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Special Edition

Conductional heat transfer in magmatic intrusions

Transferência de calor por condução em intrusões magmáticas

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ABSTRACT

The thermal effect that occurs due to the insertion of igneous intrusions in sedimentary basins has been widely investigated in different geological contexts, either to obtain more precise information about the development of the basin and or for the purpose of exploring and evaluating the mineral resources existing there. We can verify that the knowledge of the thermal gradient is fundamental in studies of heat distribution through means such as the Earth's crust or mantle, as this way, we obtain the thermal evolution of magmatic intrusions and adjacent rocks over geological time. For the present work, the determination of the temperature gradient and consequently the thermal evolution of a 13-meter-thick sill and adjacent rocks located in the Paraná Basin - Irati Formation, was obtained through the use of the one-dimensional heat dispersion model in transient regime of finite time, in which, in the spatial variable the numerical method of finite differences (FDM) is used and in the temporal variable the Euler method. Although in cases of large and thick magmatic bodies or sections that include the terrestrial lithospheric and asthenospheric mantles, the mechanism of convection and radiation has an expressive role in the energy transfer process. However, in most geological situations, conduction is the most important mechanism in the heat distribution process.

Keywords: Conduction, Transference, Heat, Sill, Paraná

RESUMO

O efeito térmico que ocorre diante da inserção de intrusões ígneas nas bacias sedimentares tem sido amplamente investigado em diferentes contextos geológicos, seja para obter informações mais precisas sobre o desenvolvimento da bacia e ou para fins de exploração e avaliação de recursos minerais ali existentes. Podemos constatar que o conhecimento do gradiente térmico é fundamental nos estudos de distribuição de calor através de meios como a crosta ou manto terrestre, pois assim, obtemos a evolução térmica das intrusões magmáticas e das rochas adjacentes ao longo do tempo geológico. Para o presente trabalho a determinação do gradiente de temperatura e consequentemente a evolução térmica de uma soleira de 13 metros de espessura e das rochas adjacentes localizada na Bacia do

Paraná – Formação Irati, foi obtida através do emprego do modelo de dispersão de calor por condução unidimensional em regime transiente de tempo finito, em que, na variável espacial é empregado o método numérico de diferenças finitas (MDF) e na variável temporal o método de Euler. Apesar de em casos de grandes e espessos corpos magmáticos ou de seções que incluem os mantos litosférico e astenosférico terrestres, o mecanismo de convecção e radiação possui um expressivo papel no processo de transferência de energia. Entretanto, na maioria das situações geológicas, a condução é o mais importante mecanismo no processo de distribuição de calor.

Palavras-chave: Condução, Transferência, Calor, Soleira, Paraná

1 INTRODUCTION

The thermal effect caused by igneous intrusions in adjacent rocks has been widely investigated in different geological scenarios. Knowing the temperature gradient is essential for the development of mathematical models of heat flux obtaining as a result the thermal evolution of the medium. The present work presents the thermal evolution of a sill and adjacent rocks through a mathematical model of one-dimensional heat conduction in a transient regime, where the spatial and temporal variables are manipulated by different numerical methods, the finite difference (position) and midpoint method (time) methods. The parameters used were taken from Wang et al. (2012) in which the object of study was a sill of 13 meters thick with adjacent limestone rocks from the Permian Irati Formation, located in the Paraná Basin in South America, which represents the last geological period of the Paleozoic Era - Permian, which extends from 298.90 ± 0.15 to 252.17 ± 0.06 million years ago.

It is worth mentioning that the economic potential that an igneous intrusion can generate in a sedimentary basin is vast, specially in formations like Irati Formation, which is basically formed by shales and limestones rich in organic matter. These structures are initially immature under normal conditions of burial, and the influence of the heat emitted by the magmatic intrusion to the other rocks causes the maturation of these rocks, yielding the generation of oil and gas.

The isotopic geochemistry studies carried out by Santos et al. (2003) showed that, for the Irati Formation, there is a limited geochemical interaction between sills and host rocks, and concluded that heat transfer from sills to shales and limestones of the permian unit is preferably done by conduction.

In this paper we present a heat conduction model to be applied in the Irati Formation, together with a methodology and results in comparison with Wang et al. (2012). We used the traditional heat equation considering effects of solidification of magma, and the space-time results are obtained using the finite difference and midpoint methods.

1.1 Geological context

The Paraná Basin is an intracratonic basin located in the central-eastern portion of South America (Figure 1). It has an oval shape, with major north-south semi-axis, and its current outline is defined by erosional limits largely related to the Meso-Cenozoic geotectonic continent history (Milani et al., 2007). Filled with sedimentary and volcanic rocks from the Ordovician Period (488 to 443 million years) to the Createaceous Period (145 to 66 million years), it shelters in its depocenter a sedimentary-magmatic package of the order of 7000 meters thick, including some horizons with characteristics of source rocks and others with reservoir attributes. The basin extends over an area of approximately 1 500 000 km^2, of which 1 100 000 km^2 are located in the Brazilian territory, covering the states of Rio Grande do Sul, Santa Catarina, Paraná, São Paulo, Goiás, Mato Grosso do Sul and Mato Grosso; and 300 000 km^2 in Paraguay, Uruguay and Argentina (Zálan et al., 1990).

The tectonostratigraphic record suggests the interaction of orogenic phenomena on the edges of the South American plate, with epirogenic events marked by epochs of subsidence, uplift and magmatism in the interior of the plate (Milani and Ramos, 1998).

According to Zálan et al. (1990), the set of sedimentary and volcanic rocks that fill the basin represents the superposition of packages deposited, at least, in three different tectonic environments resulting from the plate dynamics that led to the evolution of Gondwana.

The study area of the present work is located in the Gondwana I supersequence, in the Step Two Group in the Irati Formation. In Brazilian territory, the Irati Formation has the shape of a large "S", and it appears in the states of Rio Grande do Sul, Santa

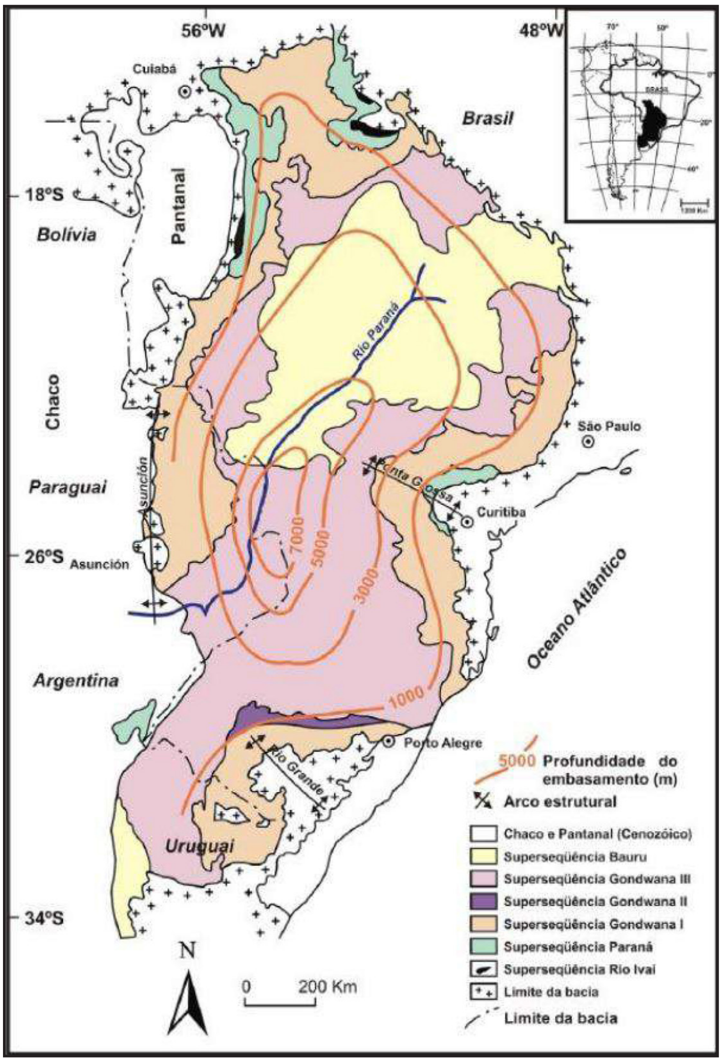
Catarina, Paraná, São Paulo, and Goiás, in which it extends for approximately 1700 km (Padula, 1969).

According to Schneider et al. (1974), the Irati Formation (Permian) is divided into two members, from base to top: Taquaral and Assistência members; considered consistent from the crustacean fauna (Barbosa and Gomes, 1958), whose sediments were deposited in restricted sea conditions, progressively more saline from the base to the top (Milani et al., 1994).

The Taquaral Member is formed by light gray pelites deposited on a silexitic basal conglomerate. This conglomerate demonstrates an important erosional unconformity, which marks the beginning of the sedimentation of the Irati Formation. The upper member, Assistência, is characterized by black shales and cream and dark limestone, containing flint and pyrobitumen, in which its lithological and sedimentary characteristics suggest deposition in a marine environment of shallow waters, presenting restrictions that created conditions of low oxygenation for the deposition of pyrobituminous shales associated with limestone.

Thus, like other units of the Paraná Basin, this formation harbors post-Triassic igneous bodies of basic and subsidy alkaline rocks (Gomes, 1959). It is estimated that approximately 70% of the area of the Irati Formation is intruded by sills, which vary from a few meters to about 200 meters (Petri and Fúlfaro, 1983). The relevance of igneous intrusions in sedimentary sequences bearing organic matter lies as in the increase in temperature, which influences the degree of maturation of organic matter (Araújo et al., 2000), as in the migration of fluids (Sant'anna et al., 2006) and in the formation of traps for hydrocarbons (Eiras and Wanderley Filho, 2003).

Figure 1 – Simplified geological map of the Paraná Basin, with geographic references and basement depth



Source: Milani (1997)

2 MODEL AND METHODOLOGY

Here we present the mathematical modelling of heat conduction in Irati Formation considering a magmatic intrusion and the computational implementation of the methodology we used to obtain the temperature profile in time.

2.1 Simulation case

The case discussed in the present work deals with a basic sill with 13 meters of thickness located in the Paraná Basin – Irati Formation, from 1667 to 1680 meters depth, derived from Wang et al. (2012). The thermophysical parameters used are all listed in Table 1.

2.2 Heat conduction model

Heat transfer models have been widely used in reconstructing the thermal evolution of magmatic intrusions and adjacent rocks in sedimentary basins (Fjeldskaar et al., 2008; Wang et al., 2011b). One-dimensional heat transfer models are the most popular for the evaluation of the thermal effects of igneous intrusions (Santos et al., 2009; Stewart et al., 2005).

Table 1 – Input parameters (most from Wang et al. (2012))

Symbol	Meaning	Value	Unit
k_h	Thermal conductivity of host rocks	3	W/m ◦C
k_m	Thermal conductivity of molten magma	2.1	W/m ◦C
k_d	Thermal conductivity of solid magma	2.1	W/m ◦C
ρ_h	Density of host rocks	2700	kg/m3
ρ_m	Density of molten magma	2700	kg/m3
ρ_d	Density of solid magma	2700	kg/m3
c_{ph}	Specific heat molten magma	820	J/kg ◦C
c_{pm}	Specific heat of solid magma	1213	J/kg ◦C
c_{pd}	Specific heat of host rocks	1213	J/kg ◦C
T_{mo}	Initial temperature of magmatic intrusion	1100	◦C
T_f	Temperature at final depth	70	◦C
T_s	Temperature at initial depth	70	◦C
T_{ml}	100% liquid (molten) magma temperature	1150	◦C
T_{ms}	100% solid magma temperature	950	◦C
L	Latent heat of fusion	376	kJ/kg
z_S	Initial depth	1602	m
z_1	Initial intrusion depth	1667	m
z_2	Final intrusion depth	1680	m
z_F	Final depth	1745	m

Source: Authors

In particular, one-dimensional heat conduction models have proved particularly useful for reconstructing the thermal evolution of organically rich host rocks that generally have relatively low permeability (Galushkin, 1997; Hanson, 1995; Hayba and Ingebritsen, 1997; Peters et al., 1978; Santos et al., 2009; Stewart et al., 2005; Wang et al., 2007, 2008, 2011a; WoldeGabriel et al., 1999).

Thus, from the use of the Heat Conduction Equation, we begin to express the temperature changes (T) that occurred in the intrusion and the adjacent rocks according to the position (z) and time (t), through the product of the thermal conductivity and the partial derivative of the thermal gradient as a function of distance, which is expressed in a simplified form, for magma intrusion:

$$\frac{\partial}{\partial z}\left(k_{magma}\cdot\frac{\partial T_{magma}}{\partial z}\right)=\frac{\partial}{\partial t}\left(\rho_{magma}\cdot c_{magma}\cdot T_{magma}\right)+\frac{\rho_{magma}}{L_2-L_1}\frac{\partial T_{magma}}{\partial t} \quad (1)$$

And to the host rock:

$$\frac{\partial}{\partial z}\left(k_{host}\cdot\frac{\partial T_{host}}{\partial z}\right)=\frac{\partial}{\partial t}\left(\rho_{host}\cdot c_{host}\cdot T_{host}\right) \quad (2)$$

As intrusion and cooling of intrusive bodies are essentially instantaneous events on a geological time scale, the numerical method adopted for solving the partial differential equation was the finite difference method (FDM).

From the parameters z_j = 1667 m, the depth of the upper part of the intrusion, h_j = 13 m the thickness and z_f = 1745 m the final depth, it is possible to define any position of z and determine if the node is located in the host rock or in the intrusion.

According to Galushkin (1997), the initial temperature of the host rocks is calculated based on the surface temperature, the geothermal gradient, and the depth of deposition. In this case, it was assumed that the initial temperature of the adjacent rocks is equal to the surface temperature of the basin, $T_S = T_F = 70\ ^\circ C$. And the temperature of the host rocks at the model boundaries is specified to be constant during sill cooling (Wang et al., 2012).

Density, specific heat and thermal conductivity parameters were defined for adjacent rock (ρ_h, c_{ph}, k_h), molten magma (ρ_m, c_{pm}, k_m) and solidified magma (ρ_d, c_{pd}, k_d); of which are functions of z, t and T.

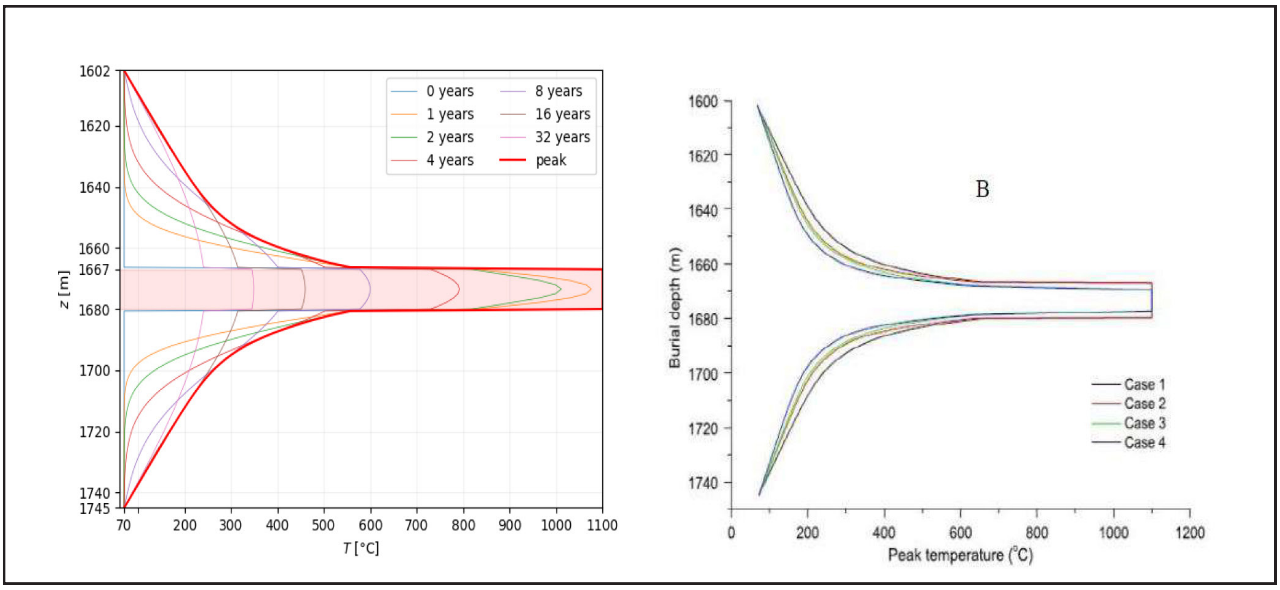
Thermal conductivity and basic igneous intrusion density vary only slightly with temperature (Wang et al., 2010). Therefore, the specific heat c_p and the matrix density of adjacent rocks ρ_h are specified to be equal to the average values of most rocks.

For the initial conditions, a linear variation between z_S = 1602 m and z = z_F = 1745 m was used; except in the magmatic intrusion, where the initial temperature of the adjacent rock is considered the same as the initial temperature of the magma T_{mo},

$$T|_{t=0} = T_s + \frac{T_f - T_s}{z_f} z \tag{3}$$

Regarding the phase change that occurs inside the intrusion, the parameters were calculated from the arithmetic mean weighted by the liquid fraction. When it is between the temperatures of 100% solid and 100% liquid magma, it means that it is in the process of changing phase.

Figure 2 – Graphs of temperature variation with depth



Source:Authors

That is, if the evaluated temperature is lower than the crystallization temperature of the magma, $T < T_{ms}$, the magma is solidified; if the temperature is greater than the temperature of the molten magma, $T > T_{ml}$, the magma is in liquid state.

Once the physical state of the magma is determined at each point of the intrusion, we obtain the thermal conductivity k_i and the density ρ_i and later on the specific heat c_{pi} is weighted by the specific mass.

3 RESULTS

For comparison, we used the Case 1 from Wang et al. (2012) in a spatial mesh of 103 nodes (equally spaced, except for one node in the beginning and in the end of the intrusion) and a time step of 5000 s.

It is possible to observe in Figures 2(a) and 2(b) that even applying a simplified model of heat transfer by conduction, very similar results were obtained for the temperature in the sill and in the host rocks in time. Note that the results from Wang et al. (2012) are the peak temperature profiles for 4 different cases. Their Case 1 is the one we are comparing with, as its model is closer to the used in this paper.

In certain positions where the magma and host rock maintain their initial temperatures, the temperature in contact will remain constant, since, in contact, the second derivative is equal to zero. We can see in the time curves in 2(a) that over time, nowhere in the intrusion will have the initial intrusion temperature, as expected, indicating that the heat is slowly being dissipated.

Also, due to the small differences in the models and methodologies, we can observe that the simulated peak temperatures of (Wang et al., 2012) has a slightly narrower profile than the present methodology. This happens probably because the authors may not have simulated for a long period of time.

We also simulated a “complete” z domain. The results are shown in comparison with the ones obtained from the restrict domain used by (Wang et al., 2012). The intrusion is the same, however we also considered a different initial condition on the host rock. We considered the geothermal gradient model, which states that the temperature is linearly increasing from the surface to the final depth, which should not exceed 80 ◦C. We considered then

$$z_S = 0\,, \quad z_F = 3000\ \mathrm{m}\,, \quad T_S = 20\ {}^{\circ}\mathrm{C} \quad \text{and} \quad T_F = 80\ {}^{\circ}\mathrm{C}\,,$$

and the remaining parameters are the same as in Table 1. We used the same time step of 5000 s and a regular mesh o 3001 nodes plus one node in each rock–magma intersection. The results for the peak temperature of both original and expanded z domain are shown in comparison in Figure 3.

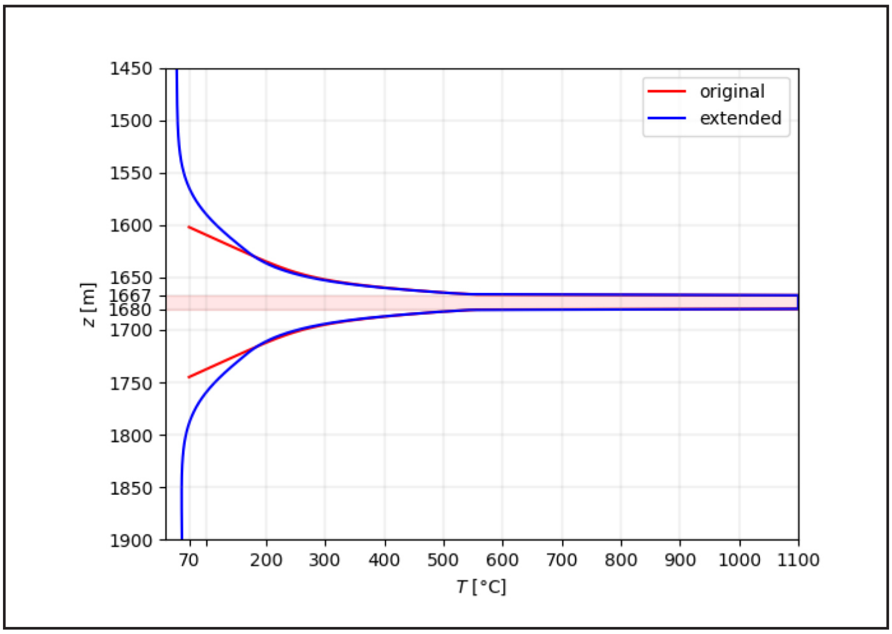
In this last case, the original short z range case "forces" the heat to dissipate in very restricted domain, where in its boundaries the temperature is 70 ◦C. However, we can see that this is not the case, as when expanding the domain to depths where we can obtain more accurately(-ish) the boundary conditions, we obtain a wider curve, indicating higher temperatures around the original boundaries. Also, there are some depths where the temperature is higher in the original case than in the extended domain case.

4 CONCLUSIONS

After carrying out and analyzing the transient numerical models of thermal flow by conduction, it is possible to draw some conclusions regarding the results obtained.

The simulation technique using the finite difference method in a PYTHON environment proved to be very favorable for the implementation of the numerical algorithm, representative of the physical equation of thermal flow by conduction. The results obtained were quite satisfactory, even with the numerical models having a relatively low level of discretization.

Figure 3 – Peak temperatures for the original and expanded z domain



Source: Authors

The numerical algorithm built in this work allows the inclusion and modification of several input parameters and initial conditions, as well as the more detailed discretization of a geological model. In this way, it becomes possible to study the thermal behavior of the host rocks for the case of the injection of numerous sills, at different times.

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