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Geology, Mineralogy and Fluid Geochemistry of Wells Discharging Acid Fluids in Hatchobaru Geothermal Field, Kyushu Island, Southwestern Japan

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ABSTRACT

The Hatchobaru field is located in Kyushu, Japan. Hatchobaru geothermal power plant has been operating since 1977 by Kyushu Electric Power Co., Inc. (KEPCO). The geothermal reservoir with fluid temperature ranging from 240 to 300°C, is water-dominated. Neutral-chloride fluid in the reservoir is dominant. However, some wells discharge acidic fluid. In Hatchobaru, acidic alteration zone is developed at shallower depth, which infers the acidic fluid is stored mainly at the shallower depth. On the other hand, feed zones of wells discharging acidic fluid are located at deeper depth where acidic minerals are not observed. Considering these occurrence, there still remains uncertainties of distribution and origin of acidic fluid at subsurface.

We have conducted well geological and mineralogical studies by petrographic observation and XRD analysis to characterize alteration minerals. The results are; 1) acidic alteration minerals dominate at shallower depths (1,200 to 400 m asl.) 2) regardless of pH of discharged fluid, illite, chlorite and interstratified clay minerals occur below the acidic alteration zone, 3) acidic alteration minerals such as kaolinite, alunite pyrophyllite and diaspore are not identified at the deeper feed zones of the wells which discharge acidic fluid. In the results of XRD analysis, differences of mineral assemblage and spatial distribution of alteration minerals are not found among the wells discharging acidic fluid and neutral-alkaline fluid. These results suggest some possible mechanisms of discharging acidic fluid; 1) fluid acidity at subsurface is not so low for the formation of acidic minerals 2) migration of acidic fluid from the surrounding areas.

In this paper, we discuss the origin of acidic fluid from the production area based on the results of the alteration mineral paragenesis, its distribution, and geochemistry of discharged fluids.

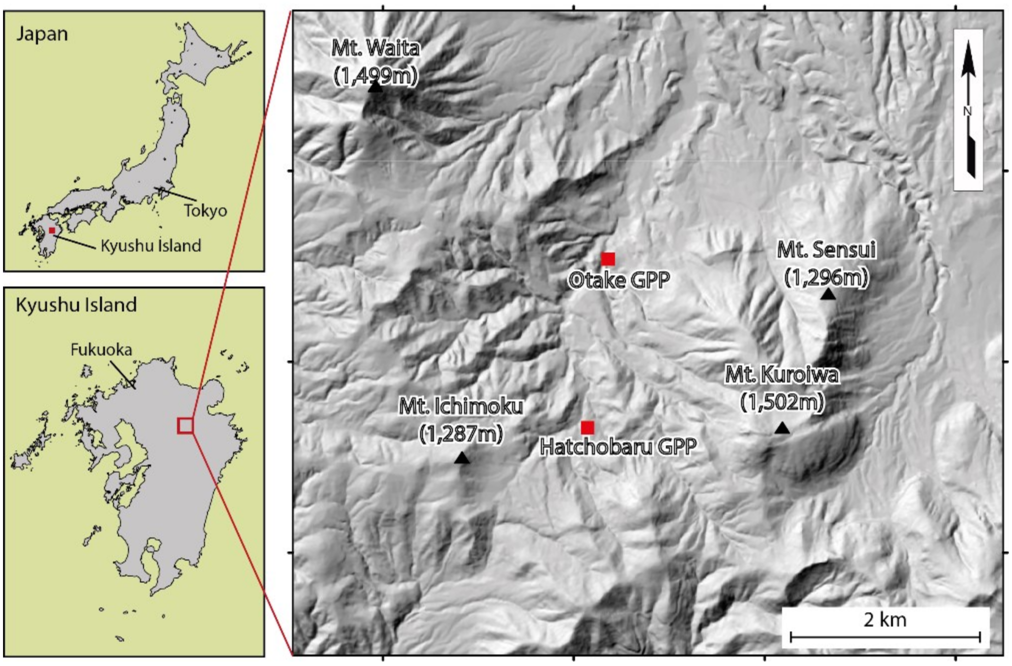

Figure 1: Topography in and around Hatchobaru Geothermal Power Plant. Base map is shaded relief map made by DEM of Geospatial Information Authority of Japan. Black triangles show peak of Quaternary volcanoes.

1. INTRODUCTION

The Hatchobaru geothermal field is located in the Oita Prefecture, northeast Kyushu, Japan (Fig.1). The geothermal power plant unit No.1 has been operating since 1977 with an output capacity of 55MW and followed by the unit No.2 (55MW) since 1990 by Kyushu Electric Power Co., Inc. (KEPCO) with the total power output is 110 MW. In addition, a 2 MW binary power plant has been installed in 2006. The geothermal reservoir has characteristic of fluid temperature ranging from 240 to 300^{o}C and water-dominated system, dominant by neutral-chloride fluid in the reservoir. However, some drilled wells reported discharge acidic fluid in the Hatchobaru (Shimada *et al*., 1985, Matsuda *et al.*, 2000). Acidic fluid discharge from wells causes corrosion in casing and surface facilities such as pipe lines. Presence of acidic fluid is one of the big issue for geothermal exploration and for sustainability of power plant operation.

A project has been started by Japan Oil, Gas and Metals National Corporation (JOGMEC) to understand the distribution of acidic fluid, and to identify the origin of acidic fluid in geothermal field in Japan in order to avoid some risks caused by acidic fluid. Aiming to characterize the mineralogy and distribution of alteration minerals of wells discharging acidic fluid, we have conducted well geological and mineralogical studies of the wells in Hatchobaru through the petrographic observation and XRD analysis using cuttings from both acid and neutral wells. This paper presents the characteristics of mineralogy and distribution of hydrothermal alteration of wells discharging acidic fluid by comparing the wells discharging neutral-alkaline fluid for better understanding of the origin and behavior of acidic fluid in Hatchobaru geothermal field.

2. GEOTHERMAL CONCEPTUAL MODEL IN HATCHOBARU GEOTHERMAL FIELD

2.1 Geological Setting

The Hatchobaru geothermal field is located in the Kuju volcano region, an active volcanoes sitting on the volcanic front on Kyushu Island in the Beppu-Shimabara Graben. Based on the eruption stages, Kuju volcano region was formed from Stages 1 to 4 ((Kawanabe *et al,* 2015) as shown in Fig.2. The first stage of volcanic activity started at about 200 ka ago at the western part, which produced the Mt. Kuroiwa, Mt. Goto and Mt. Ryoshi volcanoes in the western and Mt. Kutsukake, Mt. Naruko and Mt. Io lava in the central. Stage 2 was defined to the Handa pyroclastic flow deposits which considered as the product from the largest eruption of Kuju Volcano from the central part covered the volcanic edifice (ca. 54 ka). It consists of dacite pumice with a very small amount of andesite scoria. During stage 3 (ca. 54-15 ka) it was formed Mt. Ogigahana, Mt. Hosshozan, Mt. Nakadake, Mt. Mimata and Mt. Daino at the eastern part. The volcanic products from stage 1 to 3 consists of mostly hornblende andesite and dacite. The last stage began in Mt. Hijidake in the eastern part at ca. 15 ka. followed by Mt. Taisen, Mt. Kitataisen and Mt. Kurodake. In this stage, it is characterized by a large amount of mafic magma without hornblende phenocryst. The latest andesitic magma eruption formed Mt. Kurodake lava dome at 1.6 ka ago (Kamata and Kobayashi, 1997) where located at the eastern part.

The Hatchobaru geothermal field is located in the western part of Kuju volcano group, western part of Mt. Kuroiwa (Fig. 2). The geology in the Hatchobaru field is divided into four groups in descending order 1) Kuju volcanic rocks (Middle - Upper Pleistocene) consists of hornblende andesite lava that formed several lava domes, 2) Hohi volcanic rocks (Lower Pleistocene) composed of pyroxene andesite lava flows with thickness abut 800m, 3) Usa group (Miocene) consists of mainly altered andesite lava flows and tuff breccias with thickness more than 800 m and 4) Basement rocks (Paleozoic - Mesozoic) composed of the Cretaceous granite rocks and Paleozoic metamorphic rocks (Fujino and Yamasaki, 1985).

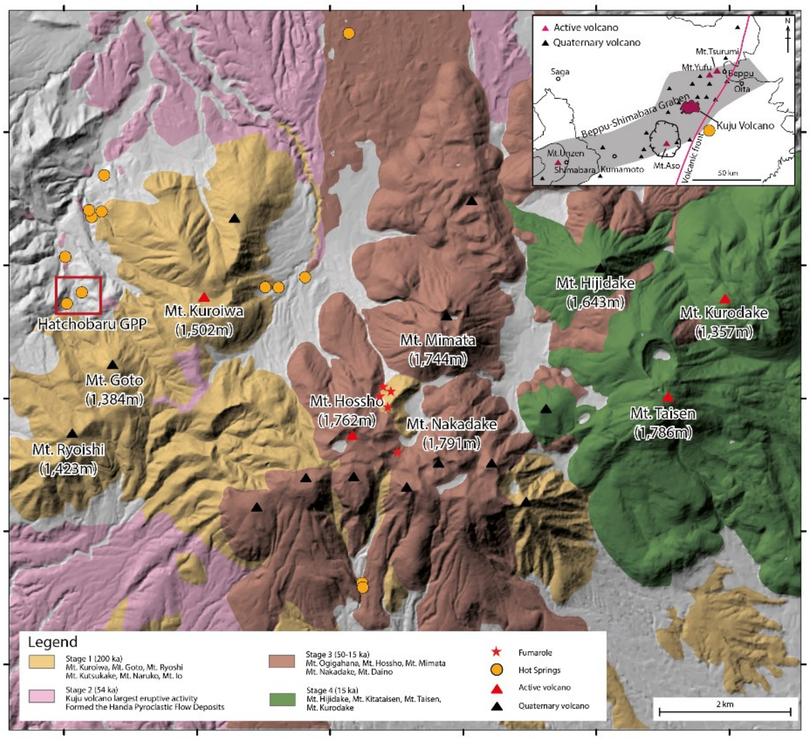

Figure 2: Geological map of Kuju Volcano Group, modified from Kawanabe, *et al* (2015). Base map is shaded relief map made by DEM of Geospatial Information Authority of Japan. Red triangle shows active volcanoes, black triangle shows peaks of major Quaternary volcanoes.

2.2 Geothermal conceptual model in Hatchobaru field

The conceptual model of Hatchobaru geothermal field was constructed by integrating the entire result of analysis and interpretation from a lot of data on geology, geophysics and hydrogeology, etc. conducted since exploration and development stage of Hatchobaru Geothermal Power Plant ((Fujino and Yamasaki, 1985; Momita *et al*., 2000).

The geothermal reservoir of Hatchobaru geothermal field is a water-dominated type with temperatures in the range between 240-300^{o}C and has been tapped from depths between 1,000 m and 2,300 m within andesitic volcanic rocks (Hohi volcanic rocks and Usa group). The heat source in this area is related with the late Quaternary volcanic activity of Kuju Volcano. Based on the interpretation of isotope data, the geothermal fluid in Hatchobaru geothermal field are derived from meteoric water. The meteoric water is infiltrated into deeper level in the southeast area of the field at the high elevation area in the Kuju volcanoes (Fig. 3 and Fig. 4), then being heated up to about 300^{o}C by the heat source. The upflow zone of parental fluid is assumed to be located beneath Mt. Kuroiwa (Fig. 3). The geothermal fluid is mainly stored along fracture zones of the five faults namely: Komatsuike fault, Komatsuike-sub fault, NE3 fault, NE4 fault and Hatchobaru fault in the study area (Fujino and Yamasaki, 1985). The geothermal fluid migrates toward northwest and southwest along the permeable zones related with faults and stored in the andesitic volcanic rocks of Hohi volcanic rocks and Usa group below the clay cap rock (Momita *et al*., 2000). The clay cap rock developed at an elevation higher than 500 m asl. characterized by the presence of smectite, alunite and kaolinite.

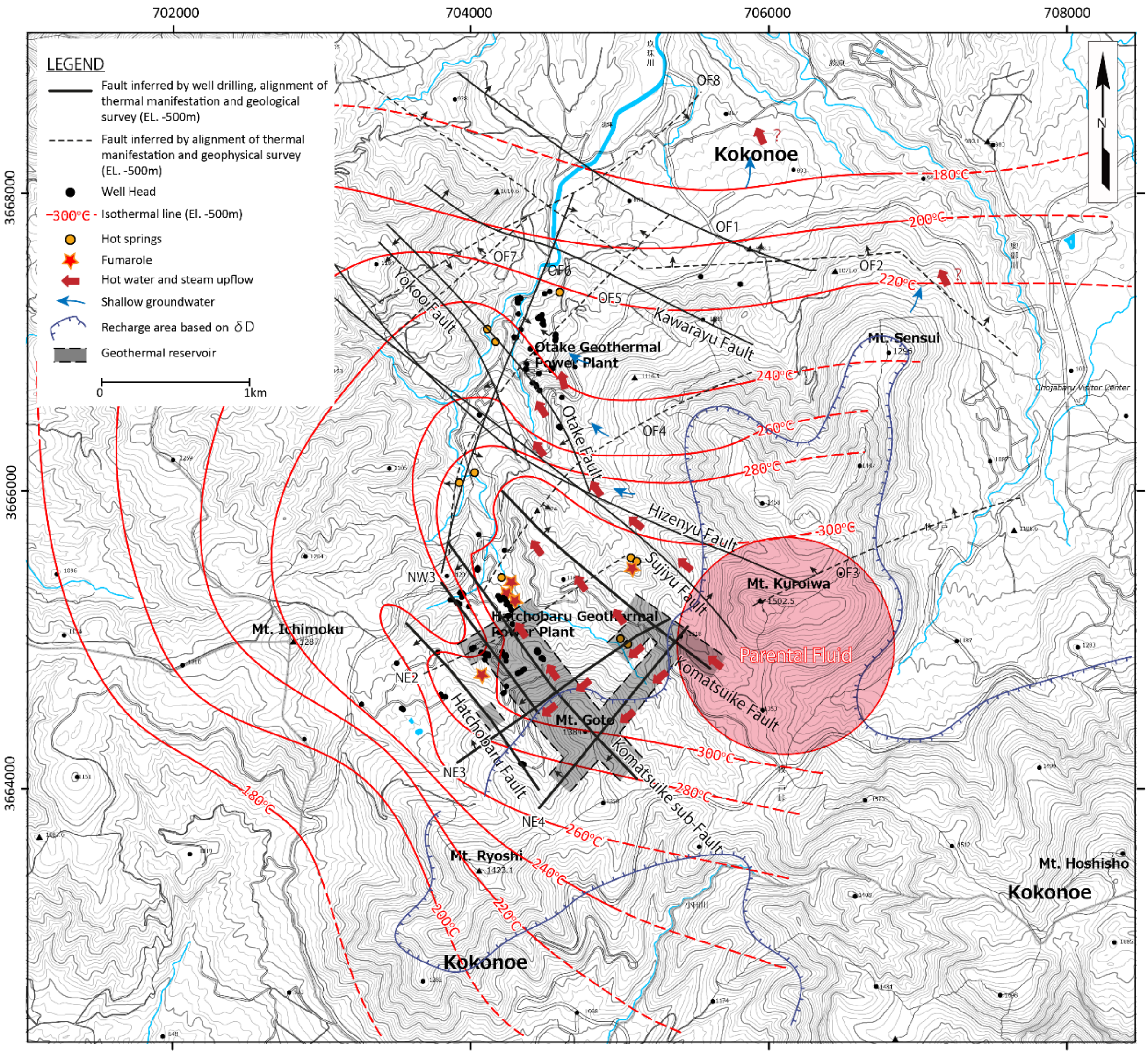

Figure 3: Plan view of the geothermal conceptual model in Hatchobaru (modified from Momita *et al*., 2000)

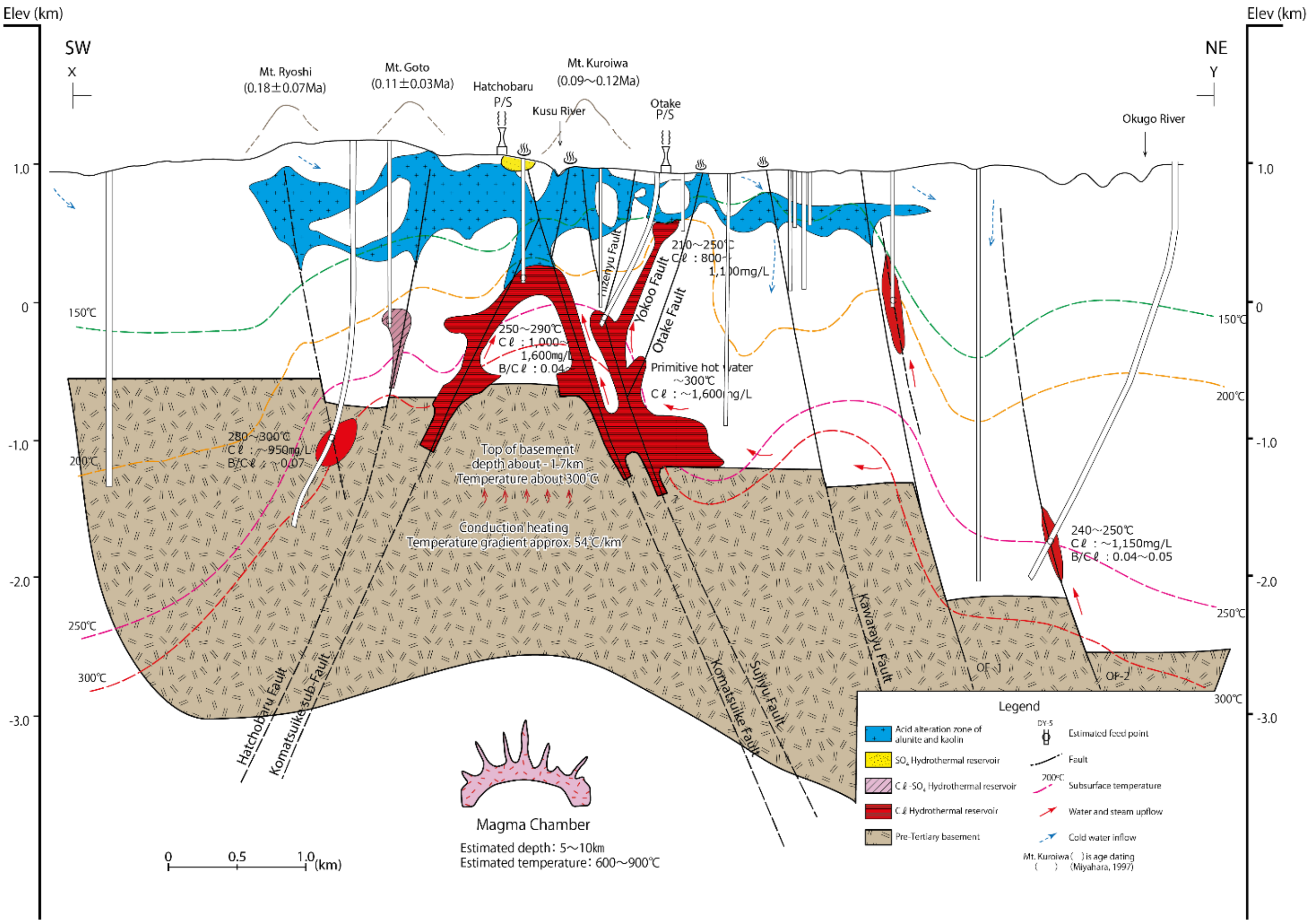

Figure 4: SW-NE cross section of the geothermal conceptual model in Hatchobaru (from Momita *et al*., 2000)

3. WELLS DISCHARGING ACIDIC FLUID

In Hatchobaru geothermal field, acid fluids have been encountered in some wells. These wells are located in the northern and the southern part of the main production area. The origin of acid geothermal fluids of Hatchobaru was discussed by Shimada *et al*. (1985) and Matsuda *et al.* (2000) mainly from view point of fluid chemistry. Acid fluids confirmed in the Hatchobaru geothermal field are considered to be the result of mixing of neutral-pH fluid with low temperature SO_4-rich fluid from shallower levels. The distribution of acid fluid reservoirs in the Hatchobaru geothermal field is believed to be restricted to the relatively shallow level. As described here, origin of acidic fluid has studied from geochemistry, meanwhile characteristics of mineralogy and hydrothermal alteration of acidic wells have not been well examined. In this study, we focused on 4 acidic wells named H-28, H-33, H-35 and HS-1 to obtain geological and mineralogical information. The pH have been monitored in these four wells from time to time measured from the discharge fluid as shown in Fig. 5.

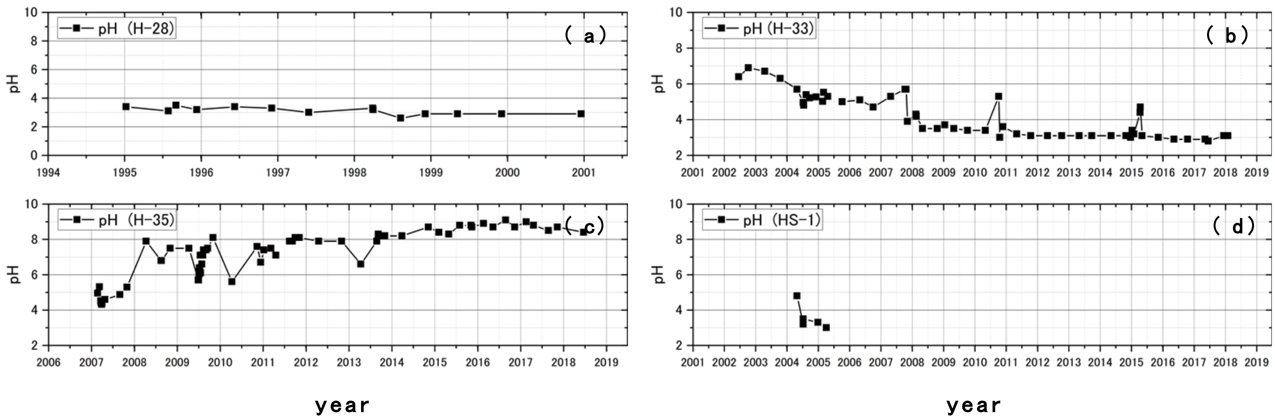

Figure 5: Measured pH of discharging fluid with time in (a) H-28, (b) H-33, (c) H-35 and (d) HS-1

H-28 is located at the southwestern portion of the production area and it produces SO_4-rich fluid. The acidic fluid tapped by H-28 is considered to be stored along the NW-SE trending Hatchobaru Fault. Measured pH of H-28 fluid shown value of 3.4 in 1995 and 2.9 in 2001 which shows pH gradually decreased from 1995 to 2001(Fig. 5a).

H-33 and HS-1 are located at the southeastern portion of the production area and these produced SO_4-rich fluid. The acidic fluid considered to be stored along the NE-SW trending NE4 Fault. At the first 5 years of the production, H-33 produced neutral fluid with pH = 6.4. However, pH of the fluid dropped from neutral to acidic (pH = 3.1) in the end of 2008 HS-1 produced acidic fluid (pH = 3.0). Currently as of 2020, the wells are not used, but the monitoring of pH is still conducted.

H-35 is located at the southern portion of the production area and it also produces SO_4-rich fluid. The acidic fluid is considered to be stored along the NE-SW trending Komatsuike-sub Fault. H-35 produced weakly acidic fluid (pH = 4.5) at the initial stage of the production in 2007. The pH of the fluid is gradually turned into neutral with pH of 8.4 by continuing the fluid production.

4. GEOLOGICAL AND MINERALOGICAL CHARACTERISTICS OF WELLS DISCHARGING ACIDIC FLUID

In order to characterize the alteration mineralogy of the wells discharging acidic fluid, a detail mineralogical study was carried out. Geological information was obtained using cuttings collected every 5m from the wells H-28, H-33, H-35 and HS-1. Petrographic observation and X-ray diffraction analysis have been conducted to interpret the stratigraphy and hydrothermal alteration.

The lithology has been encountered in the shallow depth of wells includes andesite belong to the Kuju volcanic group. Hohi volcanic group are found with lithology of pyroxene andesitic lava and some tuff breccia. Below the above lithology unit is Usa group consisting of mostly pyroxene andesitic lava. Figure 6 shows results of petrographic analysis at a depth of 698m in H-28 well. Mainly clay minerals and anhydrite are formed. At a depth of 2,250m in H-33 well. It is indicated that some plagioclase is altered to pyrophyllite as shown in Fig. 6.

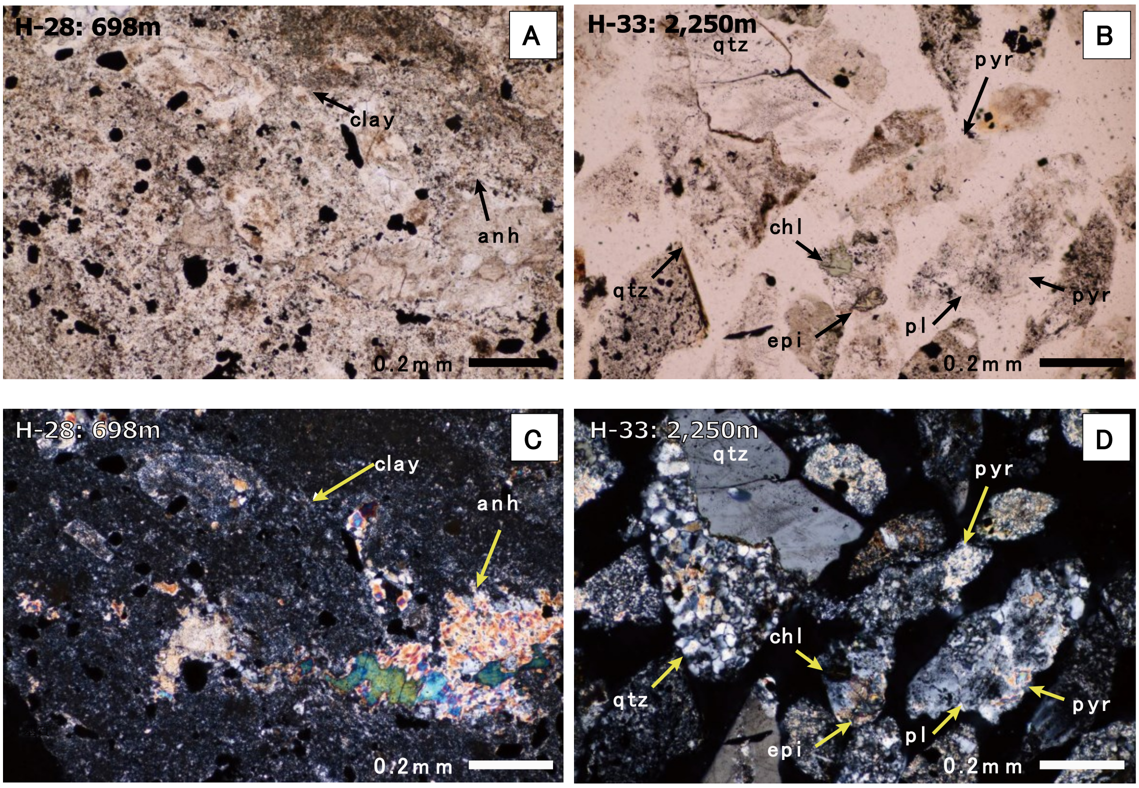

Figure 6: Petrographic observation showing texture of mineral assemblage of H-28 (at a depth of 698m) and H-33 (at a depth of 2,250m) cuttings sample. A and B shows photographs of open nicol and C and B shows cross nicol. Abbreviations are; qtz: quartz, anh: anhydrite, chl: chlorite, epi: epidote, pyr: pyrophyllite, pl: plagioclase

The major hydrothermal minerals of the wells derived from XRD analysis are: quartz, cristobarite, alunite, kaolinite, pyrophyllite, smectite, chlorite-smectite mixed layer, illite-smectite mixed layer, chlorite, illite, anhydrite, pyrite and feldspar in all wells. Near feed zones, the major hydrothermal minerals of the wells derived from XRD analysis are: quarts, chlorite, illite, anhydrite, pyrite and feldspar.

H-28 : Acid alteration minerals are encountered at the shallower depth. Alunite presents from the depths of 140 m to 320 m with lithology of Hohi volcanic group. Kaolinite occurs at depth of 150 m to 644 m with lithology of Hohi volcanic group. Pyrophyllite are not recognized in this well.

H-33 : Acid alteration minerals are found at the shallower depth. Alunite occurs from the depths of 265 m to 405 m with lithology of Hohi volcanic group. Kaolinite presents at depths of 725 m to 865 m with lithology of Hohi volcanic group. Pyrophyllite are found at depths of 765 m with lithology of Hohi volcanic group, and deeper depth of 2,250 m and 2,255 m with lithology of Usa volcanic group.

H-35 : Acid alteration minerals present at the shallower depth. In this well, alunite occurs from the depths of 5 m to 925 m. Kaolinite found at depths of 105 m to 345 m. Pyrophyllite presents at depths of 725 m to 925 m with lithology of Hohi volcanic group. Fig. 7 shows well lithology and hydrothermal alteration of the well H-35

HS-1 : Acid alteration minerals present at the shallower depth. Alunite occurs from the depths of 140 m to 320 m. Kaolinite is found at depth of 150 m to 644 m. Pyrophyllite occur from depth of 1,105 m and 1,145 m in this well with lithology of Hohi volcanic group.

Through the examination, it found that the acid alteration minerals were not presented around feed zones in 4 acidic and neutral wells (H-28, H-35, HS-1 and Neutral well), though in H-33, acidic alteration mineral is found in one samples near feed zone, but presence of acidic fluid is not continuously. We have also reviewed characteristics of hydrothermal alteration of wells discharging neutral fluid. Figure 7 shows comparison of assemblage of alteration minerals in acidic well (H-35) and neutral well. Comparing hydrothermal alteration between acid wells and neutral wells, it is revealed that mineral assemblage of alteration mineral are relatively similar between wells discharging acidic fluid and wells discharging neutral fluid. Acid alteration minerals such as alunite, kaolinite and pyrophyllite were identified at shallower depth than 1,000 m in both acidic and neutral wells. Chlorite and illite continuously present deeper than 500m.

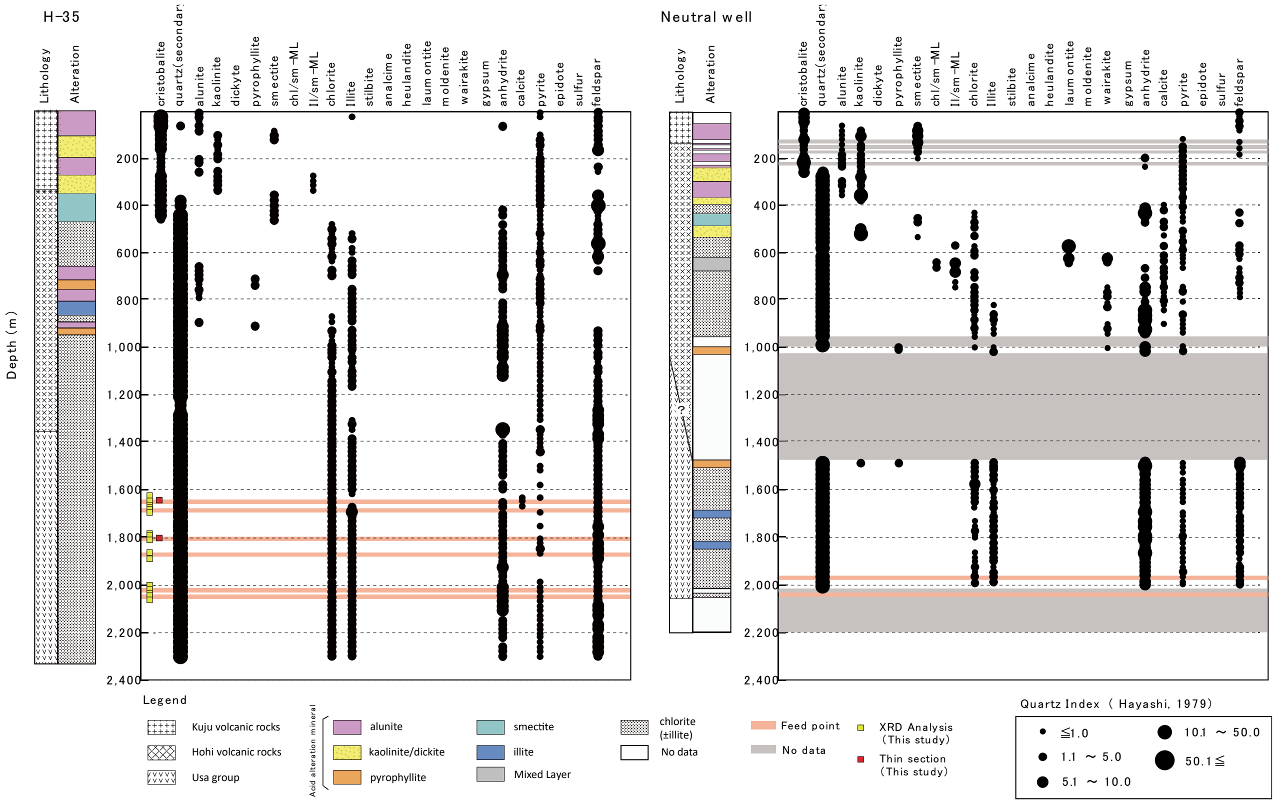

Figure 7: Lithology and occurrence of hydrothermal alteration minerals in acidic well (H-35) and neutral well

To examine hydrothermal alteration pattern at subsurface and acidity of fluid, we categorized three alteration zones based on detected minerals. Figure 8 shows alteration zonation of acidic wells and a neutral well. Alteration zonation between acidic wells and a neutral well shows similar zonation.

1) Alunite + kaolinite + pyrophyllite zone (acidic alteration zone)

Acidic alteration zone characterized by the presence of alunite, kaolinite and pyrophyllite is formed at relatively shallower depth which is above the top of the reservoir.

2) Mixed layer mineral zone (Transition zone)

Mixed layer mineral is dominated at above the depth where chlorite and illite are continuously occurred.

3) Chlorite + illite zone

Chlorite and illite are presented from a depth of 500m to the bottom hole.

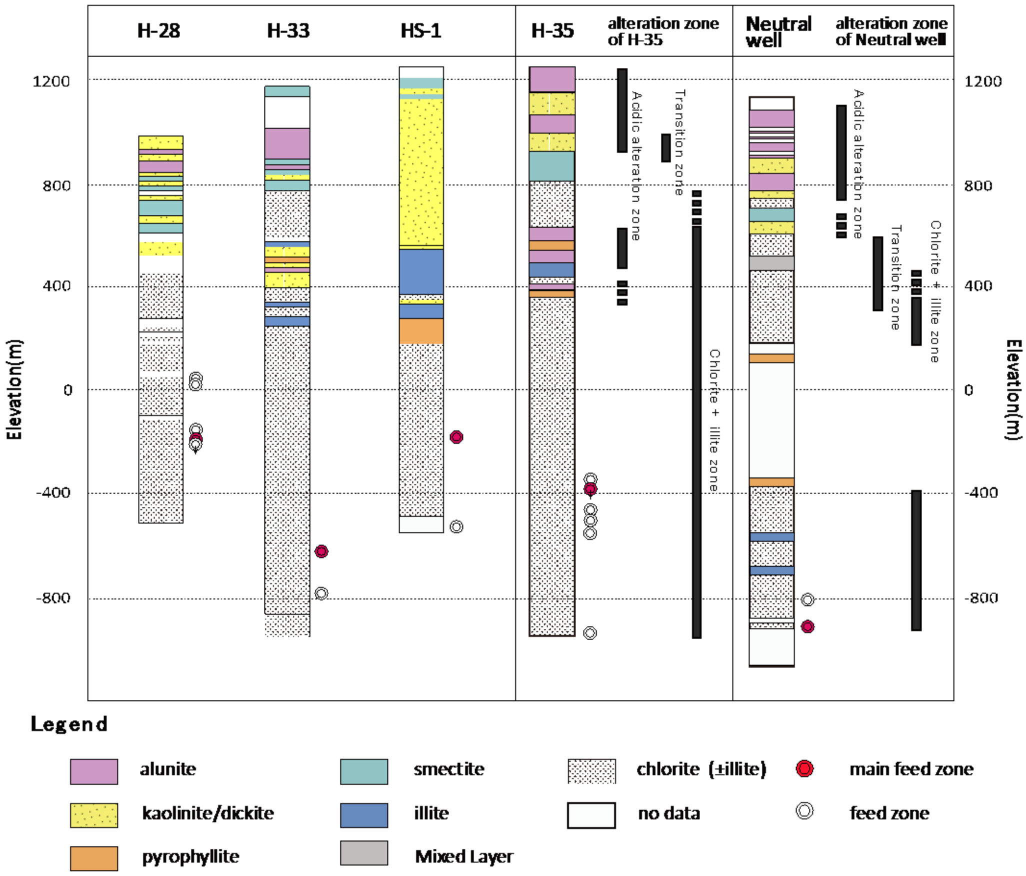

Figure 8: Alteration zonation of acidic wells and a neutral well

5. INTERPRETATIONS AND CONCLUSIVE REMARKS

Through the geological and mineralogical studies by petrographic observation and XRD analysis to characterize alteration minerals, the results we obtained are;

- Acid alteration minerals only present at the depth of shallower zone.
- Regardless of pH of discharged fluid, illite, chlorite and interstratified clay minerals occur below the acidic alteration zone.
- Mineral assemblage zonation of alteration mineral are relatively similar between wells discharging acidic fluid and wells discharging neutral fluid. The acidic alteration minerals include alunite, kaolinite, pyrophyllite.
- Acidic alteration minerals are not found around feed zone in wells of H-28, H-35, and HS-1. In H-33, acidic alteration mineral is found in one samples near feed zone, but presence of acidic fluid is not continuously around feed zone.

These results indicate some possibility of mechanisms of acidic fluid flow. One of the possible mechanism is that acid fluid stored in the permeable zone has not enough low pH to form acidic alteration minerals. Other possibility is that acid fluid migrating from the surrounding areas to the wells due to pressure drop by the production area.

In this paper, we attempted to examine distribution and origin of acidic fluid at subsurface from geological and mineralogical information obtained from well geology. Obvious difference of mineral assemblage between wells discharging acidic fluid and wells discharging neutral fluid is not observed in Hatchobaru field. These results suggested some possible mechanisms of discharging acidic fluid. For further examinations of distribution and origin of acidic fluid at subsurface, fluid inclusion analysis, raman spectroscopy analysis and sulfur isotopic studies are considered to be effective approach. We will continue the study adopting such approaches for better understanding of acidic fluid in geothermal fields.

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