Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Geothermal Resources of the Yamagata Prefecture, Northeast Japan

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Keywords: Yamagata, Zao, Hijiori, Azuma, Akayu, geothermal, geology, volcano, hot spring.

ABSTRACT

Yamagata prefecture, located in the northeast of Japan, has many Quaternary volcanoes with high temperature hot springs and hydrothermal alteration zones. Typical Quaternary volcanoes are Funagata, Zao and Azuma in the Ou Mountains, and Chokai, Gassan, 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 above 60 ^{o}C associated with hydrothermal acidic alteration zones. Azuma and Hijiori areas are characterized by volcanic depression and maximum temperatures around 250 ^{o}C as measured in the exploration wells. A HDR (Hot Dry Rock) project was also conducted in Hijiori geothermal field.

Furthermore, many hot springs are distributed in this district. Yamagata prefecture has about 140 hot spring areas, containing more than 400 hot spring sources, with a total flow rate of about 48,000L/min. High temperature hot springs are distributed close to the Quaternary volcanoes and also distributed in the basins and volcano-tectonic depression in the north-south direction, having suitable structures favorable for the formation of thermal water reservoirs.

1. INTRODUCTION

Japan has more than 3,000 hot spring areas and it is the most advanced country for the utilization of hot springs in the world. Yamagata prefecture has about 140 hot spring areas, containing more than 400 hot spring sources, with a total flow rate of about 48,000 L/min (Yamagata Pref., 2018). Fig. 1 shows geothermal resources map in Yamagata prefecture. Hot spring water is believed to be good for the treatment of chronic disease and the promotion of a healthy lifestyle, and for these reasons, Japanese people enjoy bathing in hot springs. Several hot springs, such as the Zao, the Hijiori and the Akayu hot spring, have been used for bathing for more than a thousand years. Especially, the Akayu hot spring used to be visited by the Uesugi house, which is a famous feudal lord (daimyo) of the Edo period. The Uesugi house built a palace around 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, where geothermal investigations were carried out from late 1960's by Yamagata prefectural office (Tamiya, et al., 1973). Afterwards, a 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 New Energy and Technology Development Organization (NEDO) in Hijiori, Azuma, Ginzan and Akakura areas. Temperature profiles of the exploratory wells drilled by NEDO and indicated in Fig. 2. Furthermore HDR project was carried out by NEDO in Hijiori area.

2. GEOLOGICAL FEATURES

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 distributed eastern and central region of Yamagata prefecture, respectively. Inland basins situated between the Ou and the Uetsu mountains is divided by the E- W trending uplift zones (Tamiya, 1983).

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

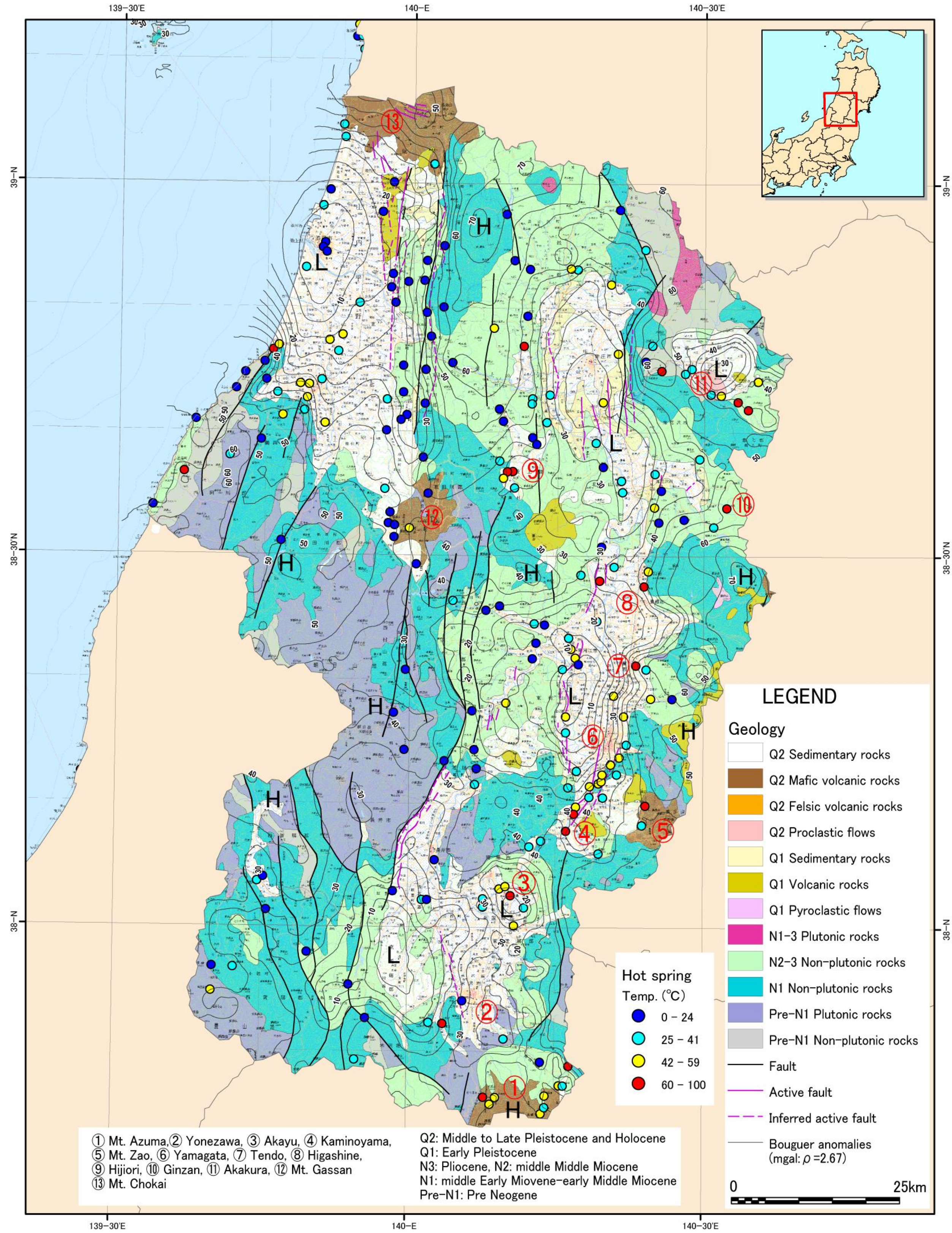

Figure 1; Geothermal resources map of Yamagata prefecture. (Modified after Sakaguchi and Takahashi, 2002)

3. CHEMICAL COMPOSITION OF THERMAL WATERS

Fig. 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 four water types, i.e., (a) Neutral pH, Cl type thermal water (from exploration wells DZ-6 and AHD-1), (b) Neutral pH, Cl-HCO_3/SO_4 type thermal water (Akayu, Ginzan, Higashine, Hijiori hot spring, and exploration well AZ-6), (c) Neutral pH SO_4 type thermal water (Tendo, Akakura, Shirabu hot spring), and (d) Acidic pH, SO_4 type thermal water (Zao, Ubayu hot spring). Fig. 4 shows the relation between $\delta^{18}O$ and δD for thermal waters from Azuma, Ginzan and Akakura areas. Most of the thermal waters of the hot springs plots within the meteoric water line.

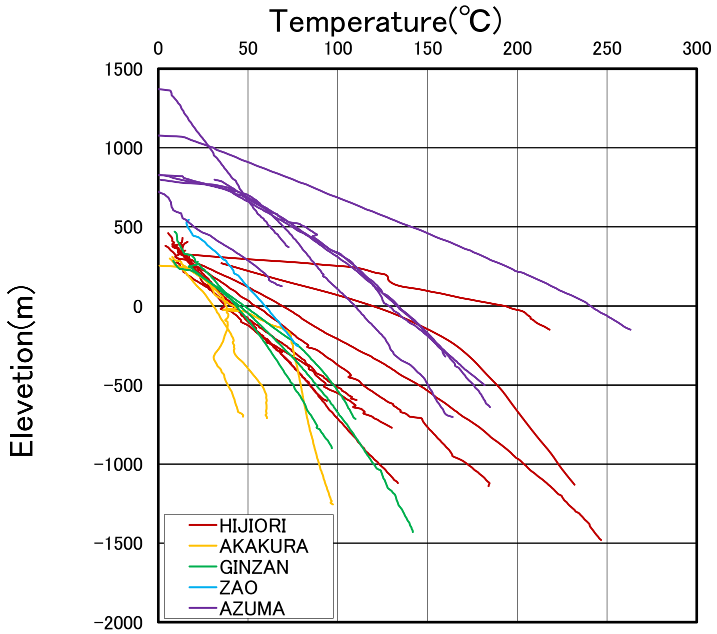

Figure 2: Temperature profiles of geothermal wells in Hijiori, Akakura, Ginzan, Zao and Azuma geothermal fields.

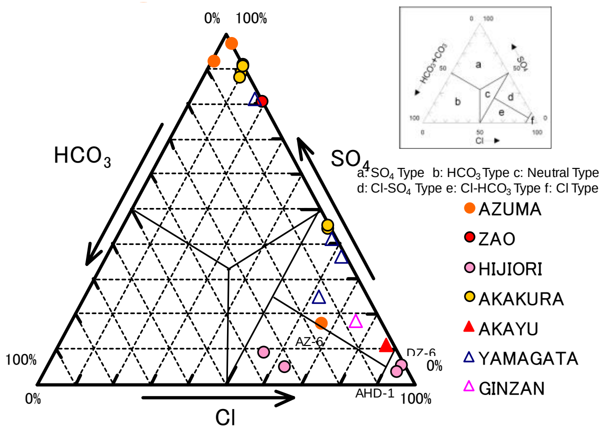

Figure 3; Chemical compositions of the major high temperature hot springs and thermal water from geothermal exploration wells in Yamagata Pref.

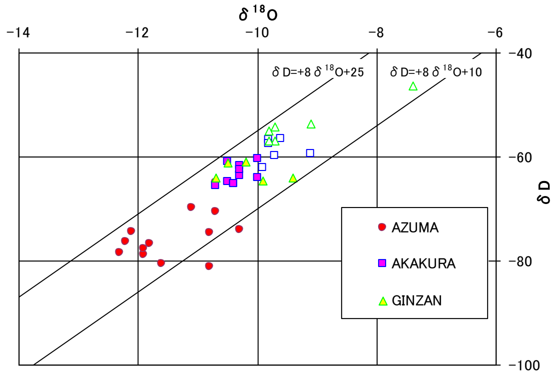

Figure 4; Relation between $\delta^{18}O$ and δD for thermal waters from Azuma, Ginzan and Akakura geothermal fields.

4. GEOTHERMAL RESOURCES

4.1 Quaternary volcanic area

Geothermal resources of Quaternary volcanic areas are accompanied by high temperature hot springs, and therefore it is possible to believe that the hot springs are caused by volcanic activity in the area. The Quaternary volcanic area have numerous indications for the existence of a potential for geothermal resource such as hydrothermal alteration zones with fumaroles and SO_4 type acid hot springs.

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 unconformable the Neogene formations and granitic basement rocks (Fig. 1, Fig 5). Volcanic activities are geologically divided into five stages during the period from 1.2-0.8Ma, 0.8-0.6 Ma, 0.6-0.4Ma, 0.4-0.3Ma, and <0.3Ma (Ban et al., 2016). 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 Ohdaira and Itaya. Azuma volcano is distributed within the up rift zone and volcanic rocks erupted from it are mainly andesitic. The Ubayu depression is located within the up rift zone and filled with acidic welded tuff. The Ohdaira and the Itaya depression zones are located to the north of the up rift zone. The Ubayu hot spring, located 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).

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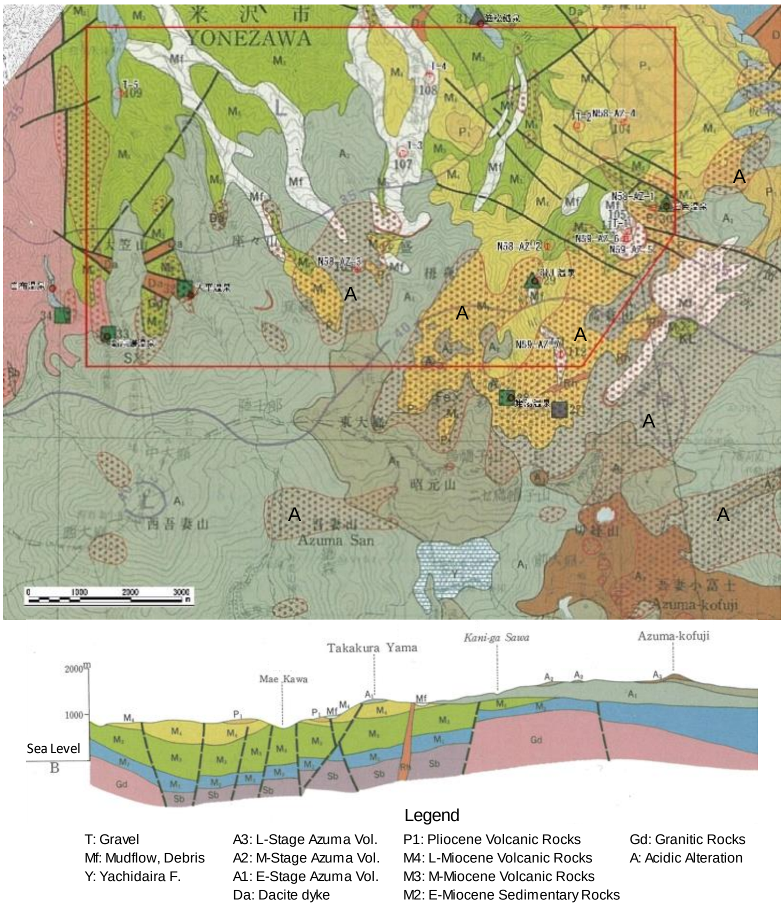

Figure 5; Geological Map of Northern Azuma geothermal field (NEDO, 1991).

The discharge temperature of the Ubayu acid SO_4 type of hot spring is 49 °C (Takahashi et al., 1993). Fig. 6 shows the chemical compositions of the major hot springs in the area. The Shirabu hot spring is discharged from granitic basement rocks in the southern margin of the area with discharge temperatures of 58-62°C (Yamagata HSA, 1973). The Goshiki spring is located on the western margin of the Namekawa east depression. The discharge temperature of the Goshiki hot spring is 47 °C and the chemical composition of hot spring is neutral-pH HCO_3 type (NEDO, 1991a). On the other hand, at the east margin of the depression, the hot spring water discharged from the well recorded a temperature about 100 °C (Abiko, 1990). As shown in Fig. 7, 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 coming from the well show a little oxygen isotopic positive shift, which can be explained by water-rock interaction.

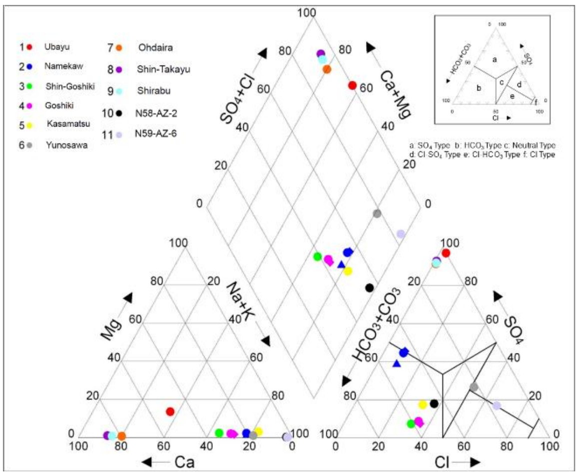

Figure 6: Chemical compositions of the major hot springs in Azuma geothermal field.

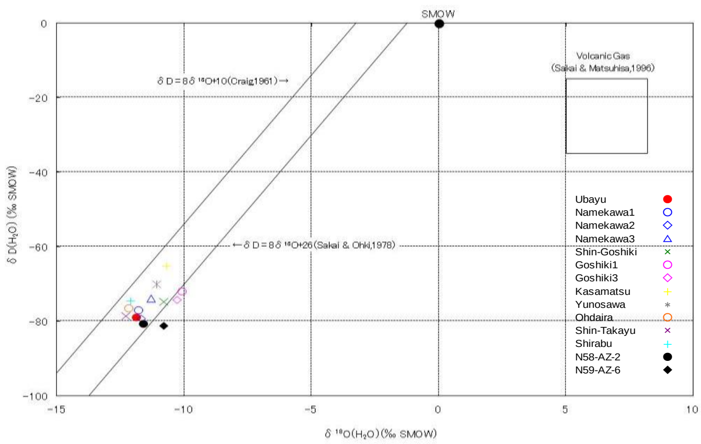

Figure 7: Relation between δ18O and δD for thermal waters from Azuma geothermal field.

Drilling was conducted by NEDO at depths between 600 and 1,500 meters, encountering temperatures around 67 ºC to 267ºC (NEDO, 1987). The Ubayu depression was confirmed by a drilling well named N58-AZ-7 which encountered a temperature of 267 ºC (Fig. 8). 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 chemical composition of thermal water from the well AZ-6 is neutral Cl-SO_4 type. The thermal fluid from the wells AZ-6 and AZ-2 indicating that the fluid has reached a state of partial equilibrium (Fig. 9). It is estimated that the fluid ascends in a certain state of equilibrium with the underground rocks, and therefore, the underground temperature would be comparatively high.

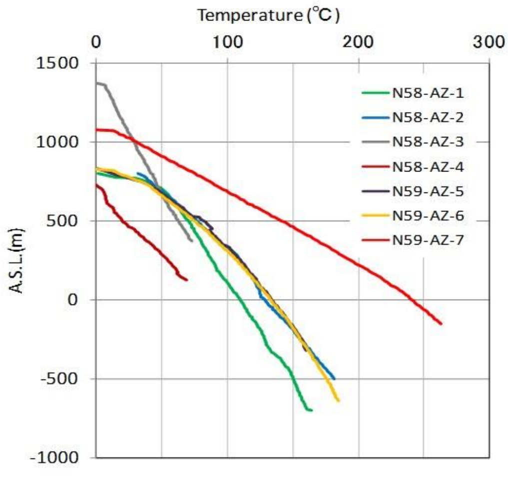

Figure 8; Temperature profiles of Azuma geothermal field.

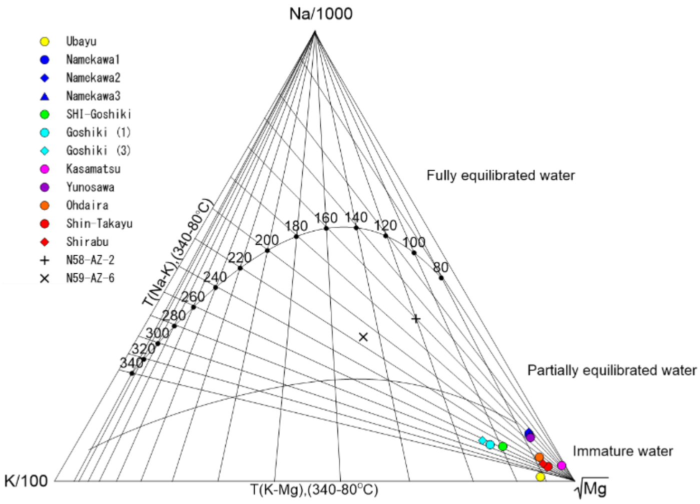

Figure 9: Ternary diagram for Na-K-Mg from Azuma geothermal field.

Azuma geothermal field is located south of Yonezawa district. The geothermal structure of Azuma area is characterized by E-W trending up rift zone and surrounded by two depression zones as suggested by the two detected low gravity zones in Ohdaira and Itaya (Fig. 10). The Ubayu depression is also located within uplift zone. Acidic alteration zone is distributed southeast of this area and Ubayu hot spring of acid SO_4 type, gushes out from acidic alteration zone (Fig.11). The center of geothermal activity in this area is around Ubayu hot spring, where underground temperature of above 260 ºC is encountered.

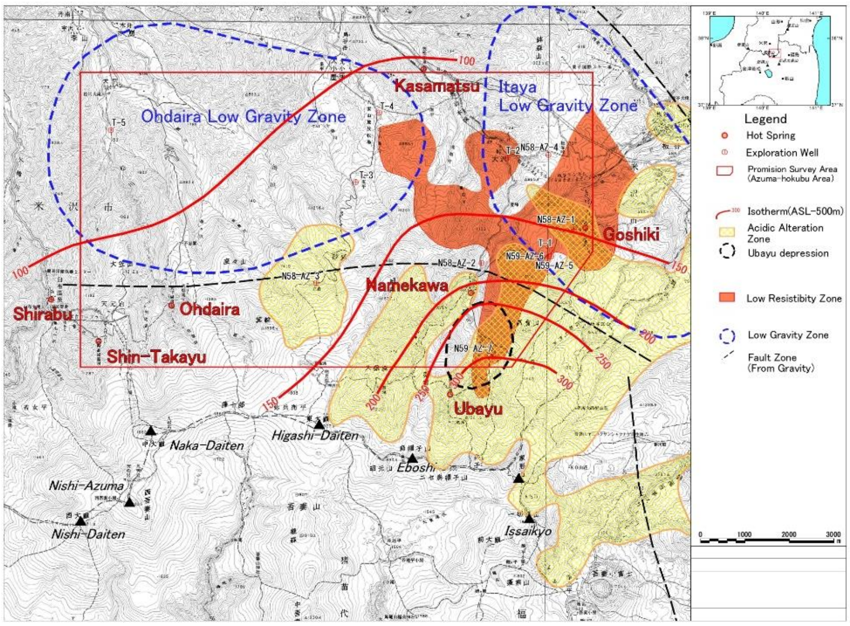

Figure 10: Geothermal interpretation map of Azuma geothermal field.

Figure 11: Hydrothermal alteration zone at the Ubayu hot spring in Azuma geothermal field.

Figure 12: The Crater Lake, diameter of about 300 meters in Zao geothermal field.

4.1.2 The Zao area

The Zao area, related to Zao volcano, is located in the east part of Yamagata prefecture and is accompanied by the Zao hot spring and by fumaroles. The Zao volcano is famous for its large crater lake which has a diameter of about 300m (Fig. 12) and its basement rocks consist of Cretaceous granitic rock, Neogene volcanic and sedimentary rocks. The Zao volcano is located close to the Quaternary volcanic front of the Northeast Japan arc. The volcanic activity was geologically divided into six stages (Ban et al., 2015). The first stage of volcanism started about 1Ma (Takaoka et al., 1989), whereas 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).

The Zao hot spring is discharged from Neogene volcanic rocks in the explosion crater extending about 3 km wide. The discharge temperature of the Zao hot spring is 65°C (Takahashi et al., 1993) with a discharge rate above 6,700 l/min (Yamagata pref., 2018). The Zao hot spring is also an acidic SO_4 type, however, the major difference from the Ubayu hot spring in Azuma area 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 the major eruptive products of Hijiori volcano are composed of dacitic pumice flow deposits (Fig.13). The 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 the central part of the caldera (Kimbara and Sakaguchi, 1989). The Hijiori hot spring and Kogane hot spring, discharged from central region of the caldera, are a neutral-pH Cl-HCO_3 type with relatively high chloride concentration of 1,155 to 1,390mg/l and the discharge temperature is 75 to 84 °C (Takahashi et al., 1996). On the other hand, Ishidaki and Imagami hot spring distributed outside of the caldera are a neutral-pH HCO_3 type. The Japanese government including NEDO, drilled several wells to depths between 500 and 1,800 meters until 1983, encountering temperatures of 94 °C to 248 °C (NEDO, 1983). The temperature profile of the exploration wells were almost conduction type, with a maximum temperature of 248 °C at the depth of 1500m in the well DZ-6. On the other hand, the temperature profile of the well HO-1 was convection/up-flow type with a maximum temperature of 218 °C at the shallow depth of 500m (Fig. 14). The geothermal fluid from well DZ-6 consisted of almost fully equilibrated water and Cl type with high chloride concentration of 9,230mg/l (Fig.15). Na-K, Na-K-Ca geothermometer indicated 210-240 °C

NEDO also conducted research on HDR development techniques from FY1985 to FY2002. In this project, three wells were drilled at a depth of around 2,300 meters, and in addition, 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 depth and temperature of the upper and the lower reservoirs were 1,800m, 250 °C and 2,200m, 270 °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 with a discharge temperature of 74 °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 were plotted on the meteoric water line, suggesting that the water originated from meteoric water. NEDO drilled at depths between 1,000 and 1,500 meters, encountered temperatures of 47 °C to 97 °C (NEDO, 1990).

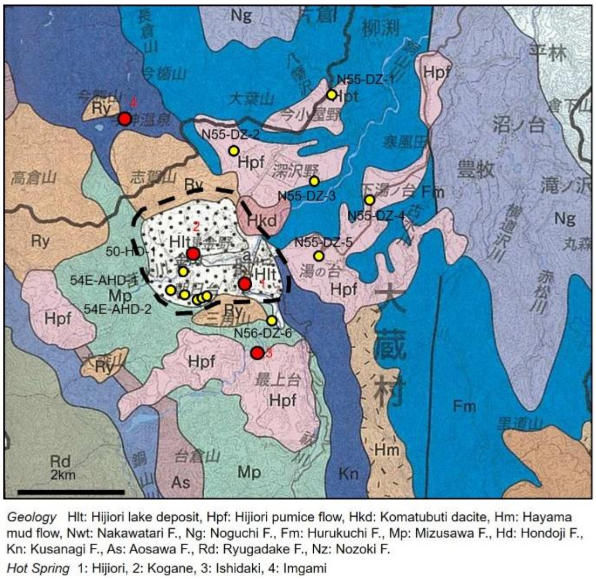

Figure 13: Geological map of Hijiori geothermal field (Modified after AGS of Yamagata, 2016).

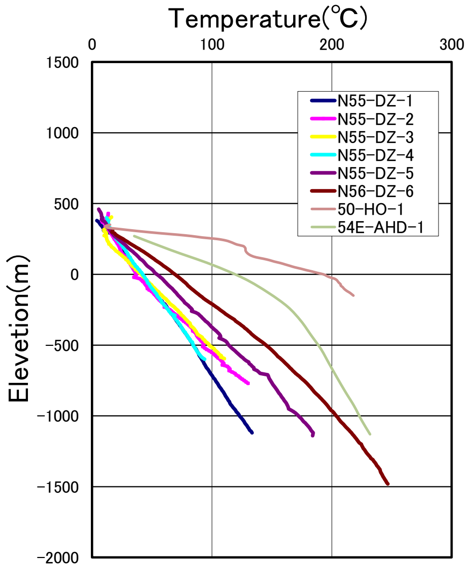

Figure 14: Temperature profiles of Hijiori geothermal field.

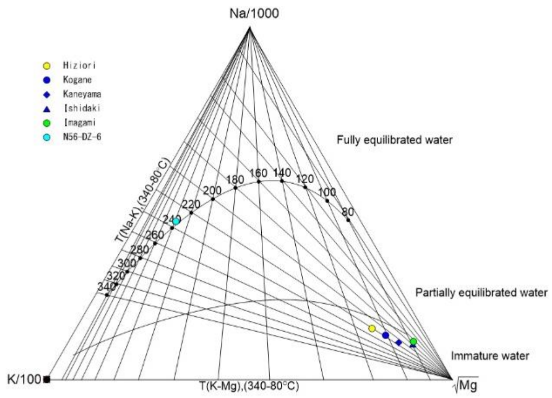

Figure 15: Ternary diagram for Na-K-Mg from Hijiori geothermal field.

Figure 16: Photograph of Hijiori Caldera.

4.2 Non Quaternary volcanic areas

Many hot springs not directly related to volcanic activities are scattered mainly along the Yonezawa basin and the Yamagata basin (Fig.1). Some of the hot springs are located at the margins of these basins or in the volcano-tectonic depression.

4.2.1 The Akayu area

The Akayu area is located at the north margin of Yonezawa basin in southern Yamagata prefecture and the related volcano-tectonic depression was formed in late Miocene (Fig.17). The Akayu depression is filled with submarine acidic pyroclastic flow of 1,500m thick (Honda et al., 1985). This depression, which seems to correspond to the low gravity anomaly (Fig.1), characterizes a geological structure suitable for providing favorable conditions for thermal waters. Several hot springs are distributed in Akayu depression including the Akayu hot spring situated in the central part of Akayu depression (Fig.1). According to the result of the geological survey, it is considered that the fracture trending NE-SW 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 the depth of 400m, is 63 °C. Geochemical characteristics of thermal waters from the Akayu hot spring are neutral chloride type (Fig.3) with a chloride concentration of 1,118mg/l (Takahashi et al., 1993).

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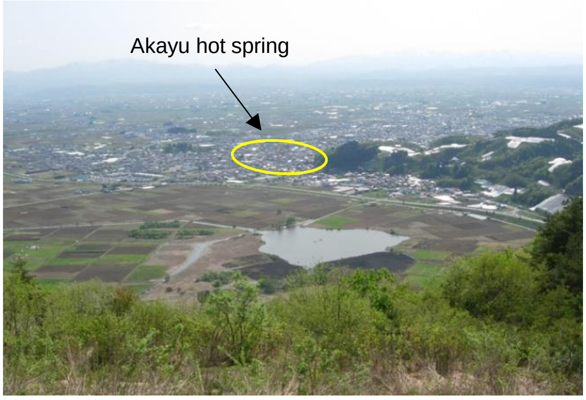

Figure 17: Akayu area is located at the margin of the Yonezawa basin and Akayu depression.

Figure 18: "Motoyu", main public bath of Akayu hot spring

4.2.2 The Yamagata basin and its surrounding area

The Yamagata basin is located between the Ou and the Uetsu Mountains (Fig.1). 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, which were 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 range from 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. On the other hand, a hot spring with a discharged temperature of 96 ^{o}C , has been developed in recent years near Tendo hot spring (Tamiya, 2015).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, range from 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 of 300 to 500m depth that encountered granitic rocks with temperatures of about 60 to 70 ^{o}C. The up flow of these thermal water seems to be controlled by the NNE-SSW fault system (Mashiko, 2015).

4.2.3 The Ginzan area

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

5. CONCLUSIONS

The geothermal features of Quaternary volcanic areas presented many indicators that show the existence of potential geothermal resources, such as, fumaroles, acid SO_4 type hot springs and acidic hydrothermal alteration zones on the surface. The Azuma, the Hijiori and the Zao areas are accompanied by high temperature hot springs and acidic hydrothermal alteration zones. Volcanic activity in Azuma and Zao areas started at about 1Ma. High temperature thermal waters (above 60 ^{o}C) gush out in the Zao and Hijiori hot spring. The Azuma and the Hijiori areas are related to volcanic depression/caldera and the exploration wells detected maximum temperatures around 250 ^{o}C. On the other hand, the HDR project conducted in the Hijiori geothermal field confirmed the artificial HDR reservoir. The Akakura area, also related to the existence of a 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 the Yamagata basins. Both basins are distributed along the up-rift zones of N-S direction. 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. To make effective use of geothermal energy as renewable energy, a continuous investigation for geothermal energy utilization is, therefore, necessary in the future.

REFERENCES

Abiko, M.: Current states of hot springs. *Applied geology of Yamagata*, 10, (1990), 24-32 (in Japanese).

Applied Geological Society of Yamagata: Explanatory text of 1:100,000 geological map of Yamagata Prefecture. *Yamagata University Press*, (2016), 61p (in Japanese).

Ban, M., Oikawa, T. and Yamasaki, S.: Geological map of Zao volcano. *Geological map of volcanoes 18*, Geological Survey of Japan, AIST, (2015), (in Japanese with English abstract).

Ban, N., Takebe, T., Adachi, T., Matsui, R. and Nishi, Y.: Eruption Histories of Zao and Azuma volcanoes and their magma feeding system for recent activities. *Bulletin of Earthquake Research Institute, University of Tokyo*, (2016), 91, 3/4, 25-39.

Honda, Y., Kato, H., Kita, T., Suzuki M., Takahashi, S., Tamiya, R., Yamagata, O., Yamada, K., Yoshida, S. and Zinbo N.: Geology of the Neogene series around of Yonezawa basin, with special reference to the volcanic rocks, Geology of Yamagata Prefecture, Japan. *Professor Sinya Minakawa Memorial Volume*, (1985), 177-192 (in Japanese).

Kimbara, K. and Sakaguchi, K.: Geology, distribution of hot spring and hydrothermal alteration zones of major geothermal areas in Japan, Report No.270, Geological Survey of Japan, (1989), 482p.

Mashiko, T.: On the development of new wells in Kaminoyama onsen, Yamagata prefecture. *Journal of the balneological society of Japan*, 65, (2015), 40-53 (in Japanese with English abstract).

Matsunaga, I., Niitsuma, H. and Oikawa, Y.: Review of the HDR Development at Hijiori Site, Japan, *Proceedings*, World Geothermal Congress 2005, (2005).

Miyagi, I.: Stratigraphy and volcanic activities of Hijiori volcano, Northeastern Japan arc, *Bulletin of the Volcanological Society of Japan*, 52, (2007), 311-333(in Japanese with English abstract).

Nanyo City: History editing document of Nanyo City. History editing committee of Nanyo City, 24, (1994), 160p. (in Japanese)

NEDO: Report of the Geothermal Promotion survey "the Dozangawa karyu area". The New Energy and Technology Development Organization, (1983), 474p (in Japanese).

NEDO: Report of the Geothermal Promotion survey " the Azuma Hokubu area". The New Energy and Technology Development Organization, (1987), 846p (in Japanese).

NEDO: Report of the Geothermal Promotion survey " the Mogamiakakura area". The New Energy and Technology Development Organization, (1990), 808p (in Japanese).

NEDO: Report of the Geothermal Promotion survey " the Obanazawa toubu area". The New Energy and Technology Development Organization, (1991a), 773p (in Japanese)

NEDO: Nationwide Geothermal Resources exploration survey project " Bandai area", (1991b), 88p (in Japanese).

Oba, Y.: Zao volcano, *Applied geology of Yamagata*, 19, (1999), 1-3 (in Japanese).

Oikawa, Y. and Tosha, T.: Outline of hot dry rock development project at Hijiori site, *Journal of the Geothermal research Society of Japan*, 23, (2001), 275-282 (in Japanese).

Sugai K.: On the Pre-Neogene rocks of the Yamagata prefecture, northeast Japan, - with special reference to the Paleozoic groups and their metarmorphic rocks, Geology of Yamagata Prefecture, Japan, *Professor Sinya Minakawa Memorial Volume*, (1985), 1-13. (in Japanese) .

Sakaguchi, K. and Takahashi, M.: Geothermal Resources Map of Tohoku and Kyushu (CD-ROM Version). Digital Geoscience Map GT-1, Geological Survey of Japan, AIST, (2002).

Takahashi, M., Yamaguchi, Y., Noda, T., Komazawa, M., Murata, Y. and Tamanyu, S.: Geothermal resources map of Niigata area, scale 1:500,000. Miscellaneous Map series (31-1) , Geol. Surv. Japan, (1993), 116p (in Japanese with English abstract 2p).

Takahashi, M., Komazawa, M., Murata, Y. and Tamanyu, S.: Geothermal resources map of Akita area, scale 1:500,000. Miscellaneous Map series (31-2) , Geol. Surv. Japan, (1996), 162p (in Japanese with English abstract 2p).

Takaoka, N., Konno, K., Oba Y. and Konda, T.: K-Ar dating of lavas from Zao volcano, northeastern Japan, *Journal of the Geological Society of Japan*, 95, 3, (1989), 157-170 (in Japanese with English abstract).

Tamiya, R.: On the state of development and reserves of deep hot water-type spring in Yamagata prefecture, *Journal of the New Energy Foundation*, 8, (1983), 9-26 (in Japanese).

Tamiya. R.: Geological environment and the hot springs in Yamagata prefecture. *Journal of the balneological society of Japan*, 65, (2015), 26-39 (in Japanese with English abstract).

Tamiya, R., Tamanoi, M., Yokoyama H., Ishiyama, H., Abe, K., Ishida, T., Endo, K. and Tanji, Y.: Preliminary surveys of geothermal fields in Yamagata prefecture, *Journal of the Japan Geothermal Energy Association*, 10, (1973), 7-14 (in Japanese).

Ui, T. and Shibahashi, K.: Quaternary volcanoes in Yamagata prefecture, northeastern Japan - A review, Geology of Yamagata Prefecture, Japan, *Professor Sinya Minakawa Memorial Volume*, (1985), 33-44 (in Japanese with English abstract).

Urakami, K.: Thermal water flow systems in the Higasine hot spring area, Yamagata prefecture, Japan, *Journal of the balneological society of Japan*, 44, (1994), 45-73 (in Japanese with English abstract).

Urakami, K.: Thermal water flow systems in the Tendo hot spring area, Yamagata prefecture, Japan, *Journal of the balneological society of Japan*, 45, (1995), 247-267. (in Japanese with English abstract)

Yamagata hot springs association: History and description of hot springs in Yamagata prefecture, (1973), 541p (in Japanese).

Yamagata prefecture: Hot springs in Yamagata prefecture 2018, (2018), 10p (in Japanese).