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Geological Structure and Underground Temperature in the Nobi Plain, Central Japan

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ABSTRACT

A study on the relationship of geothermal gradient and geological formation is performed using borehole data in the Nobi plain, central Japan. For ground-coupled heat pumps, it is better to understand the underground distribution of the effective thermal conductivity to search the areas where the deep boreholes are not necessary for heat exchange, because drilling cost in the initial cost of the geothermal heat pumps is high in Japan. In some boreholes, geothermal gradient is higher in conglomerate layers. This may suggests that groundwater flows and thermal convection is performed in conglomerate layers. In some other boreholes, however, geothermal gradient is lower in conglomerate layers. This cannot be explained by thermal convection in conglomerate layers. These indicate that thermal convection is performed in conglomerate layers but groundwater flow is also important for the formation of underground thermal distribution.

1. INTRODUCTION

In the five-year period from 1990 to 1995, carbon dioxide emissions in the Japanese industrial sector remained relatively flat, while there were increases of approximately 16% in the residential and commercial sector and transportation sector (http://www.meti.go.jp/english/about meti/data/a226201e.html). To meet the present increase in energy demand, the energy supply is supported by fossil fuels such as petroleum, which contributes to the already serious problem of global warming through carbon dioxide emissions. Renewable energy and energy conservation techniques are studied in Japan to help prevent global warming, with particular attention to the technological development of effective uses of unused energy and energy conservation in supplying heat for the residential and commercial sectors. Many researchers and companies are interested in potential underground thermal utilization such as geothermal heat pumps; although underground thermal utilization is still relatively unfamiliar in Japan, growing interest in such techniques is evidenced by events such as the World Geothermal Congress 2000, which was held in Japan. The techniques used in heat exchangers have already been well developed and have come into wide use in several countries. Nevertheless, geological and hydrological settings in Japan are significantly different from those of other countries and these should be examined in detail in order to establish underground thermal utilization economically and efficiently in Japan.

2. TECHNOLOGICAL CONSIDERATIONS FOR DRILLING IN JAPAN

The two major types of underground thermal utilization such as geothermal heat pumps, borehole heat exchangers and underground thermal energy storage are closed loop and open loop systems. Japan experienced severe land subsidence during the 1960s and 1970s in several cities. Now, many local governments, especially those of large cities, regulate or prohibit pumping of groundwater. For this reason, closed loop systems are preferable in Japan.

Although underground thermal utilization is already in wide use in several countries such as the United States and Switzerland, it is not yet common in Japan, possibly due to the high cost of drilling cost and Japan’s complex geological background. Drilling costs in Japan are almost three times higher than in other countries, and it is believed to be difficult to reduce this expense because it depends on not only drilling technology but also on the social and economic situation in the country in question. In Japan, shorter boreholes should be used to keep the initial costs to a minimum.

The geological setting of Japan is an island arc. There are many earthquakes and volcanoes, and most cities are situated on very thick unconsolidated sediment. For example, unconsolidated sedimentary beds in Tokyo, which consist of Quaternary and Tertiary sediments, have a maximum thickness of 3,000 m. These beds often include gravel, and the mixture of gravel and soft sediment often makes drilling difficult. This is one possible explanation for the high expense of drilling in Japan.

Table 1. Thermal conductivity of soils and rocks (Clark, 1966).

■ Soil (Muck soil)	(water content 4%)	0.15 $W\cdot m^{-1}\cdot K^{-1}$
	(water content 67%)	0.51 $W\cdot m^{-1}\cdot K^{-1}$
■ Water	(0°C)	0.56 $W\cdot m^{-1}\cdot K^{-1}$
■ Sand (Hudson River sand, USA)	(water content 0.2%)	0.27 $W\cdot m^{-1}\cdot K^{-1}$
	(water content 30%)	1.65 $W\cdot m^{-1}\cdot K^{-1}$
■ Limestone (Toronto, Canada)		2.57 $W\cdot m^{-1}\cdot K^{-1}$
■ Granite (Loetschberg Tunnel, Switzerland)		3.25 $W\cdot m^{-1}\cdot K^{-1}$

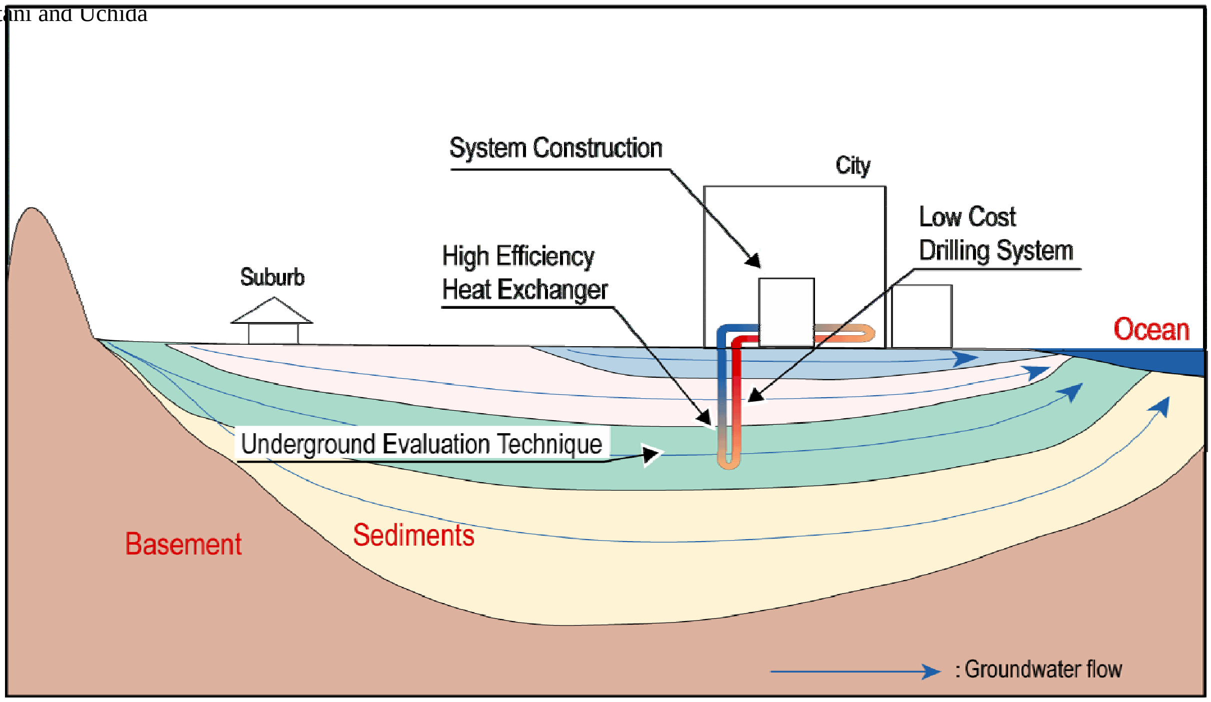

Figure 1. Research and development subjects which are needed for underground thermal utilization in Japan.

The thermal conductivity of unconsolidated sediments such as soil and sand depends on water content and is lower than that of rocks such as granite (Clark, 1966) (Table 1). Effective thermal conductivity is an important factor in a closed loop system because it depends not only on the type of rock but also on water content and the velocity of groundwater flow, especially for unconsolidated sediments. Groundwater flow in Japan is very active due to thick unconsolidated sediments and steep geographical gradients. Therefore, an understanding of groundwater flow is of critical importance for underground thermal utilization in Japan.

Figure 1 shows the technological subjects that need to be researched in order to develop underground thermal utilization in Japan. First, an underground evaluation technique is necessary to evaluate underground thermal properties including direct measurement of thermal properties and indirect methods of estimating thermal properties based on geological structure and the velocity and temperature of groundwater. Groundwater is known to flow particularly well in permeable layers such as the gravel bed. The distribution of groundwater temperature may vary considerably in sedimentary basins. Moreover, heat extraction at the area where groundwater flows influences the heat environment on the side of the lower reaches of groundwater flow. Therefore, evaluation of environmental impact is also important.

An understanding of thermal properties based on geological and hydrological information enables us to evaluate the necessary length of boreholes for underground thermal utilization. The length of boreholes is shorter where groundwater flow is active, and longer where groundwater flow is inactive. As the necessary length of boreholes affects drilling costs, the initial cost of underground thermal utilization depends on the specific drilling sites. Although drilling is expensive in Japan, the development of a technique to estimate those initial costs which differ with location will make it possible to select the most cost-effective areas for underground thermal utilization.

Underground thermal utilization which has been installed in several countries has been designed to use only conduction to extract needed heat from underground. However, heat convection by groundwater flow should be also considered in Japan as another method of keeping drilling costs to a minimum.

Another technique which can be used to make the length of boreholes shorter is the development of a high efficiency heat exchanger. For heat exchange between underground and circulation fluid, boreholes, grout and pipes for circulation fluid produce heat resistance. Improvement of the thermal conductivity of these materials would make it possible to reduce the necessary length of boreholes.

It must also be kept in mind that if drilling costs become lower directly, the initial cost of underground thermal utilization will be lower. Countries in which underground thermal utilization has been widely used have developed specialized drilling machines for this purpose. Such drilling machines can also be used in Japan to decrease the initial cost of underground thermal utilization.

3. DEVELOPMENT OF AN UNDERGROUND EVALUATION TECHNIQUE

For efficient and economical development of underground thermal utilization, it is important to understand underground geological information. The geological and hydrological characteristics which should be considered are the heat properties of the underground, the temperature and velocity of groundwater, the geological structure and the potential environmental impact.

For suitable area selection using geological data, three-dimensional geological beds are examined using a three-dimensional geological structure analysis software MVS (Mining Visualization System, C Tech Development Corp., Huntington, USA). This software allows us to visualize and analyze the distribution of aquifers and gravel beds which are expected to be important for site selection for underground thermal utilization. If the estimated distribution of geological beds is accurate, it is possible to calculate the risk of installation and thereby achieve cost-efficient installation.

There is considerable borehole data available from Nagoya, central Japan because land subsidence was a severe problem during the 1960s and 1970s. Borehole data based on geotechnical data of subsoils in Nagoya was analyzed using MVS. The publication Geotechnical data of subsoils in Nagoya (Japan Society of Soil Engineers - Chubu division, 1988) records the data of 4190 boreholes. Borehole data is available for almost the entire area of Nagoya. Most boreholes are less than 70m long, with the longest in this data set at 152m. In beds recorded in Geotechnical data of subsoils in Nagoya, gravel beds are expected to be important for underground thermal utilization because they may have highly effective thermal conductivity due to groundwater flow. The present study examines the distribution of such gravel beds.

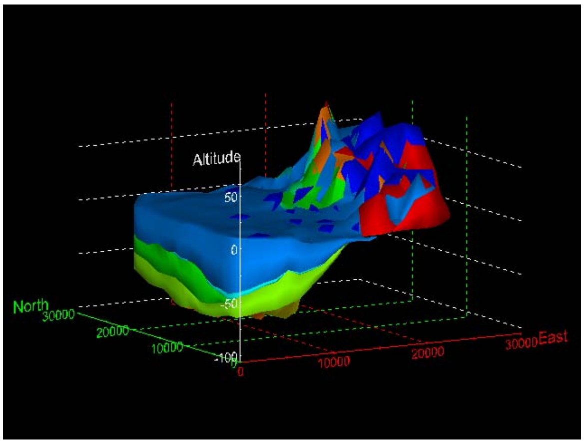

Figure 2. Three-dimensional distribution of geological beds in Nagoya, central Japan. This image is a view from SSW and 20° of depression. The Toriimatsu gravel is light blue. The unit of measurement of the axes is the meter.

Figure 2 shows the three-dimensional geological bed distribution deduced from borehole data and interpolation by MVS. The western part of Nagoya is lowland area and the eastern part is hilly. The Toriimatsu gravel bed is deeper toward the west and is overlaid by a thick layer of alluvium. Figures 3A and 3B make use of other imaging options to show the Toriimatsu gravel bed more clearly. Both figures indicate that the Toriimatsu gravel bed is not especially thick and is not distributed across the entire area. Figure 4A is an image to express depth of the top of the Triimatsu gravel bed, and Figure 4B is bed thickness. Figure 4A indicates that the Toriimatsu gravel bed is not present in all areas and is distributed deeper from surface toward the west; however, it becomes thicker at the northern end of the area (Figure 4B). These images allow us to confirm the three-dimensional distribution of gravel beds and to estimate the depth of their upper limit as well as their

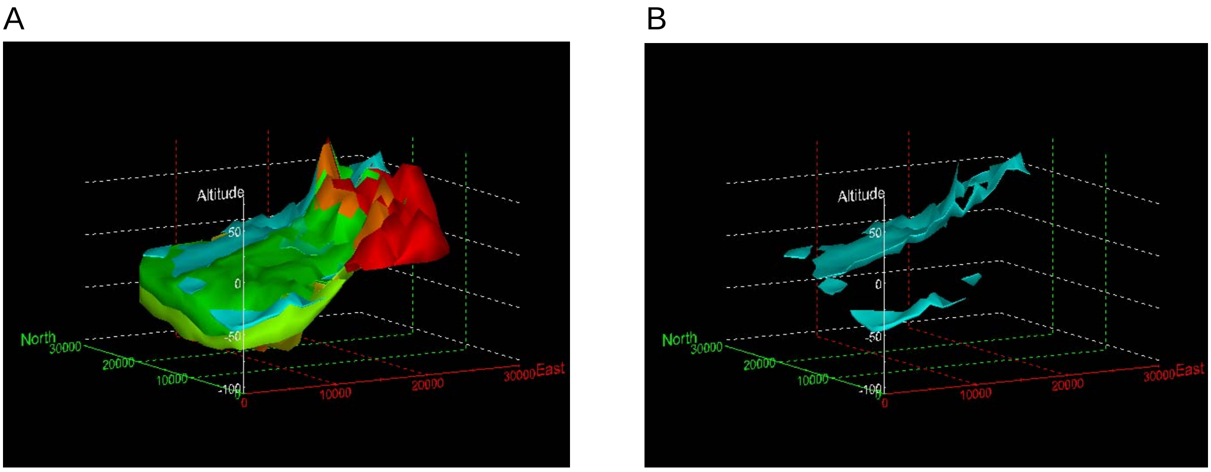

Figure 3. Three-dimensional distribution of the Toriimatsu gravel bed: A) with beds overlying the Toriimatsu gravel bed transparent; B) with all beds except the Toriimatsu gravel bed transparent.

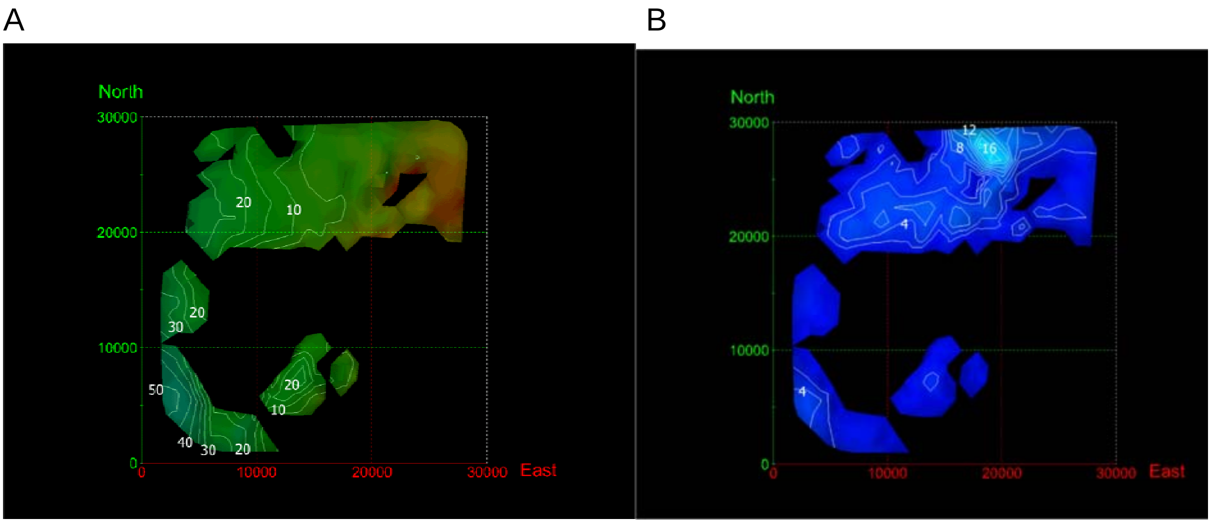

Figure 4. A) Depth of the top of the Toriimatsu gravel bed. B) Bed thickness of the Toriimatsu gravel bed.

thickness in any location.

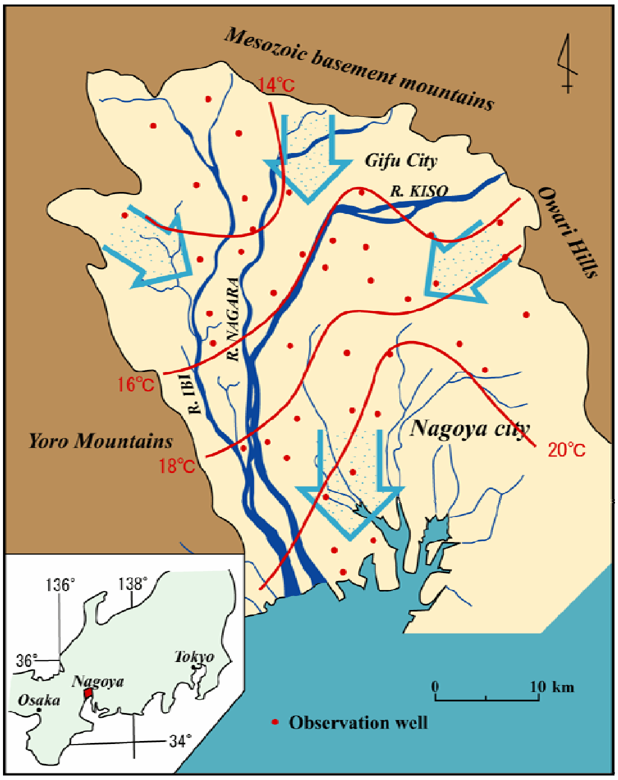

Figure 5. Temperature distribution of the Nobi plain at –100m below sea level. Arrows indicate the flow direction of groundwater (Uchida and Sakura, 1999).

In order to decrease the initial cost of underground thermal utilization, it is better to reach effective aquifers at shallower depths. In the case of Nagoya, the distribution of the Toriimatsu gravel bed is shallower in the east than in the west, and needed heat may therefore be extracted using a shorter heat exchanger in the eastern part of the area. Although gravel beds with strong groundwater flow have higher effective thermal conductivity, the gravel bed alone does not constitute the entire depth of the borehole in many cases. The velocity of groundwater flow and the heat properties of other beds are also important factors.

The underground temperature distribution of the Nobi plain including Nagoya was estimated based on temperature measurements from observation wells for land subsidence (Uchida and Sakura, 1999) (Figure 5). In the Nobi plain, groundwater is recharged in the northern part of the plain and flows toward the central part and toward the ocean. Based on this groundwater flow, temperature is predicted to be lower at the recharge area and higher in the central area. It is also important to collect temperature data for underground thermal utilization and to develop appropriate techniques to evaluate the suitability of installation.

4. GEOTHERMAL GRADIENT AND GEOLOGICAL STRUCTURE

Effective thermal conductivity is an important factor for a closed-loop type of underground thermal utilization. In a plain with a constant heat flow, thermal conductivity may be estimated from geothermal gradient using the equation below.

$$Q = K \cdot dT / dZ \qquad (1)$$

where Q, K, dT/dZ are heat flow, thermal conductivity and geothermal gradient, respectively.

The relationship between geological columns and geothermal gradient along the boreholes in the Nobi plain has been studied (Figure 6). Shallow part of all boreholes has strong anomaly of temperature gradient. This is an effect of seasonal temperature change of ground surface. Geothermal gradient in the Tatsuta borehole may reflect effective thermal conductivity of each bed, as gravel distribution is consistent with the zones with lower geothermal gradient. The zones with anomaly of geothermal gradient in the Yatomi, Tobishima and Nan'yo boreholes are not consistent with geological structure, these anomaly of geothermal gradient would be due to focused

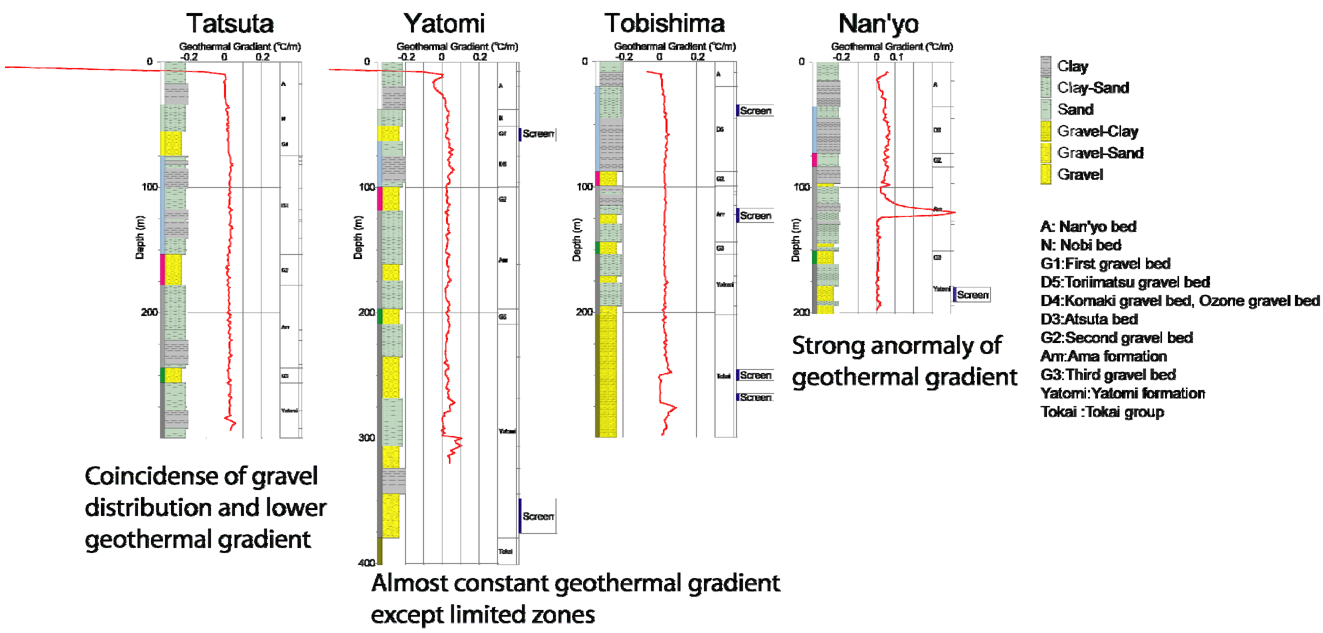

Figure 6. Geological column and geothermal gradient of Tatsuta, Yatomi, Tobishima and Nan'yo boreholes

fluid flow within limited zones.

5. CONCLUSION

The technological development of a borehole heat exchanger has almost been completed and underground thermal utilization is already in wide spread use in several countries. Because underground thermal utilization is a method of using natural energy, energy use depends on natural conditions such as the geological and hydrological characteristics of the area under consideration. In order for underground thermal utilization to be both efficient and effective, it is important to examine the geological and hydrological properties of the area and to construct appropriate evaluation techniques prior to installation; this is particularly important in Japan where the cost of drilling is a persistent issue.

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