# HEAT FLOW AND RADIOGENIC HEAT PRODUCTION IN THE PARANÁ BASIN

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**Abstract**

Heat flow at the surface of the Paraná Basin in southeastern Brazil increases from the central part to the margin of the basin by about 10 - 20 mW $m^{-2}$. The lower values are located in the central part of the basin, most of which is covered by the Serra Geral flood basalts. Higher and more variable heat flow occurs along the eastern margin, where the basalt cover is absent. We examine the contribution of lateral variation of the radiogenic heat production rate of the basement to the heat flow contrast at the surface. The mean of more than 150 measurements of the radiogenic heat production rate of rocks sampled from various basement provinces is 1.7 $\mu$W $m^{-3}$, ranging from 0.35 to 6.2 $\mu Wm^{-3}$. Although the heat production measurements at the surface show local anomalies of high and low heat production, a coherent regional pattern that can be related to the large scale heat flow variation is not evident. An underplate in the lower crust associated with the flood basalt eruption could provide a region of lower heat production rate. The mobile belts that surround and underlie the eastern margin of the basin contain granitic rocks (of higher heat production rate) and the hypothetical existence of an Archean cratonic nucleus (with low heat production rate) underneath the basin could also be a source of lateral heat production variation. Numerical models indicate that heat production contrasts due to the flood basalts and mafic undeplate in the lower crust contribute less than 5 $mW/m^2$ to the surface heat flow. Additional numerical models are needed to examine the effects of the high heat production units extending underneath the basin.

## Introduction

Hurter and Pollack (1996) examined several surficial and intrabasinal causes of heat flow variation across the Paraná Basin: basin scale advective flow due to subsurface fluid flow, the thermal conductivity contrast between flood basalts and sediments and the effect of sedimentation, uplift and erosion. They conclude that the thermal regime of the basin is dominantly conductive and that intrabasinal causes explain only up to 1/4 of the observed heat flow variation. The remaining possibilities for explaining the heat flow variation are: lateral variations in lithosphere thickness, with higher heat flow at the margin of the basin being related to thinner lithosphere or a systematic increase in the contribution of the basement heat production to the surface heat flow from the center to the margin of the basin.

The lack of data of radiogenic heat production of the basement rocks has precluded even a first order examination of the effects of basement heat production. This is the purpose of the present study, made possible by the recent work of Andrade (1998).

## The Paraná Basin

The Paraná Basin covers an area of about 1,400,000 $km^2$ most of which is in Brazil, but with extension also into Argentina, Paraguay and Uruguay. The major axis of the basin lies approximately parallel to the Paraná River. The basin contains up to five kilometers of Paleozoic and Mesozoic predominantly siliciclastic sediments in its thickest central part. The depositional history of this Gondwana basin initiated in the Ordovician came effectively to completion in the Cretaceous following a large volcanic event related to the opening of the South Atlantic, which extruded the flood basalts of the Serra Geral Formation over most of the basin surface up to 1.7 km thick. The basalt today covers about 75% of the basin surface. Associated with this extrusive event ubiquitous sill and dyke intrusion occurred. The igneous rocks comprise up to 30% of the stratigraphic column in some localities (Zalán *et al.* 1991).

The crystalline basement beneath the basin is formed of a mosaic of Precambrian nuclei welded together by mobile belts. This basement is originally of Archean age and has been affected with varying intensity by the Brasiliano orogenic cycle (corresponding to the Pan-African orogeny in Africa). This tectonomagmatic event represents one aspect of the assembly of Gondwana; it began during the Late Proterozoic, and extended into the Early Ordovician (Brito Neves and Cordani 1991; Zalán *et al.* 1991). The exposed basement at the eastern and south-eastern margin of the Paraná basin is made up of the Neoproterozoic Ribeira and Don Feliciano mobile belts, which are separated by gneisses and migmatites of the Luis Alves and Curitiba terrains. The southern tip of this exposed basement consists of Transamazonian rocks of the Rio de La Plata craton. Trompette (1994) reviews the aggregation of South America during the Pan-African/Brasiliano orogenic cycle. The later Paleozoic tectonic and sedimentary evolution of the Paraná Basin has been strongly influenced by the reactivation of old preexisting basement faults. Following the opening of the South Atlantic Ocean, the entire south-eastern margin of the Paraná Basin was uplifted along a trend inherited from the Brasiliano cycle, forming the Serra do Mar coastal range.

## Heat Flow Data

The mean heat flow for the Paraná basin is 56 ± 11 mW $m^{-2}$ (standard deviation of the mean); individual values range mostly between 40 mW $m^{-2}$ and 75 mW $m^{-2}$. Hurter and Pollack (1996) discuss previous geothermal investigations in this basin and present a comprehensive body of thermal data comprising 56 heat flow sites. The geographic distribution of heat flow values reveals a coherent pattern (Fig.1). Generally lower heat flow values of 40 - 50 mW $m^{-2}$ occur in the northern and south central region of the Paraná Basin, roughly parallel to the Paraná River, that flows along the basin's major axis and overlies the locus of greatest flood basalt thickness. Along the eastern basin margin, where flood basalt is absent, higher heat flow values in the range of 50 - 75 mW $m^{-2}$ are encountered, although with greater variability than in the areas covered by flood basalt. Although there is considerable scatter, a variation of the order of 15 - 20 mW $m^{-2}$ occurs between the center and the margin of the basin, a distance of a few hundred kilometers.

## Heat Production Measurements

Samples of granitic and volcanic rocks (granites, granodiorites, monzogranites, tonalites and rhyolites) as well as metamorphic rocks (gneisses, migmatites, metabasites and granulites) were assembled for heat production determination, so that a good representation of the various lithologies that make up the basement was achieved.

The radiogenic heat production rate is a function of the concentration of uranium, thorium and potassium. Gamma spectrometry was used to measure the concentration of these radioactive elements on more than 150 samples from the exposed basement. The heat production rate was calculated according to Rybach (1988). Furthermore, heat production was calculated from published geochemical data, increasing the collection to 200 values of radiogenic heat production rate.

Heat production for granitic rocks from the basement of the Paraná Basin varies from 0.8 to 4.6 $\mu W\ m^{-3}$ with a mean of 1.9 $\mu W\ m^{-3}$. The metamorphic rocks show more variation, with a range of 0.35 to 6.2 $\mu W\ m^{-3}$ and a geometric mean of 1.5 $\mu W\ m^{-3}$. The mean heat production for the basement is 1.7 $\mu W\ m^{-3}$. Average values for the Ribeira Belt and the Rio de la Plata cratonic block are 2.5 $\mu W\ m^{-3}$ and 1.5 $\mu W\ m^{-3}$, respectively. Andrade (1998) describes measurement procedures and discusses this data in detail.

Heat production varies significantly over short distances and it is likely that some values are anomalies of only local significance. Regional trends are difficult to recognize when plotting all values in a map. Fig. 2 shows a map in which heat production was gridded and interpolated. First mean values were taken for blocks 0.3° x 0.3° and then gridded and interpolated with a grid size of 0.2° x 0.2°. Areas with no data were blanked out. In this smoothed representation, local areas of higher than average heat production can be recognized in all 3 major areas of sampling (indicated with the white squares representing sample locations). Lower than average heat production seems extend over a greater area in the Rio de la Plata cratonic block in the south. A systematic regional trend is not evident, even considering the extension of the tectonic units underneath the basin.

## Contribution of Heat Production to Surface Heat Flow

When the geographic pattern of heat flow (Fig. 1) and of heat production (Fig. 2) are compared, a case could be made that, at least locally, areas of higher heat production coincide with higher heat flow values. Lower heat production values cannot be related to low heat flow because, unfortunately, the heat flow measurements are located in the basin covered by sediments, while the heat production values derive from samples of the exposed basement.

The basalt cover of the Serra Geral formation and the possible existence of a large underplate in the lower crust associated to this igneous event provides a large heat production contrast because mafic rocks generally exhibit low heat production (< 0.3 $\mu W\ m^{-3}$). These rocks also cause a large lateral thermal conductivity contrast (mafic rocks have thermal conductivities a factor of 2 lower than the other rocks making up the basement and the sediments). Hurter (1995) investigated the effects the low heat production and low thermal conductivity contrast on surface heat flow with 2-D numerical models. The contribution of low heat production combined with the low thermal conductivity of these rocks is less than 6 $mW\ m^{-2}$, i.e. a small portion of the observed heat flow variation.

In order to determine the contribution of heat production to the heat flow observed at the surface and its spatial variability, (1) the lateral extension of the tectonic units making up the basement covered by the Paraná Basin deposits and (2) the vertical distribution of heat production need to be known.

(1) Geophysical studies, especially the modeling of gravimetric data, has been used to infer the continuation and extension of some of the tectonic and lithologic units underneath the basin sediments (Hallinan *et al.* 1993; Quintas 1995). The Ribeira mobile belt is interpreted to extend underneath the sediments, with an alignment of granitic bodies along NE-SW.

(2) A greater problem is the depth distribution of heat production. Although various distribution functions have been suggested, there is still no single largely applicable model of vertical heat production distribution for the continental crust. There seems, however, to be a general agreement that heat production must diminish with depth (Lachenbruch *et al.*, 1994). A frequently used model is the exponential decrease of heat production with depth in the crust. This model is valid for the Sierra Nevada in California (Saltus and Lachenbruch, 1991), although its application in other regions is controversial, since some of the data are inconclusive or insufficient for such an analysis and specific regions do not show any coherent vertical pattern in the first few kilometers of depth. The exponential model also remains valid when differential erosion occurs, which is considered an advantage over other types of distribution. It probably fails in regions of intense lateral tectonic deformation (Sass *et al.*, 1994).

We now examine the implications of using a model of uniform heat production for the crust and of exponentially decreasing heat production with depth.

The average heat production at the surface from the basement is 1.7 $\mu W\ m^{-3}$, so that a crust of 30 km thickness with an uniform heat production would contribute 51 $mW\ m^{-2}$ to heat flow at the surface. This is close to the mean heat flow for the Paraná basin and would imply an irrealistically low heat flow (< 10 $mW\ m^{-2}$) from the mantle. Hence, heat production must diminish with depth and the uniform heat production model is not applicable here.

We assume an exponential decrease with depth, according to:

$$A(z) = Ao \exp(-z/D)$$

so that Ao is heat production at the surface and D the decrement of the exponential function. D can be intrepreted as the thickness of the layer containing most of the crustal heat production. D = 10 km is reasonable considering that granitic plutons are rarely much thicker or deeper than that. Integrating this expression over the depth range of the crust provides the contribution of heat production to the surface heat flow. In this case, 30 km of crust with a surface heat production of 1.7 $\mu W\ m^{-3}$ would contribute 17 $mW\ m^{-2}$ to the surface heat flow. Therefore the heat flow from the mantle would be on the order of 40 $mw\ m^{-2}$.

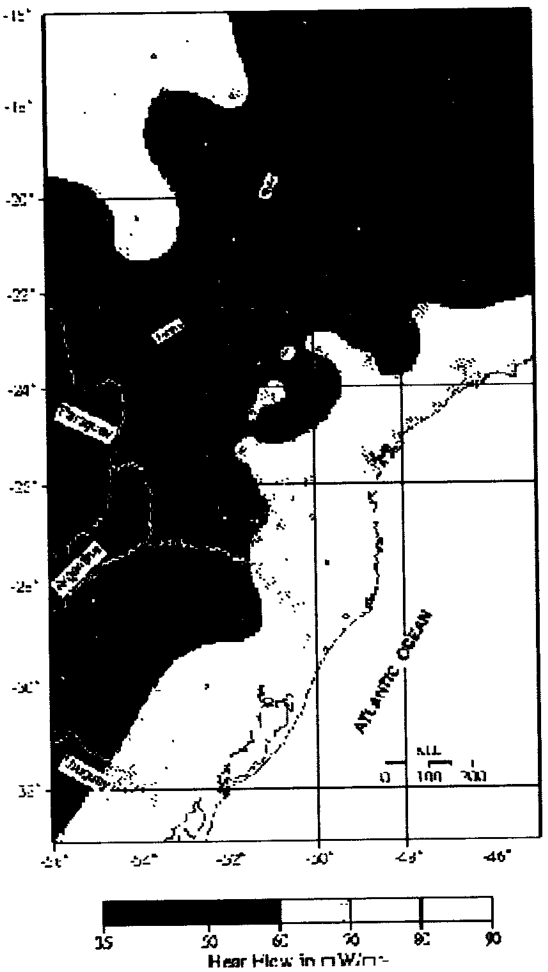


Fig. 1. Heat flow in the Paraná Basin. White dots are measurement sites.

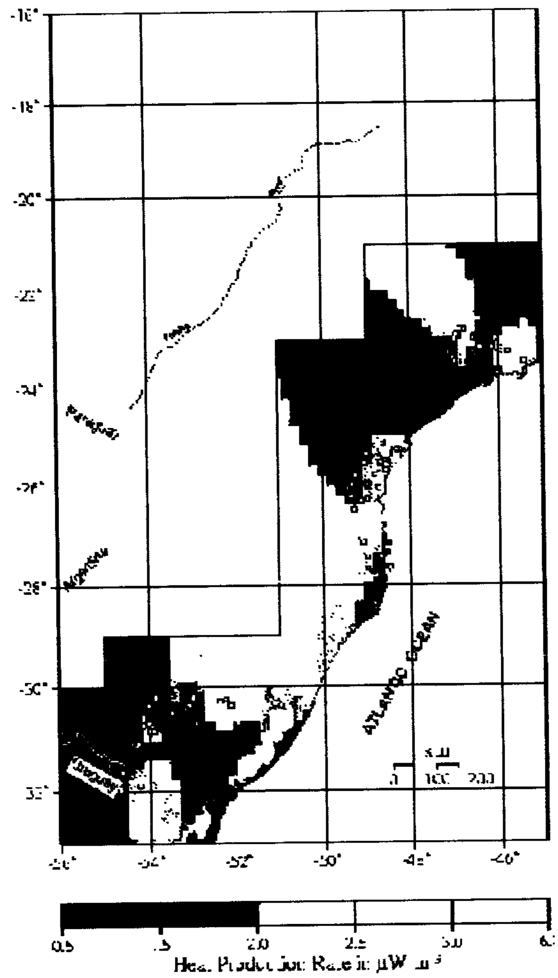


Fig. 2. Heat production rate in the Paraná Basin. White squares are sampling locations. Areas with no measurements are blanked out.

In order to relate the heat flow pattern to heat production contrasts in the basement of the Paraná Basin, we examine the effects of the alignment of granitic intrusions along the eastern margin of the basin. We assume that these bodies have a high heat production, of the order of the upper range measured by Andrade (1998), 6.2 $\mu W\ m^{-3}$, which results in a contribution of 60 $mW\ m^{-2}$ to the surface heat flow. We would then expect to see heat flow in the range of 90 to 100 $mW\ m^{-2}$ at the surface along large distances. This is not observed. It indicates that such high values are probably of local importance and represent shallow crust. The mean value determined for granitic rocks, 1.9 $\mu W\ m^{-3}$ produces a variation of only a 2 - 3 $mW\ m^{-2}$ compared to the mean for the basement of 1.7 $\mu W\ m^{-3}$.

A regional coherent pattern may arise if we consider the influence of larger scale tectonic units. The mean heat production for the rocks in the Ribeira Belt is 2.5 $\mu W\ m^{-3}$. This is in contrast to the mean for samples from the Rio de la Plata cratonic block (1.50 $\mu W\ m^{-3}$). The contribution to heat flow at the surface from 30 km of Ribeira Belt crust, assuming an exponential decrease with depth, is 24 $mW\ m^{-2}$, which results in surface heat flow of about 65 $mW\ m^{-2}$. This value is within the range of values measured at the eastern margin of the Paraná Basin. The same amount of cratonic crust at 1.5 $\mu W\ m^{-3}$ would produce 15 $mW\ m^{-2}$, or a surface heat flow of 45 $mw\ m^{-2}$, which is of the same order as heat flow measured in the central part of the Paraná Basin.

## Conclusion

The pattern of heat flow observed at the surface across the Paraná Basin can be related to various causes: crustal scale thermal conductivity heterogeneity, variations in lithosphere thickness and lateral changes in heat production rate of the basement.

Recent measurements of radiogenic heat production from the exposed basement of the Paraná Basin allow for the first time an assessment of the contribution of heat production to the surface heat flow. Despite the unsatisfying spatial data distribution, we have performed an, albeit preliminary, analysis of the effect of variations in basement heat production, using models of uniform crustal heat production and of an exponential decrease of the heat production with depth. The uniform crustal heat production overestimates the surface heat flow. The exponential model yields surface heat flow in the range of the values measured in the basin. Numerical models in a previous study show that low heat production units (flood basalts and lower crustal mafic intrusions and underplating) are insufficient to produce the heat flow variation that is observed. The contribution from high heat production rocks may explain locally the measured heat flow, however, a coherent regional effect remains to be examined with numerical models.

The possibility that heat production is capable of explaining all of the regional variation in heat flow needs to be examined together with other factors, such as thermal conductivity heterogeneity and lateral changes in crustal and lithosphere thickness. Numerical models allow the effects of several processes to be evaluated separately or jointly and is the only means to examine different scenarios independently yielding results that can be confronted with data.

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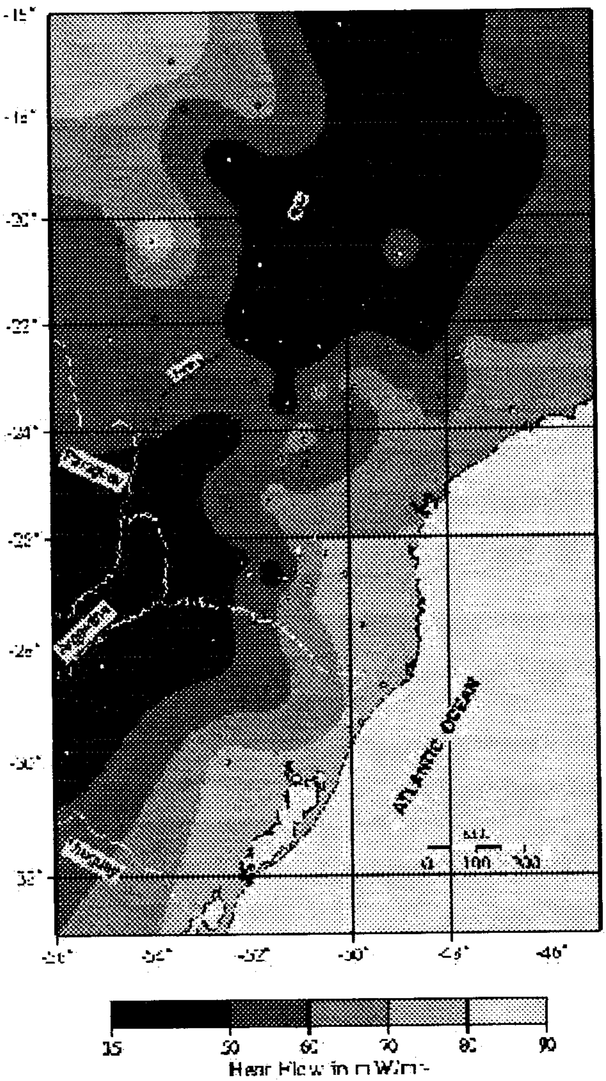


Fig. 1. Heat flow in the Paraná Basin. White dots are measurement sites.

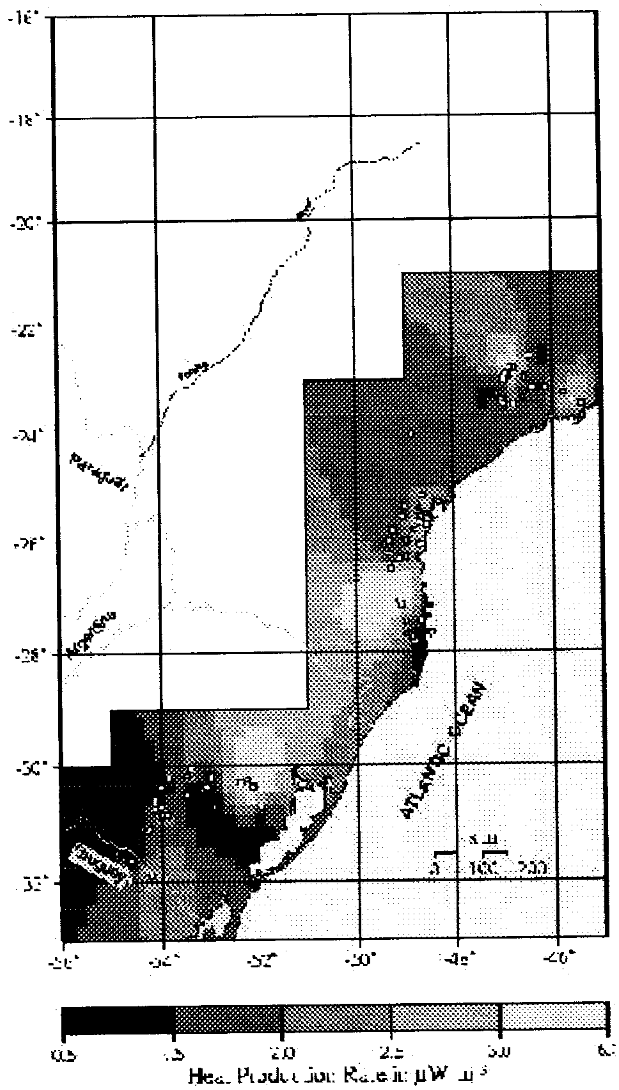


Fig. 2. Heat production rate in the Paraná Basin. White squares are sampling locations. Areas with no measurements are blanked out.