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MATHEMATICAL MODELING APPLIED TO THE ANALYSIS OF MAGMATIC INTRUSIONS THERMAL INFLUENCE IN PARANÁ BASIN

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Abstract *- This paper has the objective to present equations capable of generating one-dimensional models that permit to quantify the thermal influence caused by igneous intrusions. In Paraná Basin, the petroleum systems were great influenced by igneous activities in which they are presented by a thick lava effusion, large number of dykes in the entire sedimentary section and various levels of sills intruded in stratifications to provide thermal energy for organic maturation. Thus, a better understanding of how and how much the intrusions affect the generation of oil and gas is extremely necessary since the knowledge related to the effects of intrusions in such atypical petroleum system is still insufficient. The obtained results show: the thermal influence caused by igneous intrusions is much higher than that proposed in the literature; the greater the number of intrusions and the thicker they are, the thermal influence is unfavorable at short distances and favorable at large distances.*

Keywords: *Thermal Modeling; Igneous Intrusions; Thermal Influence*

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1. INTRODUCTION

The Paraná Basin (Fig. 1) has an area of approximately 1.5 x 10^6 km^2 and is filled by a sedimentary package of sedimentary and magmatic rocks with a maximum total thickness around 7.000 m, with ages ranging from Silurian to Upper Cretaceous (Milani et al. 2007).

This basin is included in the intracratonic basins group that is classified as a new exploratory frontier in oil and gas industry nowadays. As an example, the existence of shale gas reserves in shales of Paraná Basin can be cited. These reserves of shale gas have been known for some time, but the subject has been widely discussed presently in front of technological advances that are making viable their exploration (Huguenin et al. 2009, Gomes 2011). Although it is little explored, if compared to the coastal basins, the Paraná Basin presents rocks in its statigraphic sequence that may have been able to generate hydrocarbons under the thermal contribution of igneous intrusions.

The thermal maturation caused by intrusions in source rocks varies with the distance and thickness of intrusions (Monreal et al. 2009, Daniels et al. 2014). Many papers establish a relationship between intrusions and their thermal influences (Zhao et al. 2003, Corrêa 2007, Fjeldskaar et al. 2008, Souza et al. 2008, Monreal et al. 2009, Valente et al. 2010, Fernandes 2011, Liu et al. 2012, Wang 2012 and Wang et al. 2012) and demonstrate how relevant are intrusions on maturity of organic matter.

Considering the scenario above it becomes necessary a quantitative approach of the issue, providing a better understanding of magmatic processes and their influence on petroleum systems appearing in the basin. Therefore, the use of analytical solutions of differential equations allowed to quantify thermal influence of intrusions and to delimit zones of hydrocarbon generation potential (Senger et al. 2017).

The main purpose of this paper is to demonstrate that mathematical modeling is an effective tool not only to comprehend the evaluation of the thermal influence of igneous intrusions in source rocks, but also to emphasize how relevant are the igneous intrusions on maturity of organic matter in atypical petroleum systems.

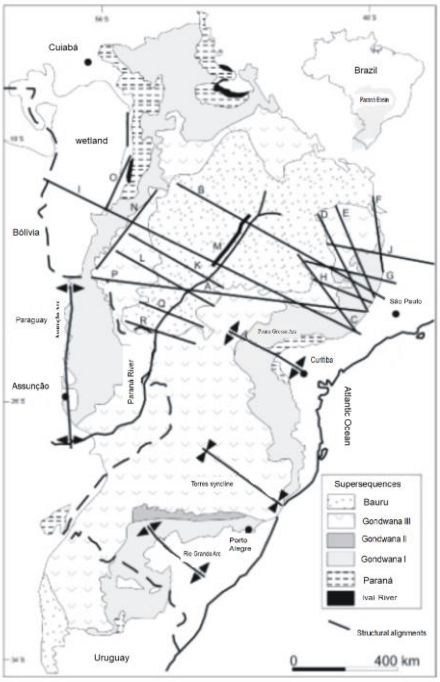

Figure 1. Geological map simplified of Paraná Basin with stratigraphic supersequences distribution (Milani e Ramos, 1998) and major structural lineaments (Sallun et al. 2007). A: Rio Paranapanema; B: Rio Tietê; C: Ibitinga-Botucatu; D: Rio Mogi-Guaçu; E: Ribeirão Preto-Campinas; F: Rifaína-São João da Boa Vista; G: São Carlos- Leme; H: Barra Bonita-Itu; I: Guapiara; J: Cabo Frio; K: São Gerônimo-Curiúva; L: Paranapanema; M: Sutura Crustal de Três Lagoas; N: Serra de Maracaju; O: Sutura Crustal de Coxim; P: Rio Alonzo; Q: Amambaí- Ribeirão do Veado; e R: Rio Piriqui.

2. THEORETICAL FUNDAMENTATION

The Paraná Basin is considered a cool basin, or a basin where only flexural subsidence was not enough for temperatures to reach the window of maturation of organic matter (Thomaz Filho 2008). Igneous intrusions are pointed out as the main supplier of the thermal energy that causes the maturation of organic matter in potential hydrocarbon-generating rocks (Wang et al. 2010).

Fjeldskaar et al. (2008) introduce a model where the effect of maturity, considering the heat coming from the intrusion, is considerably higher.

Magmatism in the Paraná Basin is present in several places in the stratigraphic sequence, mainly as dikes or sills. Neumann et al. (2003) define dike as tabular discordant intrusions that cut the geological layers and are commonly sub-vertical, while the sills are igneous intrusions parallel to the geological layers and are commonly sub-horizontal. Magmatic intrusions of different types are observed in nature such as dikes, sills, batholith, laccolith, lopolith (Holmes 1964, Neumann et al. 2003, Dutra 2006). However, in this paper, the tabular intrusions will only be considered for modeling.

The heat transfer can occur by conduction, convection or radiation. As conduction is a dominant process in the lithosphere (Turcotte & Schubert 2002), this heat transfer mechanism is used in the modeling proposed as the main form in which heat is transferred from the intrusion to the host rocks.

The relation for the mechanism of transfer of heat conduction is given by Fourier's law Eq. (1) which empirically admits that the heat flow Q is directly proportional to the temperature gradient (Allen & Allen 2004). The equation is presented as follows:

$$Q = -K\frac{dT}{dy}, \qquad (1)$$

where K is the thermal conductivity coefficient, T is the temperature at a given point and y is the coordinate in the direction of analisys.

The ratio of heat loss and gain of a lithosphere element is represented by the heat equation, Eq. (2):

$$\frac{dT}{dy} = \frac{K}{\rho c}\frac{d^2T}{dy^2} + \frac{A}{\rho c} - u_y\frac{dT}{dy}, \qquad (2)$$

where K is the thermal conductivity coefficient, ρ is the density, c is the heat capacity, A is the heat generation, u_y is the advective term, T is the temperature at a given point and y is the coordinate where temperature varies.

For a better understanding of the relationship of heat input of igneous intrusions in the host rocks is possible to use mathematical modeling. This is the mathematical description of a real-world phenomenon. The purpose of these models is to understand the phenomenon, thus allowing the realization of prognostics about their future behavior (Stewart 2011). There are several types of models proposed in the literature that can be used for the analysis of thermal effects (Carslaw & Jaeger 1959, Stüwe 2002, Zhao et al. 2003, Corrêa 2007, Fjeldskaar et al. 2008, Monreal et al. 2009, Aarnes et al. 2010, Valente et al. 2010, Fernandes 2011, Oliveira et al. 2012 and Wang et al. 2012).

Many studies use numerical methods for detailed solutions since they allow to obtain a result without the needing of analytically solving a differential equation (Zhao et al. 2003, Corrêa 2007, Monreal et al. 2009 and Wang et al. 2012). However, the numerical solutions are only approximations of the results, and even if they allow the accuracy of the models to be always improved, this requires time to be implemented. Although analytical solutions require knowledge of differential calculus to obtain the solution of differential equations, they are the best solutions for a first approximation in trying to understand the nature of geological problems

3. METODOLOGY

In order to quantitatively analyze the thermal influence of magmatism in the host rocks, analytical solutions of differential equations have been used in the present study. The mathematical solutions and parameters used are described below.

3.1 Parametrization

Before entering the modeling, itself it is necessary to define what parameters were used in the models and specify the considerations and simplifications that were made.

The necessary considerations for the use of the proposed solutions are: 1) The shape of the intrusion must be regular; 2) Movements of convection in the intrusion and the latent heat of crystallization of the magma were not considered; 3) Heat loss due to escaping fluid, decarbonisation and dehydration are neglected; 4) There is no difference between the parameters of the intrusion and the host rock; 5) The transformation of organic matter into hydrocarbon occurs.

The parameters used in the models were: 1) The initial temperature of the intrusion in the modeling is 1200°C and the host rocks is considered to 0°C because of the notable temperature contrast between intrusion and host rocks, 2) The oil window, ranging from 60°C to 120°C and gas window ranging from 120°C to 220°C (Thomas, 2004), considering a geothermal gradient about 25°C / km, 3) is used a singlevalue for the thermal diffusivity constant (=10-6m2/s), which is equivalent for continental crust. So, the diffusivity of intrusive rock is considered equal to the host rock, 4) the thickness of the intrusions used were taken from Table 1.

3.2 Solutions

One of the solutions proposed by this article aims to develop an one-dimensional model, where the domain is not limited. This solution and its respective development will be shown in detail in supplementary files[LINK] of this scientific paper.

Using such solutions, it has become possible to construct 1D thermal models (using Eqs. 13, 36, 37 and 38 in supplementary files LINK] between the intrusions and the host rocks. The use of MATLAB computer package allowed the construction of these models that provide graphical solutions for temperature and distance, using time and thickness of the intrusion as variables. Thus, it becomes possible to examine the heat flux associated with this intrusion into the host rocks. The data generated by thermal influences presented solutions which allow us to discuss the ways that igneous intrusions influence in the generation of hydrocarbons in the petroleum system.

4. RESULTS AND DISCUSSIONS

Using the parameters and considerations previously defined and the mentioned above solutions, models were generated to assist in understanding of how the intrusions thermally affect the host rocks. Consequently, these data would permit a better comprehension of the atypical petroleum systems.

A model was generated (Fig. 2), using Eq. (13) to the thickness of 10 m withdrawn of Table 1. Based on Fig. 2, it is noticeable that:

- The area where the destruction of organic matter occurs is about 6.7 meters from the contact of the intrusion with the host rock.
- The potential zone for gas generation is about 13 meters.
- The potential zone for the generation of oil is about 14 meters.
- The thermal influence caused by the intrusion reaches a distance greater than 150 meters.
- The intrusion does not influence the host rock thermally, to the point that it reaches the temperature of the oil and gas windows considered, after 100 years. However, more time is needed so that the intrusion is in thermal equilibrium with the host rock.

It is suggested the use of Eq. (13) for cases where the desired information is only the thermal influence caused by intrusion into host rock since intrusions are small compared with its surroundings. For example, the thickness of the intrusion is smaller than the distance all the way to the surface or to the bottom of the lithosphere. So, the utilization of the boundary conditions in this equation, ranging from -∞ to +∞ is appropriate (Stüwe 2002). What happens beyond the chosen segment of the domain (in the case of Fig. 2) from – 200 to -200 meters does not matter. The Figu. 3 shows a second model generated using Eq. (36) using the same input parameters except for the intrusion thickness, which is 10 meters. This thickness was taken from the values compiled in Table 1.

Table 1. Table containing data compiled with values of thicknesses of intrusions in the Paraná Basin according to the authors: 1) Massoli (1981) 2) Raposo (1995) 3) Maniesi & Oliveira (1997) 4) Romanini (2000) 5) Machado et al. (2005) 6) Valente et al. (2010) 7) Machado (2012).

Type of intrusion	Thickness (m)	Reference	Type of intrusion	Thickness (m)	Reference	Type of intrusion	Thickness (m)	Reference
Sill	60	1	Dike	0.3	2	Dike	40	2
Sill	60	1	Dike	5	2	Dike	20	2
Dike	100	2	Dike	30	2	Dike	60	2
Dike	70	2	Dike	20	2	Dike	70	2
Dike	500	2	Dike	100	2	Dike	150	2
Dike	200	2	Dike	80	2	Dike	100	2
Dike	40	2	Dike	20	2	Dike	80	2
Dike	300	2	Dike	10	2	Dike	10	2
Dike	20	2	Dike	20	2	Sill	200	3
Dike	50	2	Dike	10	2	Sill	100	3
Dike	150	2	Dike	100	2	Sill	2 -200	4
Dike	50	2	Dike	80	2	Sill	20 – 50	4
Dike	20	2	Dike	30	2	Sill	80	4
Dike	100	2	Dike	10	2	Sill	27.4 -136.8	4
Dike	100	2	Dike	20	2	Sill	60 – 140	4
Dike	30	2	Dike	4	2	Sill	8 – 15	4
Dike	50	2	Dike	10	2	Sill	100	4
Dike	150	2	Dike	50	2	Sill	90 -110	4
Dike	30	2	Dike	200	2	Sill	100	4
Dike	20	2	Dike	100	2	Dike	500	4
Dike	100	2	Dike	30	2	Dike	150	4
Dike	100	2	Dike	100	2	Dike	20	4
Dike	50	2	Dike	3	2	Dike	60	4
Dike	20	2	Dike	10	2	Sill	180	5
Dike	50	2	Dike	100	2	Sill	250	5
Dike	10	2	Dike	15	2	Sill	200	5
Dike	30	2	Dike	50	2	Sill	120	5
Dike	40	2	Dike	100	2	Sill	80	5
Dike	100	2	Dike	70	2	Sill	230	5
Dike	30	2	Dike	50	2	Sill	280	5
Dike	40	2	Dike	30	2	Sill	300	5
Dike	50	2	Dike	40	2	Sill	73	5
Dike	30	2	Dike	40	2	Dike	7	6
Dike	50	2	Dike	20	2	Dike	200	7
Dike	100	2	Dike	120	2	Dike	80	7

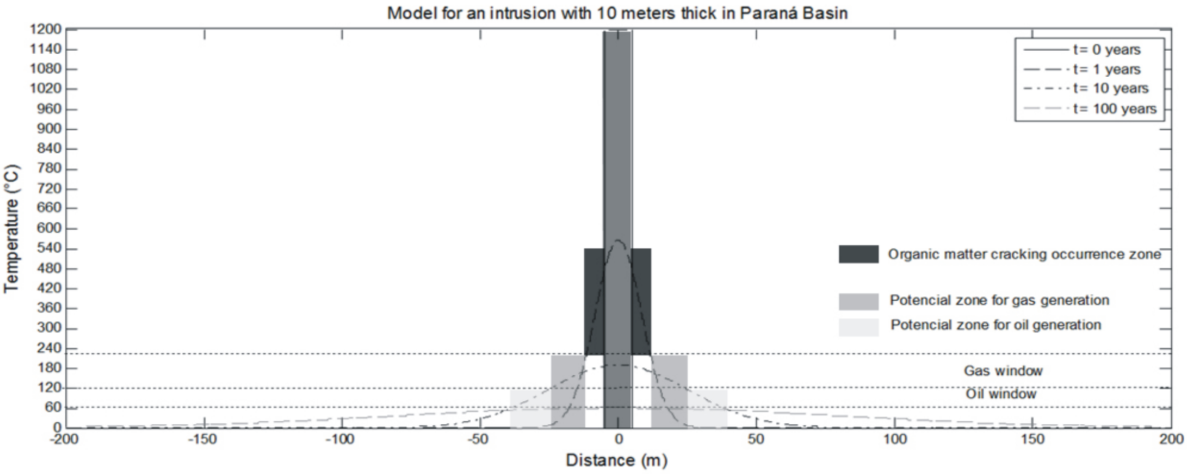

Figure 2. Thermal model for an intrusion with 10 meters thick. The dark gray area in the center of the model represents the intrusion. The value of this intrusion thickness was withdrawn from Table 1.

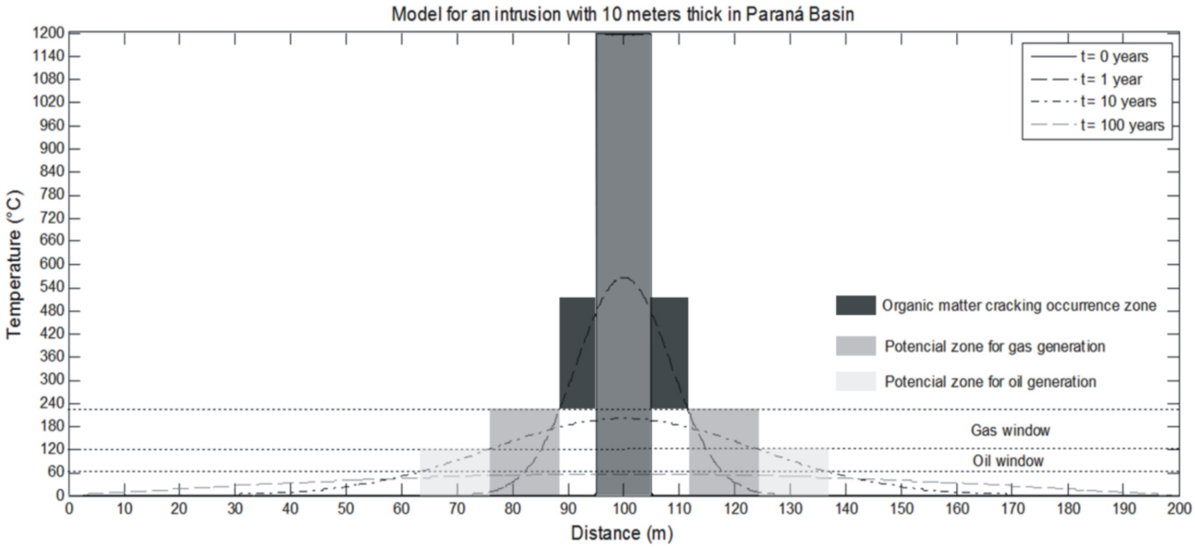

Figure 3. Thermal model for an intrusion of 10 m thick using equation (36) with j= 1000 and h= 100. The dark gray area in the center of the model represents the intrusion. The value of this intrusion thickness was withdrawn from Table 1.

Based on Fig. 3, it can be observed that:

- The area where the burning of organic matter occurs is about 6.7 meters from the contact of the intrusion with the host rock.
- The potential zone for gas generation is about 13 meters.
- The potential zone for the generation of oil is about 14 meters.
- The thermal influence caused by the intrusion reaches a distance greater than 190 meters.
- The intrusion does not influence the host rock thermally, to the point that it reaches the temperature of the oil and gas windows considered, after 100 years. However, more time is needed so that the intrusion is on thermal equilibrium with the host rock.

Eq. (36), due to the boundary conditions, limits the thermal influence of the intrusion only in the domain considered (from 0 to 200 in Fig. 3). This equation can be applied to a case where an intrusion is in a layer of known dimensions and when the information to be obtained is only the thermal influence in this layer. The maximum distance that the intrusion thermally affects the host rock cannot be obtained by the Eq. (36) as the temperature at distances 0 and 2h were defined to be 0. However, this does not affect the accuracy of the solution since it presents results equal to the solution using Eq. (13), where the boundary conditions are assumed to infinity.

A third model was generated (Fig. 4) using Eq. (37) with the same thickness of 10 meters withdrawn from Table 1.

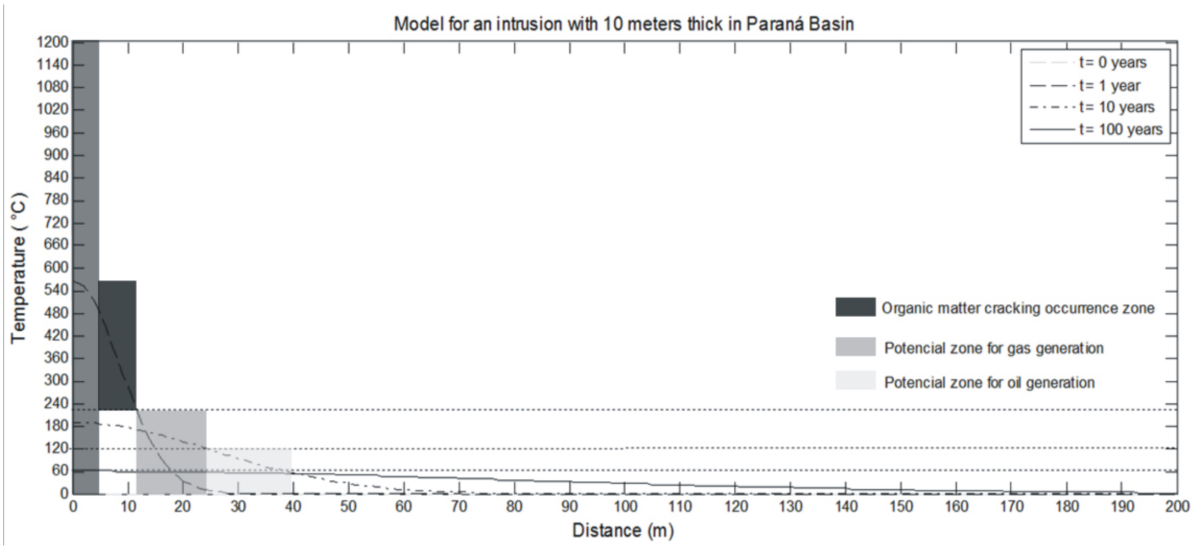

Figure 4. Thermal model for an intrusion with 10 meters thick. The dark gray area on the left side is half the thickness of the intrusion. The value of this intrusion thickness was withdrawn from Table 1.

Based on Fig. 4, we note that:

- The area where the burning of organic matter occurs is about 6.7 meters from the contact of the intrusion with the host rock.
- The potential zone for gas generation is about 13 meters.
- The potential zone for the generation of oil is about 14 meters.
- The thermal influence caused by the intrusion reaches a distance greater than 190 meters.
- The intrusion does not influence the host rock thermally, to the point that it reaches the temperature of the oil and gas windows considered, after 100 years. However, more time is needed so that the intrusion is in thermal equilibrium with the host rock.

Eq. (37) was proposed by Carslaw & Jaeger (1959) to solve the problem of latent heat released by the crystallization of magma (376 kJ / kg according to (Wang 2012). To account for this additional heat in the model and obtain a cooling rate closer to the real,   may be replaced by (T0 +) the initial temperature of the melt, where L is the latent heat of melting / crystallization and   the thermal capacity of the magma. In this case, the surface solidification migrates over time toward the center of the sill, where there is still magma (Corrêa 2007). However, the latent heat released by the crystallization of magma was not considered in this modeling.

As expected, the results generated by the Eqs. (13), (36) and (37) are equal. However, the approach suggested for each of the different solutions is due as much to mathematics as geological limitations.

Using Eq. (38), it is possible to model a case in which two intrusions are in the same domain (Fig. 5).

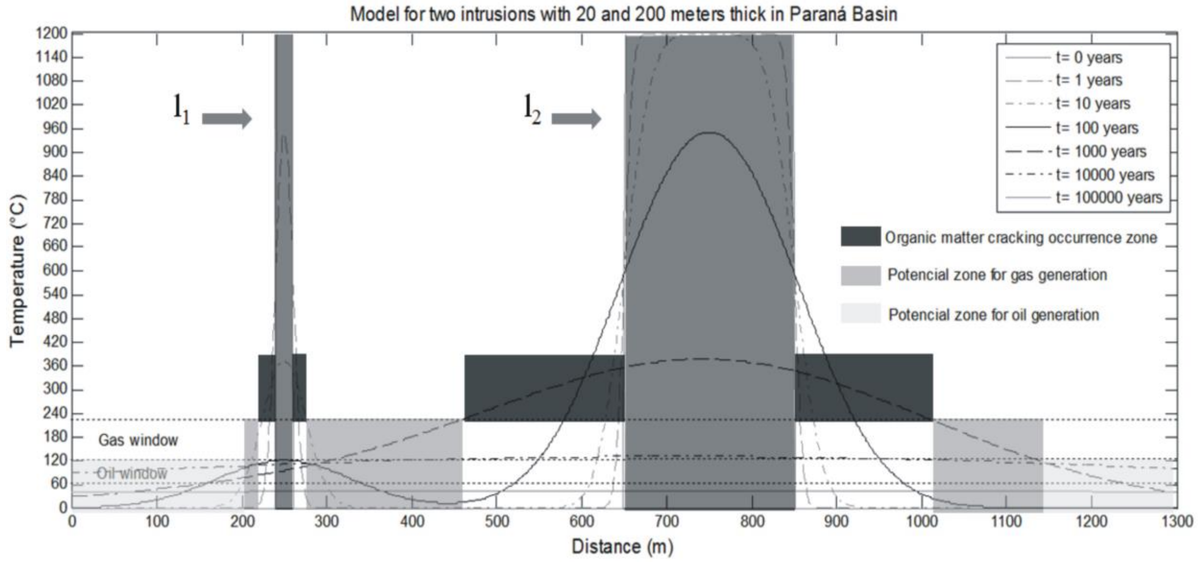

Figure 5. Thermal model for two intrusions 20 (l1) and 200 (l2) feet thick located at 250(z1) and 750(z2) in the domain. The value of this intrusion thickness was withdrawn from Table 1.

Based on Fig. 5, it is noticeable that:

- The zone in which the burning of organic matter occurs for the intrusions with 200 meters and 20 meters is approximately 165 meters and 17 meters respectively. The zone is calculated from the contact of the intrusion with the host rock.
- The potential zone for generating gas in case of the intrusion of 200 meters, on the right, is about 120 meters. For the intrusion of 20 meters, the potential area for gas generation, at the left side of the intrusion, is about 12 meters. Among the intrusions, the potential zone for gas generation is about 178 meters. The temperatures in the host rock between the intrusions are higher due to the thermal influence of both intrusions.
- The potentials zones for the generation of oil occur in the horizontal axis from 0 to 212 meters and after 1135 meters. There is no potential oil zone between the intrusions due to the high temperatures resulting from the thermal influence of both intrusions.
- Analyzing the potential zones is remarkable that the non-occurrence zone with potential to generate oil between the intrusions is due to the high temperatures in rocks. These temperatures are caused by the sum of the thermal effects of both intrusions in the area.
- The thermal influence caused by the intrusions reaches a distance greater than 240 meters from the left contact of the intrusion with 20 meters of thickness (l1) and 450 meters from the right contact of 200 meters intrusions (l2).
- The curve of 1000 years shows that the heat flux from both intrusions are being added as the temperature in the region between the intrusions is higher than in the region outside the group intrusions
- The intrusion does not influence thermally the host rock until the point it reaches the temperature of the oil and gas windows considered, after 100,000 years. However, more time is needed for the intrusion to reach the thermal equilibrium with the host rock.

Raposo (1995) provides data containing thicknesses, coordinates (latitude and longitude) and direction of various structural intrusions in Ponta Grossa Arch in the Paraná Basin. It was built a hypothetical thermal model (Fig. 6) to three intrusions of 30, 100 and 30 meters thick with same structural direction. The intrusions l1, l2 e l3 were considered parallel to each other so that the Eq. (38) can be used.

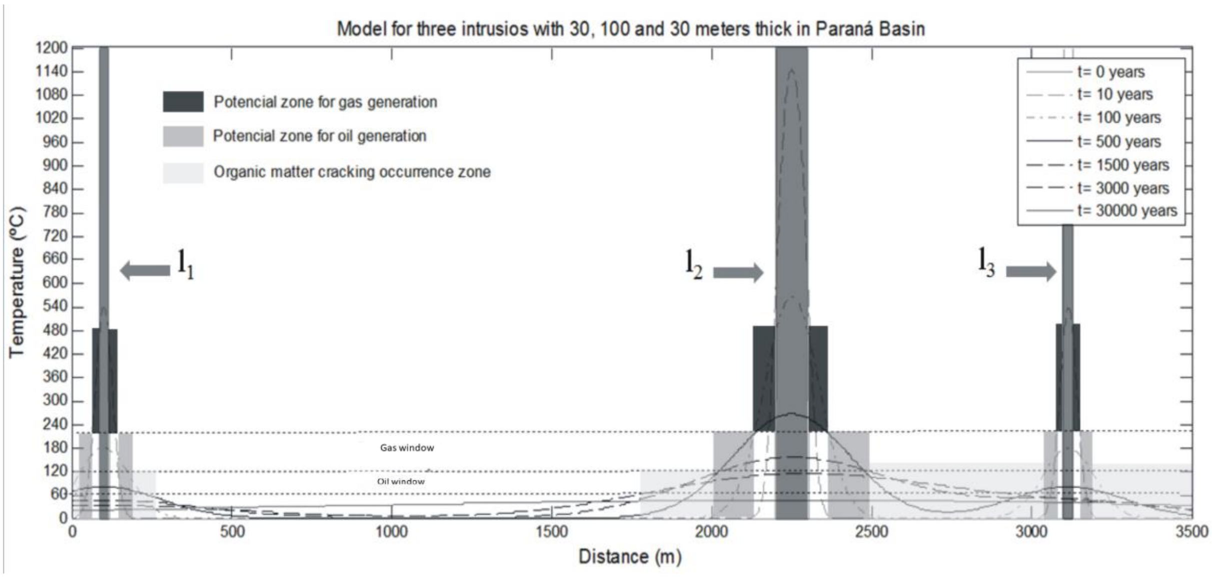

Figure 6. Thermal model for three intrusions: l1 with 30 meters thick located on value 100(z1) of the domain; l2 with 100 meters thick located on value 2250(z2) of the domain; l3 com 30 meters thick located on value 3114(z3) of the domain. The value of this intrusion thickness was withdrawn from Table 1.

Analyzing the model presented in Fig. 6 it is observed that small distance between intrusions l2 and l3 subjects the rock to a temperature range favorable for hydrocarbon generation considering the defined oil and gas window.The prone zones to gas generation, for l1, occur from 136 to 175 meters and from175 to 221 meters to oil. The gas zones occur from 2022 to 2135 meters and from 2360 to 2485 meters. In the case of oil, the zones to l2, vary from1835 to 2022 meters and from 2485 to 2860 meters. In l3, the prone zones to gas ranges from 3040 to 3079 meters and from 3150 to 3185 meters, while the prone zones to generate oil is from 3185 to 3235 meters and from 3000 to 3040 meters.

When using the Eq. (38), a particular attention is required to the distance between the intrusions. The region between the intrusions l2 and l3, in Fig. 6, has prone zones to the generation of gas and oil. However, if these intrusions were closer, temperatures would be higher due to the sum of the thermal influences.

Another model (Fig. 7) was generated for an intrusion of 27.2 m thick, located in Irati Formation using the Eq. (13) and comparing with the profile of vitrinite reflectance near an intrusion (the same thickness) in a well. The profile data of the vitrinite reflectance were obtained from Souza et al. (2008).

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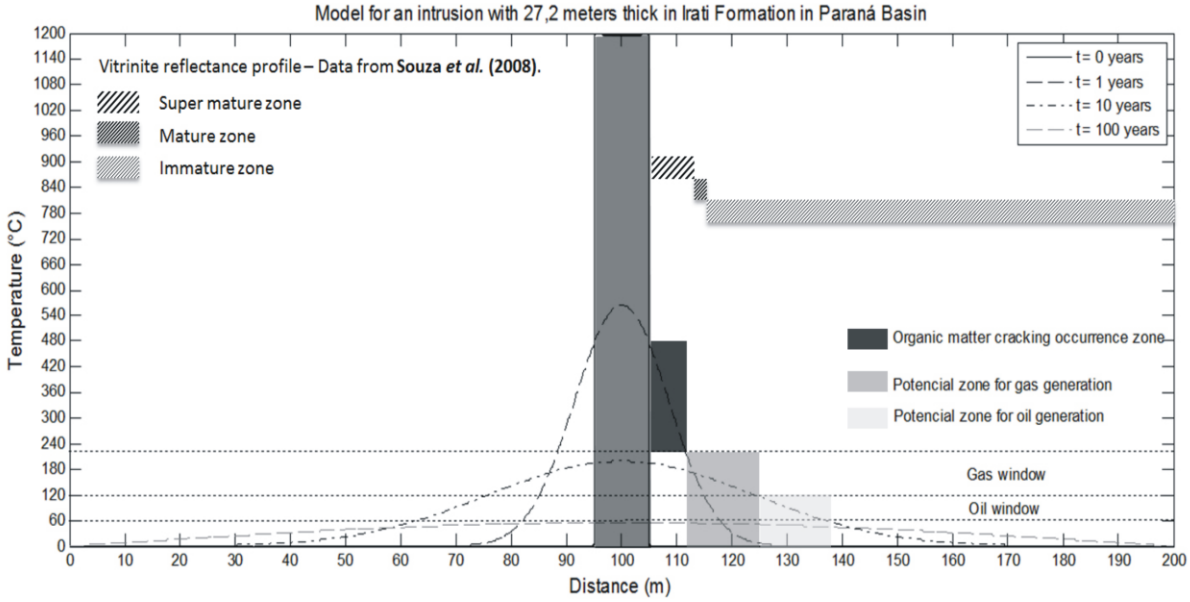

Figure 7. Thermal model to an intrusion 27.2 m thick using equation (13). The dark gray area in the center of the model represents the intrusion. The value of the thickness of the intrusion was withdrawn Souza et al. (2008).

Analyzing Fig. 7 you can see that supermature and mature zone, with 14.4 meters and 4.4 meters respectively, defined based on data obtained by Souza et al. (2008) is much lower compared with areas proposed by the thermal model that utilizes the Eq. (13). In the latter case, the area where the organic matter burns present 20.4 meters and potential zone to generate hydrocarbons is 78 meters.

The thermal profile generated using Eq. (13) defines potential areas for generating hydrocarbons (19.5 times) and place that burning of organic matter (1.41 times) higher than that proposed by the vitrinite reflectance profile.

It is noteworthy, however, that many parameters were not considered in the modeling to facilitate the obtaining of mathematical solutions, and this can affect the results. Wang (2012) said that neglecting the latent heat of crystallization of the magma and does not vary the parameters in space (for example, the specific heat for each type of rock) is underestimate the effect that the heat intrusions cause the host rocks. Pepper & Corvi (1995) and Pepper & Dodd (1995) apply a type of modeling using kinetic chemical reactions and demonstrate its importance in the generation of oil and gas. Wang et al. (2012) analyze the effects of evaporation of water in the pores, dehydration and decarbonization in the modeling. It is very likely that the use of the parameters increase the accuracy of the models proposed here.

5. CONCLUSIONS

Mathematical modeling is a great alternative when the intention is to represent a geological environment. This reality consists of several parameters that must be considered, which this environment becomes very complex. The use of all parameters that make up the geological environment will increase the accuracy of the models. However, the inclusion of all factors that influence or are derived from this thermal influence process into a mathematical equation in the form of variables or constants is very complicated. Therefore, some simplifications are necessary and even essential for a better understanding of the problem.

The models created by the Eqs. (13, 36, 37 and 38) show temperature profiles regarding the heat transfer the intrusions (i.e, dikes, and sills) cause to the host rocks. The fundamental difference between the models is the way of approaching the problem. This article has focused, through modeling, the use of thermal profiles to define potential areas for the generation of oil and gas, but there are no impediments that the same technique can be used in mining, as well as the delineation of contact metamorphism aureoles among other applications.

The solution using the Eq. (13) considers a source, in which case it is the center of the intrusion, located in the center of the model. The domain is not limited, as there is no interest in what happens in it. There is nothing to limit the heat to reach its maximum distance, i.e., the boundary conditions vary from -∞ to +∞. The use of this type of model is recommended when the interest of geological study is only the thermal influence caused by the intrusion.

In the solution using the Eq. (36), the thermal profiles represent the homogeneous distribution of heat in a limited range from the center of the intrusion by a distance h on each side of the same. The values of h have a certain influence on how the temperature is distributed. Therefore, in actual cases the values of h must be respected. The use of this model brings better results in localized cases in which the intrusions are slightly thick and are in a layer of known dimensions, thus permitting the delimitation of h.

Eq. (37) yields a solution that shows the same results that using the equations (13) and (36) but allows the implementation of the thermal influence of the latent heat of crystallization of the magma. The results obtained considering multiple intrusions (Eq. (38)) are: the thermal influence caused by multiple igneous intrusions is much higher than the thermal influence of one intrusion, so the intrusions cannot be individually modeled; the presence of multiple intrusions, based on the oil and gas window considered and as a function of it thickness, causes between them, unfavorable thermal influence to the generation of hydrocarbons in small distances and favorable thermal influence in large distances; Potential zones for hydrocarbons often occur outside of the group of intrusions; much more time is needed for the intrusions to reach the thermal equilibrium with the host rock when they are modeled in same domain.

Thermal profiles show that thermal influences caused by intrusions in host rocks reach greater distances to the widespread value of twice the thickness of the intrusion greater distances to the widespread value of twice the thickness of the intrusion (Dow 1977). The models in question are one-dimensional and do not take into account many factors related to the timing of organic matter or the evolutionary process of the basin where the intrusion is located.

These are some factors that can justify the fact that the thermal profile generated using Eq. (13) defines potential areas of hydrocarbon generation and places the organic matter burning above that proposed by the vitrinite reflection profile compiled by Souza et al. (2008). Although it does not accurately indicate the zones, for a simple equation it is possible to identify the region of interest to be investigated at a higher level of detail.

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