

# Natural State Model of the Kotamobagu Geothermal System, North Sulawesi, Indonesia

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# Natural State Model of the Kotamobagu Geothermal System, North Sulawesi, Indonesia

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## Keywords

Natural state model, numerical simulation, geothermal reservoir, Kotamobagu, Indonesia

## ABSTRACT

A three-dimensional numerical reservoir modeling of the Kotamobagu hydrothermal system was carried out. A natural state model of Kotamobagu was obtained by conducting simulations by changing parameter values of permeability, heat and mass recharges. The results of simulation were calibrated to temperature data from hot spring of Liberia and Bongkudai villages. The developed model confirmed that mass flows upward from the bottom layer to the surface, then travels laterally. The dominant mass flows through faults running northeast and to southwest. The mass from the bottom of Mt. Muayat flows to the southwest through the andesitic lava and the pumice tuff layers. Further, at the surface of Liberia and Bongkudai area, 3kg/s of mass is being discharged to the hot spring, the portion of mass flows through the fault to the southwest and continues further to the west. In the southwest area, mainly in Bakan, there is no mass discharge corresponding to related modeling blocks. Simulation results implies that the source of heat and mass discharge at the Bakan hot spring is not derived from Mt. Muayat, but from some source below sedimentary formation.

## 1. Introduction

The Kotamobagu geothermal field is located in North Sulawesi Province, Indonesia, 200 km to the southwest of Manado city, capital of the province as shown in Figure 1.

The field has been proved to be one of the geothermal prospects in Indonesia (Hochstein and Sudarman, 2008). Pertamina Geothermal Energy Co. (PT. PGE) conducted reconnaissance and feasibility studies in Kotamobagu and concluded that the field has high potential for power generation. In 2011 two wells, KTB-B1 & KTB-B2 were drilled at Liberia village on the southern slope of Mt. Muayat by Pertamina Geothermal Energy Co. Production

tests at these wells were not successful because of low temperature, 160°C at the well bottom, for both wells.

Geological setting of Kotamobagu is shown in Figure 2.

Tertiary and the Quaternary rocks are distributed in the area. Tertiary sedimentary rocks consist of shale and sandstone with intercalations of limestone and chert, and are overlain by the Tertiary and Quaternary volcanic rocks. The Tertiary volcanic rocks are the products of old volcano and consist of andesitic to rhyolitic breccia, tuff, lava to form Mt. Simut and Mt. Lembut located to the north of Mt. Muayat. The Quaternary volcanic rocks consist of the Ambang volcanic. Pumice tuff and andesitic tuff breccia are the products of the old Ambang Volcano. The young Ambang volcanic rocks con-

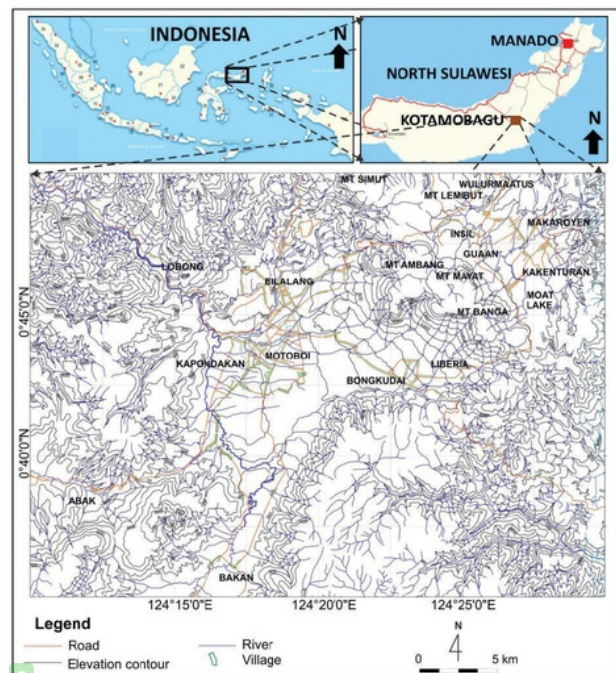


Figure 1. Location map of study area.

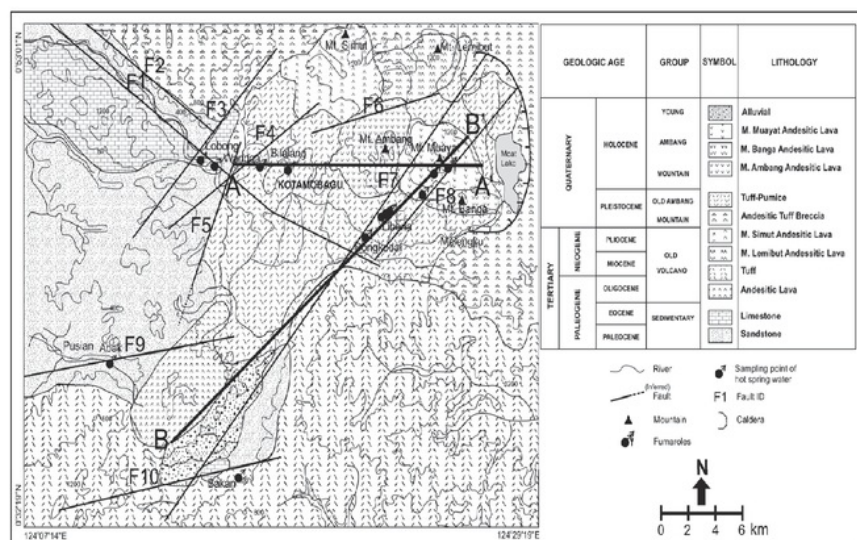


Figure 2. Geological map of Kotamobagu (Modified from geological map of Kotamobagu by Pertamina Geothermal Energy Co. 2005).

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 consist of andesitic lava and volcanic breccia, overlain asymmetrically by Mt. Muayat, Mt. Banga, and Mt. Ambang.

Figure 2 shows geological map with fault distributions in Kotamobagu. Faults of F1 and F2 in Kotamobagu strike north-west to southeast, faults F3, F4, F5, F7 and F8 northeast to southwest and faults F6, F9 and F10 west to east. A fault system with a direction of west to east crossing the sedimentary rocks controls the occurrence of hot springs at Pusian and Bakan with temperatures of 87.0°C, located to the southwest and south of Kotamobagu. Another fault system with a direction of northwest to southeast controls the hot springs at Lobong (water temperature of 70.0°C) in the east of Kotamobagu (Pertamina Geothermal Energy Co., 2005). Fumaroles on top of Mt. Muayat located in the east of Kotamobagu have a high temperature (102.7°C) and are associated with faults running northeast to southwest (Pertamina Geothermal Energy Co., 2005). This fault system also controls an appearance of hot spring at Liberia village as well as Bongkudai village (water temperatures ranging from 43.4°C to 52.2°C).

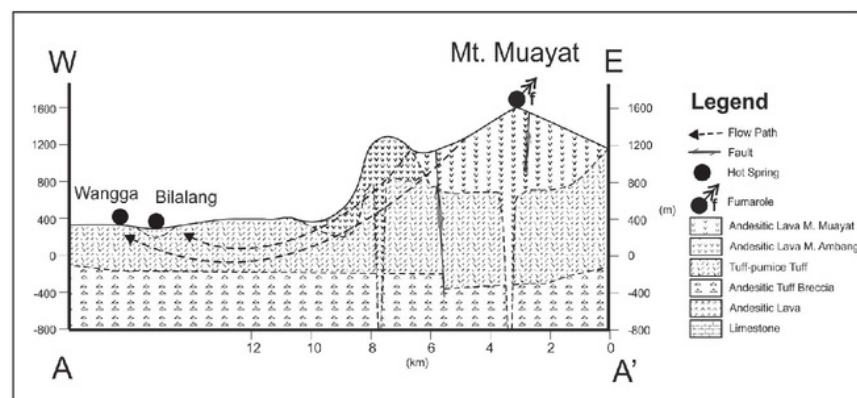


Figure 3. Cross section of A-A'. Conceptual model of hydrothermal system, the water flows from east to west through the fault and the high permeable formations.

The aim of this study is to develop a numerical model of the Kotamobagu geothermal system. Natural state simulation was conducted with this model for reproducing temperature profiles of the system and natural discharges of the hot springs. The effects of fault systems on the formation of hot springs located in the southern part of Kotamobagu were investigated.

## 2. Conceptual Model

A conceptual model of hydrothermal system of Kotamobagu geothermal field was developed as shown in Figures 3 and 4 (Riogilang et al., 2012)

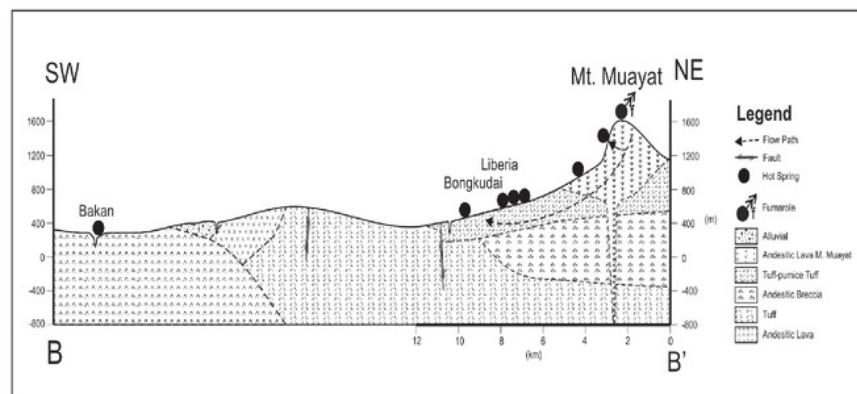


Figure 4. Cross section of B-B'. Conceptual model of hydrothermal system, the water flows from NE to SW through the fault and the high permeable formations.

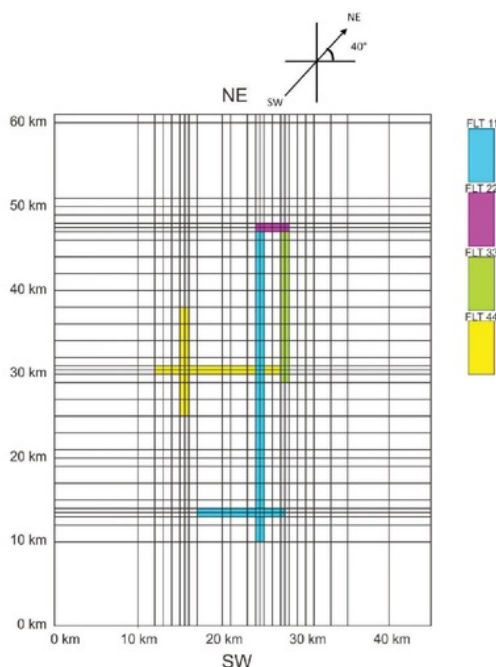
Figure 3 shows a cross section A-A' in Figure 2 with meteoric water recharging from Mt. Muayat and flowing to the west through the shallow aquifer. The pathway of water in the shallow aquifer may be channeled in the pumice tuff formation of high permeability or along permeable fault before discharging as hot springs in the lower elevation at Bilalang and Wangga villages.

Figure 4 shows a cross section of B-B' in Figure 2 with meteoric water recharging from Mt. Muayat and flowing through a shallow aquifer at low temperature to the

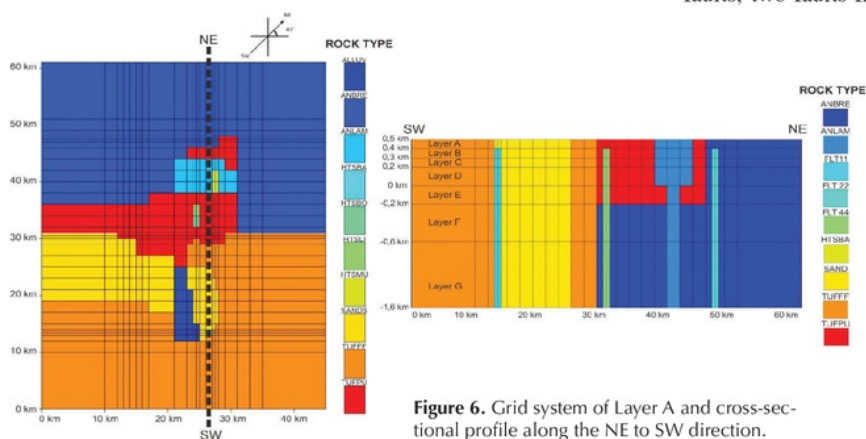


**Table 1.** Fault name, rock type for grid model and the rock formation.

Fault ID (Figure 2)	Rock Type	Rock Formation
F7, F10	FLT11	F7 (NE to SW): andesitic tuff breccia, Mt. Muayat andesitic lava, Mt. Ambang andesitic lava, pumice tuff, tuff, sandstone, and alluvial F10 (W to E): tuff, alluvial, limestone and sandstone
Caldera	FLT22	Andesitic tuff breccia
F8	FLT33	F8 (NE to SW) pumice tuff and Mt. Muayat andesitic lava
F1, F2, F3, F4, F5	FLT44	F1 (NW to SE): pumice tuff F2 (NW to SE): andesitic tuff breccia and sandstone F3 (NE to SW): andesitic tuff breccia, limestone and sandstone F4 (NE to SW): andesitic tuff breccia, tuff pumice, and sandstone F5 (NE to SW): andesitic tuff breccia, tuff pumice, and sandstone



**Figure 5.** Distributions of rock types for fault system. High permeable rock types of FLT11, FLT22, FLT33, and FLT44 are assigned to faults in Figure 2.



**Figure 6.** Grid system of Layer A and cross-sectional profile along the NE to SW direction.

south-west. This continues to the hot springs discharging at lower elevations of the slope of Mt. Muayat such as Liberia and Bongkudai villages.

### 3. A three Dimensional Numerical Model

A numerical modeling was derived using the TOUGH2 simulator (Pruess, 1999). TOUGH2 is a numerical simulator for non-isothermal flows of multi-component, multiphase fluids in one, two and three-dimensional porous and fractured media (Pruess, 1999). In this study the author used the thermodynamic module of EOS1 which has capabilities to simulate

water single component for both single phase and two phases under non-isothermal condition.

#### 3.1. Numerical Model

A grid system was developed on the basis of the geological and structural data and fluid flow patterns of Kotamobagu as follows:

Fault systems depicted in Figure 2 seem controlling the fluid flow in the reservoir as a hydrothermal system. Thus, rock types of high permeability were assigned to their faults system for a grid model. Names of rock types assigned for faults are FLT11, FLT22, FLT33 and FLT44 as shown in Table 1 and Figure 5.

Fault F7 with direction of northeast (NE) to southwest (SW) which lies near Mt. Lemibut and continues to Bakan village plays as the main fault. This fault is assigned with rock type FLT11. Fault F10 running from east (E) to west (W) crossing the main fault in the SW area is also cuts the formations of andesitic tuff breccia, Mt. Muayat andesitic lava, Mt. Ambang andesitic lava, pumice tuff, tuff, sandstone, and alluvial from NE to SW and tuff, alluvial, limestone and sandstone from west to east.

Fault F8 crossing Mt. Muayat from NE to SW at the east of main fault is assigned with rock type FLT33. This fault cuts the formations of pumice tuff and Mt. Muayat andesitic lava.

There is a caldera structure in the eastern part of Kotamobagu as shown in Figure 2. Faults F7 and F10 seem to be originated with this caldera. This caldera is assigned with rock type FLT22.

The NW part of this field, which is mainly composed of limestone, sandstone and pumice tuff formations has five different faults; two faults from NW to SE (F1 and F2) that are crossed by three other faults (F3, F4 and F5) from NE to SW. These faults are treated into one single rock type in the model; FLT44. Rock type FLT44 represents the formation of pumice tuff type of rocks. Faults F7 and F10 is running from NW to SE, and is crossing F7 near Bongkudai area.

The Bakan hot spring is located on Fault 7 and discharges to the surface. This fault may play a flow path of high permeability for hot water flowing south west from Mt. Muayat. Hot springs at Liberia and Bongkudai are also located on Fault 7 as shown in Figure 6. The hot springs at the cliff Mt. Muayat and on the summit of Mt. Muayat are located on Fault F8.

### 3.2. Grid System and Layers

A grid system is developed in the area of 45 km NW to SE and 60 km NE to SW of Kotamobagu down to 1.6 km depth below the sea level (b.s.l.) as shown in Figure 6.

The model consists of 7 horizontal layers, with thickness intervals of 100 m, 200 m, 400 m and 1000 m. A total of 14 rock types on the basis of lithology and fault distribution are used as shown in Table 2.

**Table 2.** Rock types in each layer of the model.

Layer	Rock type	Thickness (m)
A	ALLUV, ANLAM, ANBRE, TUFFPU, TUFFF, SANDS, HTSLI, HTSBO, HTSBA, HTSMU.	100
B	ALLUV, ANLAM, ANBRE, TUFFPU, TUFFF, SANDS, FLT11, FLT22, FLT33, FLT44.	100
C	ANLAM, ANBRE, TUFFPU, TUFFF, SANDS, FLT11, FLT22, FLT33, FLT44.	100
D	ANLAM, ANBRE, TUFFPU, TUFFF, SANDS, FLT11, FLT22, FLT33, FLT44.	200
E	ANLAM, ANBRE, TUFFPU, TUFFF, SANDS, FLT11, FLT22, FLT33, FLT44.	200
F	ANLAM, ANBRE, TUFFF, SANDS, FLT11, FLT22, FLT33, FLT44.	400
G	ANLAM, ANBRE, TUFFF, SANDS, FLT11, FLT22, FLT33, FLT44.	1000

**Table 3.** Permeability values of the best model.

Rock Type	Permeability (m <sup>2</sup> )	
	k <sub>xy</sub>	k <sub>z</sub>
ATM	1×10 <sup>-10</sup>	1×10 <sup>-10</sup>
ALLUV	1×10 <sup>-12</sup>	1×10 <sup>-14</sup>
ANLAM	1×10 <sup>-15</sup>	1×10 <sup>-16</sup>
ANBRE	1×10 <sup>-15</sup>	9×10 <sup>-17</sup>
TUFFPU	1×10 <sup>-13</sup>	1×10 <sup>-14</sup>
TUFFF	1×10 <sup>-16</sup>	1×10 <sup>-17</sup>
SANDS	9×10 <sup>-17</sup>	9×10 <sup>-18</sup>
HTSLI	4×10 <sup>-12</sup>	4×10 <sup>-10</sup>
HTSBO	5×10 <sup>-12</sup>	5×10 <sup>-10</sup>
HTSBA	6×10 <sup>-12</sup>	6×10 <sup>-10</sup>
HTSMU	1×10 <sup>-12</sup>	1×10 <sup>-10</sup>
FLT11	5×10 <sup>-12</sup>	4.5×10 <sup>-14</sup>
FLT22	1×10 <sup>-11</sup>	1×10 <sup>-14</sup>
FLT33	3×10 <sup>-11</sup>	3×10 <sup>-13</sup>
FLT44	1.5×10 <sup>-11</sup>	1×10 <sup>-13</sup>

Three Layers of A, B, C with thickness of 100m and Layer D with 200 m are showing the study area from the surface to the sea level, Layers E, F, and G were assigned to area below sea level with thickness of 200 m, 400 m, and 1000 m respectively. Each layer has 660 grid blocks with various horizontal sizes ranging from 0.5 km x 0.5 km up to 10 km x 10 km.

The total number of grid blocks of the model is 4620. Hot springs of Mt. Muayat are present in the two blocks of 2 km x 1 km. Hot springs at Liberia and Bongkudai are located in each block of 2 km x 1 km. Hot spring at Bakan is located in a block of 1 km x 1 km.

Faults are represented with rock types of FLT11, FLT22, FLT33 and FLT44 with various length of several grids and with 1 km width of grid.

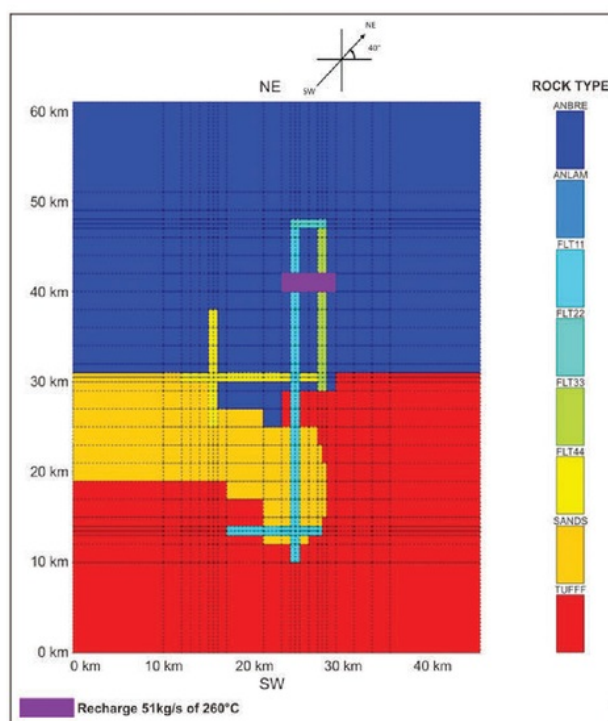
### 3.3. Rock Properties

Parameter values of density, porosity and specific heat were given as 2450 kg/m<sup>3</sup>, 0.1, and 900 J/kg C, respectively (Republic of Indonesia, and Japan International Cooperation Agency Economic Development Department (2006)). Permeability's were assigned to each of the grids on the basis of lithology, structure (fault and caldera) and zones of geothermal manifestation such as hot springs. The permeability values of rock types of the best model are summarized in Table 3.

### 3.4. Initial and Boundary Conditions

The initial condition of the model was assigned under an isothermal of 25°C and a hydrostatic pressure of 1 bar. The initial condition was obtained by executing the model without fluid recharges and fluid discharges in the system.

The boundary condition of the top layer of the model was assumed and specified as a single block of atmosphere, which was filled with water at a constant pressure of 1 bar and a constant temperature of 25°C. The lateral boundary of the model was set as impermeable to mass and adiabatic to heat. The bottom boundary was designated as impermeable by allowing 0.01 W/m<sup>2</sup> of heat flow. High temperature of 260°C mass recharge of the total flow rate of 51kg/s was specified at eight blocks at the center of Mt. Muayat area of the bottom layer: Layer G, blocks: 473, 474, 475, 476, 477, 478, 479, 480 as shown in Figure 7.



**Figure 7.** High temperature fluid of 260°C at 51 kg/s was assigned at 8 grid blocks in purple in the bottom layer of Layer G.

## 4. Results and Discussion

On the basis of exploration data and the developed conceptual model, rock parameters and permeability distribution were assigned. The best natural state model was obtained by conducting runs of model in a try and error manner by changing parameter values such as permeability, heat and mass recharges. The results of simulation were calibrated to the temperature of hot springs.

Temperature of hot springs at Liberia (43.4-52.2°C) and Bongkudai villages (46.4°C) were used as the measurement to calibrate the simulated results for introducing the best model as shown in Figure 8a.



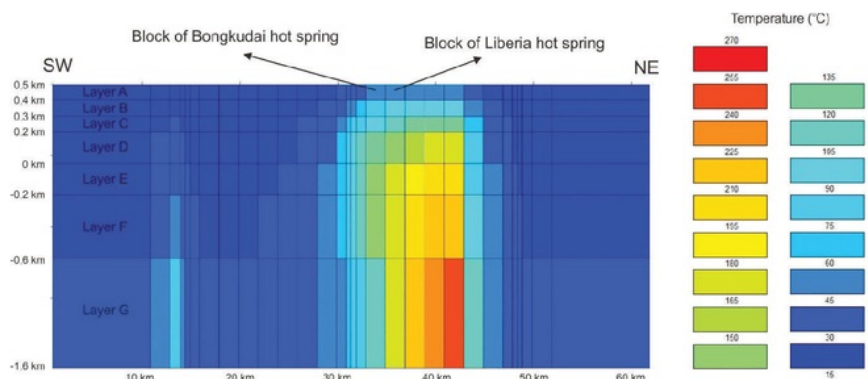


Figure 8a. Vertical cross section of temperature along the main fault from SW to NE and blocks of Liberia and Bongkudai hot springs.

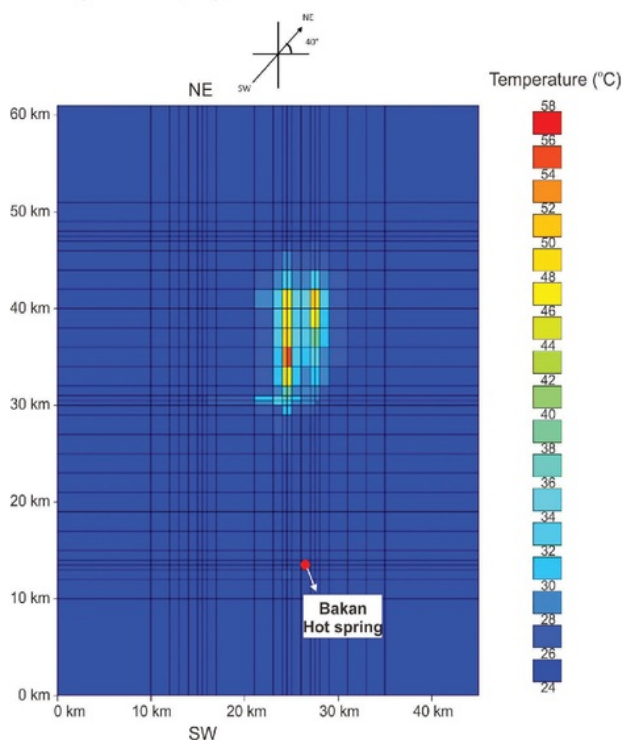


Figure 8b. Temperature distribution of the natural state model in Layer A.

The high temperature fluid of 260°C below of Mt. Muayat flows from the bottom layer to the lateral and vertical directions. In the southwestern area of the model mainly in Layers A and B temperature is about 25°C.

Figure 8b, the Bakan hot spring indicated by red circle is located in the southwest area of model. The temperature of natural state simulation for this block show 25°C that is much lower than the measured temperature of hot spring water 87.0°C discharging naturally in Bakan. This supports the idea that the heat source of hot spring in Bakan is from the source different from Mt. Muayat (not designated in this).

The mass rises from the bottom layer to the surface in horizontal and vertical directions as shown by flow vectors in Figures 9a and 9b.

Figure 9a shows distributions of flow vectors in the cross section of Fault 7.

The mass from Mt. Muayat flows to southwest through andesitic lava and pumice tuff formations. At the surface of Liberia and Bongkudai areas, 3 kg/s of mass are being discharged to the hot springs. Further, this mass is flowing in Layer B and that below to the southwest which is through the pumice tuff, tuff, sandstone and alluvial formations.

The dominant mass is flowing through the Faults F7 and F8 to the northeast and to the southwest as shown by flow vectors in Figure 9b.

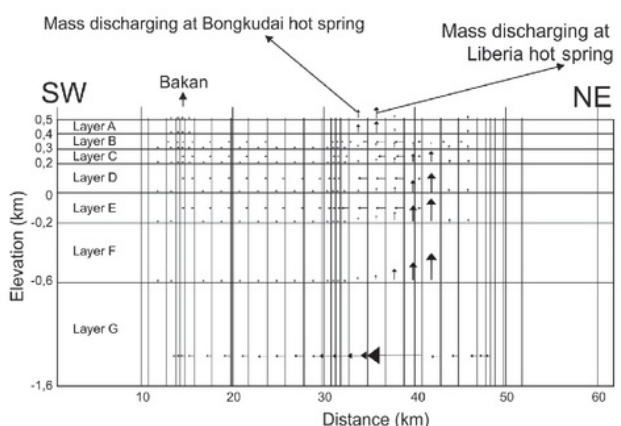
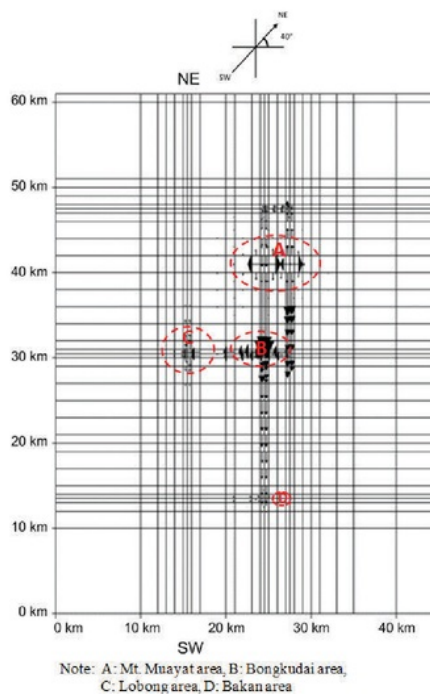


Figure 9a. Distribution of flow vectors along vertical cross section Fault F7.



The mass that flows through Fault 7 to the southwest is divided into two directions at Bongkudai area that part of it flows through F7 to the southwest and another portion through Faults F1 and F2 to the west. The mass that flows through these faults to the west is di-

Figure 9b. Distribution of flow vectors at bottom layer (Layer G).

vided again into two flow directions at the end of the Faults F1 and F2 mainly at Lobong area. A portion of mass flows to the northeast through Faults F3, F4 and F5 or high permeable section of pumice tuff formation to Wangga and Bilalang areas, and other portion flows to the southwest through Faults F3, F4 and F5 or a high permeable section of pumice tuff to Kapondakan area.

Figure 9c shows the southwestern area at the end of Fault F10, 1 kg/s of mass is discharging in an alluvial formation.

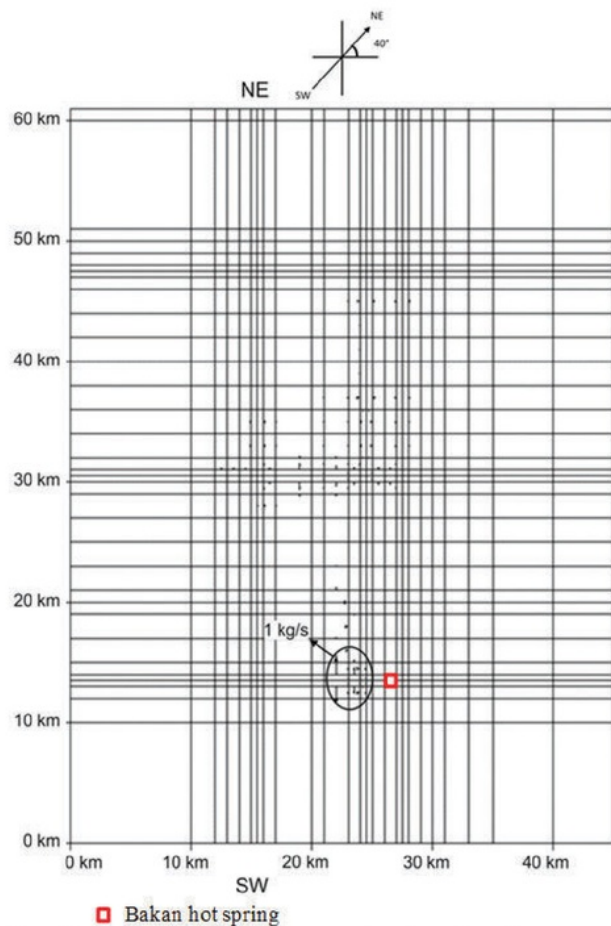


Figure 9c. Distribution of flow vectors at surface layer (Layer A).

The grid where Bakan in Layer A is located presents in tuff formation of low permeability. In Bakan, there is no mass dis-

charge corresponding to the designated model block. This result suggests the source of mass discharge at the Bakan hot spring is not from Mt. Muayat, but might come from another source below sedimentary formation which requires further investigation.

### 5. Conclusions

A three-dimensional numerical reservoir model of the Kotamobagu hydrothermal system was derived. The results can be summarized as follows:

1. A natural state model of the Kotamobagu geothermal field was developed.
2. The heat and mass flows upward from depth at Mt. Muayat, then flows to the surface in horizontal and vertical directions controlled by faults or stratigraphy.
3. The dominant mass flows through Fault F7 and F8 is to the northeast and to the southwest.
4. The source of heat and mass discharges at the Bakan hot spring is not derived from Mt. Muayat.

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