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Crustal heat flow mapping in Rio de Janeiro, SE Brazil, using boreholes: implications for geothermal resources

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ABSTRACT

The results of geothermal investigations carried out in the State of Rio de Janeiro, southeastern Brazil, have been compiled with the aim of producing regional distribution maps of terrestrial heat flow and measuring the lithospheric geoenergetic storage capacity and temperature distribution at depth in the region. The compilation included 42 direct temperature measurements in shallow wells (up to 200 m), typically used for groundwater exploration. The entire state was covered, prioritizing windows of 0.5x0.5 degrees of latitude/longitude. The methodology combined direct temperature measurements with modelling of the heat conduction equation, isolating the deep geothermal flow from surface climatic perturbations. The heat flow, calculated from the geothermal gradient and thermal conductivity data, shows values between 55 and 75 mW/m^2, with peaks of 90 mW/m^2 observed in the southern region and associated with crystalline rocks. In the central region, lower fluxes (27–55 mW/m^2) correlate with sediments. The geological context reflects crustal thermodynamics, mainly marked by orogenic events of the Brasiliano Cycle (Proterozoic to Paleozoic) and the influence of pre-, syn- and post-collisional magmatism, where crystalline units such as the Rio Negro Complex and the Rio Doce Orogen favour high thermal conductivity ($\lambda > 3$ W/m·K) and high geothermal gradients (up to 54.6°C/km). The more central sedimentary formations have low conductivity ($\lambda < 2.5$ W/m·K) and reduced fluxes. This heat flow distribution reflects the thermophysical dynamics of the crust, revealing a region of low to medium enthalpy, with limited potential for geothermal energy, a resource with direct applications such as domestic heating or agricultural greenhouses.

Introduction:

Heat flow in the crust is a fundamental parameter in hydrocarbon maturation and geothermal energy assessment (Guimarães, 2022; Chao Zang, 2024). The Proterozoic-Paleozoic Brasiliana orogeny generated pre-, syn- and post-collisional magmatism (Heilbron, 2016), as well as distinct lithologies that created lateral and vertical variations in thermal properties. In order to assess the regions geothermal energy potential, this study aims to characterize the region geothermally and map the depth to the 150°C isotherm. This is critical for binary cycle electricity generation in the shallow crust of Rio de Janeiro (Torres, 2014; Guimarães, 2024).

Methodology:

To estimate the temperature variations in relation to depth in the shallow crust, we analysed data from 42 artesian wells (up to 270 m deep) located across Rio de Janeiro (onshore), as well as 71 wells in the Campos Basin and 15 wells in the Santos Basin, totaling 86 wells offshore.
This variation is obtained through the relationship between the average surface temperature *(T_0)*, depth *(z)*, heat flow *(q)*, thermal conductivity *(λ)*, radiogenic production rate *(A)* and depth of radiogenic decay *(D)* and the lateral thermal variation coefficient *(α)*.
The equation is given by:

$$T_z = \frac{1}{\propto}\{(1+\propto T_0)\left(e^{\left[\left(\frac{\propto}{\lambda}\right)\left(q\times z - A\times D\times z + A\times D^2\right)\left(1-e^{-\left(\frac{z}{D}\right)}\right)\right]} - 1\right)\} \quad (1)$$

According to Guimarães (2024), fixed parameters were used for *α*, *D* and *A* at values of 0.0011°C^{-1}, 10000 m and 1.1×10^{-6}, respectively. The T_0 values were direct measurements of the thermal profiles, while *λ* and *q* were measurements calculated from these profiles.
Heat flow is obtained through the geotherm, which was calculated using the CBT/BHT ($\Gamma = \frac{T_{CBT}-T_0}{z_{CBT}}$), or CVL ($\Gamma = \frac{N\Sigma z_i T_i - \Sigma z_i - \Sigma T_i}{N\Sigma z_i^2 - (\Sigma z_i)^2}$) method. The latter is applicable only to onshore wells and times thermal conductivity ($\bar{\lambda}_{pond} = \frac{\sum_{i=1}^{n} e_i \lambda_i}{\sum_{i=1}^{n} e_i}$). We applied this equation to the 128 wells, calculating T_z and extrapolating z to depths of up tp 10 km to find the 150°C isotherm.
To determine the precise depth at which a well intersects the 150°C isotherm, linear interpolation is performed in:

$$z_{(150)} = z_1 + (150 - T_1) \times \left(\frac{z_2 - z_1}{T_2 - T_1}\right) \quad (2)$$

For the interpolation, a well must have a depth pair z_1, z_2 such that $T_{(z1)} < 150 < T_{(z2)}$. To optimize these calculations, a Python program was developed to automate the above steps.

Results and Discussions:

Analysis of onshore data revealed a predominantly terrestrial heat flow of between 55 and 75 mW/m^2. Heat flows below 55 mW/m^2 were correlated with Cenozoic deposits characterized by low thermal conductivity (λ < 2.5 W/m·K).
Analysis of the 42 onshore thermal profiles using linear interpolation revealed that 36 of the wells satisfied the condition $T_{(z1)} < 150 < T_{(z2)}$. The depths of the 150°C isotherm ranged from a minimum of 2.686 m to a maximum 9455 m. The remaining 6 profiles did not cross the 150°C isotherm at depths of up to 10000 m, with maximum temperatures of 141°C at this depth limit.
Figure 1.a shows the heterogeneity of the thermal profiles, plotting temperature as a function of depth for the 42 analyzed wells. Despite an average gradient consistent with regional geology (20-25°C/km), itcan be seen that the depth of the 150°C isotherm varies significantly.
The offshore profiles (Figure 1.b.c) are more clustered and consistent with an average thermal conductivity of 2,50 W/m·K. This suggests a significant influence from a larger sedimentary column compared to the onshore profiles.
The depths calculated for the 150°C isotherm in offshore wells ranged from 2892 to 5291 m (in the Santos and Campos basins), with an average depth of 4155 m. Thus, all the wells satisfied the condition $T_{(z1)} < 150 < T_{(z2)}$.
The offshore geothermal regime revealed an average heat flow of around 75,14 mWm^2, comparable to the maximum values observed in onshore areas. This indicates that marine areas are, on average, as thermally active as the hottest continental zones.

Figure 1. Perfis térmicos dos poços onshore (a) e offshore (b), (c). (a) The six profiles that did not cross the 150°C isotherm are shown in grey. (b) Campos Basin. (c) Santos Basin.

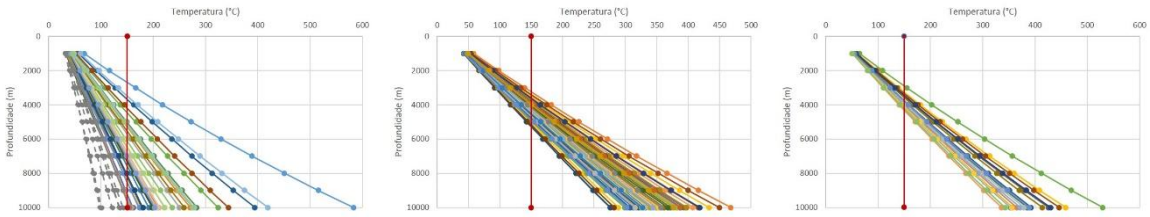
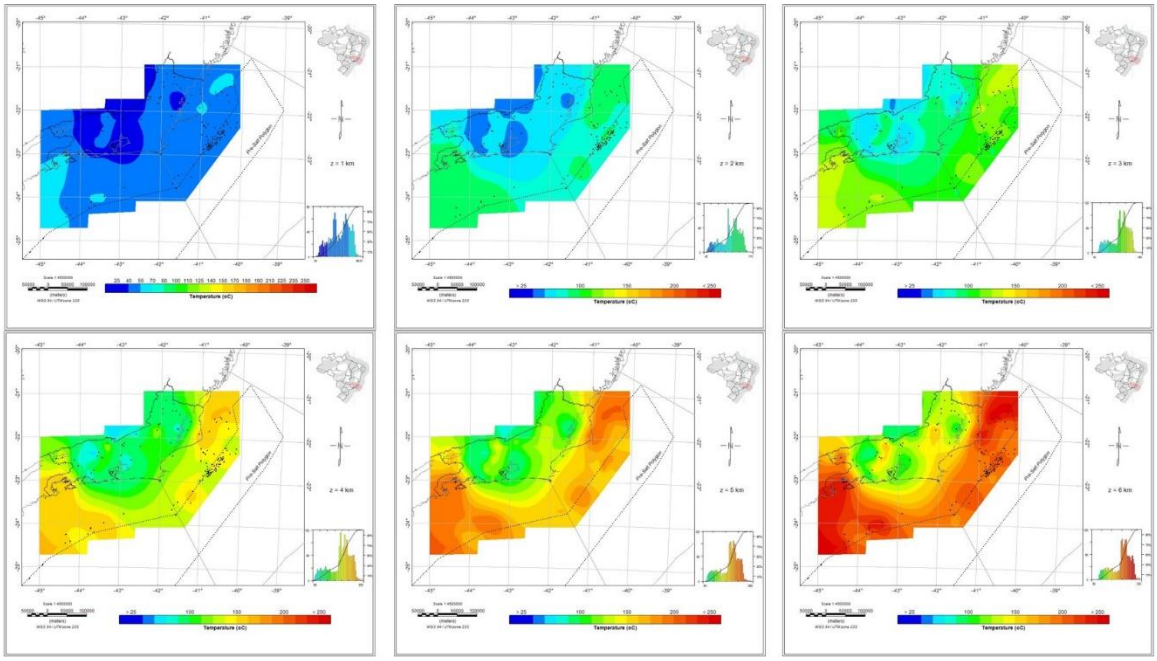


Figure 2 shows the spatial distribution of temperature and summarizes the evolution of the crustal geothermal regime, revealing the influence of different geological structures. Depth maps (1-6 km) confirm the signature of a higher heat flow in the offshore domain, where temperatures of interest (150°C) are reached at shallower depths than in the onshore domain.

Figure 2. Map showing the crustal geothermal evolution at depths between 1 and 6 km.



Conclusions:

Comparing the geothermal parameters onshore and offshore reveals regional tendencies and differences. The average offshore heat flow aligns with the maximum onshore well values. The onshore average depth of the 150°C isotherm is approximately 7000 m, whereas the offshore average depth is 4155 m.

However, the 150°C isotherm is more accessible at greater depths in offshore wells. This leads us to conclude that the geological factor that drive the 150°C isotherm to greater depths on the continental side are not influential in the offshore area. Although offshore wells offer shallower depths to the isotherm, they are not economically viable projects precisely because of their distance from production plants.

The reservoir temperature would need to exceed 150°C to ensure that it still reaches this critical temperature at the production plants after heat dissipation during transport.

In conclusion, the geothermal resources of the studied areas in Rio de Janeiro, both onshore and offshore, can predominantly be classified as low-enthalpy, meaning they have low potential for generating electricity from heat. It is important to emphasize that this low-enthalpy classification does not preclude using the heat for other purposes, such as air conditioning in urban areas.

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