DIKES AS HYDROTHERMAL RESERVOIRS IN SEDIMENTARY BASINS

Hirofumi MURAOKA[1]
[1]AIST, Institute for Geo-Resources and Environment, 1-1-3 Higashi, Tsukuba, Ibaraki 305-8567, Japan
E-mail: hiro-muraoka@aist.go.jp

ABSTRACT

Dikes often play a key role of permeable reservoirs in impermeable host rocks. Cooling joints penetrate the entire dike body, providing a permeable conduit for aquifer. The dike reservoir phenomenon is typically observed in the flysch-type sedimentary basins where sediments are commonly impermeable. If we have such a deep aquifer conduit as dikes from the surface to a depth from a several km to a few tens km in a high geothermal gradient region, hydrothermal convection will inevitably occur. The genesis of the Hongu hot spring is a typical example for the dike reservoir phenomenon.

Keywords: dike, sedimentary basin, hydrothermal reservoir, permeability, Kii Peninsula, Hongu hot spring

1. INTRODUCTION

Dikes are a tabular shape of consolidated magma conduits discordant to the host strata where magma ascended from the magma source region or shallow-depth magma chamber to the near-surface. Dikes are a space-filler and preferably intrude into a $\sigma 1$-$\sigma 2$ plane that minimizes the stress rise in host rocks. Dikes play two roles in geothermal systems: one is geothermal heat sources (Muraoka et al., 2002; 2005) and the other is hydrothermal reservoirs. This paper draws attention to an important role of dikes as hydrothermal reservoirs.

Pre-Neogene sedimentary basins are commonly composed of rhythmical alternation of sandstone and shale, where sandstone tends to be permeable but shale tends to be impermeable. They are macroscopically impermeable by the constraint of shale beds as penetrative barriers. A permeability map of 1 km skin depth in Japan actually suggests that most of pre-Neogene sedimentary basins correspond to impermeable zones (Muraoka et al., 2006).

Most of pre-Neogene sedimentary basins were commonly suffered by later magmatism and were intruded by dikes. In such a geological setting, dikes often play a role of permeable bodies in contrast with host sedimentary strata.

Only two boiling hot springs (> 90 ºC) are known in non-volcanic region in Japan: the Arima hot spring in Hyogo Prefecture and the Hongu hot spring in Wakayama Prefecture. The genesis of the former is ascribed into the deep aquifer rising from the brittle-plastic transition of the subducted Shikoku Basin slab (Iio et al., 2002; Zhao et al., 2002). The genesis of the latter is still controversial.

This paper describes an important role of dikes as hydrothermal reservoirs with special reference to the Hongu hot spring in the Kii Peninsula, Japan, and extends it to other geothermal fields in Japan.

2. TECTONIC AND GEOTHERMAL SETTINGS OF THE KII PENINSULA

Figure 1 shows distribution of the 3686 hot spring in Japan (Muraoka et al., 2006). Two boiling hot springs (>90 ºC) are only known in the fore-arc region to the volcanic front in Japan: the Arima hot spring in Hyogo Prefecture and the Hongu hot spring in Wakayama Prefecture (Fig. 1). Both of them are situated in Kinki Province and are known as non-volcanic hydrothermal systems. The former is controlled by the Rokko Fault System, and probably derived from the dehydration of the subducted Shikoku Basin slab by its brittle-plastic transition, as seen in the high 3He/4He ratio of discharge water (Sano and Wakita, 1985; Iio et al., 2002; Zhao et al., 2002). The genesis of the latter is still controversial. The Hongu hot spring is often associated with the Miocene intrusions named the Omine Granitic Rocks but their ages 14.8 - 14.6 Ma are obviously too old to serve for heat sources (Sumii and Shinjoe, 2003). The relatively young and hot Shikoku Basin, northern part of the Philippine Sea plate, that was formed during 28-15 Ma is underplating the Kii Peninsula and Shikoku Island. Particularly, its rift system that still has large heat flow as high as 200±20 mW/m^2 is underplating the southeast off Shikoku Island (Yamano et al., 2003). This regional high heat flow could be an ultimate heat source for the Hongu hot spring. There still remains a subject for its reservoir system.

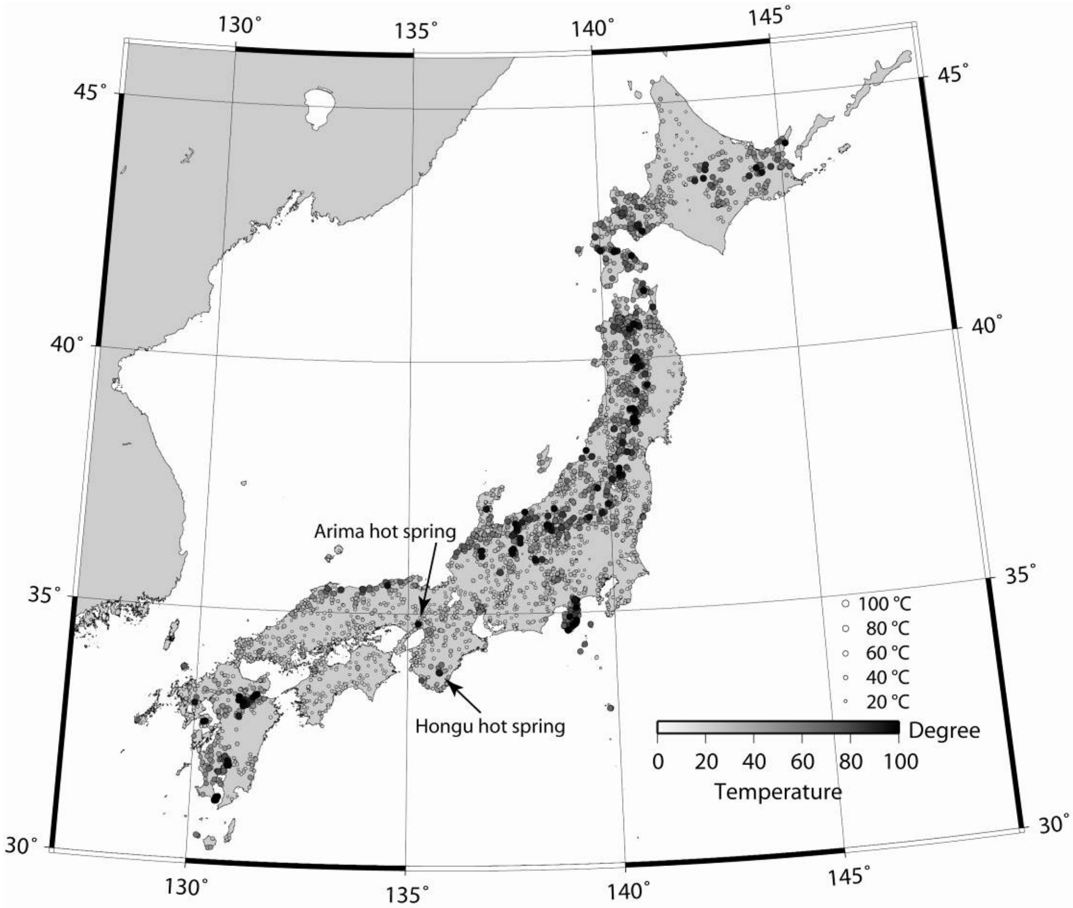

Fig. 1 Distribution of hot springs in Japan (modified from Muraoka et al., 2006).

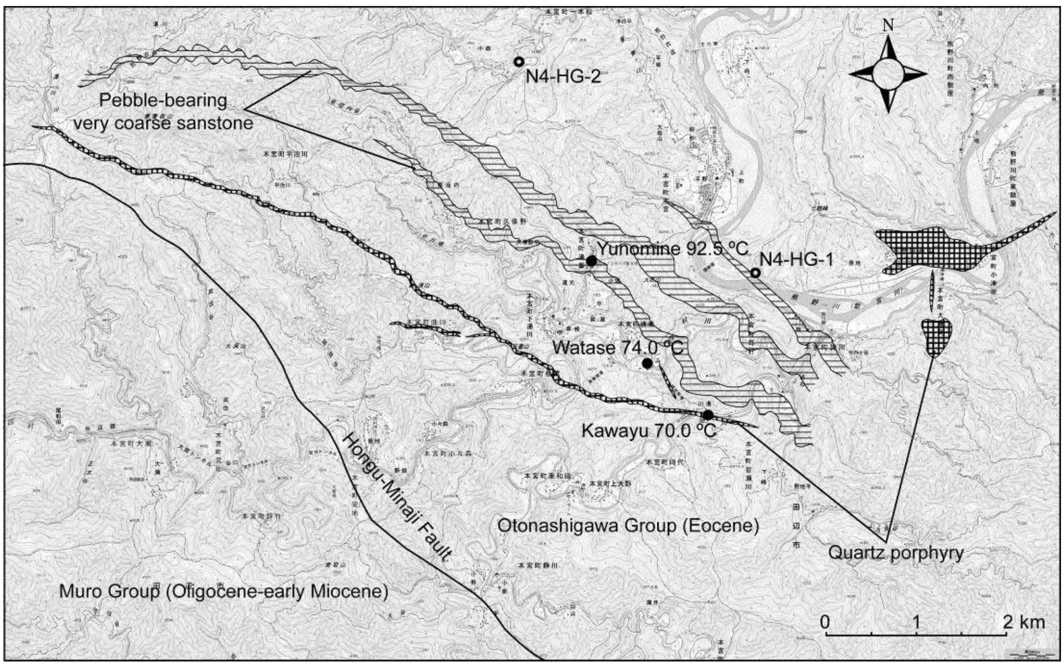

Fig. 2 Geological sketch map of the Hongu hot spring area.

3. A ROLE OF DIKES AT THE HONGU HOT SRING IN THE KII PENINSULA

Figure 2 summarizes a geological sketch map based on the author's survey during January 2006. The Yunomine hot spring is the highest-temperature natural spring with a temperature of 92.5 ºC that has long history over 1800 years and is known as one of the oldest hot spring spas in Japan. The Kawayu hot spring is a natural spring with a temperature of 70.0 ºC. The Watase hot spring with a temperature of 74.0 ºC was developed by drilling to a depth from 110 to 500 m

Fig. 3 Rhythmical alternation of sandstone and shale in the Hongu area.

Fig. 4 The Kawayu hot spring discharged from the Kawayu dike.

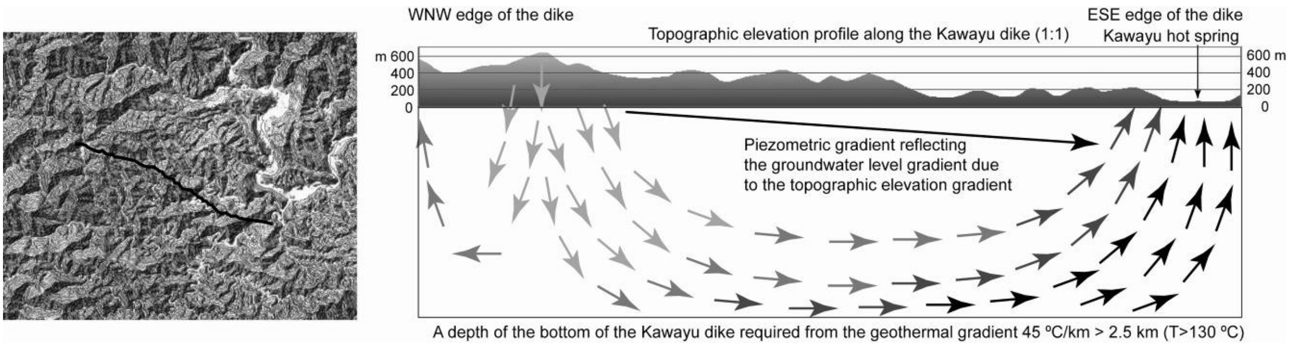

Fig. 5 Topographic profile and hydrothermal convection along the Kawayu dike (the trajectory of the dike on the surface is given in the left inlet).

between the Yunomine and Kawayu hot springs since 1965. These three hot springs are collectively called Hongu hot spring, representing the highest hot spring area in the Kii Penisula.

Since the area lies at a far outer zone to the volcanic front of the Southwest Japan arc, there are not any young volcanoes in this area. The youngest volcanic rocks are the Kumano Acidic Igneous Rocks and the Omine Granitic Rocks with their ages of 15-13 Ma (Sumii, 2000). They are obviously too old to serve for geothermal heat sources to the Hongu hot spring.

Figure 3 shows the Eocene Otonashigawa Group of the Shimanto Super Group in the area. The strata are typical of flysh sediments that are composed of rhythmical alternation of sandstone and shale. The single stratum consists of the lower sandstone and upper shale with normal grading and its thickness is 5-15 cm. Sandstone tends to be permeable and shale tends to be impermeable, so that their piles are macroscopically impermeable due to the constraint of shale beds as penetrative barriers.

The Kawayu hot spring is obviously discharged from a quartz porphyry dike that extends to 10 km in the WNW-ESE direction (Fig. 4). The dike appears to be permeable owing to the cooling joints penetratively developed over the dike body in contrast with the host strata, suggesting that the dike plays a role of a pathway as well as hydrothermal reservoir in such the flysh sediments. This dike was described by Tokuoka et al. (1982), but the name has not been given so far. We name it Kawayu dike hereinafter. The thickness perpendicular to the dike surface is about 40 m. The Kawayu dike is dipping north at 50º. The Otonashigawa Group is also dipping north at 30-50º in this area. The dike is almost concordant to the host strata like a sheet in some places, but is discordant in other places.

As shown in Fig. 2, the Kawayu dike is terminated between the Kawayu hot spring area and its neighboring valley on

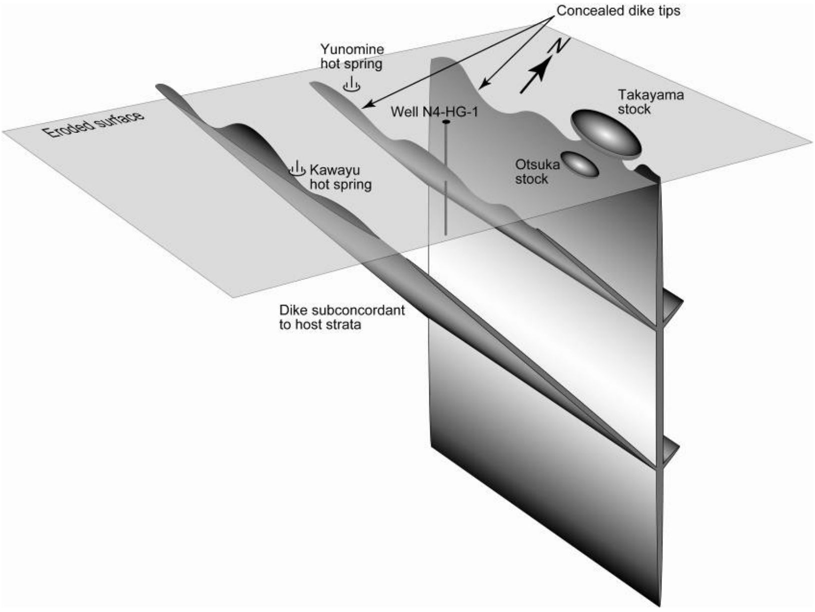

Fig. 6 A model of the Hongu geothermal system driven by dikes.

the east. Figure 5 shows a topographic elevation profile along the dike trajectory on the surface where the elevation is higher in the west and lower in the east. It should be noted that the Kawayu hot spring is situated at the lowest point along the elevation profile of the dike. Since the groundwater level is constrained by the topographic elevation along the dike body, a piezometric gradient works from the higher areas to the lowest point that inevitably makes the Kawayu hot spring area an up-flow zone. The localization of the Kawayu hot spring is thus explained by the piezometric gradients due to the topographic elevation along the dike reservoir.

The Yunomine hot spring is discharged from the pebble-bearing very coarse sandstone as shown in Fig. 2. This bed is also relatively permeable among a variety of lithology of the Otonashigawa Group. However, to the 4 km east of the Yunommine hot spring, a stock of quartz porphyry is exposed in the Takayama area. To the 2 km east of the Yunomine hot spring, the New Energy and Technology Development Organization (NEDO) drilled a 1 km depth of well named N4-HG-1 that encountered a quartz porphyry dike at a depth between 453.05 and 573.35 m where a lost circulation with 80-90 liters per minute was observed (NEDO, 1994). Based on these observations, the Yunomine hot spring is also supposed to be ultimately derived from dikes as reservoirs at a depth. These observations are summarized in a model shown in Fig. 6.

4. OTHER EXAMPLES OF DIKES AS HYDROTHERMAL RESERVOIRS IN JAPAN

Other examples of hydrothermal reservoirs controlled by dikes are briefly introduced from Japan.

Himekawa hot spring

The Himekawa hot spring is situated in Itoigawa City, Niigata Prefecture, and the discharge temperature is 44-79 ºC. The original and natural spring is observed along a quartz porphyry dike at a river side of the Himekawa River (Fig. 7). The host rocks are the Permian strata that belong to the Hida Marginal Belt and impermeable, so that the dike forms a prominent permeable body in this area.

Nogurizawa mineral spring

The Nogurizawa mineral spring is situated in Ueno-mura, Gunma Prefecture. The area lies at an outer zone to the volcanic front of central Japan and only a mineral spring with a temperature less than 25 ºC is discharged along a porphyrite dike (Fig. 8). The porphyrite dike is 7 km long and penetrates not only the Jurassic Chichibu Belt but also the Cretaceous Sanchu graben. This dike exhibits columnar joint networks where the mineral spring is discharged.

Raiden hot spring

The Raiden hot spring is situated in the western foot of Raidenyama volcano, one of the Niseko volcano complex, Niseko, Hokkaido. This area is not a sedimentary basin, and the host strata are composed of the Quaternary Raidenyama Pyroclastic Rocks (NEDO, 1986). The raiden hot spring is discharged from an andesite dike with columnar joint networks (Fig. 9).

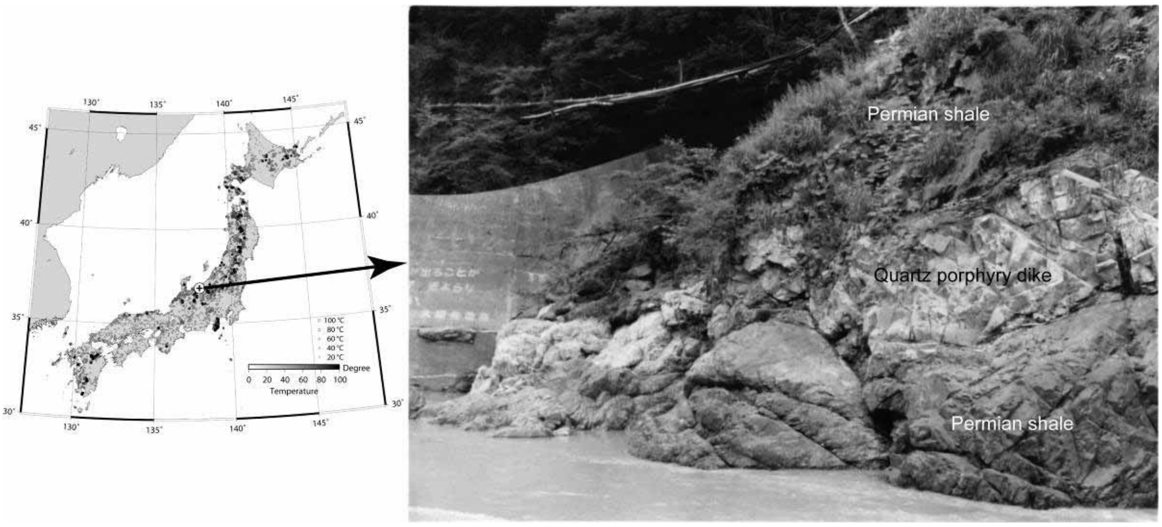

Fig. 7 A quartz porphyry dike in the Himekawa hot spring, Niigata Prefecture.

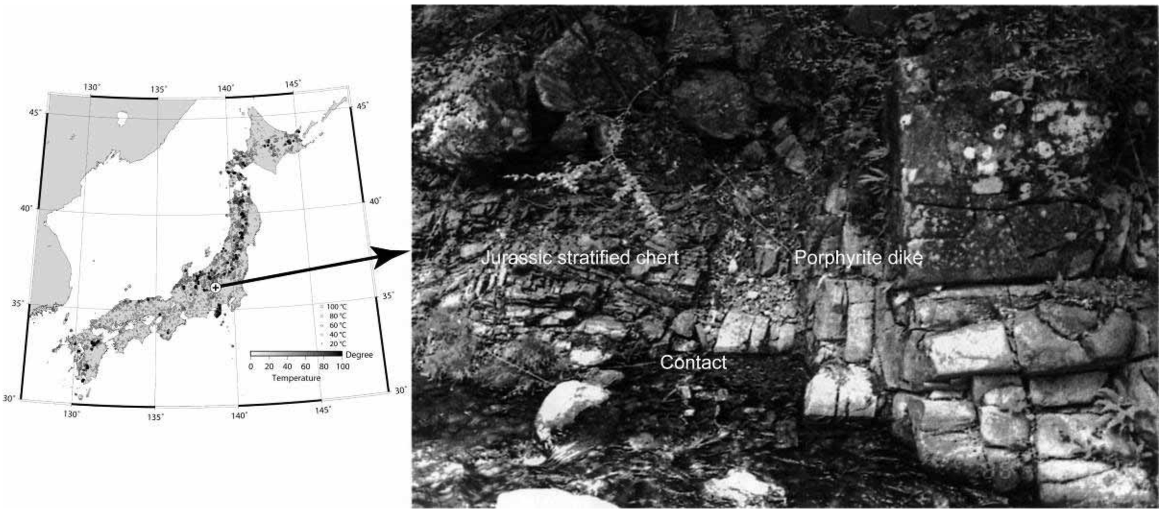

Fig. 8 A porphyrite dike in the Nogurizawa mineral spring, Gunma Prefecture.

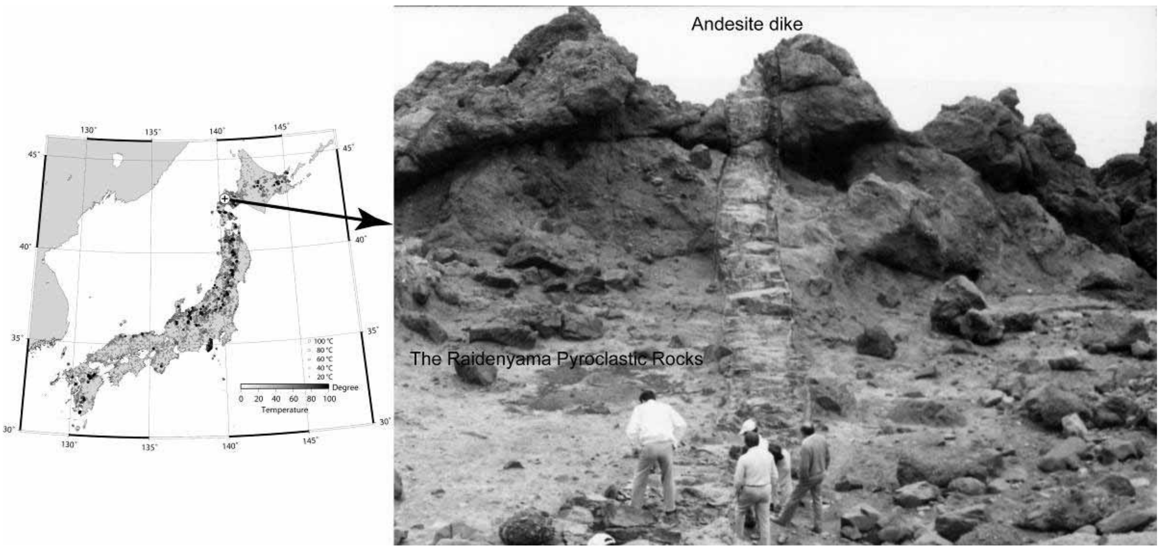

Fig. 9 A andesite dike in the Raiden hot spring, Hokkaido.

Tenei-mura geothermal field

The Tennei-mura geothermal field is situated in Tenei-mura, Fukushima Prefecture. According to the Report of the Geothermal Development Promotion Survey “Tenei Area” (Tenei-mura Consortium, 2006), most of hot springs are controlled by dikes in this area. Actually, a well was drilled for subsurface dikes as a target, but unfortunately, the well

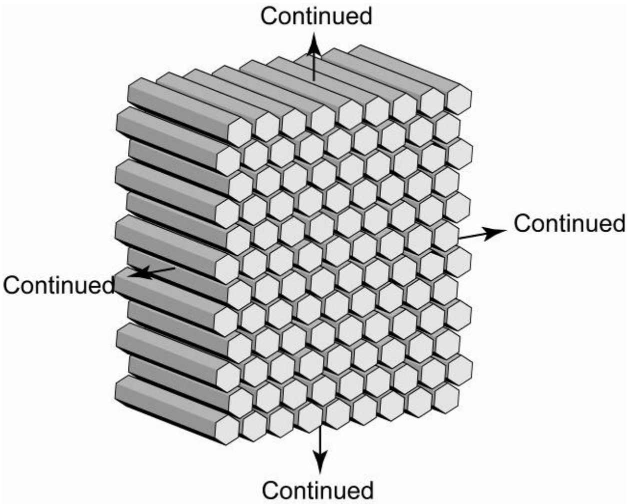

Fig. 10 A model of permeability of dike in a case of columnar joints.

could not have penetrated dikes by the appearance of the unexpected granite body, probably a co-magmatic host of dikes.

5. DISCUSSION

It is no doubt that faults and fractures are primarily important as hydrothermal reservoirs. Porous-media type formations are also important as hydrothermal reservoirs, including conglomerate, sandstone and carbonate strata. Even if these permeability conditions are not available in host rocks, there still remains the third possibility. One of the cases is a dike reservoir phenomenon. Dikes often play a key role of permeable reservoirs in impermeable host rocks as described above. The origin of the dike reservoir phenomenon will be here discussed.

Dike is a consolidated magma conduit that once occupied a tabular shape of space when the magma intruded into the host strata. After the magma occupies the space, the magma will drastically reduce the volume with a solidification process. To compensate the volume reduction, open cracks will be formed as cooling joints. The cooling joints occur as columnar, blocky and platy joints and are penetrative over the entire dike body. In other words, the cooling joints are linked to each other over the entire dike body. This is the reason why dikes provide a permeable conduit for aquifer (Fig. 10).

The dike reservoir phenomenon is typically observed in the flysch-type sedimentary basins where the host strata consist of rhythmical alternation of sandstone and shale. The sandstone layer is mesoscopically permeable but the shale layer macroscopically cancels this effect. The permeability of dike is then relatively prominent in such the host rock conditions. Actually, the dike reservoir phenomenon is often observed in the flysch-type sedimentary basins in Japan, such as in the Jurassic Chichibu Belt and the Cretaceous-Paleogene Shimanto Belt. A typical example is observed in the Hongu hot spring.

Another important fact is that, as indicated by the definition of dike, dikes are discordant to beddings of the host strata. In other words, most of dikes are highly dipping or nearly vertical. We are not sure about the vertical extents of dikes. However, the order of the vertical extents of dikes can roughly be estimated from the lateral extents of dikes that range from a several km to a few tens km. If we have such a deep fluid conduit in the high geothermal gradient region, hydrothermal convection will inevitably occur. A typical example is again observed in the Hongu hot spring.

6. CONCLUSIONS

This paper concludes the following points.

1. Dikes often play a key role of permeable reservoirs in impermeable host rocks.
2. Cooling joints penetrate the entire dike body, providing a permeable conduit for aquifer.
3. The dike reservoir phenomenon is typically observed in the flysch-type sedimentary basins where sediments are commonly impermeable.
4. If we have such a deep aquifer conduit as dikes from the surface to a depth from a several km to a few tens km in a high geothermal gradient region, hydrothermal convection will inevitably occur.
5. The genesis of the Hongu hot spring is a typical example for the dike reservoir phenomenon.

REFERENCES

Iio, Y., Sagiya, T., Kobayashi, Y. and Shiozaki, I. (2002) Water-weakened lower crust and its role in the concentrated deformation in the Japanese Islands. *Earth and Planetary Science Letters*, **203**, 245-253.

Muraoka, H., Nasution, A., Urai, M., Takahashi, M., Takashima, I., Simanjuntak, J., Sundhoro, H., Nanlohy, F., Sitorus, K., Takahashi, H. and Koseki, T. (2002) Tectonic, volcanic and stratigraphic geology of the Bajawa geothermal field, central Flores, Indonesia. *Bull. Geol. Surv. Japan*, **53**, 109-138.

Muraoka, H., Nasution, A., Simanjuntak, J., Dwipa, S., Takahashi, H., Matsuda, K. and Sueyoshi, Y. (2005) Geology and geothermal systems in the Bajawa Volcanic Rift Zone, Flores, Eastern Indonesia. *Proceedings of the World Geothermal Congress 2005*, 13p (CD-ROM).

Muraoka, H., Sakaguchi, K., Nakao, S. and Kimbara, K. (2006) Discharge temperature -discharge rate correlation of Japanese hot springs driven by buoyancy and its application to permeability mapping. *Geophysical Research Letters*, **33**, L10405, doi: 10.1029/2006GL026078.

NEDO (1986) Report of the Nationwide Geothermal Survey, Volcanic Hydrothermal System Areas Type-1 "the Niseko area" (Abstract). New Energy and Technology Development Organization, 209p (in Japanese).

NEDO (1994) Report of the Geothermal Development Promotion Survey "the Hongu area". New Energy and Technology Development Organization, 885p (in Japanese).

Sano, T. and Wakita, H. (1985) Geographical distribution of $^3He/^4He$ ratios in Japan: implications for arc tectonics and incipient magmatism. *J. Geophys. Res.*, **90**, 8729-8741.

Sumii, T. (2000) The Setouchi Volcanic Rocks and the Outer Zone Acidic Rocks in Southwest Japan; re-compilation of their ages. *Fission Track News Letter*, **13**, 43-47 (in Japanese with English abstract).

Sumii, T. and Shinjoe, H.（2003）K-Ar ages of the Ohmine Granitic Rocks, south-west Japan. *The Island Arc*, **12**, 335-347.

Tenei-mura Consortium (2006) Report of the Geothermal Development Promotion Survey "the Tenei area" (Second phase). New Energy and Technology Development Organization, 178p (in Japanese with English summary).

Tokuoka, T., Harata, T., Suzuki, H. and Yao, A. (1982) *Geological Map of Tanabe, scale 1:200,000*. Geological Survey of Japan.

Yamano, M., Kinoshita, M., Goto, S. and Matsubayashi, O. (2003) Extremely high heat flow anomaly in the middle part of the Nankai Trough. *Physics and Chemistry of the Earth*, **28**, 487-497.

Zhao, D., Mishra, O.P. and Sanda, R. (2002) Influence of fluids and magma on earthquakes: seismological evidence. *Physics of the Earth and Planetary Interiors*, **132**, 249-267.