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Heat-Transfer-Model Analysis of the Thermal Effect of Intrusive Sills on Organic-Rich Host Rocks in Sedimentary Basins

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1. Introduction

Numerous geological explorations demonstrate that magmatic intrusions may increase the geothermal gradient in sedimentary basins, accelerating the thermal maturation of organic matter in strata, and promoting the hydrocarbon generation (Fjeldskaar et al., 2008; Jones et al., 2007). They may also be beneficial to the migration and accumulation of oil and gas by providing them with pathways, reservoirs, covering conditions and trapping constructions (Feng and Tang, 1997; Li, 2000; Othman and Ward, 2002; Othman et al., 2001; Wang et al., 1990). Therefore, it is of great significance to study the thermal effect of igneous intrusions on organic-rich host rocks.

A lot of the organic-rich host rocks are argillaceous rocks, e.g., shales in the DSDP 41-368 hole near Cape Verde Rise in eastern Atlantic and mudstones in Xia 38 well block in the Huimin Sag of Bohai Bay, which generally have the relatively low permeability (e.g., $<10^{-16} \text{ m}^2$). Under such circumstances, the hydrothermal convection in host rocks can be reasonably ignored, and heat conduction models can be used to approximately describe the heat transfer in host rocks (Hanson, 1995; Hayba and Ingebritsen, 1997). Thus, these models are often used as a geothermometer to indicate the temperature range in which the thermal metamorphism of these host rocks takes place (Barker et al., 1998; Santos et al., 2009; Stewart, 2005; Turcotte and Schubert, 1982; Wang et al., 2007, 2008). Several types of heat conduction models have been constructed and used in some geological researches (Galushkin, 1997; Wang et al., 2007, 2011). However, only a small portion of these researches specially compare and quantify the difference in the prediction results of different heat conduction models (Jeager, 1959; Galushkin, 1997; Wang et al., 2011). Due to the apparent importance of the accuracy of heat conduction models in these researches, it is still required to further explore and distinguish the applicable conditions of these models based on some geological cases.

In this study, we accordingly investigate the difference in the prediction results of three types of commonly used heat conduction models by taking an intrusive sill in the Bellata-1 Well in the Gunnedah Basin, Australia as an example. These models assume different intrusion mechanisms of magma and different evolution states of pore water during cooling of magma. By comparing the prediction results of these models with the measured vitrinite-reflectance (R_o) geothermometer, we also discuss the potential intrusion mechanism of the sill and the state of pore water in host rocks during cooling of the sill.

2. Geology of the Bellata-1 Well in the Gunnedah Basin, Australia

The Bellata-1 Well is located in the Gunnedah Basin of northern Australia and intersects Permian, Triassic, Jurassic and Cretaceous strata in turn (Fig 1). The total thickness of the Permian and Triassic strata reaches 451 m, overlain by the 640m thick Jurassic and Cretaceous sediments. A 15.68m thick mafic basaltic sill was found in the lower part of Triassic Napperby Formation. The intrusion of the sill took place between the Late Triassic and Early Jurassic with a current burial depth of 847.60 m (*Othman and Ward, 2002; Othman et al., 2001*). The Triassic strata are mainly composed of organic-rich mudstones. The *Ro* profile adjacent to the sill shows the effect of the significant local heating: the *Ro* value can be as high as up to 2.43% within the contact aureole, whereas the *Ro* value in the unaffected parts is only 0.57-0.74%. The oil generated by these organic-rich rocks due to the thermal effect of the intrusive sill is found in the Jurassic Pilliga Sandstone (*Othman et al., 2001*). Therefore, the igneous sill of the Bellata-1 Well and its host rocks constitute an ideal geological example for numerically investigating the thermal effects of igneous intrusions on organic-rich host rocks.

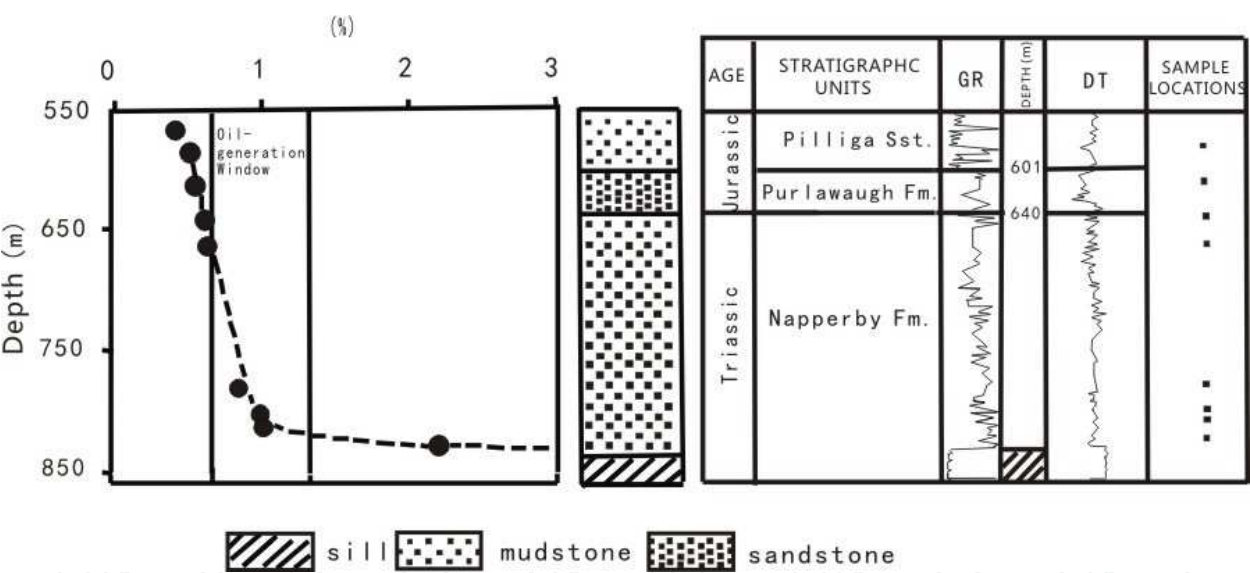


Fig. 1. Stratigraphic characteristics and vitrinite reflectance profile around an igneous sill in Well Bellata-1 (*Othman and Ward, 2002; Othman et al., 2001*)

3. Method

3.1 Heat conduction models

Some general assumptions are required in constructing heat conduction models: 1) The shape of the intrusion is regular, dike-like or sill-like; 2) Convection motion in the intrusion is not considered; 3) Heat loss due to the escape of volatiles is neglected. Thus, the basic heat conduction equations in one dimension which can be used to describe the heat transfer

between intrusive magmas and host rocks are expressed (Barker *et al.*, 1998; Shan *et al.*, 1998; Stewart *et al.*, 2005):

For magma intrusions :

$$\frac{\partial}{\partial Z} \left(K_{\text{magma}} \cdot \frac{\partial T}{\partial Z} \right) = \rho_{\text{magma}} \cdot \frac{H}{L_2 - L_1} \cdot \frac{\partial T}{\partial t} + \frac{\partial(\rho_{\text{magma}} \cdot C_{\text{magma}} \cdot T)}{\partial t} \quad (1)$$

For host rocks :

$$\frac{\partial}{\partial Z} \left([1 + [Nu] \cdot K_{\text{host}}] \cdot \frac{\partial T}{\partial Z} \right) = \frac{\partial}{\partial t} (\rho_{\text{host}} \cdot C_{\text{host}} \cdot T) + A_1 + [A_2] \quad (2)$$

Where T is the temperature; t represents the time; K means the thermal conductivity; C is the specific heat; ρ denotes the density; A_1 and A_2 represent the latent heat consumed by the dehydration and decarbonation reactions and pore-water volatilization per unit volume of host rocks and per unit time; the subscripts, i.e., magma and host, denote magma and host rocks, respectively. H represents the latent crystallization heat of melted magma; $L_1 - L_2$ is the crystallization temperature range of intrusive magma. Nu represents the Nusselt number and can be used to implement approximately the hydrothermal convection in host rocks (Galushkin, 1997). In this study, a finite difference method is used to obtain the numerical solution of Eqns. (1) and (2).

3.2 Model parameters

As the host rocks were located on or near the ground surface at the intrusion moment of the sill (between Late Triassic and Early Jurassic), we approximately assume that the strata with the current depth of 640 m is located on the ground surface during the intruding of magma. The surface temperature and the geothermal gradient are assumed to be approximately equal to 25 °C and 30 °C/Km, respectively. The temperature of the melted mafic magma is usually about 1250 °C (Barker *et al.*, 1998; Wohletz, 1999). Its thermal conductivity and density are usually equal to 2.1 J m⁻¹ s⁻¹ °C⁻¹ and 2700 Kg/m³ (Barker *et al.*, 1998; Wohletz, 1999), respectively. We specify the specific heat of the sill to be equal to 1200 J/Kg (Galushkin 1997; Wang *et al.*, 2010). The latent heat of crystallization of melted magma equals 400 KJ/Kg, and the corresponding crystallization temperature range is 1150 °C - 1250 °C. According to Wang *et al.* (2007), Organic-rich mudstones generally have the relatively low thermal conductivity. For example, the thermal conductivity of mudstones in the region of England is 1.4-1.6 W/mK (Midttømme *et al.*, 1998), and the thermal conductivity of mudstones at the depth of 850 m in the Huimin Sag of Bohai Bay is about 1.4 W/mK (Wang *et al.*, 2007). The specific heat and density of mudstone matrix can be specified to be equal to 820 J/Kg and 2700 Kg/m³, respectively. We specify 1.9 J m⁻¹ s⁻¹ °C⁻¹ as its thermal conductivity. This value is the same with that of the host rocks of the diabase sill of Well Xia38 in the Huimin Sag of Bohai Bay, as the latter has the same lithology and the similar intrusion depth with our example. At the buried depth of about 200 m, the boiling point of pore water may reach 200 °C, and its latent volatilization heat is about 1939.73 KJ/Kg. The porosity of the host rock is about 0.5 in terms of the depth - porosity relationship of mudstones (Allen and Allen, 2005). We calculate the total specific heat and total thermal conductivity of host rocks based on the computational equations of Galushkin (1997), Travis *et al.* (1991), Wang *et al.* (2007) and Wohletz *et al.* (1999).

3.3 Simulated cases

Three types of one-dimensional heat conduction models are built to simulate the heat transfer between the sill and its host rocks (Table 1). We adopt the method of Galushkin (1997) to implement the finite-time intrusion mechanism of magma: The temperature at the axis of the sill is set as 300 °C when the sill begins to form; and the time of the pre-cooled shell formation is equal to 2.2 hours; the total time of the sill formation is about 4.4 hours. In order to verify the applicability of these three heat conduction models to the modeled sill, we need to compare the prediction results of the models with the measured vitrinite-reflectance (Ro) geothermometer. We adopt the vitrinite reflectance - the peak-temperature (T_{peak}) relation (i.e. $T_{peak} = (\ln Ro + 1.19) / 0.00782$) of Barker *et al.* (1998) to calculate the T_{peak} of the overlying host rocks based on the measured Ro values and then compare it with the predictions of the models.

Case No.	Intrusion mechanism of magma	Pore-water volatilization	Hydrothermal convection in overlying host rocks	Dehydration and decarbonation of host rocks
1	instantaneous	not considered	not considered	considered
2	instantaneous	considered	not considered	considered
3	finite-time	not considered	not considered	considered

Table 1. Three cases for simulation

4. Results and discussion

The T_{peak} profiles of host rocks predicted by three types of heat conduction models are shown in Fig. 2. The contact temperature (T_c) predicted by Case 2 reaches 852 °C, and is higher than that predicted by the other cases. Actually, pore-water volatilization can decrease the thermal conductivity of host rocks. As a result, the diffusion of the heat of the sill in host rocks is depressed, and near the contact, heat from the sill congregates and rapidly increases the contact temperature. Comparably, the T_c predicted by Case 3 is lowest and only reaches 706 °C. This is apparently due to the heat loss caused by the pre-cooled shell of the sill compared to the instantaneous intrusion mechanism. In addition, the computation based on Case 1 deduces the highest degree of the thermal effect of the sill on its host rocks, whereas the prediction from Case 3 results in the lowest one. This indicates that the intrusion mechanism of magma may play a more important role in lowering the thermal effect of the intrusion than the heat sinks in host rocks. By comparing the predicted T_{peak} with the measured Ro geothermometer, it is obviously observed that the T_{peak} predicted by all of these three models is much lower than the Ro geothermometer in the region where it is 75 m away from the margin of the sill (i.e. $X/D \approx 5$). This demonstrates that the increase in the temperature of strata due to the subsequent sedimentation after cooling of the sill have covered up the thermal influence of the intrusion on host rocks in this region. The heat conduction model assuming the instantaneous intrusion mechanism and ignoring pore-water volatilization matches well with the measured Ro geothermometer. Othman *et al.* (2001, 2002) once reported that the Napperby Formation is mainly composed

of low-permeability mudstones (shale) and has the abnormal high pressure. Consequently, volatilization and escape of pore water can likely be restricted. This is consistent with the prediction of Case 1. All of these indicate that the instantaneous intrusion mechanism likely represents natural conditions and that the effect of pore-water volatilization is insignificant.

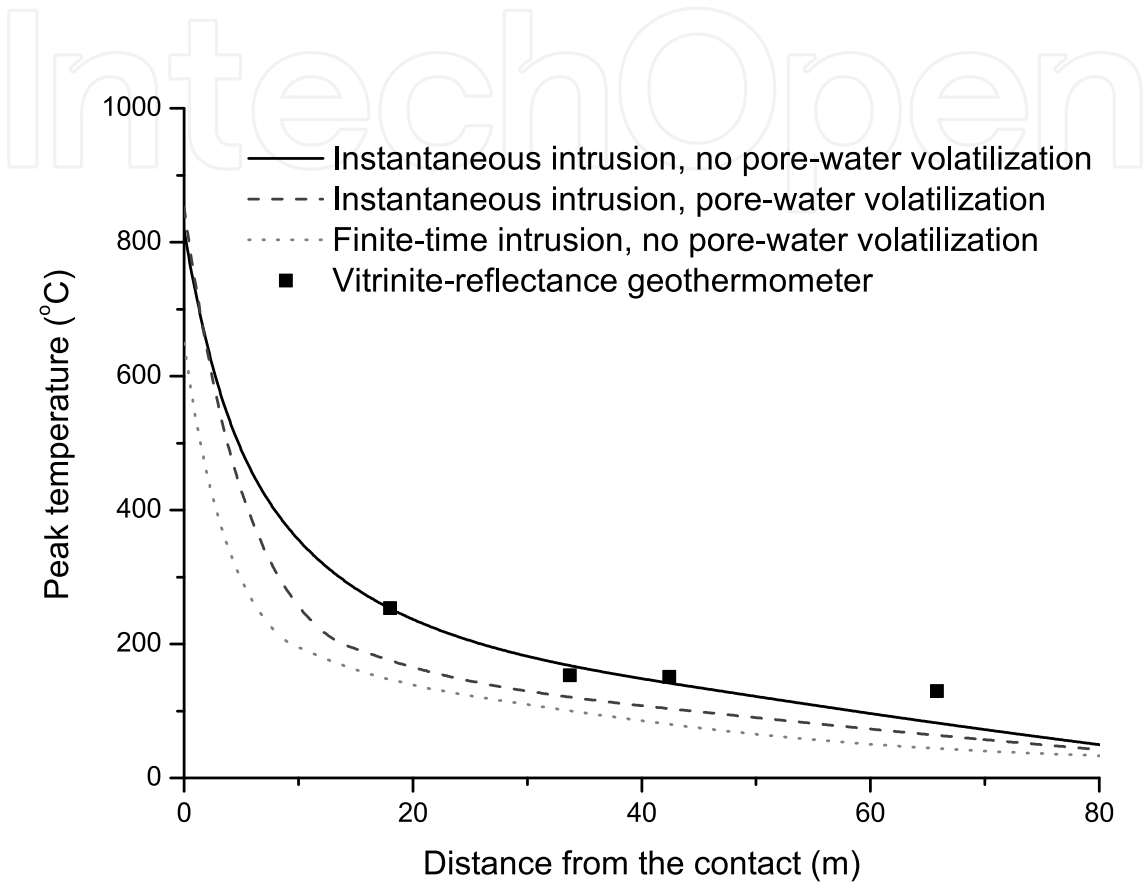


Fig. 2. Comparison between virtrinite-reflectance geothermometer of Baker et al. (1998) and peak temperature of host rocks predicted by three types of heat conduction models, assuming different intrusion mechanisms of magma and the state of pore water during cooling of magma

5. Conclusions

The following conclusions can be made based on the heat-conduction-model analysis of the T_{peak} of the host rocks of a mafic sill of the Bellata-1 Well from the Gunnedah Basin, Australia:

1. The consideration of pore-water volatilization can increase the T_c prediction, while it is converse for the finite-time intrusion mechanism. The computation based on the heat conduction model assuming the instantaneous intrusion mechanism and considering

pore-water volatilization deduces the highest T_c among three types of heat conduction models, whereas the computation based on the model assuming the finite-time intrusion mechanism and ignoring pore-water volatilization results in the lowest T_c .

2. The degree of thermal effect deduced by the heat conduction model assuming the instantaneous intrusion and ignoring pore-water volatilization is highest, while that deduced by the model assuming the finite-time intrusion and ignoring pore-water volatilization is lowest. This indicates that the intrusion mechanism of magma may play a more important role in lowering the thermal effect of the intrusion than the heat sinks in host rocks.
3. The heat conduction model assuming the instantaneous intrusion mechanism and ignoring pore-water volatilization matches well with the measured vitrinite-reflectance geothermometer. Considering the real geological characteristics of the host rocks, it can be concluded that the instantaneous intrusion mechanism likely represents natural conditions and that the effect of pore-water volatilization is insignificant.

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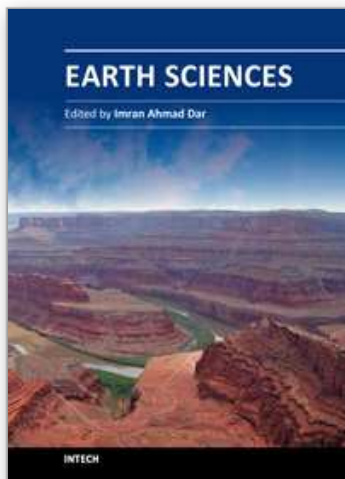
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