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THE SIMULTANEOUS TRANSFER OF HEAT AND FLUID IN THE TOKACHI PLAIN, HOKKAIDO, JAPAN

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ABSTRACT

The present paper discusses the temperature field formed by thermal advection in the Tokachi groundwater basin as modeled by the finite element method (FEM).

The Tokachi Plain is a tectonic basin located in southeast Hokkaido, the northernmost island of Japan. The plain is divided into two blocks: an uplifting eastern block and a subsiding western block or main area of the plain, via the Tokachi central fault.

Groundwater temperatures to a depth of 300m, groundwater potential distribution and stable isotopic ratios of water in the Tokachi Plain all show that the groundwater is mainly recharged in the surrounding piedmont areas of Mt. Daisetsuzan and the Hidaka Mountains. On the other hand, groundwater of the main area converges radially to the lower places, blocked by the relatively impermeable eastern block and discharges into the Tokachi River.

Hot water is located around 1000m depth in the western block, while it exists at a few hundred meters depth in the eastern block. A few hypotheses have been proposed for the heat source. One is that hot water heated in Mt. Daisetsuzan volcanic zone flows into the groundwater basin. Based on the groundwater temperature distribution, however, this contribution is considered to be slight. The second hypothesis is that groundwater in the western block is heated by an unknown high temperature rock mass which exists at depth in the eastern block, higher temperature zone influenced by the Akan volcanic area.

On the other hand, the temperature field formed by groundwater flow must be taken into account. Groundwater temperatures are lower than average in recharge areas, and higher than average in discharge areas. Based on this principle, groundwater flow in the Tokachi Plain is interpreted by using three dimensional FEM models. Firstly, ordinary terrestrial heat flow is given for the bottom boundary condition. Additionally, higher heat flow cases are analyzed in order to estimate the contribution of the underlying high temperature rock mass. The result shows that thermal advection is the primary factor, although the second hypothesis may contribute to some extent.

1. INTRODUCTION

The Tokachi Plain is a sedimentary basin located in southeast Hokkaido, the northernmost island of Japan (Figure 1). The plain is bordered by Mt. Daisetsuzan in the north and the Hidaka Mountains in the west, and is divided into eastern and western blocks by the Tokachi central fault extending from north to south. The Tokachigawa Spa exists near the point where the Tokachi River, flowing from northwest to east through the center of the plain, crosses the fault. The temperature gradients in the western block are nearly equal to the Japanese average value, 3 ± 1℃/100m, while those in the eastern block are higher, that is, 5 to 6℃/100m (Geological Survey of Hokkaido, 1985). It has vaguely been inferred that the high temperature gradients at the eastern block are caused by an unknown high temperature rock mass existing at depths and that the groundwater heated in Mt. Daisetsuzan volcanic zone flows into the depths of the western basin. Recently, there has been increased interest in the groundwater flow system and the heat source beneath the Tokachi Plain, because the hot spring temperatures and discharge amounts have decreased.

On the other hand, if the spa is located in discharge area of the groundwater flow system (Toth, 1963), advective heat transfer effects must be taken into account. Groundwater temperatures are lower than average in recharge areas, and higher than average in discharge areas at the same depth (Domenico and Palciauskas, 1973). Figure 2 shows a cross section of a simplified groundwater basin. Figure 2(a) and 2(b) show the distribution of groundwater potential and temperature, respectively. The annual mean temperature zone and groundwater table are given at the upper boundary, while a heat flux is specified along the lower boundary. No groundwater flow boundaries are specified along both sides and lower boundary. The figure indicates that groundwater flow disturbs temperature distribution.

2. HYDROGEOLOGY OF THE TOKACHI PLAIN

The Tokachi Plain has been formed since the Pliocene epoch. The plain was divided into two blocks by the Tokachi central fault in the latter half of the Pleistocene epoch: the uplifting eastern block and the subsiding western block (or main area of the plain). The eastern block is considered to be no groundwater flow boundary for the western block. Table 1 shows the simplified hydrogeology of the Tokachi Plain. Because the Pre-cretaceous and the Miocene layers are thought to be almost impermeable, the extent of groundwater flow is mostly limited to the overlying layers.

3. EVALUATION OF GROUNDWATER FLOW SYSTEM IN THE TOKACHI PLAIN

3.1 Analysis of Stable Isotopic Ratios

The analysis of stable isotopic ratios was carried out by Ikeda *et al.*(1998) to estimate the groundwater flow system in the Tokachi Plain. The results are as follows:

·The origin of groundwater in the western Tokachi Plain including hot springs is meteoric. Moreover, an isotopic shift caused by the volcanic effect was not found.
·The altitude effect on stable isotopic ratios shows that the groundwater in the deeper aquifer has mainly been recharged in the higher areas.
·The main origin of hot springs in Obihiro, central city of the Tokachi Plain, and the Tokachigawa Spa is precipitation falling on Mt. Daisetsuzan and the Hidaka Mountains, based on the altitude effect of stable isotopic ratios.
·The horizontal distribution of stable isotopic ratios is shown in Figure 3. The groundwater recharged in piedmont areas of the plain is concentrated radially to the point where the Tokachi River crosses the Tokachi central fault.

3.2 Groundwater Potential Distribution

Figure 4 shows the groundwater potential distribution in 1985 (drawn from Oka(1990)) in the cross section A-A'. It shows that the groundwater discharged at the Tokachigawa Spa comes from the piedmont area of the Hidaka Mountains in the west etc., agreeing with the estimation by stable isotopic ratios, except that the groundwater potential drop by pumping is found in the Nukanai Formation in Figure 4.

4. GROUNDWATER TEMPERATURE DISTRIBUTION AT 50M IN DEPTH

Groundwater temperature distribution at 50m in depth in the western block of the Tokachi Plain was drawn to investigate the advective heat transfer effects of the groundwater flow described in the previous section. Figure 5 shows the relationships between temperature and depth at the center of screens at each observed well to 300m depth. For the first approximation, using the mean temperature gradient, the plots in Figure 5 were converted into the temperatures at 50m in depth. The horizontal distribution is shown in Figure 6. Temperature is lower in the piedmont areas of Mt. Daisetsuzan and the Hidaka Mountains, and around the south boundary of the groundwater basin. It becomes higher toward the center of the plain. The advective effects of the groundwater flow were qualitatively clarified as consistent with the distribution of stable isotopic ratios (Figure 3). The consistency shows that the error caused by the temperature conversion is considered to be slight. This temperature distribution also suggests that the magma beneath Mt. Daisetsuzan volcanic zone hardly affects the groundwater basin.

5. TEMPERATURE ANALYSIS BY FEM

The FEM program was developed in order to simulate the temperature field of the Tokachi Plain. The program deals with three-dimensional thermal advection-dispersion analysis. The method and the results for the Tokachi Plain are shown as follows.

5.1 Method of Numerical Analysis

The governing equation describing the steady state groundwater flow may be written

$$\left(k_{ij}h_{,j}\right)_{,i} - q = 0 \tag{1}$$

where h is fluid potential, k_{ij} is the permeability tensor, and q is fluid flux. The groundwater velocity for the direction i can then be determined from

$$v_i = -k_{ij}h_{,i} \tag{2}$$

And the heat transport equation describing the steady state temperature distribution in a saturated porous medium is given:

$$\rho_w C_w v_i T_{,i} - \left(K_{avij}T_{,j}\right)_{,i} - \psi = 0 \tag{3}$$

where T is temperature, ρ_w is density of fluid, C_w is heat capacity of fluid, ρ_{av} is density of soil, C_w is heat capacity of soil, K_{avij} is the thermal conductivity tensor, and ψ is heat flux. In this method, local thermal equilibrium between the soils and the fluid is required.

The FEM program was developed using discrete model of the equations (1) and (3), which can analyze steady state temperature distribution. The governing equations of elements in matrix form are given:

$$\int_V [B]^T[k][B]dV\{h\} = \{q\} \tag{4}$$

$$\int_V \left\{\rho_w C_w [N]^T\{v\}^T[B] + [B]^T[K_{av}][B]\right\}dV\{T\} = \{\psi\} \tag{5}$$

where i is the imaginary unit, $[N]$ is the matrix of shape function, and $[B]$ is the matrix of derivative shape function. The vector of groundwater velocity is given:

$$\{v\} = -[k][B]\{h\} \tag{6}$$

In this analysis, quadratic elements are applied and numerical integration at eight points in an element is calculated. Firstly, the groundwater potential distribution is obtained in a steady state, and then the temperature distribution is calculated. This program is not fully coupled analysis. Therefore, fully coupled analysis that can include the convectional effect has been developed.

5.2 Conditions of Simulation of the Tokachi Plain

The extent of analysis is given in Figure 1. No groundwater or heat is allowed through the lateral boundaries. The upper boundary is the water table, and is set at the annual mean temperature. In addition, the lower boundary is the bottom of the Nukanai Formation with no groundwater flow and a constant heat flux, 5.0×10^{-2} W/m^2. The properties of the plain materials are shown in Table 2.

The modeled Tokachi Plain is divided into 41,580 elements (east-west 231 × north-south 12 × depth 15). Generally, an element on FEM should be similar to a cube in three-dimensional analysis, but in this case, that is impossible because of the large analytical extent. Hence east-west direction, in which the groundwater velocity is the fastest, or the advective effect is the largest, was divided into the tiniest pieces. In three-dimensional models the saving effects of computer capacity are much greater. Therefore, it can be said that such a weighted division is also useful for the object of analysis.

5.3 Results

Figure 7 shows the results of the simulation of the Tokachi Plain. Good consistency with the observed groundwater potential distribution was obtained (*cf.* Figure 4 and 7(a)) by applying the anisotropy of the aquifer, caused by the alternating beds of sand and impermeable layers. It shows that the heat is concentrated on the Tokachi central fault by the groundwater flow. The simulated temperatures were consistent with the observed temperatures at the points ① to ④ in Figure 8. Good agreement between simulated and observed temperatures suggests that the temperature distribution of the Tokachi Plain and the source of the hot springs are mainly explained by advection, or heat transfer by groundwater flow, without considering the particular heat source such as a high temperature rock mass. The observed temperature distribution around the Tokachigawa Spa in 1970s, however, includes the zone over 40℃ to a depth of 200m (Uragami, 1978), and in some wells, the observed temperatures were higher than simulated temperatures by about 10 ℃. Therefore, the case with the heat flux at the bottom of eastern block set at twice that of the western block was simulated (included in Figure 8). Since the temperature distribution of this case is consistent with the observed highest temperature distribution, there could be some effect due to a high temperature rock mass which may continue to the Akan volcanic zone (Okubo *et al.*, 1998).

In recent years, temperatures discharging of the hot springs in Obihiro and the Tokachigawa Spa have decreased. The temperature decrease in Obihiro is especially serious, and only one artesian spring source whose temperature exceeds 40℃ was present 1997. The groundwater potential distribution in Figure 4 suggests that the potential lowering in the Nukanai formation, the main aquifer of the hot spring, causes groundwater flow from the upper Ikeda formation to the Nukanai formation and the temperature lowering of the hot spring in the Nukanai formation. Therefore, groundwater management for the entire Tokachi Plain should be instituted. A partial management is unsatisfactory to preserve the groundwater flow system and springs in the plain.

6. CONCLUSION

The results of observations and analyses on the groundwater flow system in the Tokachi Plain are clarified taking advective effects into account:

- The stable isotopic ratios and groundwater potential indicate the origin of groundwater in the western block of the Tokachi Plain is meteoric. Moreover, the main origin of the groundwater in the Obihiro and the Tokachigawa Spa hot springs is precipitation falling on surrounding mountains such as Mt. Daisetsuzan and the Hidaka Mountains.
- The groundwater temperature at 50m in depth qualitatively clarifies that there is the advective thermal effect as consistent with the groundwater flow, and that the magma beneath the Mt. Daisetsuzan volcanic zone has little effect on the Tokachi groundwater basin.
- The present FEM model is suitable for quantitatively analyzing a regional groundwater flow system and temperature distribution.
- The groundwater temperature distribution in the Tokachi Plain is explained using ordinary heat flow and advection. Further, a major part of the temperature of the Tokachigawa Spa is also explained by the same reason, although some contribution of higher heat flow in the eastern block of the Tokachi Plain must be taken into account.
- Groundwater basin management for the whole Tokachi Plain should be instituted to preserve the groundwater flow system and the springs in the plain.

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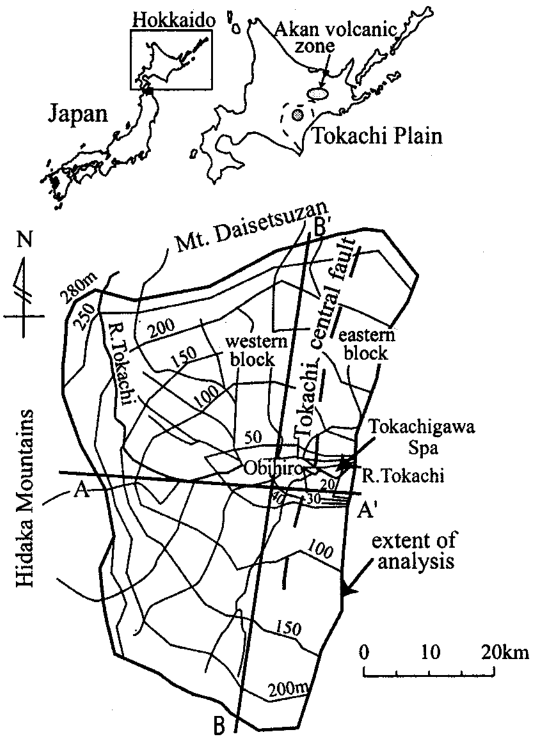

Figure 1. Location and groundwater table of the Tokachi Plain

Table 1. Hydrogeology of the study area

Geological age	Geological formation	Hydrogeology
Pleistocene	Shibusan formation Meto tuff	confining layer
	Osarushinai formation	confined aquifer
Pliocene	Ikeda formation Nukanai formation	confined aquifer
Miocene	Taiki formation Oikamanae formation	impersmeable basement
Pre-cretaceous	Hidaka supergroup	

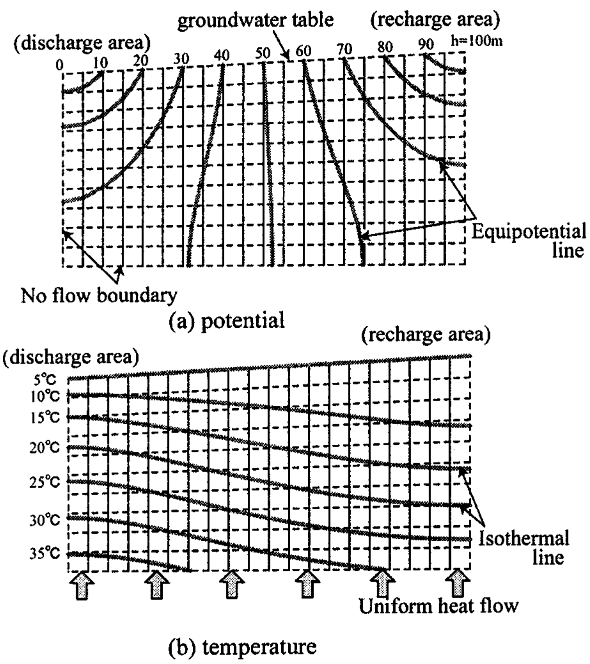

Figure 2. Goundwater potential and tmperature distribution in a groundwater basin

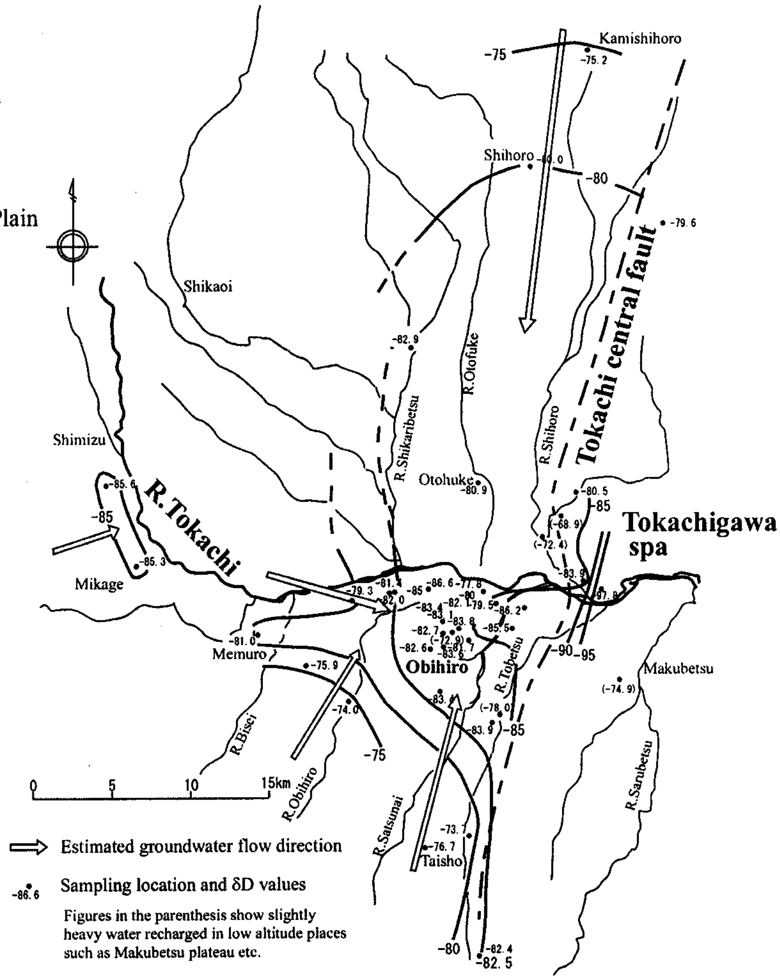

Figure 3. Stable isotopic ratio of deuterium distribution in the Tokachi Plain deep groundwater (Ikeda, 1999)

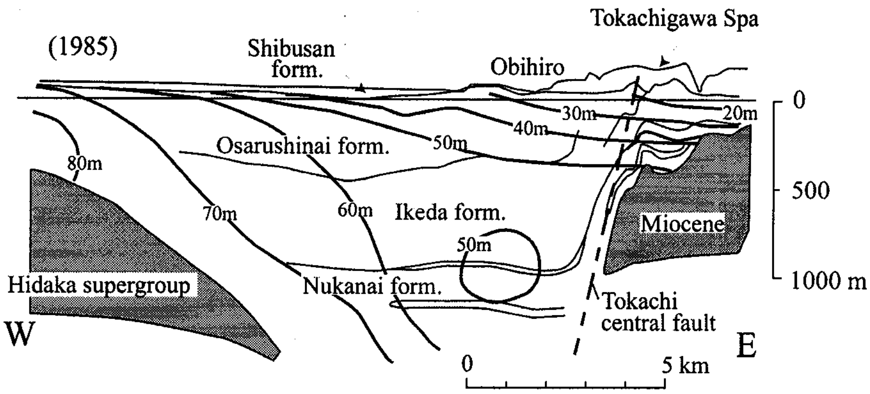

Figure 4. Groundwater potential distribution observed in 1985 in the cross section A-A'(Fig.7)
(Drawn based on Oka(1990)'s data)

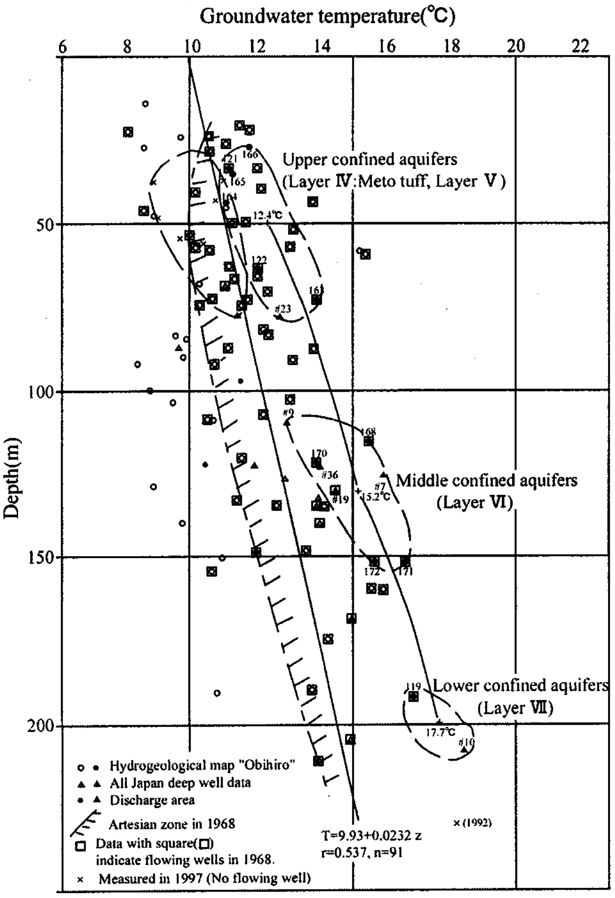

Figure 5. Relationships between groundwater temperature and depth

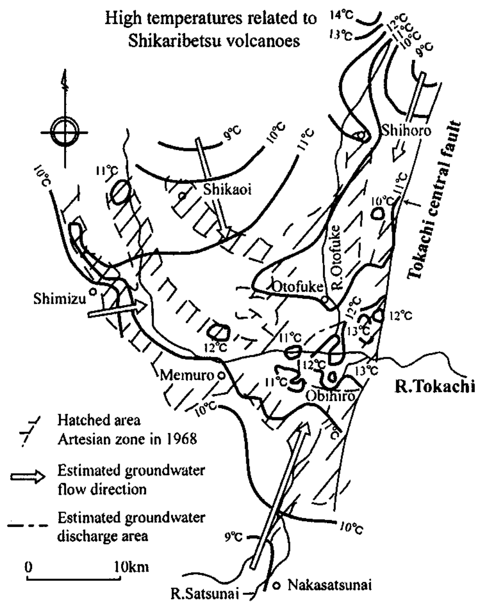

Figure 6. Distribution of 50m depth groundwater temperature

Table 2. Physical properties used in the simulation

Geological formation		density $\rho_w \times 10^3$ (kg/m^3)	horizontal permeability k_h(m/s)	vertical permeability k_v(m/s)
Shibusan formation		1.7	2.0×10^{-5}	2.0×10^{-8}
Osarushinai formation		1.7	5.0×10^{-5}	2.0×10^{-8}
Ikeda formation	1	1.8	1.7×10^{-6}	2.0×10^{-8}
	2	1.8	1.7×10^{-5}	2.0×10^{-8}
Nukanai formation		1.8	5.0×10^{-6}	2.0×10^{-8}
Miocene, Pre-cretaceous		2.0	1.0×10^{-8}	1.0×10^{-8}

specific heat C_w=2.0×10^3(J/kg m^3)
thermal conductivity K_{av}=1.34×10^3(W/m ℃)

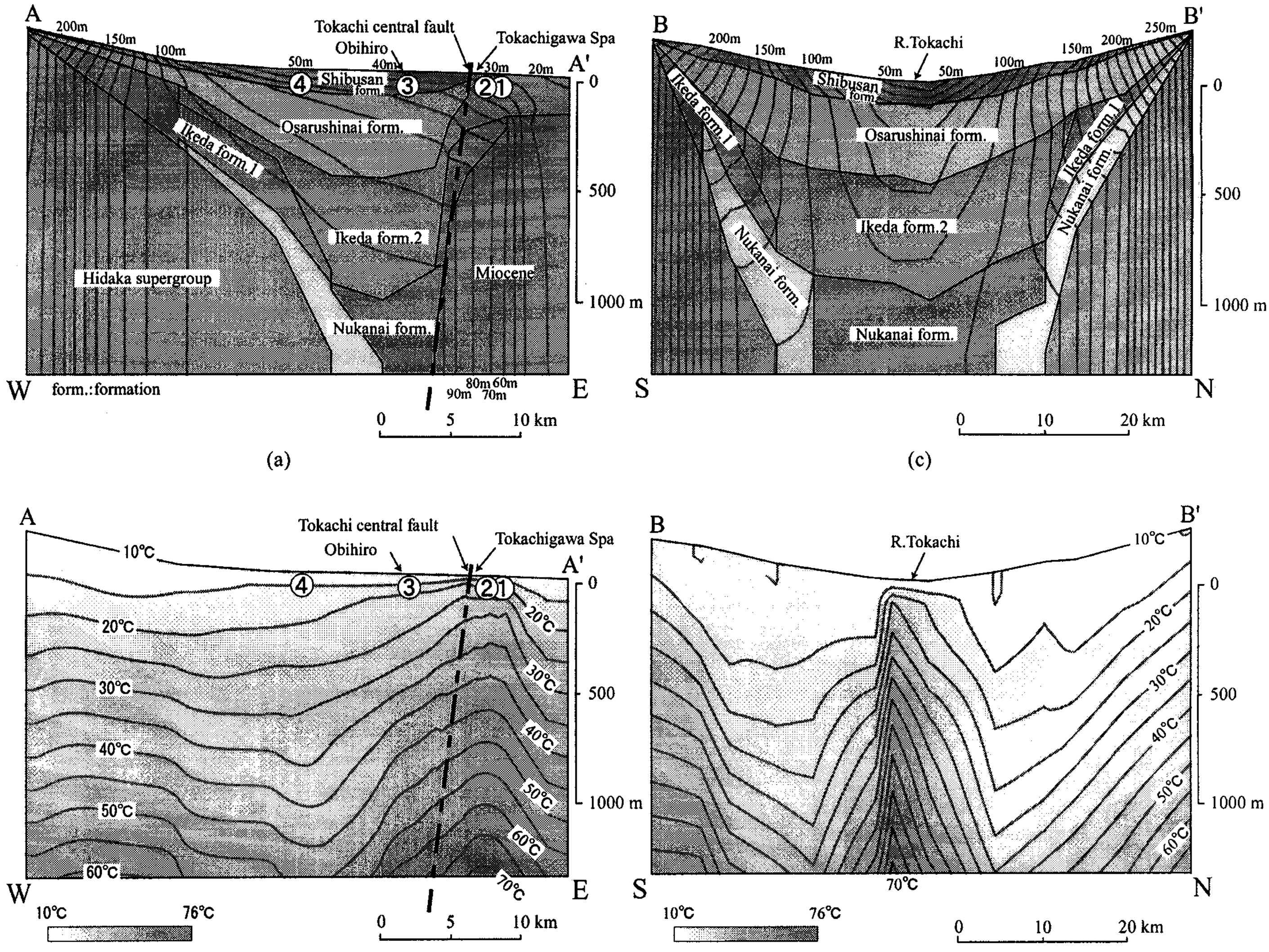

Figure 7. Result of the simulation: (a)groundwater potential(A-A'); (b)temperature distribution(A-A'); (c)groundwater potential(B-B'); (d)temperature distribution(B-B')

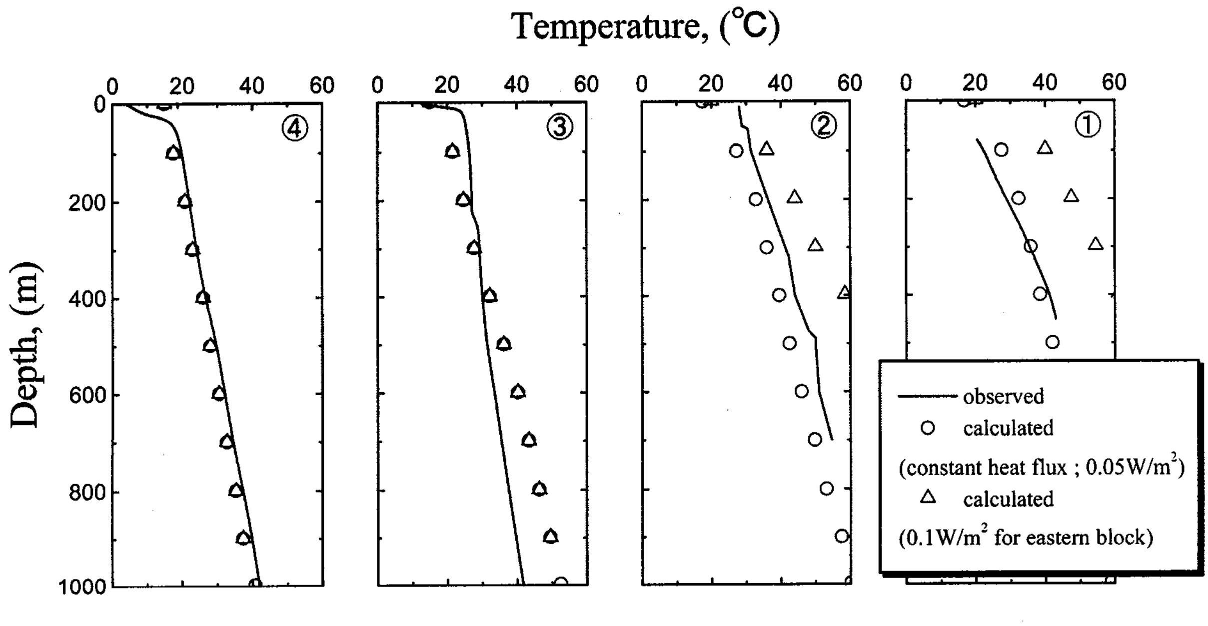

Figure 8. Comparison between observed and simulated temperatures (The location of ① to ④ is shown in figure 7)