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Geothermal Features of Yamagata Prefecture, Northeast Japan

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ABSTRACT

The Yamagata prefecture, located in northeast Japan, has about 140 hot spring areas. The area is underlain by pre-Tertiary basement rocks, Tertiary formations, Pliocene to Pleistocene deposits, and Quaternary volcanoes. Typical Quaternary volcanoes are Funagata, Zao and Azuma in the Ou Mountains, and Chokai, Gassan, Hayama, and Hijiori in the Uetsu Mountains. Geothermal resources related to Quaternary volcanoes such as Azuma, Zao, and Hijiori areas are accompanied by high temperature hot springs associated with hydrothermal alteration zones on the surface. In Azuma and Hijiori areas, maximum temperatures of the exploration wells reach above 200 ^{o}C. Hijiori and Akakura areas related with caldera are accompanied by high temperature thermal waters. Meanwhile many non-volcanic hot springs are scattered mainly along the Yonezawa Basin and the Yamagata Basin. Some of the high temperature hot springs such as Akayu, Kaminoyama, Tendo and Higashine are situated on the margins of these basins or in volcano-tectonic depressions, which are suitable structures for thermal waters reservoirs.

1. INTRODUCTION

Yamagata prefecture has about 140 hot spring areas, more than 400 hot spring sources, and the total flow rate from these hot springs is about 55,000L/min (Yamagata Pref., 2009). Figure 1 shows geothermal resources map of Yamagata prefecture. Several hot springs, such as the Zao and the Akayu hot spring, have been found and used for bathing for about a thousand years. Especially, the Akayu hot spring used to be visited by the Uesugi house, a famous feudal lord (daimyo) of the Edo period. The Uesugi house, also, built a palace in the Akayu hot spring in 17th century (Nanyo city, 1994).

Yamagata prefecture has many Quaternary volcanoes with high temperature hot springs and hydrothermal alteration zones. Geothermal investigations of these were carried out from late 1960's by Yamagata prefectural office (Tamiya, et al., 1973). Afterwards, the nationwide survey was carried out by the Japanese government from early 1980's. In Yamagata prefecture, the geothermal development promotion survey was carried out by the New Energy and Technology Development Organization (NEDO) in Hijiori, Azuma, Ginzan and Akakura areas. The exploratory wells were drilled by NEDO and temperature profiles of these were clarified (Fig. 2). Furthermore HDR (Hot Dry Rock) project was carried out by NEDO in Hijiori area.

The current technology of the binary cycle geothermal power generation system enables us to develop the small-scale geothermal power plants and the binary Kalina cycle expanded the power generation sources to most of the temperatures of hot spring (Muraoka et al. 2004). If a small-scale Kalina cycle power generation system can be incorporated into upper stream of the high-temperature hot springs, a double advantage can be attained; one is to obtain electricity and the other is to adjust the bath temperature without any dilution of balneological constituents (Muraoka, 2007; Muraoka, 2008).

2. GEOLOGICAL SETTING

The geography of Yamagata prefecture is characterized by mountain ranges and inland basins. The Ou and the Uetsu Mountains, forming north-south trending uplift zones in the area are, respectively, distributed in the east and center of Yamagata prefecture. The inland basins are situated between the Ou and the Uetsu Mountains and are divided by the E- W trending uplift zones (Tamiya, 1983).

Yamagata prefecture is geologically composed of the pre-Tertiary basement rocks, Tertiary formations, Pliocene to Pleistocene deposits, and Quaternary volcanoes. The basement rocks of this area are composed mainly of hornfels, gneiss and granitic rocks, and they are distributed in the southwestern region and in the eastern environs of the Yamagata Basin and Yonezawa basin. K-Ar dating of the granitic rocks show the Middle to the Late Cretaceous ages (Sugai, 1985). The Tertiary formations, uncomfortably overlying on or having fault contact with the basement rocks, are extensively distributed in this area. The Tertiary formations of the area, so-called Green Tuff, are mainly products of submarine volcanic activity. These Tertiary formations are mainly composed of sedimentary rocks in western region, but mainly submarine volcanic rocks in eastern region. Pliocene to Pleistocene deposits consist mostly of sands and silts. Typical Quaternary volcanoes are Funagata, Zao and Azuma in the Ou Mountains, and Chokai, Gassan, Hayama, and Hijiori in the Uetsu Mountains.

3. CHEMIAL COMPOSITION OF THERMAL WATERS

Figure 3 shows the chemical compositions of the major high temperature hot springs in study area. The chemical compositions of hot springs can be grouped into three water types, (a) Neutral pH, Cl-HCO_3/SO_4 type thermal water (Akayu, Ginzan, Higashine, Hijiori hot spring), (b) Neutral pH SO_4 type thermal water (Tendo, Akakura, Shirabu hot spring), (c) Acidic pH, SO_4 type thermal water (Zao, Ubayu hot spring). Fig. 4 shows a relation between $\delta^{18}O$ and δ D for thermal waters from Azuma, Ginzan and Akakura areas. Most of the thermal waters of the hot springs plots within the meteoric water line.

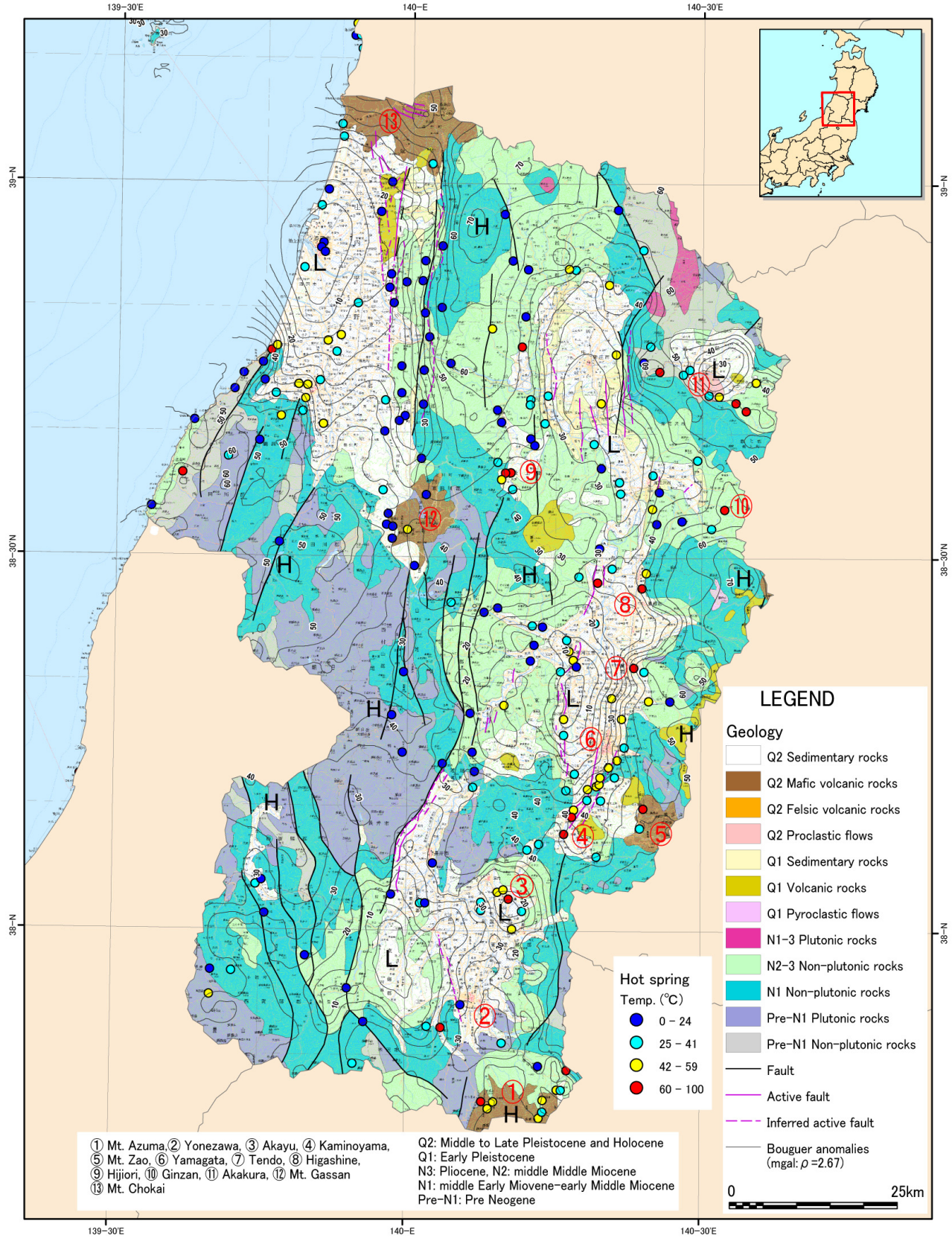
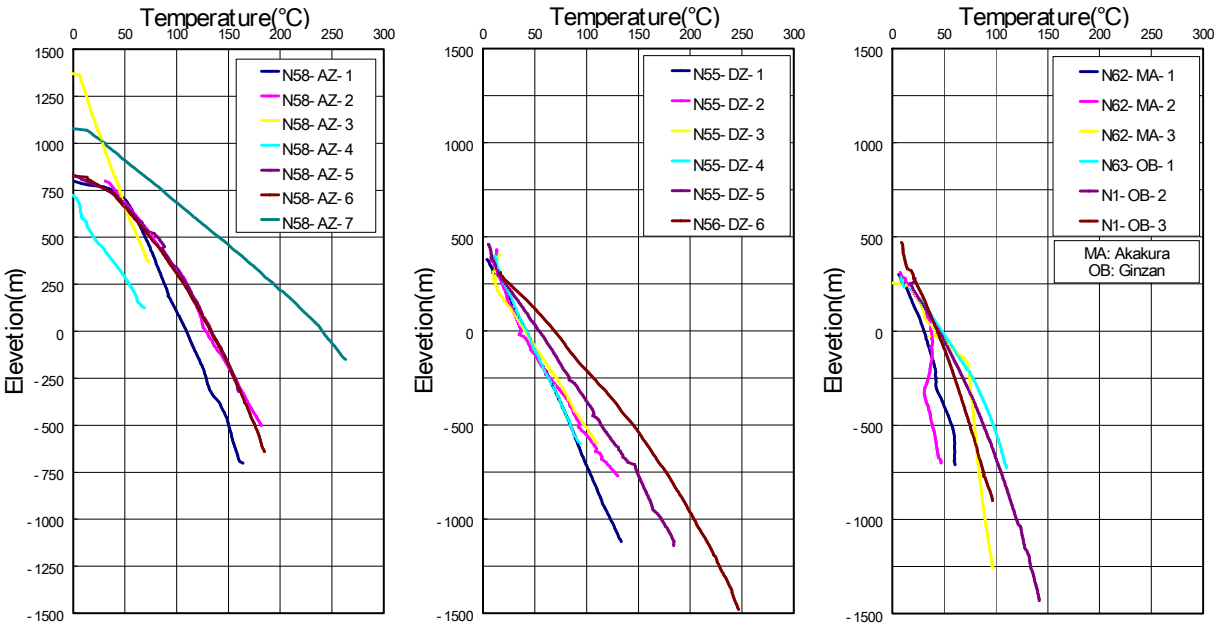


Fig.1 Geothermal resources map of Yamagata prefecture (modified after Sakaguchi and Takahashi, 2002).



(1) Azuma (2) Hijiori (3) Akakura, Ginzan

Fig.2 Temperature profiles of geothermal wells in Azuma, Hijiori, Akakura and Ginzan geothermal fields.

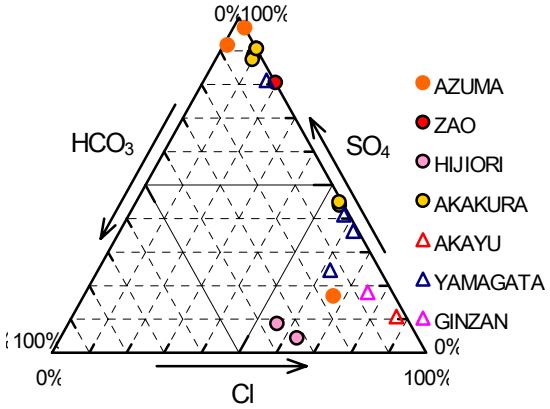


Fig.3 Chemical compositions of the major high temperature hot springs in Yamagata Pref.

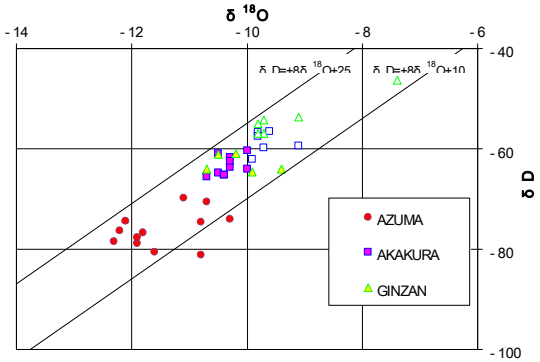


Fig.4 Relation between δ ^{18}O and δ D for thermal waters from Azuma, Ginzan and Akakura geothermal fields.

4. GEOTHERMAL FEATURES

4.1 Quaternary Volcanic Area

Geothermal features of Quaternary volcanic areas are accompanied by high temperature hot springs, and therefore hot springs are believed to be caused by volcanic activity in the area.

The Quaternary volcanic area have numerous indications for a potential geothermal resource such as fumaroles, SO_4 type acid hot springs and hydrothermal alteration zones.

4.1.1 The Azuma Area

The Azuma area, related to Azuma volcano, is located south of Yamagata Prefecture and has many hot springs. The Azuma volcanic rocks overlie uncomfortably the Tertiary formations and granitic basement rocks. Volcanic activities are geologically divided into three stages during the period from 1.3 to 0.08Ma by K-Ar dating (NEDO, 1991b). The center of volcanic activity moved from west to east and recent products erupted from fresh craters in the eastern part of the volcano. The geothermal structure of Azuma area is characterized by E-W trending up rift zone and two depression zones of the Ubayu depression and the Namekawa east depression. Azuma volcano is distributed within the up rift zone and volcanic rocks erupted from it are mainly andesitic. The Ubayu depression is also located within the up lift zone and filled with acidic welded tuff. The Namekawa east depression zone is situated north of the up rift zone. The Ubayu hot spring, situated near the Ubayu depression, is associated with an acidic alteration zone characterized by kaolinite, alunite and pyrophyllite (Fig. 5). The Ubayu alteration zone is extended over about 10km^2 (Kimbara and Sakaguchi, 1989).

Fig. 5 Hydrothermal alteration zone at the Ubayu hot spring in Azuma geothermal field.

Drilling was conducted at depths between 600 and 1,500 meters by NEDO and the temperatures of 67 ^{o}C to 267^{o}C were encountered (NEDO, 1987). The Ubayu depression was confirmed by drilling well named N58-AZ-7 which encountered a temperature of 267 ^{o}C. The geology of well AZ-7 is mainly composed of the Azuma volcanic rocks and the Ubayu welded tuff. The Azuma volcanic rocks are mainly composed of andesite lava with minor intercalations of andesitic tuff. The Ubayu welded tuff is composed of welded tuff, tuff breccia and basal conglomerate. The alteration minerals of the well AZ-7, from shallow to deeper zone, are characterized by smectite, smectite/chlorite mixed-layer, chlorite and wirakite. These alteration minerals indicate high-temperature (>200℃) neutral-pH geothermal fluids.

The discharge temperature of the Ubayu acid SO_4 type of hot spring is 49 ^{o}C (Takahashi et al., 1993). The Shirabu hot spring is discharged from granitic basement rocks in the southern margin of Azuma area and has discharge temperatures of 58-62^{o}C (Yamagata HSA, 1973). The Goshiki spring is situated on the western margin of the Namekawa east depression. The discharge temperature of the Goshiki hot spring is 47 ^{o}C and chemical composition of hot spring is neutral-pH HCO_3 type (NEDO, 1991a). The hot spring water discharged from the well higher than 100 ^{o}C was recorded on the east margin of the depression (Abiko, 1990). As shown in Fig. 4, hydrogen and oxygen isotope compositions of thermal waters are plotted close to the meteoric water line, suggesting the water originated from meteoric water. Thermal waters from the well show a little oxygen isotopic positive shift, which can be explained by a water- rock interaction.

4.1.2 The Zao Area

The Zao area, related to Zao volcano, is located east of Yamagata prefecture and is accompanied by the Zao hot spring and fumaroles. The Zao volcano is famous for its large crater lake which has a diameter of about 300m (Fig. 6). The Zao volcano is situated close to the Quaternary volcanic front of the northeast Japan arc. The volcanic activity was geologically divided into three stages (Oba, 1999). The first stage of volcanism started about 1Ma (Takaoka et al., 1989) and the volcanic activity at the Crater Lake began at 4,000 years ago (Oba, 1999). A large quantity of thermal waters gushes out from acidic alteration zone extended about 3km^2 in the Zao hot spring. The acidic alteration zone is characterized by kaolinite and alunite (Kimbara and Sakaguchi, 1989).

Fig. 6 The Crater Lake, diameter of about 300 meters in Zao geothermal Filed.

The Zao hot spring is discharged from volcanic rocks in the explosion crater extending about 3 km wide. The discharge temperature of the Zao hot spring is 65^{o}C (Takahashi et al., 1993) and discharge rate above 5,500 l/min (Yamagata pref., 2009). The Zao hot spring is also an acidic SO_4 type but the major difference from the Ubayu hot spring is the presence of relatively high chloride concentration and strong acidity. The chloride concentration is 665mg/l and pH is 1.3, suggesting that the origin of dissolved sulfate and chloride may be from high temperature volcanic gases.

4.1.3 The Hijiori Area

The Hijiori area, related with Hijiori volcano is located at the center of Yamagata prefecture. Hijiori volcano, a small caldera with a diameter of approximately 2 km, started a series of eruptions 12,000 years ago. The eruption history of Hijiori volcano was divided into four major stages and total eruptive volume of Hijiori volcano is estimated to be about 2.3 km^3 (Miyagi, 2007). The acidic alteration zone, characterized by kaolinite and alunite, covers about 1.5 km^2 in this area (Kimbara and Sakaguchi, 1989). The Hijiori hot spring is discharged from Hijiori caldera and the discharge temperature is 84 ^{o}C (Takahashi et al., 1996). The Hijiori hot spring is a neutral-pH Cl-HCO_3 type with relatively high chloride concentration of 1,390mg/l. NEDO drilled to depths between 1,000 and 1,800 meters and encountered temperature of 94 ^{o}C to 248 ^{o}C (NEDO, 1983).

NEDO also, conducted research on HDR (Hot Dry Rock) development techniques from FY1985 to FY2002. In this project, three wells were drilled at a depth of around 2,300 meters, and a heat extraction experiment called “Long-term Circulation Test” was conducted at Hijiori test site to study the life of the HDR reservoir (Oikawa and Tosha, 2001; Matsunaga et al., 2005). The temperature of the upper and the lower reservoirs were 250 ^{o}C and 270 ^{o}C respectively.

4.1.4 The Akakura Area

The Akakura area, related to the Mukaimachi caldera (Ui and Shibahashi, 1985), is located in the northeast of Yamagata prefecture and is accompanied by the Akakura hot spring. The Akakura hot spring is discharged from the central part of Mukaimachi caldera and the discharge temperature is 74 ^{o}C (Takahashi et al., 1996). The Akakura hot spring is neutral-pH SO_4 type hot water, and hydrogen and oxygen isotope compositions of thermal waters are plotted on the meteoric water line, suggesting the water originated from meteoric water. NEDO drilled at depths between 1,000 and 1,500 meters and encountered temperatures of 47 ^{o}C to 97 ^{o}C (NEDO, 1990).

4.2 Non Quaternary Volcanic Areas

Many hot springs not directly related to volcanic activities are scattered mainly along the Yonezawa basin (Fig.5) and Yamagata basin. Some of the hot springs are situated at margins of these basins or in volcano-tectonic depression.

3.2.1 The Akayu Area

The Akayu area is located on the north margin of Yonezawa basin in southern Yamagata prefecture (Fig.7) and it is related to late Miocene volcano-tectonic depression. The Akayu depression is filled with submarine acidic pyroclastic flow of 1,500m thick (Honda et al., 1985). The Akayu depression, corresponding to low gravity anomaly (Fig.1), characterizes the geomorphology of this area and has a suitable structure favorable for thermal waters. Several hot springs are distributed in Akayu depression including the Akayu hot spring situated in the central part of the depression. According to the result of geological survey, it is considered that the NE-SW trending fracture is developed around the Akayu hot spring. The shallow geothermal system in this area seems to be controlled by the NE-SW fracture system. The temperature of the thermal waters discharged from the well, drilled to a depth of 400m, is 63 ^{o}C. Geochemical characteristics of thermal waters from the Akayu hot spring are neutral –pH chloride type with a chloride concentration is 1,118mg/l (Takahashi et al., 1993).

Fig. 7 Akayu area is located at the north margin of the Yonezawa basin.

3.2.2 The Yamagata Basin and its surrounding area

The Yamagata Basin is located between the Ou and the Uetsu Mountains. Quaternary deposits up to 500 m in thickness are present within the basin. Many hot springs, such as Tendo, Higashine and South Yamagata hot spring group, are distributed along the margin of the basin, and formed during tectonic movements controlled by the NNE-SSW fault system. The Tendo and Higashine hot springs are located in the northeastern corner of Yamagata basin. Thermal waters of the Higashine hot spring with temperatures of 49 to 70 ^{o}C are pumped from six production wells drilled to depths of 120 to 130m (Urakami, 1994). Three production wells are drilled to depths of 180 to 220m at the Tendo hot spring and the discharge temperatures are 61 ^{o}C to 69 ^{o}C (Urakami, 1995). The aquifers of these hot springs consist mainly of Quaternary sediments, and thermal waters arise from deep permeable aquifers spreading out in the area. The South Yamagata hot spring group is located around Yamagata City. The temperature of the thermal waters discharged from the wells drilled to depths of 400m to 1,000m, are 40 ^{o}C to 50 ^{o}C. The Kaminoyama hot spring is located in the Kaminoyama Basin, south of the Yamagata basin. The thermal waters are discharged from shallow wells that encountered granitic rocks with temperatures of about 70 ^{o}C (Takahashi et al., 1993).

3.2.3 The Ginzan area

The Ginzan area is located in the northeastern up-lift zone and is accompanied by the Ginzan hot spring. The lithology of this area is mainly composed of Tertiary volcanics with sedimentary rocks. Thermal waters with temperatures of 45 ^{o}C to 64 ^{o}C gush out along the Ginzan River. NEDO drilled to depths of 1,000 and 1,700 meters and temperatures of 97 ^{o}C to 142 ^{o}C were encountered (NEDO, 1991a).

5. CONCLUSIONS

Geothermal features of Quaternary volcanic areas have many indications for existence of geothermal resources such as fumaroles, acid SO_4 type hot springs and hydrothermal alteration zones on the surface. The Azuma and the Zao areas are accompanied by high temperature hot springs and hydrothermal alteration zones. Volcanism of both areas stared at about 1Ma. High temperature thermal waters (above 60 ^{o}C) gush out in the Zao hot spring. In the Azuma and the Hijiori area, the maximum temperatures of the exploration wells are above 200 ^{o}C. Hijiori and Akakura area, related to caldera, are accompanied by high temperature thermal waters (70 ^{o}C). Many hot springs, not directly related to volcanic activities, are situated mainly along the Yonezawa and Yamagata basins. Some of the high temperature hot springs such as Akayu, Kaminoyama, Tendo and Higashine are situated on the margins of these basins or in volcano-tectonic depressions, which are suitable structures for thermal waters reservoirs. There are several promising areas for geothermal energy utilization in the Yamagata prefecture. A continuous investigation for geothermal energy utilization is, therefore, necessary in the future.

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