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Numerical simulation of magma intrusion on the thermal evolution of low rank coal

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Abstract: To study the effect of magma intrusion on the thermal evolution of low-rank coal with high water content, the mathematical relationship between water content variation and thermal conductivity of low-rank coal was analyzed by COMSOL Multiphysics numerical simulation and field validation. Taking Daxing Mine in Tiefa coalfield as the research background, the effects of magma finite time intrusion mechanism and water volatilization in coal on thermal evolution and organic maturity of coal seam are investigated in this paper. The results show that as the sill thickness increases, the thermal evolution temperature of the coal seam increases, the required thermal evolution time increases and the final retention temperature increases after the coal seam is cooled down. Approaching the magma, the maximum temperature that the coal seam can reach increases, the maximum temperature lasts longer, and the final temperature retained by the coal seam becomes higher. The increase of water content of coal makes the thermal conductivity increase, and the rate of heat transfer from coal seam is accelerated, and more heat is transferred to distant places in the same time. At the same time, the heat lost by the magma in the same time increases, the time required for the cooling of the magma decreases, and the maximum temperature reached by the underlying coal seam is significantly lower. The presence of moisture weakens the thermal evolution of the magma to the coal seam and reduces the expected maturity of the coal. The results of average random vitrinite reflectance (R_o) and moisture examination of coal samples collected at the Daxing Mine site verified the numerical simulation results of magma thermal evolution.

Keywords: Magmatic sill; Low rank coal; Moisture; Thermal effect; Thermal conductivity

1. Introduction

Magmatic intrusion into coal-bearing strata occurs in many regions worldwide, such as the Colorado (Dutcher et al. 1968; Finkelman et al. 1998) in the United States, the Huaibei Mining District (Wang et al. 2014) in China, the Kyushu region (Sasaki 1959) in Japan, the west coast of Australia (Charles et al. 1998), and the Karoo Basin (Aarnes et al. 2011) in South Africa. Statistics of coal and gas protrusion accident cases show that the magma intrusion zone is a high incidence area for protrusion accidents (Beamish and Crosdale 1998; Golab and Carr 2004; Sachsenhofer et al. 2012). Several researchers have used petrographic and geochemical methods to study the effect of magma intrusion on the organic maturity of coal (Sachsenhofer et al. 2012; Rahman and Rimmer 2014). The maturation process of the coal is accelerated under the high temperature and pressure environmental conditions following magma intrusion (Wang et al. 2010a). Magma intrusion changes the physicochemical properties of the coal, including molecular structure of coal (Jiang et al. 2017), degree of metamorphism (Shivanna et al. 2015; Saikia et al. 2016; Fjeldskaar et al. 2008), pore structure, and adsorption/desorption properties. Magma intrusion can cause changes or abrupt changes in the coal seam gas assignment pattern and gas prominence indicators (Jiang et al. 2011; Jiang et al. 2019).

Several researchers have used numerical simulations to study the thermal effects of magmatic intrusion on coal (Wang 2013a; Charles et al. 1998; Wang et al. 2010b). Heat flow models are widely used to study the thermal evolution of magma intrusion into surrounding rocks or nearby coal seams. Wang et al. (2013a) numerically simulated the heat transfer process of magma intrusion into coal seams to their surrounding rocks using the MagmaHeatNS1D interactive data language program (based on a complete one-dimensional heat flow models), which can respond many recent theoretical studies on one-dimensional heat transfer models of magma intrusion. Charles et al. (1998) compared results from contact metamorphic heat flow models and fluid inclusions with average random vitrinite reflectance (R_o) back-calculated paleotherm results and showed that heat flow models based on simple conduction cooling in closed geological systems do not accurately calculate the temperatures reached during contact metamorphism. A heat conduction model was established to describe the heat dissipation of magmatic intrusions, and further combined with the EasyR_o% model to perform a model test on the reflectivity R_o data of the specular mass, showing that the simulation results fit well with the measured results, and the model can better describe the organic matter maturity evolution of the surrounding rocks of magmatic intrusions (Wang et al. 2010b). Wang et al. (2012) tested the heat flow model by comparing experimental data of vitrinite reflectance and mineral geothermometer of the surrounding rocks with the simulation results, which fit well and showed that magma intrusion can significantly accelerate the rate of hydrocarbon generation in the surrounding rocks. There are also models that consider the role and importance of the latent heat of magma crystallization (Jaeger 1957; Carslaw and Jaeger 1959), the intrinsic heat of the intrusive body (Galushkin et al. 1997), the mechanism of magma intrusion (Yang et al. 1996), and the mode of heat flow (Jaeger 1959) on the thermal evolution of coal rocks.

Low rank coal is characterized by high natural water content, and the volatilization of pore water during the cooling of the magma intrusion when the coal seam contains water will significantly change the thermal evolution of the intruded coal seam (Jaeger 1959; Wang et al. 2007). The study of numerical simulation of magma thermal evolution showed that the volatilization of pore water would significantly reduce the predicted organic maturity of the surrounding rock (Wang et al. 2011). In the study of numerically simulated magmatic thermal effects, saturated water treatment of coal was considered to compare the changes of thermal conductivity and diffusion coefficient of coal before and after treatment, and the results showed that the thermal conductivity and diffusion coefficient of rocks increase with decreasing temperature, and these properties become more obvious after saturated water treatment of rocks at low temperatures (Delaney 1988). However, in the literature on numerical simulation of magmatic thermal evolution of coal, there are few papers that consider the relationship between moisture and thermal conductivity of coal, and there are few studies on the issue that changes in moisture of coal seams affect the effect of magmatic thermal evolution of coal.

The low rank coal of Daxing Mine in Tiefa, China, is severely intruded by magma, and ten coal and gas outbursts have occurred in Daxing Mine since the construction of the mine, all of which occurred in coal seams near the igneous erosion zone, and 9 of them have occurred in the No.7 coal seam, which is severely intruded by magma. In this paper, we will simulate the effects of different sill thickness, distance between magma and coal seam, and different moisture on the thermal evolution of coal seam with the help of COMSOL numerical simulation software, analyze the mathematical relationship between moisture and thermal conductivity of coal seam, and study the effect of moisture on the magma thermal evolution of coal. And the moisture and R_o were measured by sampling in the coal seam in the magma intrusion area of Daxing Mine to carry out the validation study.

2. Methods

2.1 Basic theory of heat flow

Heat conduction, heat convection and heat radiation are the three forms of heat flow (Yang et al. 2006). The way of heat flow by heat conduction only depends on the thermal motion of micro particles. The heat conduction of porous media includes three processes: the heat conduction process of solid particles; the heat conduction process between fluids in pores and between solid particles and fluids; and the heat conduction process when there is contact thermal resistance between solid particles (Yang et al. 2006). As a kind of porous medium, coal is more complex than single solid in the heat flow process. The process of heat flow is more complex and accompanied by material migration.

Magmatic intrusion is an unsteady process, which causes the strata to reach a high temperature in a short time. After magma intrusion, it mainly transfers heat to surrounding coal by means of heat conduction. Although heat convection and heat radiation also exist, it is much weaker than heat conduction. The study of heat conduction is mainly about the spatial distribution of temperature over time, expressed by T, which is expressed as Eq. (1) (Wang et al. 2014):

$$T(x,y,z)=f(x,y,z,t) \tag{1}$$

Where x, y, z are three-dimensional coordinates and t is time. The intrusion process of magma is an unsteady heat conduction process, t≠0. Fourier law reveals the relationship between the heat flux density and the temperature gradient in a heat conducting object, and the mathematical expression is Eq. (2):

$$Q=-\lambda F\frac{\partial T}{\partial n} \tag{2}$$

Where q is the heat, J; λ is the thermal conductivity, W ·(m ·K)$^{-1}$; F is the heat area, m^2; a negative sign indicates that the heat is transferred towards the direction of low temperature. The thermal evolution of magma on the surrounding rock or coal can improve the organic maturity of the surrounding rock (Rahman et al. 2014; Wang et al. 2010a). The R_o of coal is usually used to represent its organic maturity. The paleotemperature T_{peak} (Barker et al. 1994) of thermal evolution of magma can be inverted by coal rock R_o, which is expressed as Eq. (3):

$$T_{peak} = [\ln(R_0) + 1.19] / 0.00782$$

(3)

2.2 Magmatic rock heat flow model considering the influence of coal water

Magma intrusion is a long-term and complicated process, and the heat flow of porous media is also very complicated. The change of coal seam temperature is affected by many factors. In order to facilitate research, the process needs to be simplified and assumed. It is assumed that the skeleton of coal is stable and not deformed during magma intrusion; there is no internal heat source in coal and no heat is generated; magma intrusion mechanism is instantaneous intrusion mechanism; the heat flow mode is heat conduction, and the influence of convection and heat radiation on magmatic intrusion process is ignored. The coal seam has uniform moisture, and the water content is the same everywhere in the coal seam.

According to the above assumption, the mathematical heat flow model of magmatic thermal evolution coal is established under the condition of considering different water content in coal. The energy change $Q_{produce}$ in the micro-element body within dt time is the mass of the micro-element body multiplied by the heat capacity C multiplied by the temperature change of the micro-element body in time dt, and the calculation refers to Eq. (4) (Wang et al. 2014):

$$Q_{produce} = \rho dxdydzc\frac{\partial T}{\partial_t} = \left(\rho c\frac{\partial T}{\partial_t}\right) dxdydz \tag{4}$$

After intrusion, the magma condenses and crystallizes with water, resulting in phase transformation (Wang et al. 2010b; Wang et al. 2011). The heat consumption of magma micro element phase transformation is H_1, and its mathematical expression is Eq. (5):

$$H_1 = \rho_1 \cdot \frac{L_c}{T_{c1} - T_{c2}} \cdot \frac{\partial T}{\partial t} \tag{5}$$

Where ρ_1 is the density of magma, kg/m^3; L_c is the latent heat of magma transformation, kJ/kg; Tc_1-Tc_2 is the temperature range of magma transformation, that is, magma transformation occurs in this temperature range. According to the law of conservation of energy, the heat input per unit time is equal to the sum of the heat output per unit time, the change of the internal energy of the derived magma, and the internal energy consumed by the phase transformation of the magma, which is expressed as Eq. (6) (Wang et al. 2014):

$$\frac{\partial}{\partial x}(\lambda_x \frac{\partial T}{\partial \mathrm{x}}) + \frac{\partial}{\partial y}(\lambda_y \frac{\partial T}{\partial \mathrm{y}}) + \frac{\partial}{\partial z}(\lambda_z \frac{\partial T}{\partial \mathrm{z}}) = \rho_1 c_1 \frac{\partial T}{\partial \tau} + H_1 \quad (6)$$

In engineering problems, it is often considered that the thermal conductivity of an object is the same everywhere under the same condition. The formula can be simplified as Eq. (7):

$$\lambda_1(\frac{\partial^2 T}{\partial \mathrm{x}^2} + \frac{\partial^2 T}{\partial \mathrm{y}^2} + \frac{\partial^2 T}{\partial \mathrm{z}^2}) = \rho_1 c_1 \frac{\partial T}{\partial \tau} + H_1 \quad (7)$$

Where λ_1 is the thermal conductivity of magma, W·(m·K)$^{-1}$; c_1 is the specific heat capacity of magma, J·(kg·K)$^{-1}$. The coal seam is baked by magma, and the temperature rises continuously. After reaching a certain temperature, the water in the coal seam will change phase. At this time, the coal seam continues to absorb heat, but the temperature is no longer rising, and the absorbed heat is used for water phase transformation (Wang et al. 2011; Wang et al. 2013b). The heat record of phase change absorption of water in coal micro element object is H_2, and its mathematical expression is Eq. (8):

$$H_2 = \rho_w \cdot \frac{L_v \cdot w}{T_{v1} - T_{v2}} \cdot \frac{\partial T}{\partial t} \quad (8)$$

Where ρ_w is the density of water, kg/m; L_v is the latent heat of phase change of water, kJ/kg; w is the water content, dimensionless; T_{v1}-T_{v2} is the temperature range of phase change, that is, the phase change of water occurs in this temperature range.

Based on the law of conservation of energy, the heat introduced into the coal micro element in unit time is equal to the sum of the heat derived from the coal micro element in unit time, the change of the internal energy of the coal micro element and the internal energy absorbed by the water contained in the coal micro element in phase change, which is expressed as Eq. (9):

$$\frac{\partial}{\partial x}(\lambda_x\frac{\partial T}{\partial \mathrm{x}})+\frac{\partial}{\partial y}(\lambda_y\frac{\partial T}{\partial \mathrm{y}})+\frac{\partial}{\partial z}(\lambda_z\frac{\partial T}{\partial \mathrm{z}})=\rho_2 c_2\frac{\partial T}{\partial \tau}+H_2 \tag{9}$$

Assuming that the thermal conductivity of the coal seam is the same, the simplified differential equation of heat conduction is shown in Eq. (10):

$$\lambda_2(\frac{\partial^2 T}{\partial \mathrm{x}^2}+\frac{\partial^2 T}{\partial \mathrm{y}^2}+\frac{\partial^2 T}{\partial \mathrm{z}^2})=\rho_2 c_2\frac{\partial T}{\partial \tau}+H_2 \tag{10}$$

Where λ_2 is the thermal conductivity of coal, W·(m·K)$^{-1}$; ρ_2 is the density of coal, kg/m^3; c_2 is the specific heat capacity of coal, J·(kg·K)$^{-1}$.

2.3 Relationship between moisture and thermal conductivity of low rank coal

Phase change materials are involved in the mathematical model of heat flow considering the influence of water, and the physical and chemical properties will change before and after phase change, which has a great influence on the simulation results. In the process of simulating temperature change, the thermal conductivity of material is very important, and the relationship between moisture of coal and thermal conductivity needs to be studied.

Ma et al. (2017) investigated the relationship between the thermal conductivity and moisture of coal samples at different temperatures for non-stick coal, and the results are shown in Fig. 1(Ma et al. 2017).

Fig. 1 indicates that when the moisture of non-caking coal is 0-13.90%, the thermal conductivity of coal increases rapidly; when the moisture is 13.90% - 15.13%, the thermal conductivity increases greatly; when the moisture is 15.13% - 20.0%, the thermal conductivity of coal has a small increase (Ma et al. 2017). It shows that with the increase of moisture, the thermal conductivity of coal has an increasing trend; but when the moisture of coal reaches a certain critical value, it has little effect on the thermal conductivity of coal.

Xu and Zhan (2010) show that the effective thermal conductivity of unsaturated porous media is significantly affected by water content. Based on three theoretical models (parallel conduction model, series model and Woodside-Messmer model), the relationship between effective thermal conductivity and water content is calculated and verified by experiments. The results show that the experimental results are in good agreement with the theoretical values of WM model (Pan 2000). According to WM model, the relationship between moisture content and thermal conductivity is expressed as Eq. (11) (Pan 2000):

$$\lambda_e = \alpha\lambda_0 (g\frac{\lambda w}{\lambda_g})^{w\frac{\rho_2}{\rho\omega}} \tag{11}$$

Where λ_e is the effective thermal conductivity, W ·(m ·K)$^{-1}$; α is the correction coefficient, dimensionless, different values for different materials, this paper takes 0.8; λ_0 is the thermal conductivity of skeleton, W ·(m ·K)$^{-1}$; λ_w is the thermal conductivity of water, W ·(m ·K)$^{-1}$; λ_g is the thermal conductivity of air, W ·(m ·K)$^{-1}$.

2.4 Numerical simulation

In order to study the temperature change law of low rank coal with high water content after magma intrusion, COMSOL Multiphysics numerical simulation software was used to study the temperature distribution law of heat conduction between sill and Water-bearing coal seams, and the influence of different water content of coal seam on the temperature change of coal seam after magmatic intrusion.

Before the numerical simulation, the relevant parameters are assigned, and the parameter content and assignment basis are shown in Table 1 (Wang et al. 2011; Xu et al. 2010; Hu et al. 2016; Thussu and Datta 2011; Shang et al. 2012).

Since the influence of moisture is considered in the simulation, the physical property parameters before and after the phase change of the material need to be set. The setting content and basis are shown in Table 2 (Wang et al. 2017).

In this simulation, four kinds of water content are selected as 50%, 30%, 8%, and 3% respectively. According to Eq. (11), the thermal conductivity of coal can be calculated. The results are shown in Table 3.

According to the site and the need of model simplification, the upper boundary of the model is set as an open boundary, and the left and right boundaries and the lower boundary are set as thermal insulation. The transient equation of boundary application is shown in Eqs. (12-15):

$$-n\cdot(-k\triangledown T)=0 \tag{12}$$

$$T = T_0, \quad if n\cdot u<0 \tag{13}$$

$$-\triangledown Tn=0, \quad if n\cdot u\geq 0 \tag{14}$$

The open boundary defaults to $T=T_0=30°C$. The selected physical field is heat flow in solids, and the solution to the transient equation is:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla (k \nabla T) + Q \tag{15}$$

3. Results and discussion

3.1 Analysis of the influence of sill thickness on the thermal evolution of coal seams

Based on the multi-physics coupling software COMSOL with finite element solution, a numerical simulation of the heat conduction temperature distribution between magma and surrounding rock was established. Before the simulation, the relative positions of the simulated sill, coal, and surrounding rock need to be simplified and the boundary should be set, and then the three are modeled in COMSOL. Since the thermal conductivity of the three main bodies is different and the initial temperature is different, the whole model needs to be divided into three in the modeling. The model set up the minefield is 2000m long and 1000m wide; the sill is 1000m long and its thickness can be adjusted. According to No. 7 coal seam of Daxing Mine, the coal seam is located 10m below the sill, and the set coal seam is 1800m long, 3.5m thick, and 10m away from the magma floor. A model is established as shown in Fig. 2.

Set surface temperature T_1 to 20°C, surrounding rock temperature T_2 to 30°C, initial magma temperature T_3 to 1000°C, other parameter settings are shown in Table 1, magma thickness is set to 50m, 80m, 10m, simulation time is set to 1000a. The simulation results are shown in Fig. 3. Fig. 3 indicates that the temperature of the coal seam rises sharply after magma intrusion, reaching the highest temperature in the first 100 years, and then the temperature begins to decrease slowly. The greater the thickness of the magma, the higher the maximum temperature reached by the coal seam. When the thickness of magma is 50m, the maximum coal seam temperature is 380°C; when the thickness of magma is 80m, the maximum coal seam temperature reaches 420°C; when the thickness of magma is 100m, the maximum coal seam temperature is close to 450°C. As the thickness of magma increases, the maximum coal seam temperature lasts longer. When the thickness of magma is 50m, 80m and 100m, the time for the coal seam to reach the maximum temperature is 30a, 50a and 70a respectively. This is roughly consistent with the temperature variation trend in the simulation results of Wang et al. (2014). However, the distance between the sill and the coal field roof is far greater than the simulated distance set in this study, so the temperature variation is lower than the temperature variation results in this study.

3.2 Influence of the distance from magma on the thermal evolution of coal

Model 2 sets up a minefield of 2000m long and 1000m wide; the magmatic rock mass is 1000m long and 50m thick; the coal seam is 1800m long and 2m thick. The distances from the floor of the sill are 10m, 20m, 30m, 40m, and 50m, respectively. Model 2 is shown in Fig. 4.

Set the surface temperature T_1 to 20°C, the surrounding rock temperature T_2 to 30°C, the initial magma temperature T_3 to 1000°C, the other parameters are shown in Table 1, and the simulation time is set to 1000a. The simulation results are shown in Fig. 5.

Fig. 5 (a) shows the coal seam temperature rose sharply after magma intrusion, reaching the highest temperature in the first 100a, and then decreasing slowly. Closer the coal seam is to the magma, higher the maximum temperature of the coal seam is, and the required time is 20a, 40a, 60a, 90a, 120a respectively. After the magma cools, the closer the magma is, the higher the final temperature of the coal seam, but the difference is smaller. Fig. 5(b) shows that the closer the distance to the magmatic rock, the R_o of coal and the peak temperature of magma thermal evolution have an increasing trend. It shows that the thermal evolution of magma significantly improves the organic maturity of coal. From 50m to 10m away from the magma, the R_o of coal increases by 11.32% from 1.25%, and the peak temperature of magma increases from 180.18 °C to 462.50 °C.

3.3 Effect of water content on coal seam heat conduction during magma cooling

In order to study the influence of different water cuts during the cooling process of magma intrusions on the thermal evolution of coal seams, the model is further simplified, assuming that the thermal conductivity of surrounding rock and coal sea. Model 3 set up the mine field 1000m long and 500m wide; the magmatic rock mass is 400m long, 50m wide and 225m above the ground. Model 3 is shown in Fig. 6.

Set the surface temperature T_1 to 20°C, the surrounding rock temperature T_2 to 30°C, the initial magma temperature T_3 to 1000°C, the other parameters are shown in Table 1, and the simulation time is set to 1000a. The simulation result is shown in Fig.7.

The heat lost by the magma in the same time is used for its own phase change and heat flow in coal, which increases with the decrease of the central temperature of the magma.

Therefore, with the increase of coal seam moisture content, the heat loss of magma increases in the same time. Fig. 7(a) indicates that after 100a, the coal seam moisture content increases from 0% to 50%, and the maximum temperature reached by the coal seam decreases from 540°C to 280°C.Under high temperature conditions, coal will go through two stages of drying degassing and coal matrix pyrolysis (Su et al. 2020), and part of the heat of magma intrusion was absorbed in the degassing process of water in coal, so the higher the moisture of coal seam, the lower the temperature after magma intrusion.

Comparing magma intrusion at 100a, 500a and 1000a, the water content is the same, and the temperature of the coal seam at the same depth is lowered. Comparing Figs. 7(a), 7(b), and 7(c), it can be seen that as the simulation time increases, the coal temperature has a decreasing trend. The greater the water content of coal, the smaller the increase in temperature near the magmatic coal. This is because the increase of the water content of coal leads to the greater the thermal conductivity of its own, the more heat transferred to the distance. In addition, more heat is consumed for the phase transition of water, the lower the coal temperature is.

The time required for magma cooling decreases with the increase of water content. Fig. 7(c) indicates that at 1000a, when the water content is 0%, 3%, and 8%, the temperature of the magma center is higher and the temperature changes at different depths. When the water content is 30% and 50%, the temperature change is small, and the magma cools quickly. It is studied that after 8000 years of magma intrusion in coal mines, magma and surrounding rocks reach a geothermal balance, but the deep geothermal of coal mines is abnormal, and its stratigraphic characteristics, geological structure and groundwater flow activities are the main factors leading to its abnormality (Feng et al. 2020). After the magma was cooled, the greater the water content, the lower the temperature retained by the coal seam. After 1000a of magma intrusion, the water content increased from 0% to 50%, and the coal seam retention temperature decreased from 95°C to about 87°C.

3.4 Temperature variation with time for coals with different water content

Wang Dayong et al. created a magma intrusion model, compared the numerical simulation with the measured results, and studied the effect of pore water volatilization and supercritical state on the degree of coal metamorphism. The results show that when a limited time intrusion mechanism is used, the effect of pore water on the degree of metamorphism is predicted. The deviation is slightly lower, which indicates that the limited time intrusion mechanism of magma and the volatilization of pore water may represent natural conditions (Wang et al. 2011). In order to study the influence of water content on coal seam temperature and degree of metamorphism, combined with the actual situation of the Daxing Mine field, Model 4 sets the mine field 2000m long and 1000m wide; the magmatic rock mass is 1000m long and 50m wide. The coal seam is 1800m long, 4m wide, and 50m away from the magma floor. Model 4 is shown in Fig. 8.

Set the surface temperature T_1 to -10°C, the surrounding rock temperature T_2 to 30°C, the initial magma temperature T_3 to 500°C, the other parameters are shown in Table 1, and the simulation time is set to 5000a. The simulation result is shown in Fig. 9. Fig. 9(a) shows that as the moisture content increases, the maximum temperature reached by the coal seam decreases significantly, and the time to reach the maximum temperature becomes shorter. When the moisture content increases from 0% to 50%, the maximum coal seam temperature drops from about 120°C to 35°C (Fig.9a). The coal R_o is reduced from 0.78% to 0.40% (Fig.9b). The comparative analysis of Figs. 5 and 9 shows that the presence of moisture reduces the maximum temperature that the coal seam can reach, weakens the thermal evolution of magma on the coal seam, and thereby weakens the degree of coal seam metamorphism.

3.5 Verification of moisture and R_o of coal seam in in-situ magmatic intrusion area

Daxing Mine is located in Tiefa coalfield, Tieling City, Liaoning Province. magmatic movement in Tiefa coalfield can be divided into three stages in time. The early stage of late Jurassic is the first stage. The main movement form of magma is eruption, and the coalfield began to deposit in this stage. The second stage is the middle and late stage of Early Cretaceous, with the end of stratigraphic deposition, followed by more frequent magmatic activity, and eruption is still the main form of magmatic activity. The Tertiary period is the last stage, the magmatic activity is no longer dominated by eruption, replaced by the intrusion of basic magmatic rocks, with multiple intrusions into the roof and floor of coal seam and a few intrusions into rock strata.

The magmatic rock exposed in Daxing Mine field is the third stage of basic magmatic rock intrusion. There is a stable distribution of sill in the roof of $N_1$708 working face of No.7 coal seam, with an average thickness of 3.5m. The magma intruded along the roof of No.7 coal seam with a vertical distance of about 10m. The distribution plan of $N_1$708 working surface and sill in Daxing Mine is shown in Fig. 10 (Jiang et al. 2016).

In the previous study, 15 coal samples were taken from No.7 coal seam in the range of 0 to 250m from the sill, and the industrial analysis and vitrinite reflectance measurement were carried out in the laboratory. Based on the determination results of moisture and R_o (Jiang et al. 2016), the relationship between moisture content, R_o and the distance between coal sample and sill is plotted, as shown in Fig. 11.

Fig. 11 indicates that the intrusion of sill reduces the moisture content of coal and improves the metamorphic degree of coal. Near the sill, the water content of coal decreases from 7.5% to 1.6%, and R_o increases from 0.53% to 1.58% (Fig.11a). The peak temperature of magmatic thermal evolution increases from 82.52°C to 210.67°C when the distance changes from 264 m to 0.1 m (Fig.11b). The above research results to some extent verify the numerical simulation results of magma thermal evolution coal. The thermal evolution of magma increases the degree of metamorphism of low-rank coals. Magma baking or heat conduction reduces the vaporization and evaporation of water in coal. In addition, due to high water content (7.5%) of low rank coal in Daxing Mine, the thermal effect of magma intrusion on coal reduced to a certain extent, thereby reducing the degree of coal metamorphism.

4. Conclusions

In this paper, the relationship between moisture content and thermal conductivity of coal is investigated by using numerical simulation and field verification method. The relationship between sill thickness, distance from igneous sill, organic maturity of coal and time of magma thermal evolution are analyzed by numerical simulation. Further, the temperature of the cooled coal is analyzed in relation to the moisture content, and the main conclusions are as follows:

1) The establishment of magma thermal evolution coal and heat flow model shows that the main factors affecting the change of coal seam temperature are: initial magma temperature, thickness of magma, thermal conductivity of coal and the distance between coal and magma. There is an inherent relationship between the thermal conductivity of coal and the moisture content. As the moisture content increases, the thermal conductivity increases.

The calculation results show that when the water content is 3%, 8%, 30%, 50%, the thermal conductivity of coal is 0.291, 0.358, 0.887, 2.024 W·(m·K)$^{-1}$, respectively.

2) The simulation results using COMSOL numerical software show that the greater the thickness of magma, the higher the maximum temperature reached by the coal seam, the longer the duration, and the higher the final temperature retained. The closer the distance to the magma, the higher the temperature reached by the coal seam and the longer it will take. After the magma cools, the closer to the magma, the higher the final retention temperature of the coal seam, but the difference is small. Close to the magma, the R_o of coal and the peak temperature of magma tend to increase. The results show that the thermal evolution of magma significantly improves the organic maturity of coal. The distance to the magma decreases from 50m to 10m, the R_o of coal increases from 1.25% to 11.32%, and the peak magma temperature increases from 180.18 °C to 462.50 °C.

3) With the increase of water content, the thermal conductivity of coal increases, and the heat flow rate increases. The heat transferred from the magma to the distance increases, so does the heat loss from magma. With the increase of water content, the cooling time of magma decreases, the maximum temperature of coal seam decreases significantly, and the time to reach the maximum temperature is also shorter. As the water content increases from 0% to 50%, the maximum temperature of coal seam decreases from 120 °C to 35 °C. The R_o of coal decreases from 0.78% to 0.40%. It shows that the existence of water significantly reduces the maximum temperature of coal seam, weakens the thermal evolution of magma on coal, and causes the metamorphic degree of coal to be lower than expected.

4) The moisture and R_o measured by coal samples collected on the No.7 coal seam of Daxing Mine verified the numerical simulation results of magma thermal evolution to some extent. The baking or heat flow of magma reduces the vaporization and evaporation of water in coal. Therefore, the existence of low rank coal with high moisture reduces the thermal evolution of magma in Daxing Mine, resulting in the maturity of the No. 7 coal seam being lower than expected.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported of this paper in Environmental Earth Sciences.

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Tables

Table 1 Basic parameters in numerical simulation (Wang et al. 2011; Xu et al. 2010; Hu et al. 2016; Thussu and Datta 2011; Shang et al. 2012)

Name	Symbol	Unit	Value
Thermal conductivity of magma	λ_1	$W \cdot (m \cdot K)^{-1}$	2.1
Thermal conductivity of coal	λ_2	$W \cdot (m \cdot K)^{-1}$	0.286
Thermal conductivity of Surrounding rock	λ_3	$W \cdot (m \cdot K)^{-1}$	2.64
Magma density	ρ_1	kg/m^3	2700
Density of coal	ρ_2	kg/m^3	1314
Density of surrounding rock	ρ_3	kg/m^3	2510
Magma specific heat capacity	C_1	$J \cdot (kg \cdot K)^{-1}$	1213
Specific heat capacity of coal	C_2	$J \cdot (kg \cdot K)^{-1}$	883
Specific heat capacity of Surrounding rock	C_3	$J \cdot (kg \cdot K)^{-1}$	870
Thermal conductivity of water	λ_w	$W \cdot (m \cdot K)^{-1}$	0.6
Density of water	ρ_W	kg/m^3	1000
Specific heat of water	C_w	$J \cdot (kg \cdot K)^{-1}$	4180
Thermal conductivity of gas	λ_g	$W \cdot (m \cdot K)^{-1}$	0.026
Latent heat of magma phase Transition	L_c	kJ/kg	376
Latent heat of water phase change	L_v	kJ/kg	2410
Magma phase transition interval	$T_{c1}-T_{c2}$	℃	350–650
Water phase change interval	$T_{v1}-T_{v2}$	℃	297–302

Table 2 Physical parameters of phase change materials (Wang et al. 2017)

Material	Phase transition state	Density	Specific heat capacity
Magma	Before phase change	2.10	2700
	After phase change	2.64	2510
Coal	Before phase change	800	883
	After phase change	1290	1076

Table 3 Thermal conductivity of coal under different moisture content

Moisture ω	50%	30%	8%	3%
Effective thermal conductivity λ_e / $W \cdot (m \cdot K)^{-1}$	2.024	0.887	0.358	0.291

Figure captions

Fig. 1 Thermal conductivity of coal varies with moisture, modified from

Fig. 2 Numerical simulation model 1

Fig. 3 Thermal evolution of coal seam with different magma thickness

Fig. 4 Numerical simulation model 2

Fig. 5 Temperature of coal varies with time at different distances from magma

Fig. 6 Numerical simulation model 3

Fig. 7 Temperature of coal with different moisture content after magma intrusion

Fig. 8 Numerical simulation model 4

Fig. 9 Coal temperature changes with time under different moisture content

Fig. 10 Location of $N_1$708 coalface and distribution plan of sill in Daxing Mine

Fig. 11 Relationships between moisture, R_o and the distance from igneous sill in Daxing Mine (a), relationship between coal peak temperature and the distance from sill (b)

Table captions

Table 1 Basic parameters in numerical simulation

Table 2 Physical parameters of phase change materials

Table 3 Thermal conductivity of coal under different moisture content

Figures

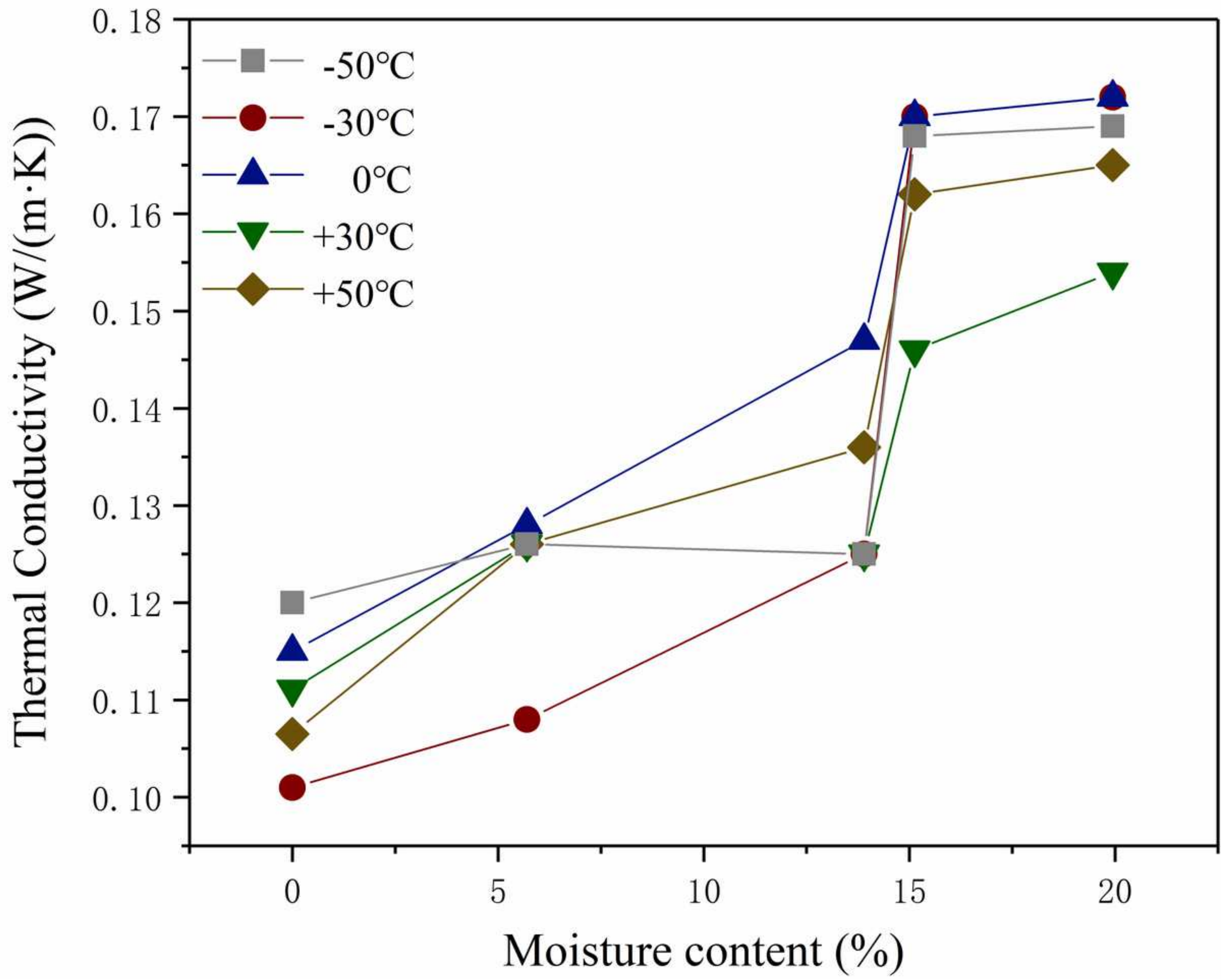

Figure 1

Thermal conductivity of coal varies with moisture, modified from

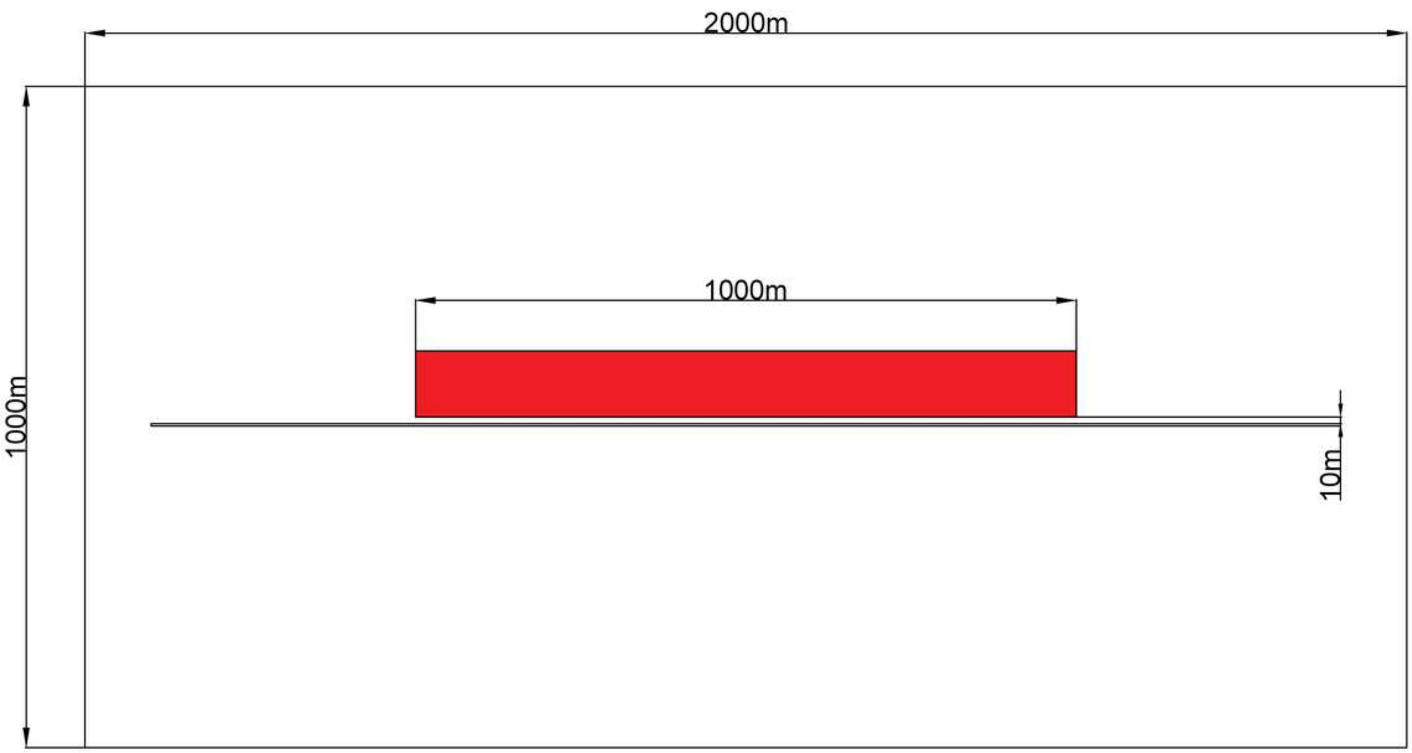

Figure 2

Numerical simulation model 1

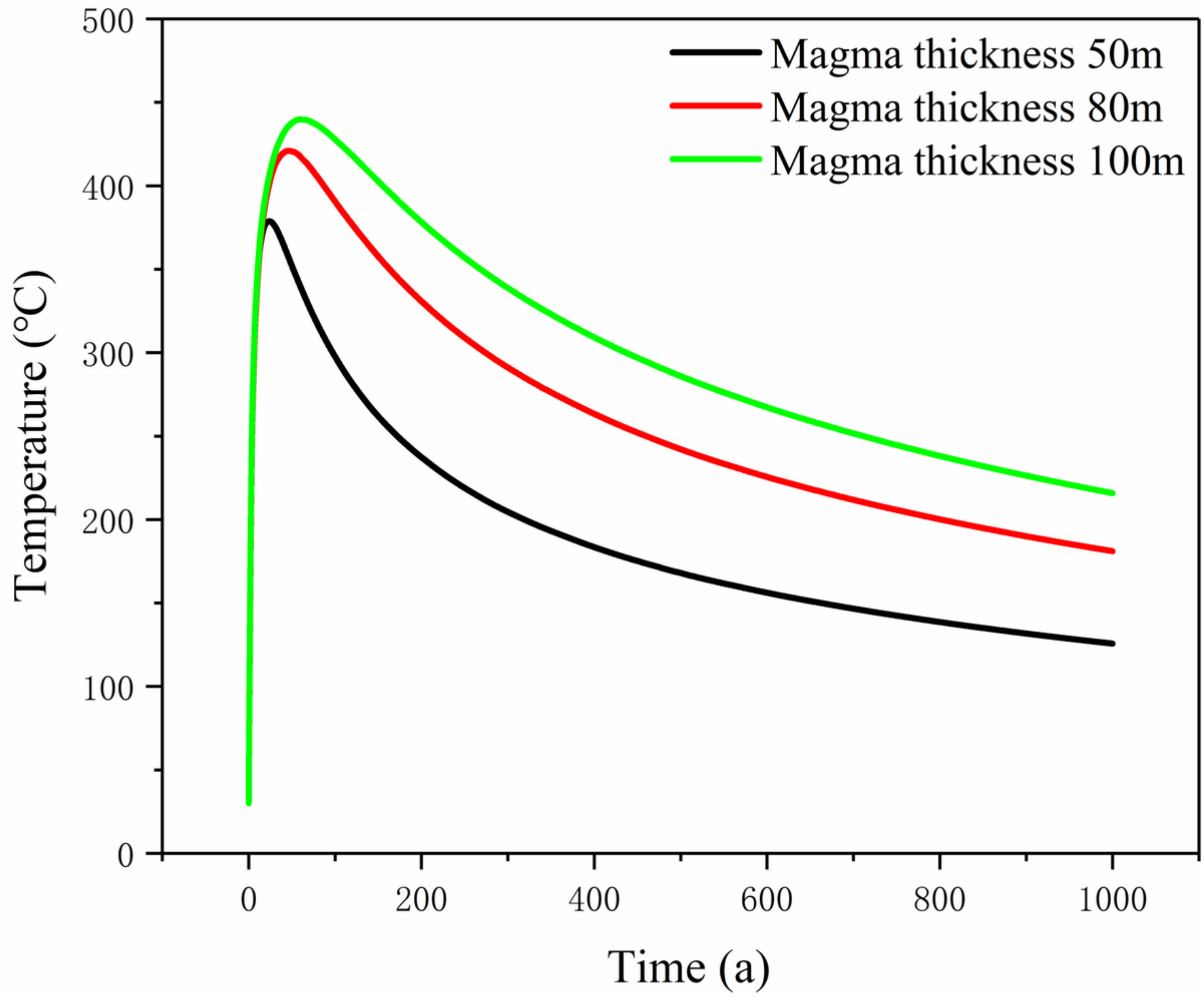

Figure 3

Thermal evolution of coal seam with different magma thickness

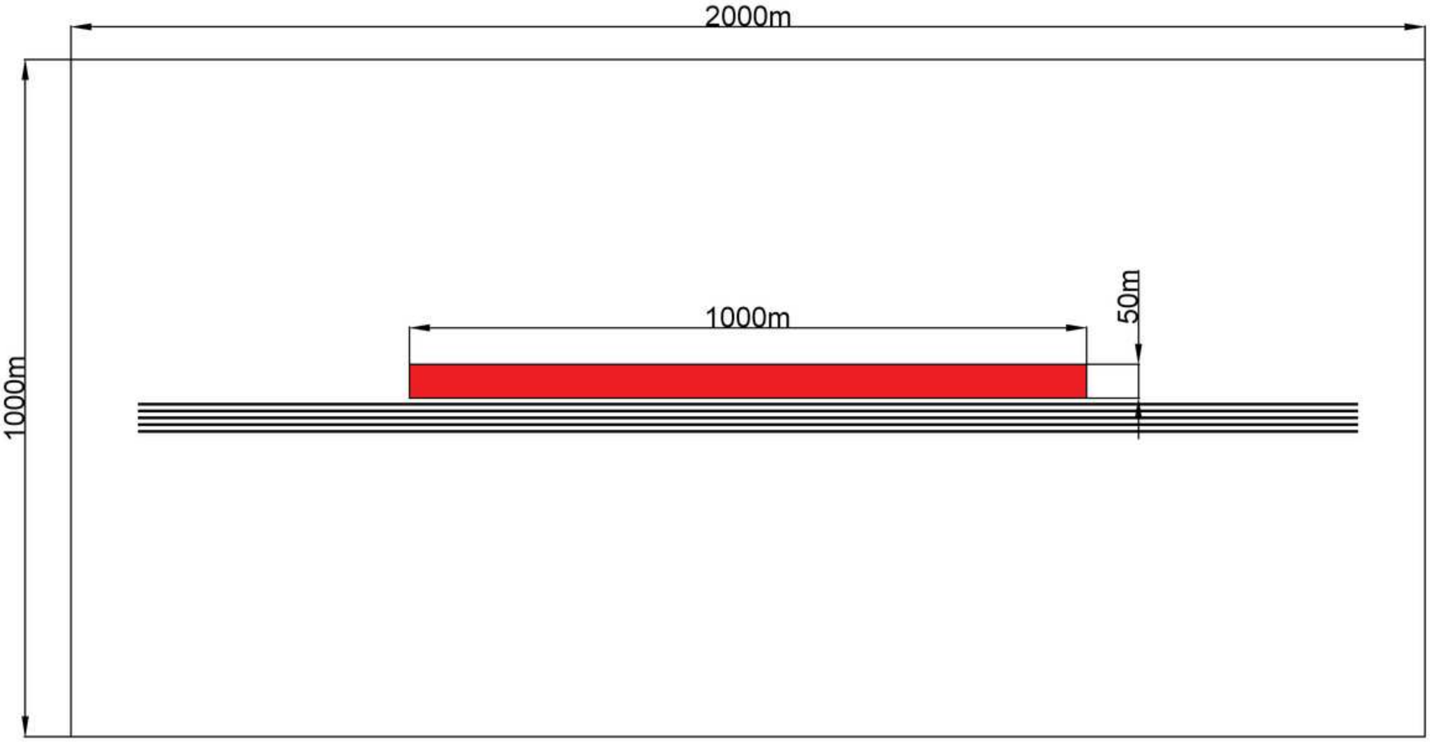

Figure 4

Numerical simulation model 2

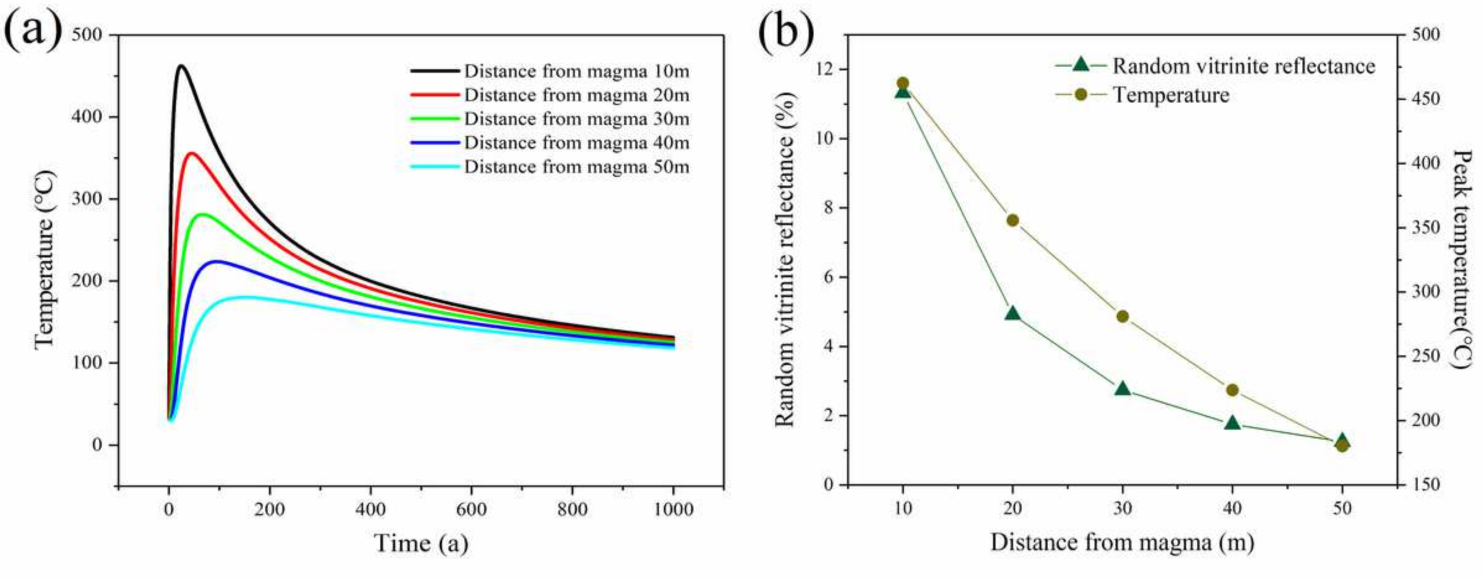

Figure 5

Temperature of coal varies with time at different distances from magma

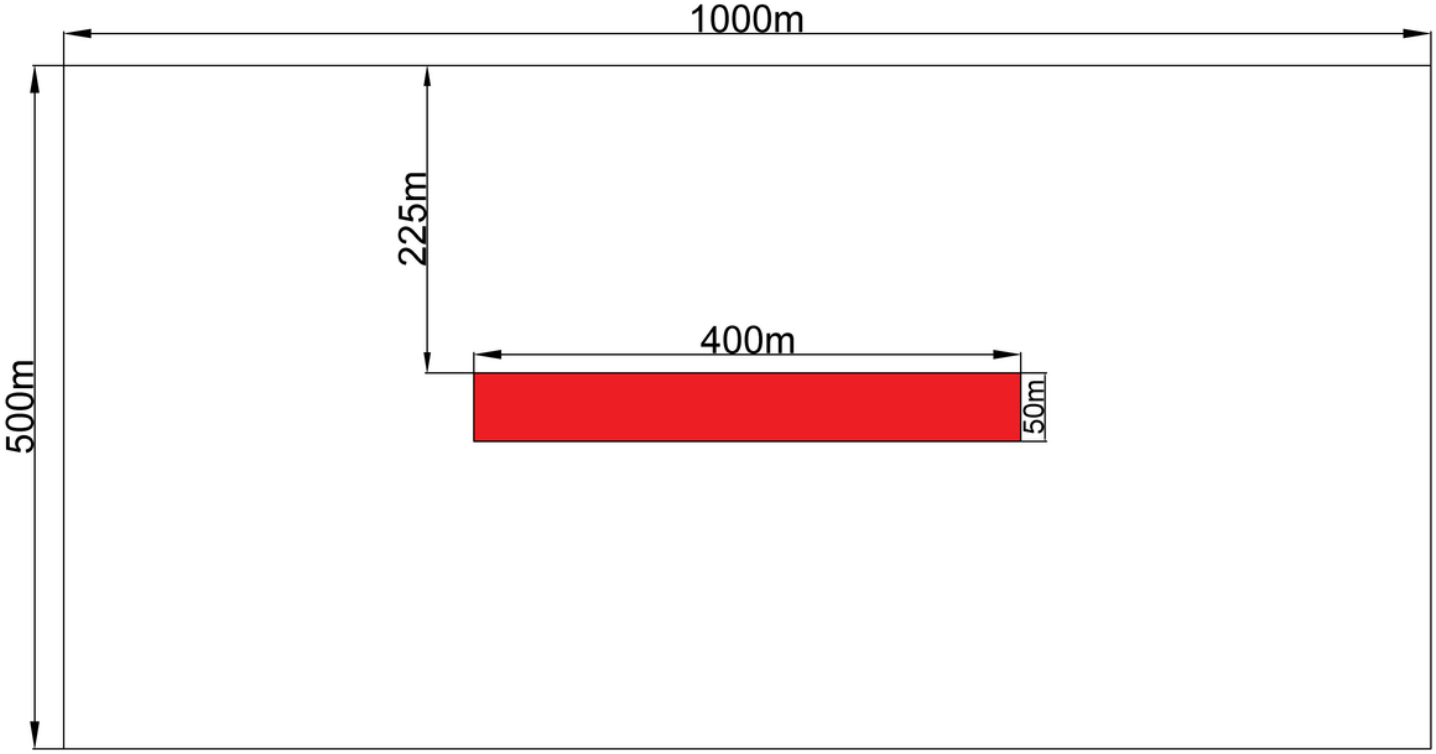

Figure 6

Numerical simulation model 3

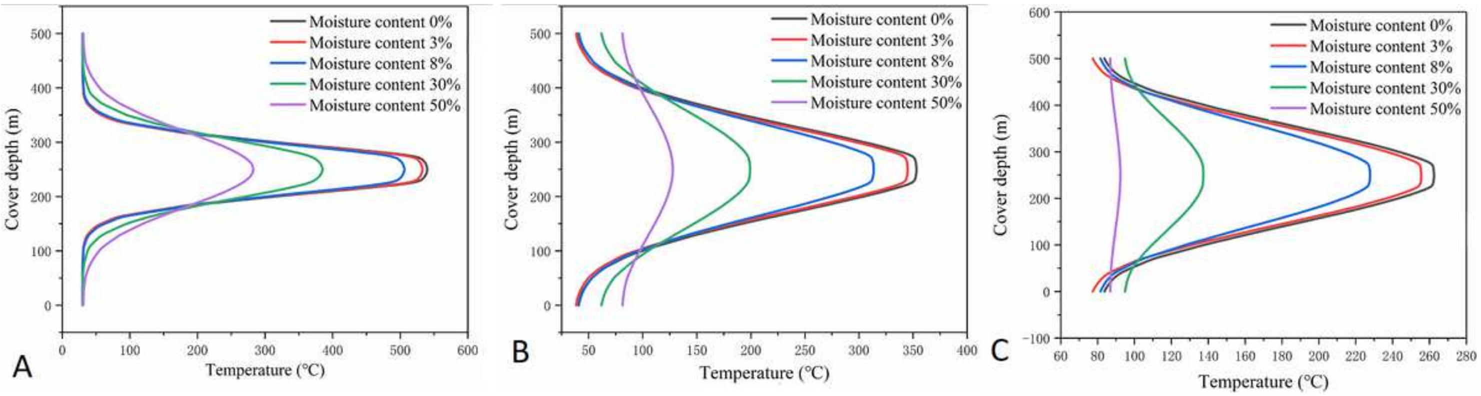

Figure 7

Temperature of coal with different moisture content after magma intrusion

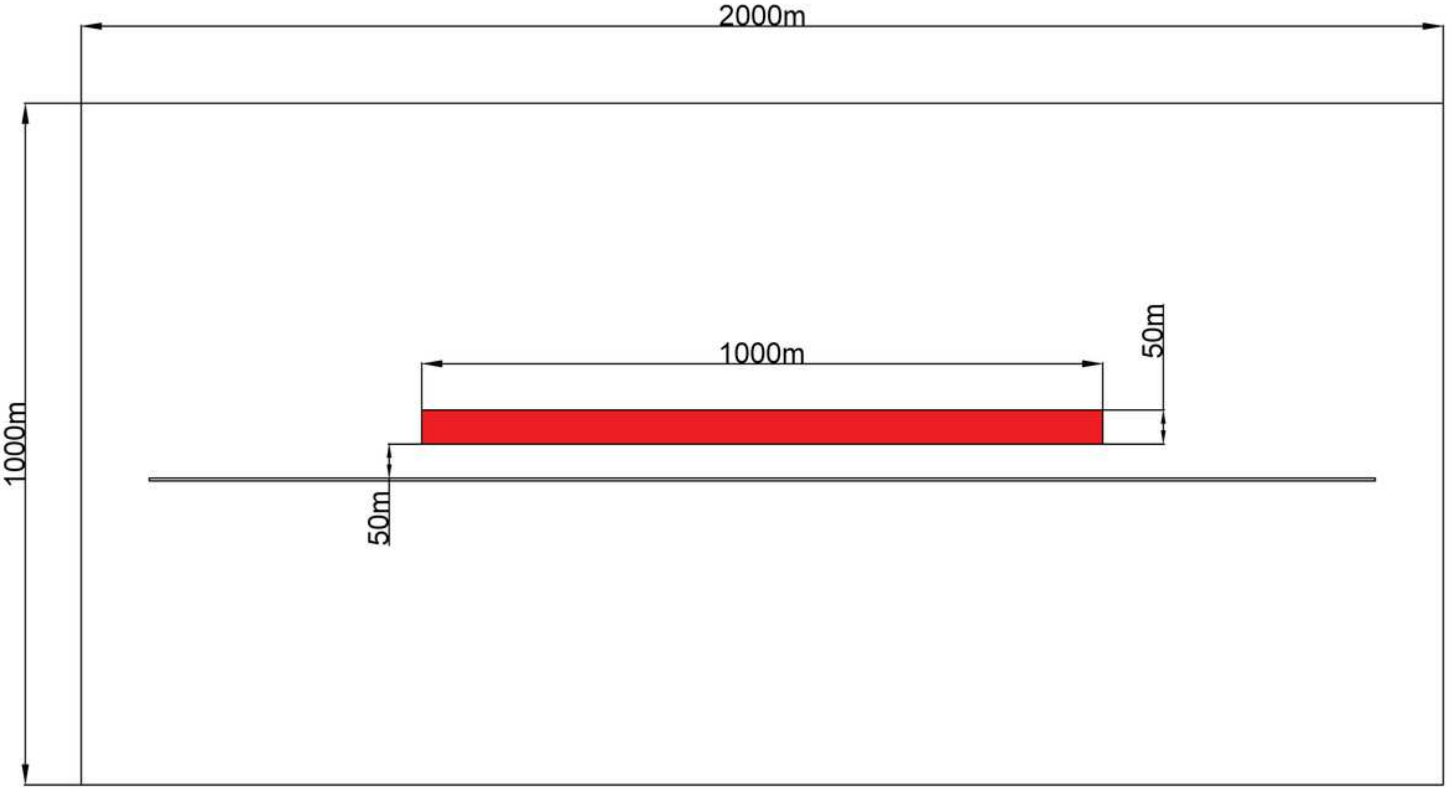

Figure 8

Numerical simulation model 4

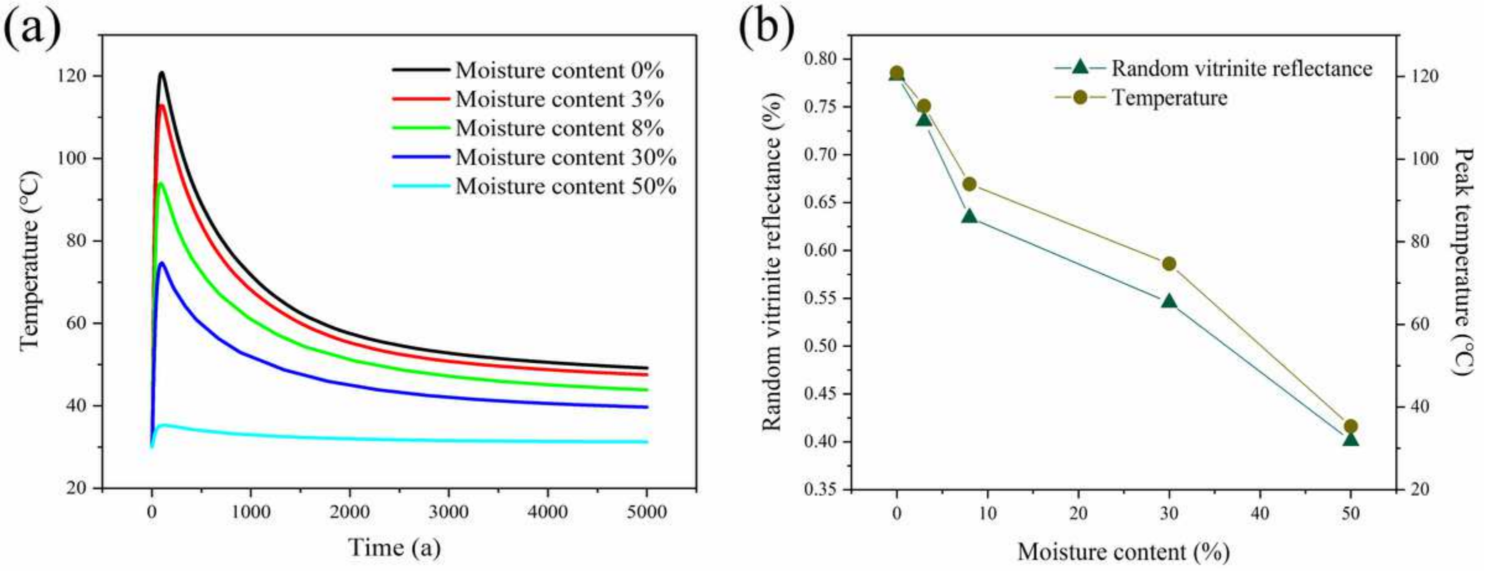

Figure 9

Coal temperature changes with time under different moisture content

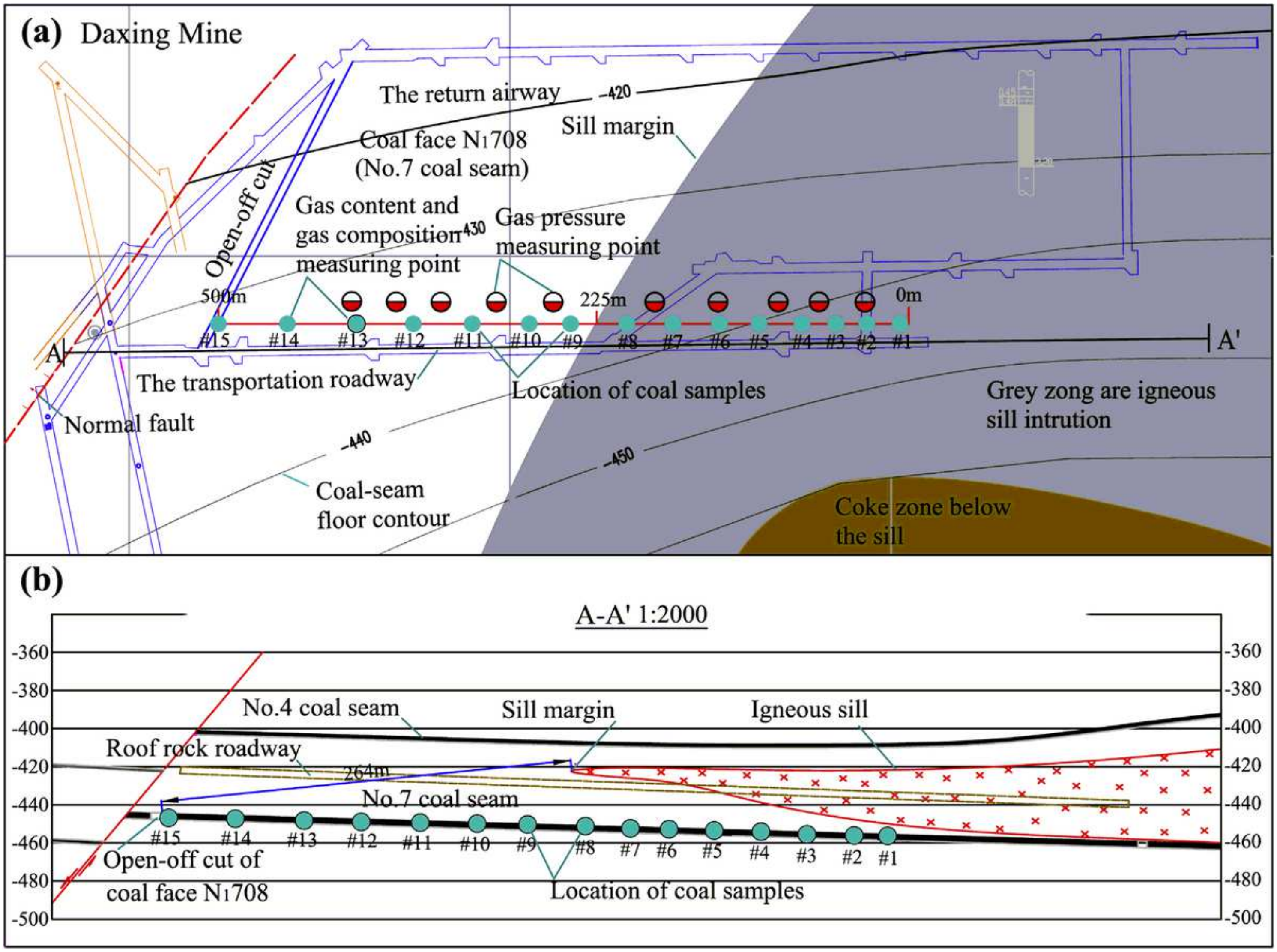

Figure 10

Location of N1708 coalface and distribution plan of sill in Daxing Mine

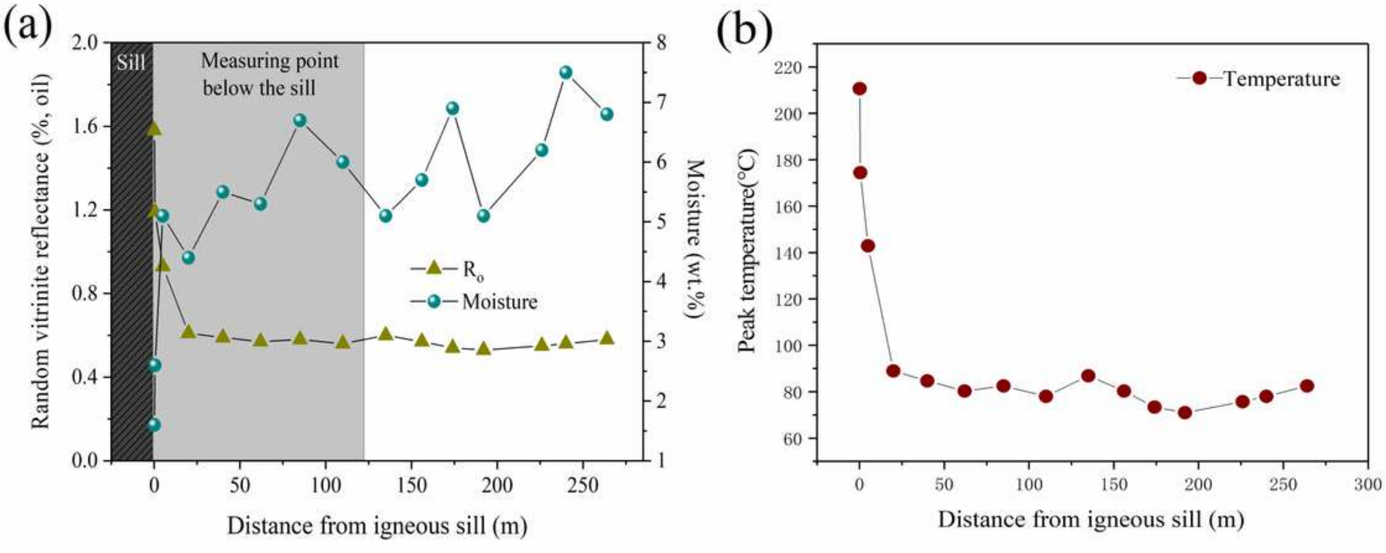

Figure 11

Relationships between moisture, Ro and the distance from igneous sill in Daxing Mine (a), relationship between coal peak temperature and the distance from sill (b)