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Numerical Simulation for Development Process of a Non-Volcanic Hydrothermal System Caused by a Permeable Fracture Zone

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ABSTRACT

Fukuoka City, in Fukuoka Prefecture, Japan, was hit by an earthquake measuring 7.0 on the Richter scale on 20 March 2005. The hypocenters of the main shock and the aftershocks exist in the offshore area of Fukuoka City and align with an extension of the Kego fault, one of the active faults in Fukuoka Prefecture. On the other hand, there are some low-to-moderate temperature hot springs along the Kego fault. Therefore, we conducted some numerical model simulations for development of a non-volcanic hydrothermal system caused by a high permeability fracture zone formed by seismic activity. We treated the Fukuoka earthquake as a model and set a permeable fracture zone that has a height of 13 km and exists 3 km below ground surface based on the hypocentral distribution. The width, extension and permeability of the fracture zone were set as parameters of the simulations. The results of the simulations up to 100,000 years after formation of the fracture zone show that relatively strong convection occurs in the fracture zone in the early stage of the development process, and changes to weaker one. And temperature homogenization in the zone and groundwater flow outside of the zone progress with time. The result of the simulation up to 1,000,000 years shows that weak convection spreads and cools over a wide area out of the fracture zone. Therefore, it is inferred that a non-volcanic hydrothermal system will be formed after formation of a permeable fracture zone without any kind of special heat source, and the distributions of underground temperature and groundwater flow will change in the long term even if no hydrothermal feature appears just after the seismic events.

1. INTRODUCTION

In recent years, there have been some examples of the strong earthquakes in the area, which had been considered as non-volcanic and aseismic, in Japan. A series of earthquakes called "2005 Fukuoka Prefecture Western Offshore Earthquakes" (the main shock of M_{JMA} 7.0 on 20 March 2005) is one of those earthquakes. After the main shock, many aftershocks including the largest aftershock of MJMA 5.8 on 20 April 2005 have occurred in a zone, which extends in a direction of NW-SE for about 30 km and aligns with an extension of Kego fault that is one of the active faults in Fukuoka Prefecture (Figure 1). On the other hand, there are some hot springs along the Kego fault (e.g., Futsukaichi Hot Springs in Chikushino City and Hakata Hot Springs in Fukuoka City). These hot springs are classified into non-volcanic hydrothermal system and are thought to be formed by the activity of Kego fault (Fujimitsu et al., 2006). Therefore, we tried to evaluate the feasibility of non-volcanic hydrothermal system development at a newly fractured area by using the settings of the Fukuoka Earthquakes as a model case.

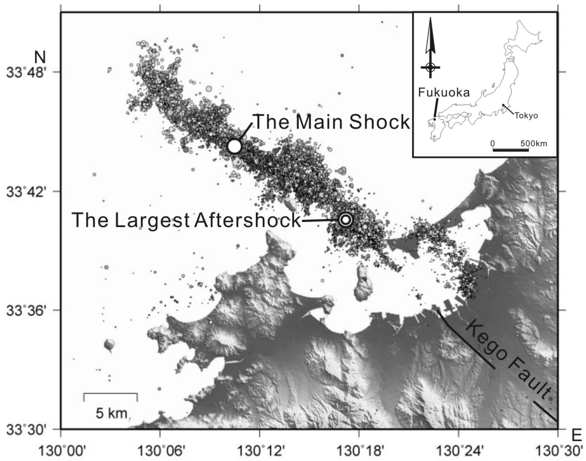

Figure 1: Epicenters of the Fukuoka Earthquakes from 20 March 2005 to 27 September 2006. The location of the Kego fault in this figure is based on Karakida et al. (1994)

2. NUMERICAL SIMULATION

Initially, we constructed a conceptual model for a non-volcanic hydrothermal system, and then performed some numerical simulations based on the conceptual model.

2.1 Conceptual Model

In this study, we set a simplified scenario, namely, a vertical fracture zone was formed in a homogeneous and isotropic granite body by a series of earthquakes. The size of the fracture zone was fundamentally based on the hypocentral distribution of the Fukuoka Earthquakes, but the width and the extension were treated as parameters (Figure 2).

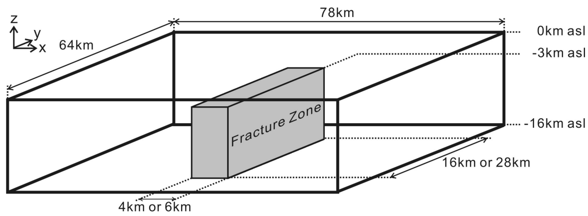

Figure 2: Conceptual subsurface structure of a non-volcanic hydrothermal system in this study

2.2 Numerical Model

We adopted HYDROTHERM (Hayba and Ingebritsen, 1994) Ver. 2.2 for the numerical modeling. The modeling area shown in Figure 2 was divided into 24 (x-direction) × 24 (y-direction) × 16 (z-direction) blocks (Figure 3). The properties of the granite body and the fracture zone are listed in Table 1, and hydraulic and thermal conditions at each boundary of the modeling area are indicated in Table 2.

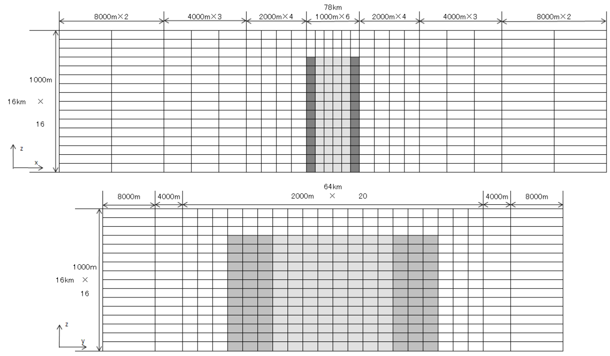

Figure 3: Block layout of the numerical model (upper: x-z slice, lower: y-z slice, colored blocks: fracture zone)

Table 1. Thermal and Hydraulic Properties of the Rocks for the Numerical Model.

	Granite body	Fracture zone
Heat capacity (J/kg K)	840	840
Density (kg/m^3)	2700	2200
Porosity (-)	0.02	0.15
Permeability (mD)	0.1	1, 10, 100
Thermal conductivity (W/m K)	2.1	2.1

Table 2. Boundary Conditions for the Numerical Model.

	Hydraulic	Thermal
Top	1.013×10^5 Pa	17 °C
Lateral	Hydrostatic pressure	0.038 or 0.029 K/m
Bottom	Impermeable	80 or 60 mW/m^2

The top boundary is a ground surface and is set at sea level, so the temperature and the pressure are fixed to the annual mean air temperature of Fukuoka and the standard atmospheric pressure, respectively. We considered two cases of heat flow at the bottom (80 and 60 mW/m^2). The two cases of initial temperature and pressure distribution are calculated by using the geothermal gradient of 0.038 K/m (in the case of 80 mW/m^2) or 0.029 K/m (60 mW/m^2), and hydrostatic pressure corresponding to the temperature distribution. And the temperatures and pressures on the lateral boundaries are fixed to the initial distribution.

Eight simulation patterns were generated by combinations of the heat flow values and the dimensions of the fracture zone (A1 - A4 and B1 - B4 in Table 3). Moreover, three values of the fracture zone permeability (Table 1) were applied in every simulation pattern.

Table 3: Simulation Patterns by Combinations of the Parameters.

Heat flow at the bottom		80 mW/m^2		60 mW/m^2	
Dimensions of the fracture zone		Width		Width	
		6 km	4 km	6 km	4 km
Extension	28 km	A1	A2	B1	B2
	16 km	A3	A4	B3	B4

3. SIMULATION RESULTS

The numerical simulation results for two simulation periods are shown in the following subsections mainly on a slice, which is located at the center of the fracture zone and is orthogonal to the strike direction of the zone (Figure 4).

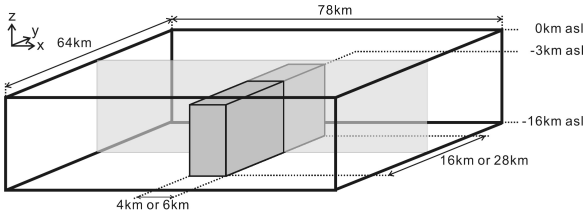

Figure 4: Location of the x-z slice for indication of the numerical simulation results (a gray vertical plane) in Figures 5 – 14 and 18

3.1 Simulation Period of 100,000 Years

We simulated the development of the hydrothermal system up to 100,000 years after formation of the fracture zone when we expected that the system would be in a steady state. To begin with, we calculated the model with no fracture zone, and confirmed that no hydrothermal development was observed in both cases of the heat flow (Figure 5).

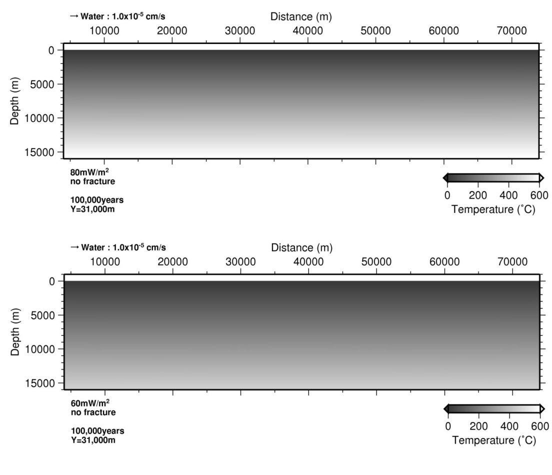

Figure 5: Temperature distribution and flow pattern on the x-z slice at 100,000 years from the initial condition with no fracture zone (upper: 80 mW/m^2, lower: 60 mW/m^2). No flow occurs in both cases

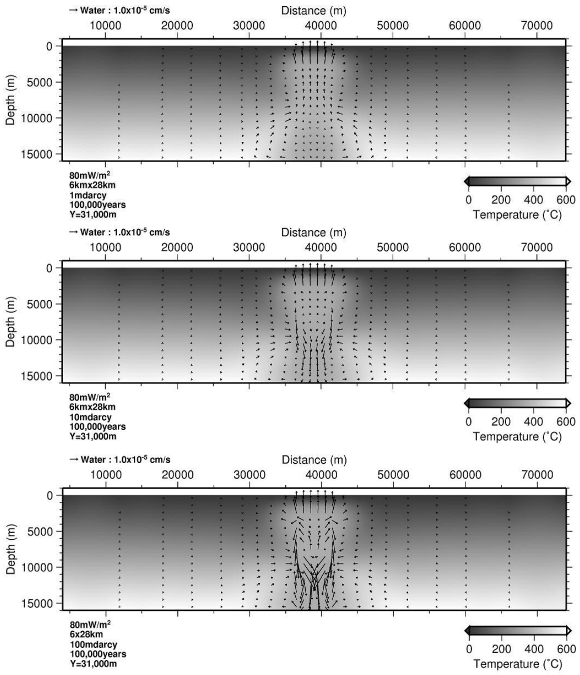

Figure 6: Temperature distribution and flow pattern on the x-z slice at 100,000 years after formation of the fracture zone in Pattern A1 (upper: 1 mD, middle: 10 mD, lower: 100 mD)

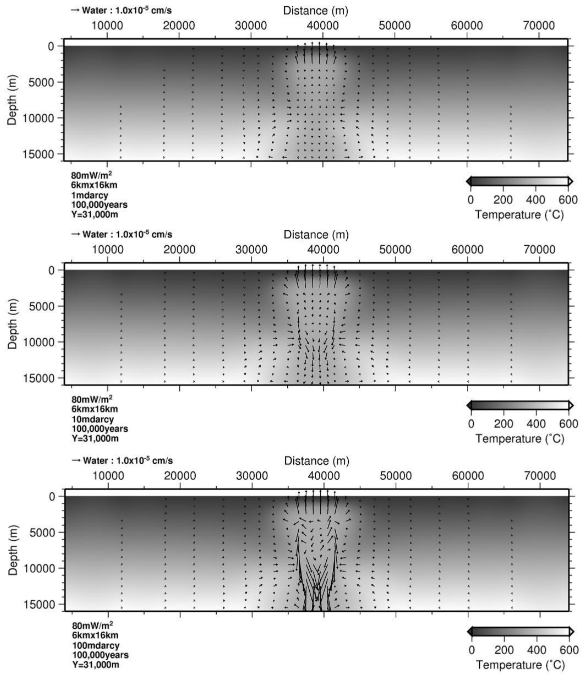

Figure 8: Temperature distribution and flow pattern on the x-z slice at 100,000 years after formation of the fracture zone in Pattern A3 (upper: 1 mD, middle: 10 mD, lower: 100 mD)

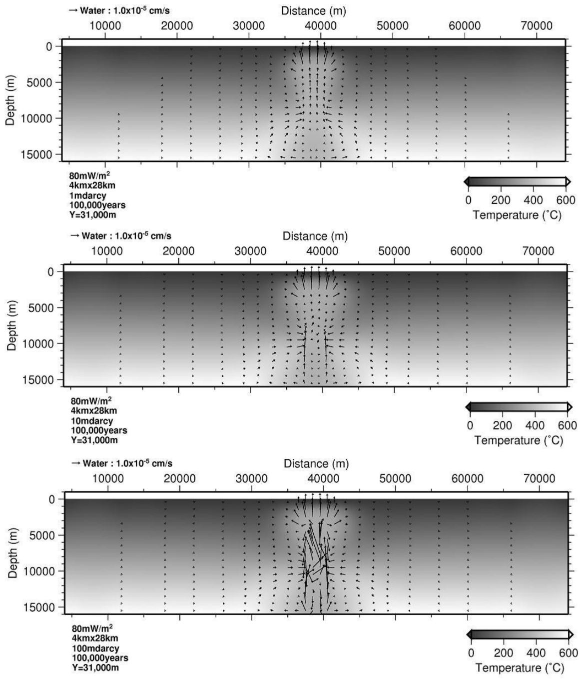

Figure 7: Temperature distribution and flow pattern on the x-z slice at 100,000 years after formation of the fracture zone in Pattern A2 (upper: 1 mD, middle: 10 mD, lower: 100 mD)

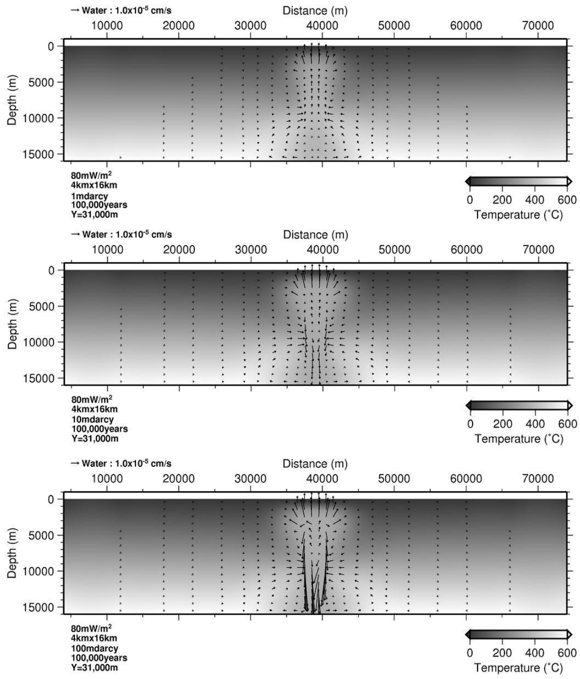

Figure 9: Temperature distribution and flow pattern on the x-z slice at 100,000 years after formation of the fracture zone in Pattern A4 (upper: 1 mD, middle: 10 mD, lower: 100 mD)

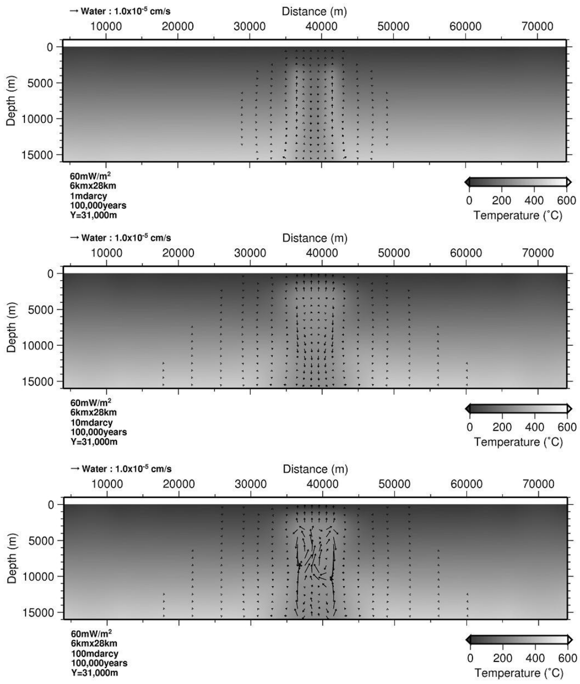

Figure 10: Temperature distribution and flow pattern on the x-z slice at 100,000 years after formation of the fracture zone in Pattern B1 (upper: 1 mD, middle: 10 mD, lower: 100 mD)

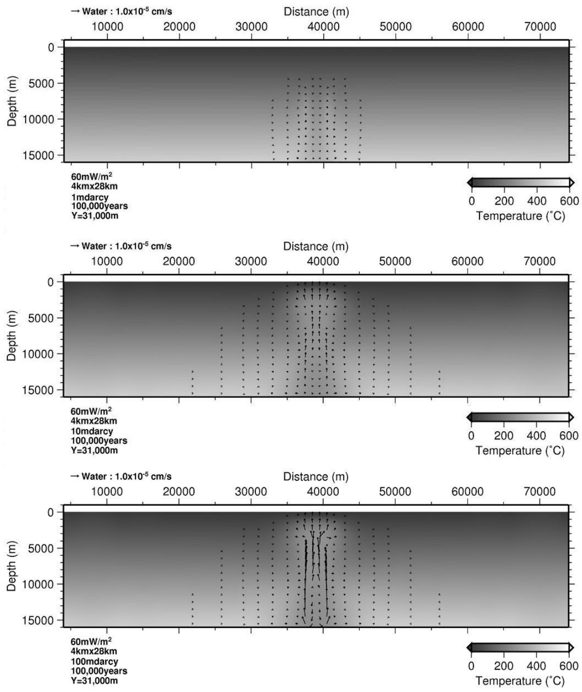

Figure 11: Temperature distribution and flow pattern on the x-z slice at 100,000 years after formation of the fracture zone in Pattern B2 (upper: 1 mD, middle: 10 mD, lower: 100 mD)

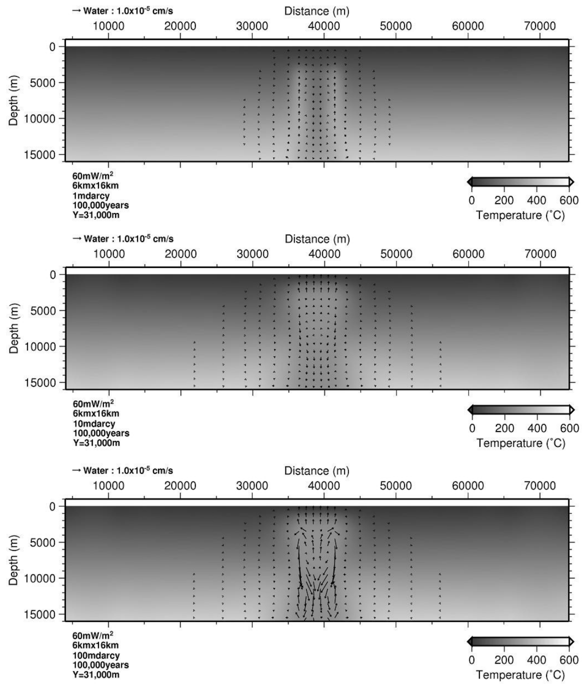

Figure 12: Temperature distribution and flow pattern on the x-z slice at 100,000 years after formation of the fracture zone in Pattern B3 (upper: 1 mD, middle: 10 mD, lower: 100 mD)

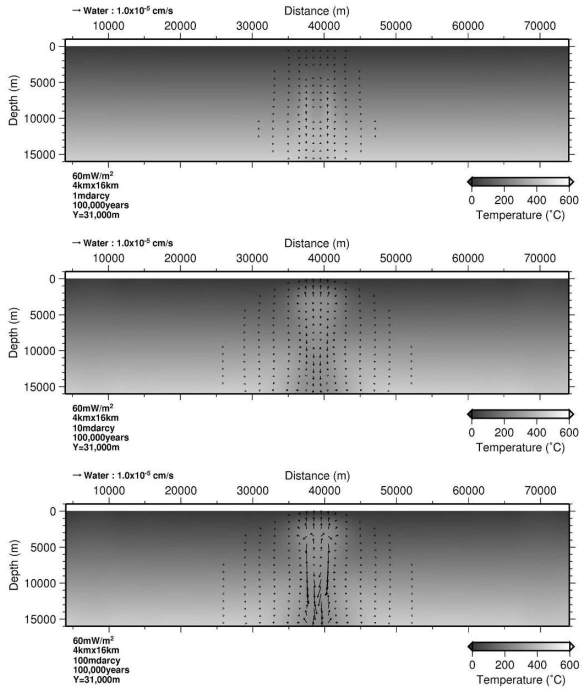

Figure 13: Temperature distribution and flow pattern on the x-z slice at 100,000 years after formation of the fracture zone in Pattern B4 (upper: 1 mD, middle: 10 mD, lower: 100 mD)

And once the fracture zone had been formed, hydrothermal convection occurred in all of the simulation patterns (Figures 6 – 13). Especially, some upward flow occurred at the shallower part above the fracture zone. This result means that some hydrothermal feature may appear at the ground surface.

According to the results of the simulation, the higher the heat flow is and the more permeable the fracture zone is, the earlier the hydrothermal convection in the fracture zone reaches the steady state. On the other hand, the temperature distribution in the fracture zone does not homogenize after 100,000 years in the case of the heat flow of 60 mW/m^2 (Patterns B1 - B4) with the permeability of 1 mD (the upper figures of Figures 10 – 13).

Figure 14 indicates an example of temporal change of temperature distribution and flow pattern. Relatively strong convection had occurred in the fracture zone in the early stage of the development process, and changed to weaker one. And temperature homogenization in the zone and groundwater flow outside of the zone progressed with time. There had been no upward flow above the fracture zone in the early stage, but the flow became prominent in the developing process of the hydrothermal system.

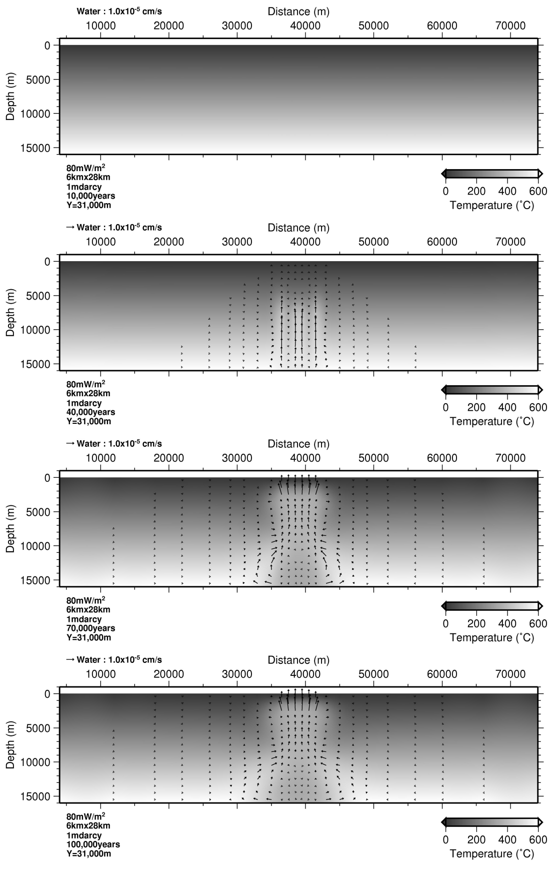

Figure 14: Temperature distribution and flow pattern on the x-z slice in the case of 1 mD of the fracture zone in Pattern A1 (10,000, 40,000, 70,000 and 100,000 years after formation of the fracture zone from upper to lower)

In order to examine the influence of the extension size of the fracture zone, another display slice was set at the center and along the strike direction of the zone (Figure 15).

The simulation results on the x-z slice shown in Figure 4 indicate that the development rate of the convection in the wider fracture zone is faster than the narrower one although the effect of the extension is not obvious (Figures 6-13). A comparison between Figures 16 and 17 also shows the similar development rate on the y-z slice. However, these results are different in number of convection cell. The size of the convection cell is about the same.

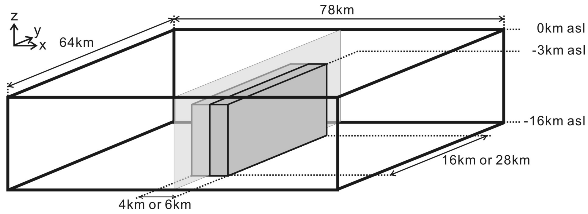

Figure 15: Location of the y-z slice for indication of the numerical simulation results (a gray vertical plane) in Figures 16 and 17

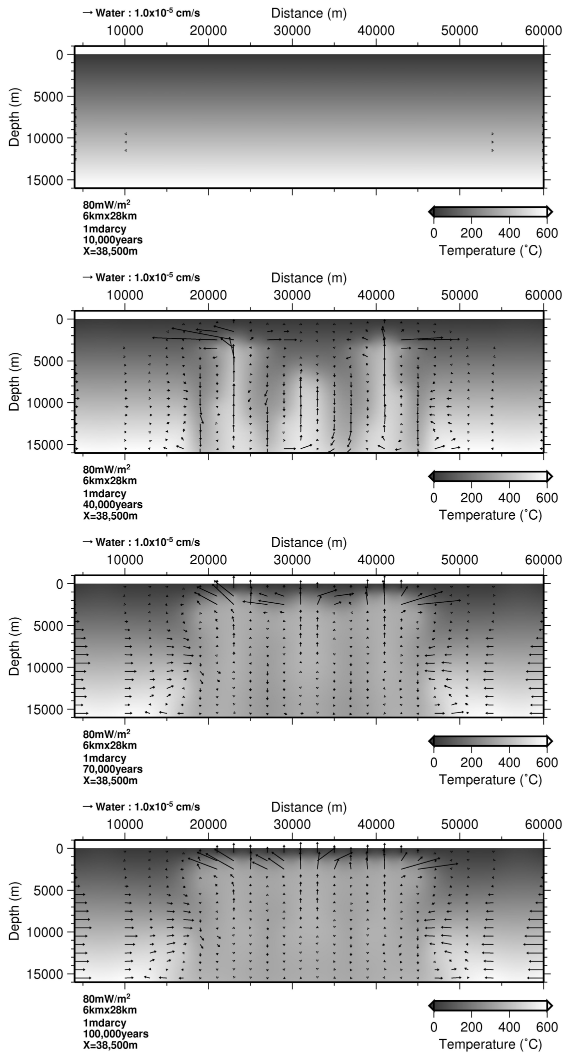

Figure 16: Temperature distribution and flow pattern on the y-z slice in the case of 1 mD of the fracture zone in Pattern A1 (10,000, 40,000, 70,000 and 100,000 years after formation of the fracture zone from upper to lower)

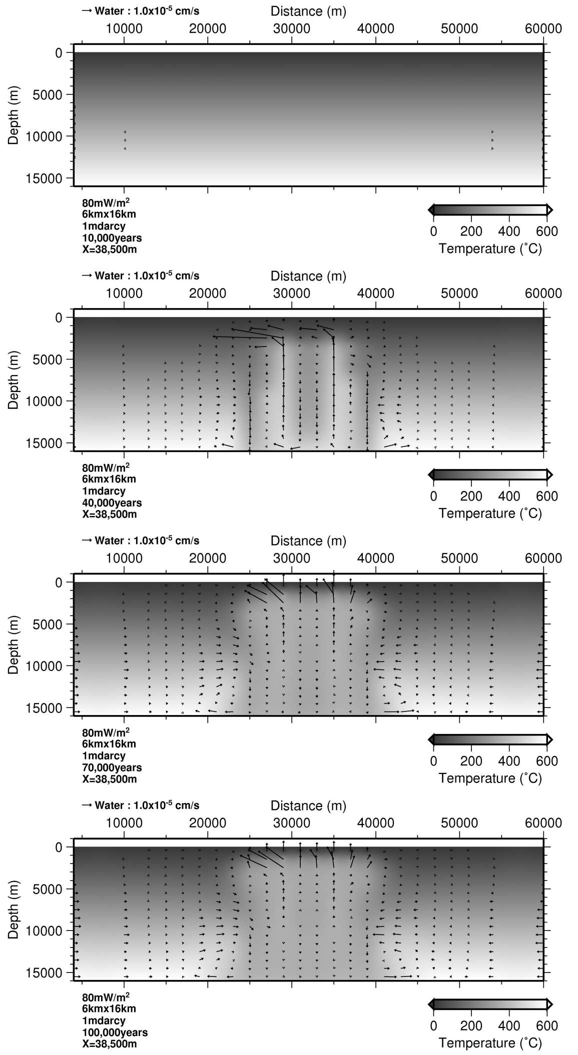

Figure 17: Temperature distribution and flow pattern on the y-z slice in the case of 1 mD of the fracture zone in Pattern A3 (10,000, 40,000, 70,000 and 100,000 years after formation of the fracture zone from upper to lower)

3.2 Simulation Period of 1,000,000 Years

The results of the simulation up to 100,000 years indicated the developing groundwater flow outside of the fracture zone although the temperature in the fracture zone has already been homogenized. Therefore, we conducted the simulation for one case (Pattern A1, 10 mD) up to 1,000,000 years.

The result of the simulation (Figure 18) shows that weak convection has spread and cooled over a wide area out of the fracture zone. And the upward flow above the fracture zone, which had been active until the simulation result of 400,000 years, altered to the downward flow after the simulation result of 700,000 years.

According to these results, it is inferred that a non-volcanic hydrothermal system will be formed after formation of a permeable fracture zone without any kind of special heat source, and the distributions of underground temperature and groundwater flow will change in the long term even if no hydrothermal feature appears just after the seismic events.

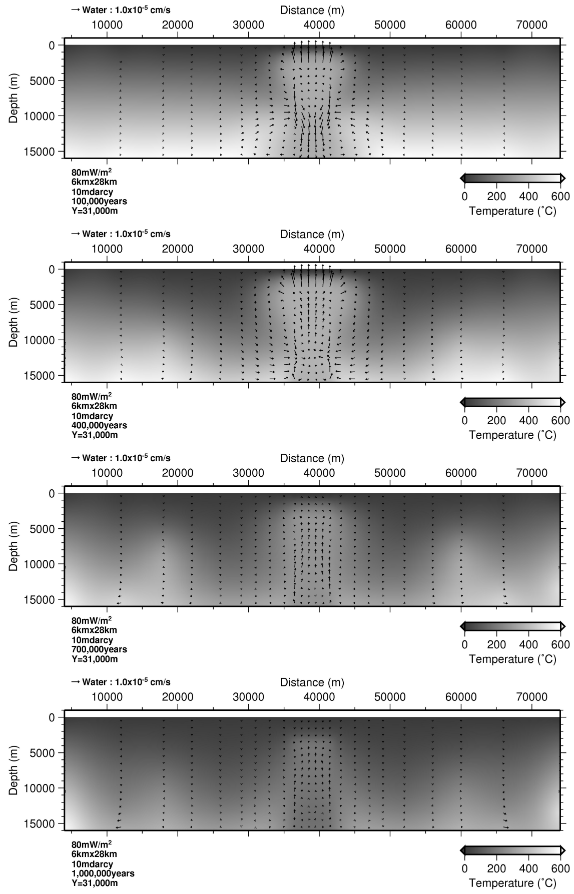

Figure 18: Temperature distribution and flow pattern on the x-z slice in the case of 10 mD of the fracture zone in Pattern A1 (100,000, 400,000, 700,000 and 1,000,000 years after formation of the fracture zone from upper to lower)

CONCLUSIONS

We conducted some numerical model simulations for development of a non-volcanic hydrothermal system caused by a permeable fracture zone formed by seismic activity. The results of the simulations up to 100,000 years after formation of the fracture zone show that the higher heat flow and the wider and more permeable fracture zone accelerate the development of the hydrothermal system in the fracture zone, and that relatively strong convection occurs in the zone in the early stage of the development process, and changes to weaker one. Additionally, temperature homogenization in the zone and groundwater flow outside of the zone progress with time. The result of the simulation up to 1,000,000 years shows that weak convection spreads and cools over a wide area out of the fracture zone. Therefore, it is inferred that a non-volcanic hydrothermal system will be formed after formation of a permeable fracture zone without any kind of special source, and the distributions of underground temperature and groundwater flow will change in the long term even if no hydrothermal feature appears just after the seismic events.

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