Models of thermal perturbations associated with deep crustal magma emplacements: Application to anomalous heat flow belt along continental margin of Brazil.

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This paper was prepared for presentation during the 15th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 31 July to 3 August, 2017.

Abstract

Recent progress in analysis of geothermal data have indicated the presence of narrow elongated belts of anomalously high heat flow in the central parts of sedimentary basins along the continental margin of Brazil. The characteristics of this belt appear to be compatible with those produced by magma emplacements at deep crustal levels. In this work, we discuss the use of an analytical model for estimating magnitudes of transient heat flow arising from such magma emplacements in the crust. Results of model simulations indicate that the origin of the anomalous geothermal belt is related to recent episodes of magma emplacement at depths of approximately 20km. Its age is no more than 2Ma. Model studies were also extended for determination of the effects of magma emplacements on paleotemperatures of sedimentary rock formations. The results indicate that a magma emplacement episode at 20km depth that occurred at about 20Ma is capable of accounting for maturity levels observed in the continental margin of Brazil. It implies that oil generation in in the central parts of Campos and Santos basins has been a much recent event with ages less than 20Ma.

Introduction

Evolutionary history of many of the basins in the continental margin of Brazil is characterized by an initial short-period phase of fault-controlled subsidence, followed by a relatively long period of thermal subsidence (e.g., Asmus and Porto, 1972; Campos et al, 1974; Ojeda, 1982). Seismic surveys have identified the presence of a number of structures in deep strata, which have been interpreted as arising from intrusive magmatic activities of early Tertiary times. Several geologic studies (e.g., Mohriak et al, 1990; Mizusaki and Mohriak, 1992; Moreira et al, 2006) have pointed out evidences of the occurrence of sporadic magmatic activity during the Eocene and Santonian-Campanian. Evidences of volcanic buildups associated with intrusive and extrusive rocks have been reported (Moreira et al, 2006). Occurrences of sub-aerial and subaqueous volcanism are well identified and its characteristics described in terms of seismic, log and lithologic evidences (Oreiro, 2002). However, no evidences have been found of volcanic or magmatic activities since Miocene times. In addition, there are no reports of occurrences of hydrothermal fluid circulation processes in the ocean floor.

On the other hand, recent progress in analysis of geothermal data points to the presence of narrow elongated belts of anomalously high heat flow values in basins along the continental margin of Brazil (Vieira and Hamza, 2014). The nature of this anomalous heat flow belt is illustrated in Figure (1). Note that heat flow is systematically high along the central parts of basins along the continental margin, with values in the range of 65 to 90mW/m^2. The width of this belt is relatively large in the southern sector when compared with those in the norther parts.

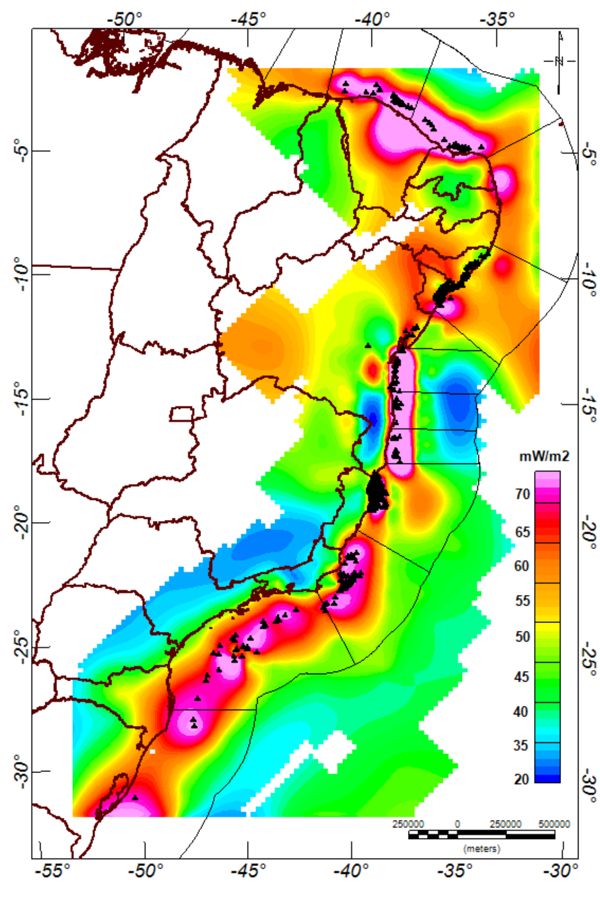

Figure (1) Anomalous geothermal belt along the continental margin of Brazil (Vieira and Hamza, 2014).

The characteristics of this high heat flow belt appear to be compatible with those produced by magma emplacements at deep crustal levels. The problem is how to reconcile observations of geologic studies (which point to absence of magmatic activity since Miocene times) with the results of geothermal studies pointing to the existence of elongated narrow high heat flow belts along the continental margin of Brazil. In this context, we note that emplacements of mantle material may occur at deep crustal levels as a result of thermo-tectonic processes in the upper mantle. Ductile deformation of mantle would easily accommodate lateral flow of material arising from deeper thermos-tectonic processes. The result is emplacement of hot mantle material at the base of the crust. This is in essence a passive tectonic process, characterized by lateral flow of mantle material beneath the crust and need not necessarily generate magmatic intrusions at near surface levels. However, the thermal field of the overlying crust undergoes significant changes as a result of enhanced heat flux from the mantle layer.

In other words, an obvious consequence of magma emplacement at deep crustal depths is alteration of temperature regime of the overlying rock formations. Usually, this alteration is in the form of an initial short-period heating followed by a relatively long period of cooling. In developing models of such perturbations, it is usual practice to assume that the time interval of the magma emplacement process is small relative to the time elapsed after it. In such cases, the magma emplacement may be considered as an instantaneous process. Models of such temperature perturbations have been proposed in the literature (Carslaw and Jaeger, 1959; Jaeger, 1964; Horai, 1974; Rikitake, 1995; Delaney, 1988; Nabelek et al, 2012). In this work, we discuss the use of an analytical model for estimating magnitudes of transient heat flow arising from such magma emplacements in the upper crust.

Model Considerations

Consider the case of magma emplacement at depths between Z_1 and Z_2 where the initial temperatures are T_1 and T_2 respectively. The initial temperature of the emplaced material itself is T_i, which is the solidification temperature of the magma. The temperatures in the medium above and below the intrusion are determined by the undisturbed geothermal gradient (g) and surface temperature T_o. A schematic illustration of the overall temperature distribution at the time of magma emplacement is illustrated in Figure (2).

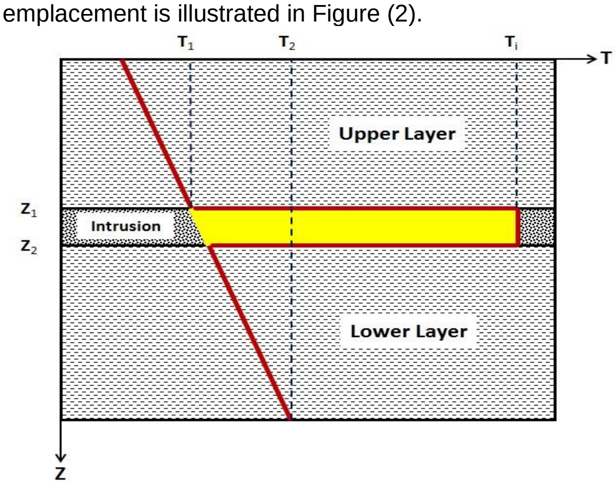

Figure (2) Schematic illustration of the initial temperature (T) distribution with depth (Z) at the time of magma emplacement.

The model assumes that the thermal properties of the magma and host rock are constant.

The initial conditions of the problem considered are:

$$T(z,0) = g\,Z \text{ for } Z < Z_1$$

$$T(z,0) = Ti \text{ for } Z_1 < Z < Z_2$$

$$T(z,0) = g\,Z \text{ for } Z > Z_2$$

The boundary condition is: T (0,t) = 0 at Z = 0

The starting point of this problem is the solution for heat conduction equation in a semi-infinite medium arising from perturbation of initial temperatures in a one-dimensional medium (Carslaw and Jaeger, 1959)

$$T(Z,t) = \frac{1}{\sqrt{4\pi\kappa t}} \int_0^\infty f(Z') \left[e^{-\frac{(Z-Z')^2}{4\kappa t}} - e^{-\frac{(Z+Z')^2}{4\kappa t}} \right] dZ' \quad (1)$$

Where T(z,t) is temperature at depth z at the instant t, κ the thermal diffusivity and f(z') the initial temperature distribution. The first term in equation (1) may be written as:

$$\int_0^\infty f(z') e^{-\frac{(z-z')^2}{4\kappa t}} dz' = \int_0^{Z_1} g\,z' e^{-\frac{(z-z')^2}{4\kappa t}} dz' + \int_{Z_1}^{Z_2} T_i\, e^{-\frac{(z-z')^2}{4\kappa t}} dz' + \int_{Z_2}^\infty g\,z' e^{-\frac{(z-z')^2}{4\kappa t}} dz' \quad (2)$$

In terms of the variable, $\xi = (z - z')/\sqrt{4\kappa t}$ the first integral on the right hand side of (2) may be written as:

$$\frac{1}{\sqrt{4\pi\kappa t}} \int_0^{Z_1} g\,z' e^{-\frac{(z-z')^2}{4\kappa t}} dz' = \frac{g}{\sqrt{4\pi\kappa t}} \int_{z/\sqrt{4\kappa t}}^{(z-z_1)/\sqrt{4\kappa t}} (z - \xi\sqrt{4\kappa t}) e^{-\xi^2} (-d\xi)\sqrt{4\kappa t}$$

$$= -\frac{g\,z}{\sqrt{\pi}} \int_{z/\sqrt{4\kappa t}}^{(z-z_1)/\sqrt{4\kappa t}} e^{-\xi^2} d\xi + \frac{g\sqrt{4\kappa t}}{\sqrt{\pi}} \int_{z/\sqrt{4\kappa t}}^{(z-z_1)/\sqrt{4\kappa t}} \xi\, e^{-\xi^2} d\xi$$

$$= \frac{g\,z}{2}\left[erf\left(\frac{z}{\sqrt{4\kappa t}}\right) - erf\left(\frac{z-z_1}{\sqrt{4\kappa t}}\right)\right] + \frac{g\sqrt{\kappa t}}{\sqrt{\pi}}\left[e^{-\frac{z^2}{4\kappa t}} - e^{-\frac{(z-z_1)^2}{4\kappa t}} \right] \quad (3)$$

Similarly, the 2nd and the 3rd integrals on the right hand side of (2) may be written as:

$$\frac{(T_i - T_0)}{2}\left[erf\left(\frac{z-z_1}{\sqrt{4\kappa t}}\right) - erf\left(\frac{z-z_2}{\sqrt{4\kappa t}}\right)\right] \quad (4)$$

$$\frac{g\,z}{2}\left[1 + erf\left(\frac{z-z_2}{\sqrt{4\kappa t}}\right)\right] + \frac{g\sqrt{\kappa t}}{\sqrt{\pi}}\left(e^{-\frac{(z-z_1^2)}{4\kappa t}} \right) \quad (5)$$

Thus, the result for the first integral of (1) is the sum of the terms in equations (3), (4) and (5). The terms of the second integral of (1) may be obtained in a similar manner. Hence, with the notation $\gamma = \sqrt{4\kappa t}$, the final solution may be written as:

$$T(Z,t)=gZ+\frac{gZ}{2}\left[erf\left(\frac{Z-Z_2}{\gamma}\right)-erf\left(\frac{Z-Z_1}{\gamma}\right)+erf\left(\frac{Z+Z_1}{\gamma}\right)-erf\left(\frac{Z+Z_2}{\gamma}\right)\right]$$
$$+g\sqrt{\frac{\kappa t}{\pi}}\left[e^{-\frac{(Z+Z_1)^2}{\gamma^2}}-e^{-\frac{(Z-Z_1)^2}{\gamma^2}}+e^{-\frac{(Z-Z_{21})^2}{\gamma^2}}-e^{-\frac{(Z+Z_2)^2}{\gamma^2}}\right]+ \tag{6}$$
$$\frac{(T_i-T_0)}{2}\left[erf\left(\frac{Z-Z_1}{\gamma}\right)+erf\left(\frac{Z+Z_1}{\gamma}\right)-erf\left(\frac{Z-Z_2}{\gamma}\right)-erf\left(\frac{Z+Z_2}{\gamma}\right)\right]$$

Results of Numerical Simulations

As an illustrative example of model results consider the results for a magma emplacement of 1km thick, occurring at a depth of 25km. The initial temperature of magma is 530 ^{0}C and the undisturbed gradient is approximately 20.4 ^{0}C/km. Figure (3) illustrates the distribution of resulting temperatures in the medium at times of 0.1 and 1 million years after the emplacement. Note that the perturbation leads to an asymmetric temperature distribution. The thickness of the layer with perturbed temperatures is higher in the medium above the emplaced magma, relative to that below the intrusion.

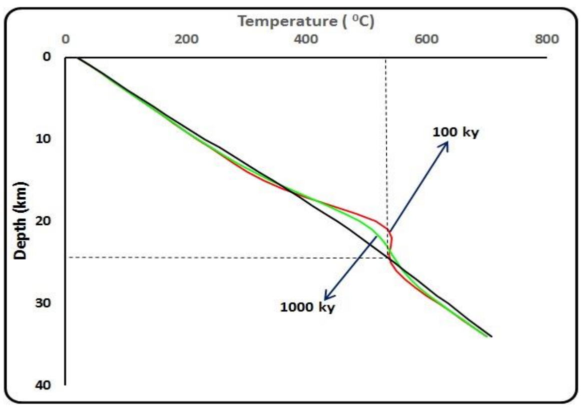

Figure (3) Results of numerical simulation of temperatures above and below magma intrusion considered in he example problem.

The distribution of perturbed temperatures at different times after the emplacement of magma is illustrated in Figure (4). Note that the magnitude of perturbation decreases rapidly with time but is significant over large distances in the medium above the emplaced magma.

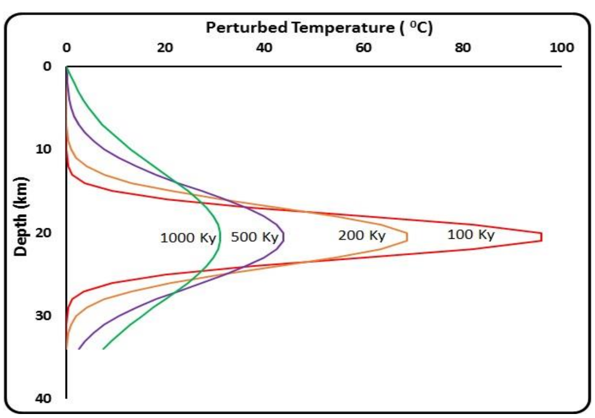

Figure (4) Distribution of perturbed temperatures, in the example problem.

As an illustrative example, we present in Figure 5 percentage variation in heat flux due to emplacement of magma at depths of 10 km, for the times of 200000, 400000 and one million years. Note that for the elapsed time of 200000 years significant positive perturbations in heat flux occur at depths less than 7km. At times greater than 400000 years the perturbation is relatively higher at depths less than 4km. For times greater than one million years the perturbations are positive for all depths less than 10km.

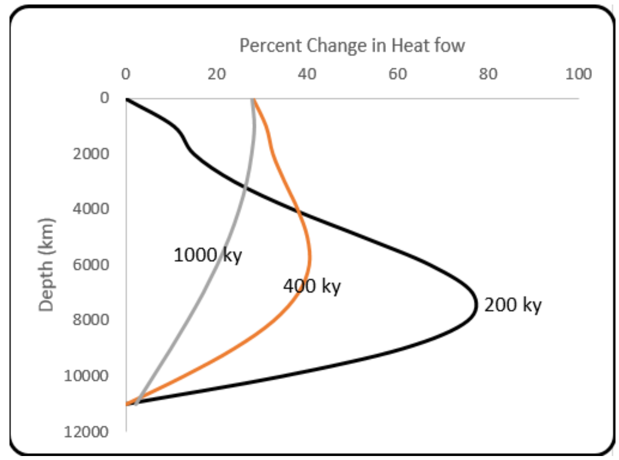

Figure (5) Percent perturbations in heat flow following magma intrusion at depth of 10km.

Origin of anomalous heat flow belt

Numerical simulations of magma emplacement episodes with at different depths and age values were carried out to select the model that best fit the observed heat flow anomaly. The results of model studies indicate that the origin of the anomalous geothermal belt is related to recent episodes of magma emplacement at depths of approximately 20km. The model results also indicate that the age of magma emplacement is no more than 2Ma.

It is important to point out that such magma emplacement need not necessarily give rise to intrusions in the upper crust. The ductile behaviour of heated mantle can allow for emplacement of magma beneath the crust as an under-plate, without giving rise to intrusives reaching upper crustal levels. Such a process may be envisaged as the end-member of the differential stretching process proposed by Royden and Keen (1980). In such cases, the crustal stretching becomes very small, while sub-crustal stretching accommodate most of the lateral flow of mantle.

Determination of Paleo Temperatures

We now consider application of the model discussed above for determination of the effects of magma emplacements on paleotemperatures within sedimentary rock formations. Note that results of model studies incorporate thermal effects of recent magma emplacements, superimposed on thermal consequences of previous crustal stretching events.

The procedure adopted starts with calculations of paleo heat flow and paleo temperatures. The relation for paleo heat flux, as per uniform stretching model of McKenzie (1978), is:

$$q_p(t) = \frac{\lambda T_m}{a}\left\{1 + 2\sum_{n=1}^{\infty}\left(\frac{\beta}{n\pi}\operatorname{sen}\frac{n\pi}{\beta}\right)e^{-n^2\left(\frac{t}{\tau}\right)}\right\} \qquad (7)$$

where λ is the thermal conductivity of basement rocks, a the thickness of the lithosphere, β the stretching factor, t the time elapsed after the initial stretching event, τ the thermal time constant of the lithosphere and T_m its basal temperature.

The temperatures during evolutionary history of the basin have been calculated using the relation:

$$T(z,t) = T_0 + \int_0^z Q(t) R_t(z,t)\,dz \qquad (8)$$

where T_0 is the surface temperature, Z the thickness of the layer under consideration, Q the heat flux at time t and R_t the thermal resistance of the layer at depth z and time t.

An example of including the thermal effects of magmatic events on paleotemperatures is illustrated in Figure (6), for the site of the well RJS-13. In this figure, the dashed curves (in blue color) indicate paleo isotherms for the range of 30 to 90ºC, at intervals of 20ºC. These are the isotherms for the case where the evolution of temperatures are determined exclusively by the stretching mechanism. The curves in red color indicate isotherms for the case where thermal effects of magma emplacement at depth of 20km is superimposed on that arising from stretching. The black lines indicate the sequences in the subsidence history of the main sedimentary formations (Emboré, Macaé, Lagoa Feia, Cabiúnas), reconstructed by back-stripping methods.

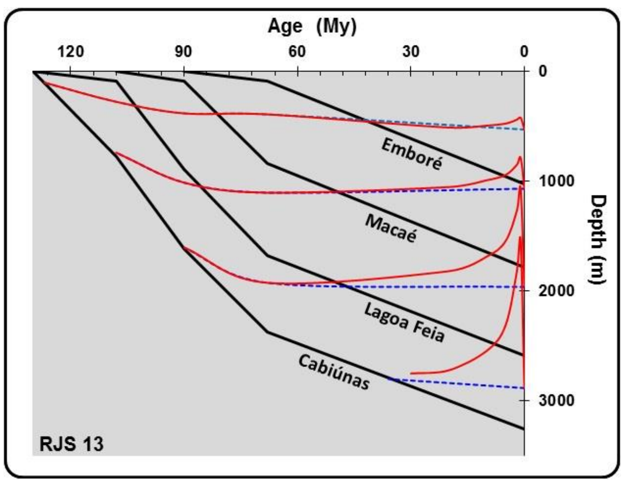

Figure (6): Paleo-temperatures at the site of well RJS-13 during the evolutionary history of the Campos basin.

A notable feature of the case illustrated in figure (6) is that it includes thermal effects of two distinct magma emplacement events. This has been achieved by superposition of temperature perturbations calculated using equations (6) and (7) for multiple thermal episodes. For the case illustrated in Figure (6) the first one is a short period perturbation arising from magma emplacement at depths of about 20km. This perturbation is capable of accounting for the presence of observed heat flow anomalies. Model results indicate that the age of this magma emplacement episode is no more than 2Ma. The second perturbation arises from a relatively long period episode. It is responsible for higher values of paleo temperatures, over the last 20 Ma. We conclude that maturity indices compatible with large-scale occurrences of oil deposits in Campos and Santos basins are possible only under the thermal effects of magma underplating that occurred in the last 20 Ma.

Conclusions

An analytical model has been used for estimating perturbations in heat flow arising from magma emplacements in the crust. It has been applied in understanding paleotemperatures in sedimentary rock formations of the Campos basin. The results have important implications in analysis of thermal maturation and oil generation in the Campos basin. According to results presented by Cardoso and Hamza (2014), the period of oil generation in this basin fall in the age range of 40 to 70Ma. However, their analysis did not take into consideration potential contribution of transient heat flow associated with recent magma emplacement at shallow crustal depths. Allowing for augmented heat flow produced by intrusions brings down the age of oil generation into much recent periods of 10 to 20Ma.

Acknowledgments

The second author is recipient of a post-graduate scholarship granted by CAPES.

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