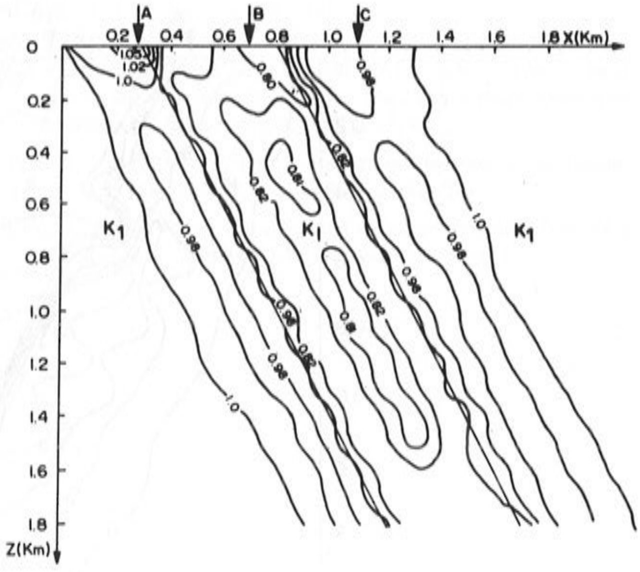

Figure 3 — Layer with an inclinatin 60° and thermal conductivity K_I lower than thermal conductivity of the surrounding medium (K_1/K_I = 1.25). Vertical heat flow.

In Fig. 4 we show some profiles of temperature and mean values of thermal gradient evaluated between two points of the mesh, corresponding to points A, B and C in Fig. 3. The gradient increase in profiles B and C corresponds to the depths where we find the material with lower thermal conductivity.

In Fig. 5 we see and inclined layer with low thermal conductivity located between two media of different conductivities. The isolines of the vertical heat flow show a more complicated situation, with a strong concentration of isolines near the border of the inclined layer. In these zones, the horizontal heat flow becomes considerable attaining values of 19% of the vertical heat flow in the inclined layer, and 80% of the vertical heat flow in the external zone. The value of the vertical heat flow at the surface are inferior to the values of the region. In deeper regions we can see a positive anomaly of the heat flow at the left side. In the inclined layer we notice an increase of the heat flow as the depth grows.

The profiles of temperature and values of mean thermal gradient (Fig. 6), corresponding to points A, B and C (Fig. 5), show pronounced changes. In profile A we see an abrupt increase of gradient at 300m depth, corresponding to the region where we find a positive anomaly of heat flow (Fig. 5). In profiles B and C we see that the more pronounced gradient correspond to depths where we find material with inferior thermal conductivity.

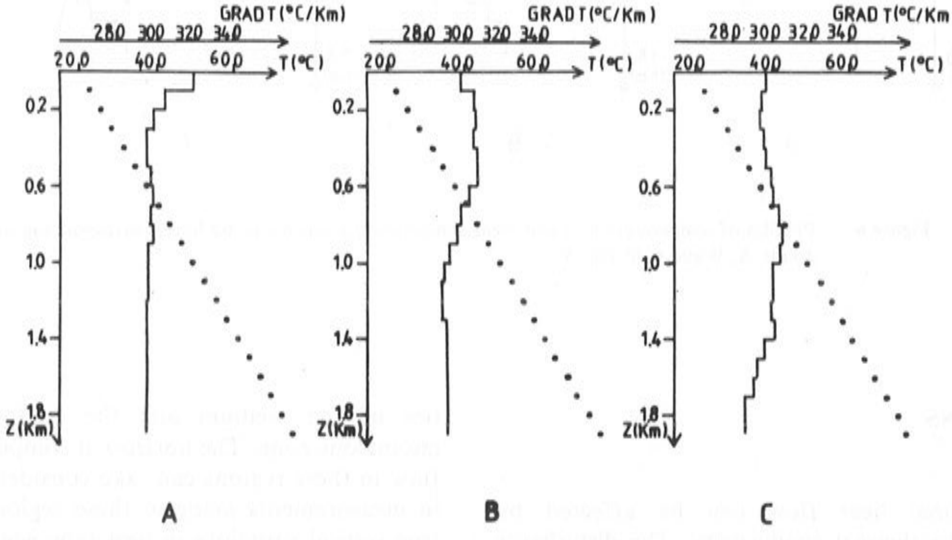

Figura 4 — Profiles of temperature (.) and mean temperature gradients (solid lines) corresponding to points A, B and C in Fig. 3.

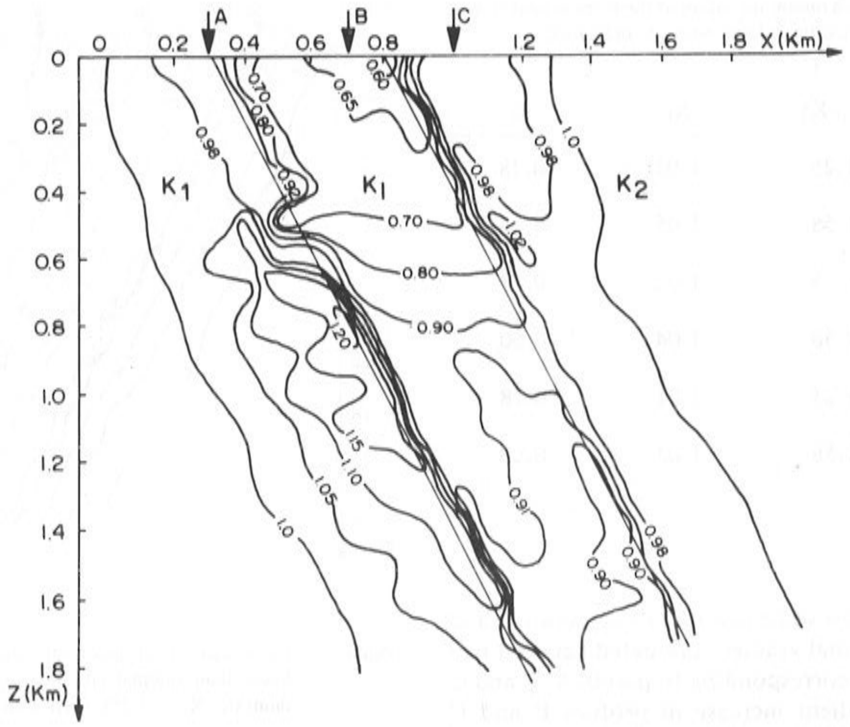

Figure 5 — Layer with low thermal conductivity located between materials with different thermal conductivities ($K_1/K_I = 1.25$, $K_2/K_I = 1.58$). Vertical heat flow.

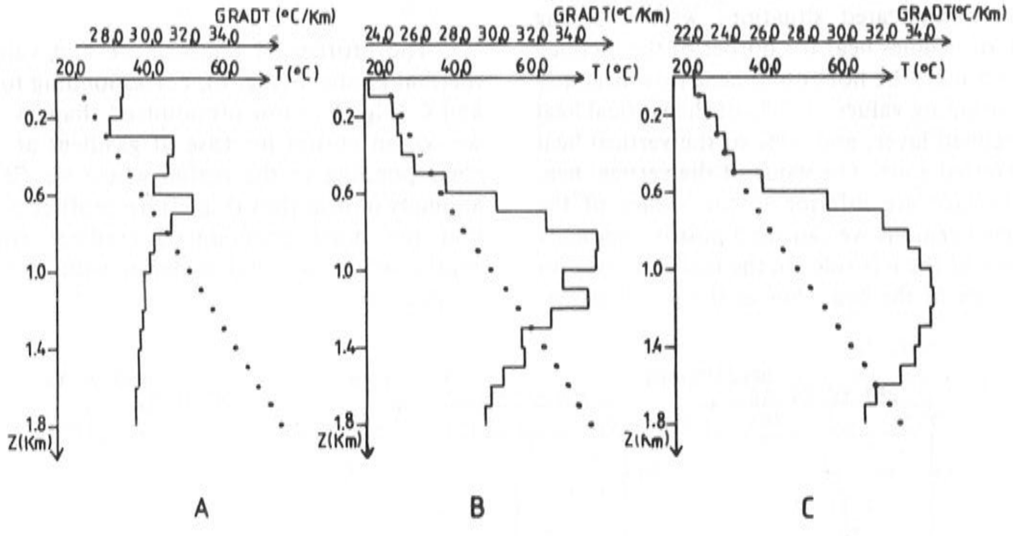

Figure 6 — Profiles of temperature (.) and mean temperature gradients (solid lines) corresponding to points A, B and C in Fig. 5.

CONCLUSIONS

The regional heat flow can be affected by anomalies in the thermal conductivity. The disturbance of the heat flow depends on the location of the measurement, the contrast between thermal conductivities of the medium and the configuration of the anomalous zone. The horizontal component of the heat flow in these regions can take considerable values. So, in measurements made in these regions there may be true vertical variations in heat flow which are explicable in terms of thermal conductivity structure. Conclusions from such measurements must be taken with care.

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