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Mineralogical and Hydraulic Characteristics of the Wasabizawa Geothermal Field, Akita Prefecture, Japan.

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ABSTRACT

The Wasabizawa geothermal power station (42 MWe) is under construction since May 2015, which will be a newly constructed first large-scale geothermal power plant after 23 years of constructing stagnation in Japan since commencement of commercial operation of the Takigami geothermal power station (27.5 MWe) in 1996. This area is known to be rich in old caldera geography and commercial hot springs. Extensive geothermal explorations, including the promotional surveys carried out by New Energy and Industrial Technology Development Organization (NEDO), has been performed for the area. However, since the stratum older than the Neogene in which the geothermal reservoir is formed is covered with thick Quaternary volcanic sediments, the pre-Tertiary basement rock could not be confirmed as the outcrops in the area, and therefore the detailed geological structure previous Neogene has not been fully delineated. Furthermore, the fact that the geology consisted primarily of homogeneous lithofacies of granite was making it difficult to elucidate the detailed geological structure. During the construction, 11 new production and reinjection wells were drilled, and new rock samples were obtained. Alteration minerals of the cuttings were identified by X-Ray diffraction analysis. Furthermore, the pressure transient tests were carried out using the new wells. We studied a geological and geothermal structure based on the newly available mineralogical and hydrological data. The result of the study suggests that the geology of the site could be divided into several alteration zones. A small amount of prehnite can only be identified at the zone with comparatively high permeability, and particularly concentrates at the lost circulation point and its surroundings during well drilling. The characteristics of those hydraulic and mineral distributions may be closely related to the geotectonic history of the caldera that occurred around the site during the late Neogene to the Quaternary. The geological and geothermal structure of this area was revised for the future make-up well drilling.

1. INTRODUCTION

The Wasabizawa power station construction has been started since May, 2015, which will be the first large scale geothermal power plant after 23 years constructing stagnation in Japan since commencement of commercial operation of the Takigami geothermal power station (27.5 MWe) in 1996. The Yuzawa-Ogachi area in where the construction site located is Tohoku mountainous backbone, and it is known as much caldera occurred for Miocene to Pleistocene which is typified by “Sanzu river caldera”. Furthermore, a lot of fumarole and commercial hot springs are also located in this area (as shown in Figure 1). Due to distribution of geothermal manifestations observed around the area, many scientists and engineer have focused on Yuzawa-Ogachi area as an attractive site for geothermal development. A major geothermal survey in the Yuzawa-Ogachi area has begun by New Energy and Industrial Technology Development Organization (NEDO) as a geothermal energy promotional survey. The survey had been performed for two areas, “Wasabizawa area” and adjacent “Akinomiya area”, and as the result of the surveys, the two areas had been recognized high potential geothermal area. After the NEDO survey, the Wasabizawa area was transferred to Electric Power Development Co. (J-Power) and Mitsubishi Materials Corporation (MMC). The Akinomiya area was also taken over by MMC. After these transferences, joint exploration was carried out for both areas by two corporations, and it became evident that the two geothermal areas are deeply interactive each other, and the “Wasabizawa” and the “Akinomiya” represent two parts of a single larger geothermal area. Subsequently, Mitsubishi Gas Chemical Company, Inc. (MGC) also participated in the geothermal development project, and Yuzawa Geothermal Power Corporation (YGP), special purpose company for manage the resource, was established in 2010 to drive the construction of the Wasabizawa geothermal power station. YGP decided to construct the Wasabizawa geothermal power station (42 MWe double flash plant) based on the results of survey and study. Nakanishi et al. (2017) described a numerical simulation study of the Wasabizawa-Akinomiya field for evaluation of electrical capacity of the field.

The environment impact assessment for the construction was carried out in 2011 - 2014, and the environmental impact appraisal report was finally submitted to Minister of Economy, Trade and Industry in 2014. The construction of the Wasabizawa geothermal power station was started in May, 2015. The construction involves drilling new production and injection wells.

In the well drilling, five injection wells and six production wells were drilled. We finally secured necessary total production flow rate and reinjection flow capacity. However, although we performed geo-structure analysis to find out high permeable zone before those drillings, drilling results of some wells were far less than expected. Fortunately, we succeeded in side track drilling to meet permeable fracture; however, we struggled to decide new target under the circumstances that new information was only cuttings obtained by drilling. In order to solve the problem, it is beneficial to find out alteration mineral indicating high permeable zone in cuttings sample obtained during drilling.

In this paper, we describe the relationship between the alteration mineral in cuttings obtained by drilling and permeability of the wells, as well as the mechanism based on the inferred geological structure development in the Yuzawa-Ogachi area. That will be helpful to improve drilling success rate in the area.

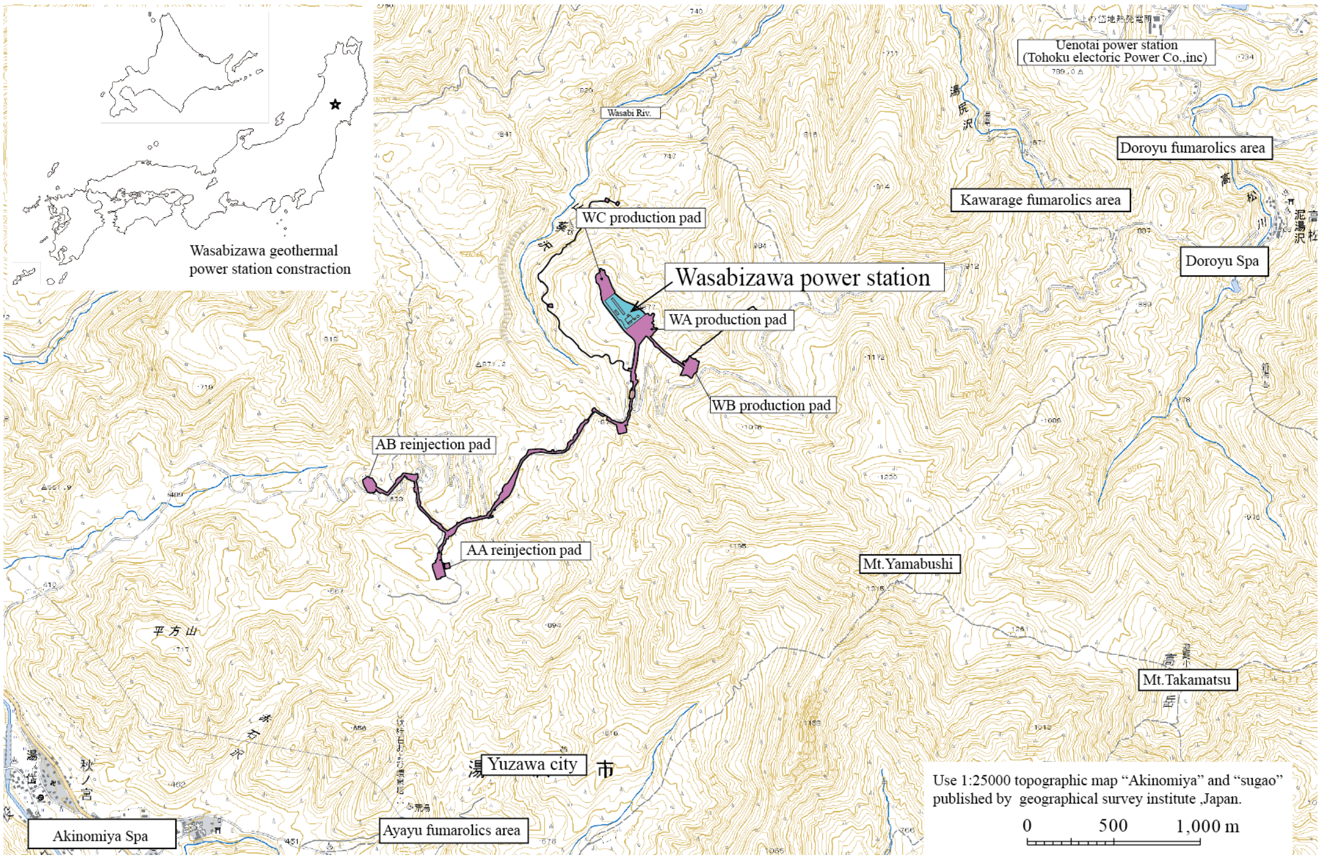


Figure 1 Location of the Wasabizawa geothermal power station construction site.

2. STRATIGRAPHY

Geological and stratigraphic studies in Yuzawa-Ogachi area, around Wasabizawa geothermal power station, have been carried out by many scientists since 1950’s. In this section, we describe the concept of stratigraphy for drilling new wells in this power station construction project. Furthermore, we also refer the stratigraphic discussion about relationship between Sanzu river formation and Mt. Torake formation conducted in 1980’s.

It has been known that the Paleogene series consisted of the basement rock, the Neogene series called the Mt. Torake formation and the Neogene series consisted of lake sediments called Sanzu river formation are widely distributed around the area (e.g. Ozawa et al. (1979), Usuda (1982)). Kato and Shimada (1953) mentioned that relationship Mt. Torake formation and lower the formation were conformity, because of wide distribution of tuffaceous stratum similar to Mt. Torake formation, and they concluded that Sanzu River formation was the sediment that deposited in basin subsidence in their study of lake sediment around Yuzawa-Ogachi area. Muto (1965) also assumed the large unconformity between Sanzu River Formation and the lower Mt. Torake Formation as well as the stratigraphic concept of Kato and Shimada (1953) taking into account the existence of the cliff-dip sediments around the lake basin. After that, geothermal development promotion surveys were carried in the area by NEDO in 1980’s. As a result of progressing geothermal survey in Yuzawa-Ogachi area, it was found that relationship between Mt.Torake formation and lower basement rocks are unconformity. Based on this finding, the studies to explain the unconformity in the area by the caldera that was occurred by volcano-tectonic depression appeared (e.g. Awata (1984), Sato (1986), Utada (1986), Takeno (1989), Ito et al. (1989)). Especially, Takeno (1989) reconsidered the stratigraphy based on age measurement using radioactive dating for rocks obtained by the NEDO’s survey, and he suggested the possibility that Sanzu River formation and Mt. Torake formation were formed simultaneously. Furthermore, he segmented both formations into several member respectively using characteristics of these lithofacies, and revealed that these members were formed by volcanic activities occurred twice continuously. On the other hand, Ito et al. (1989) mentioned that these formations distributed in the caldera should be handle as set of continuous volcanic activity, and they segmented the deposit of the caldera into three formations; lower pumice member (Minase river member / Mt. Torake member), middle pumice member (Yoshinaga tuff member) and upper sedimentation (Sanzu river member). In any case, although both studies have slight differences in the stratum division, their study suggested that volcanic activities accompanied with volcanic product occurred at least twice in Pleistocene around

Table 1 Stratigraphic comparison table around the Yuzawa-Ogachi area.

Age		Takeno(1988)	Ito et, al.(1989)	NEDO(1999)	NEDO(2001)	This study
Qauternary	Holocene		Alluvium	Talus deposit	Talus deposit	Talus deposit
Qauternary	Plaistcene	Mt. Koninai Andesite Mt.Kurikoma Volcanic rocks	Post Caldera Igneous Bed	Mt.Kurikoma volcanic rocks Mt.Takamatu volcanic rocks	Mt.Takamatsu Volcanic rocks	Mt.Takamatu volcanic rocks (TL,K-Ar:0.23 ～ 0.36Ma) *6),*4)
Qauternary / Neogene	Plaistcene	Mt. Kabuto formation	(same)	Mt. Kabuto formation	Mt. Kabuto formation	Mt.Kabuto formation *9): Mt.Kabuto welded tuff (TL:0.305 ～ 1.16Ma)*3),*5) Mt.Koninai andesite (K-Ar:0.86±0.01～ 0.71±0.04Ma) *3),*6) Mt.Okumiya andesite (K-Ar:1.74 ～ 2.1Ma) *2),*3),*4)
Neogene	Pliocene	Upper / Main / Basement grabel — Sanzu Riv. formation Mt.Torage tuff member	Samzu Riv. Formation Talus deposit	Sanzu Riv.formation	Upper Mt.Trage formation	Sanzu Riv. formation: Upper / Main / Basement grabel
Neogene	Pliocene	Minase Riv. formation	Yoshinaga Tuff Mt.Torake tuff member	Minase Riv. formation	Lower Mt. Trake formation	Mt.Torake formation Minase Riv. formation (K-Ar:4.0 ～ 6.0Ma) *2)
Neogene	Miocene	Post Mt. Torage formation	Mt. Tateishi and Mt.Kabuto Andesite (alter)	Ootoritani-sawa formation	Yakunai Riv. formation	Yakunai Riv. formation (FT:9.8Ma)*1)
Neogene	Miocene	(cont.)	(cont.)	Doro-yu formation	Semi formation	Doro-yu formation
Paleogene			Basement rocks	Basement rocks	Basement rocks	Basement rocks (K-Ar:24.3 ～ 103Ma)*1),*4)

*1)NEDO(1985),*2)Takeno(1988),*3)NEDO(1990),*5)DOWA Co. Ltd.(1996)*6)DOWA Co. Ltd.(1997)*4)Takashima et al.(1999)

FT:fission track method ,LT:Thermoluminescent Dosimetre, K-Ar:Potassioum-Argon method

Yuzawa-Ogachi area. Figure 2 shows the distribution of the calderas and the geology, in which distributions of the geology coincide with fault system suggesting the caldera.

The authors stood in the position which the two events suggested by these representative studies related to the geothermal structure in the area at the beginning of the construction project, and reconsidered geological stratigraphy by adding the research results of NEDO (1998) and NEDO (2001). Table 1 shows the stratigraphic in this paper. The stratigraphic distribution around Wasabizawa geothermal power station in the caldera was divided into two formation, Mt. Torake / Minase River formation and Sanzu River formation, and according to Takeno (1989), relationship of both formations were defined by continuous two volcanic activities. Furthermore, regarding the upper and lower levels of this layer, the stratigraphy was set by rearranging the radioactive age dating result and thermoluminescent dosimeter age result according to the past literature (NEDO (1985), Takeno (1988), Takashima et al. (1999), Dowa Co. Ltd (1996) and Dowa Co. Ltd (1997)).

Although the name of this caldera has various designations like Sanzu River caldera, Ogachi caldera, Mt. Torake caldera and so on, we call it “Ogachi caldera” in this paper.

3. GEOLOGY AND GEOTHERMAL STRUCTURE

The authors modified the geological map created by NEDO (1998) and NEDO (2001) based on the stratigraphical consideration described above. As shown in the geological map of Figure 3 and Figure 4, the geology around the power station construction site are consists of the basement rocks composed of granite and metamorphic rocks in Paleogene, Doroyu formation composed of sandstone, conglomerate and andesite lava in the early Miocene period, Mt. Torake / Minase River formation and Sanzu river Formation composed of tuff or tuff breccia in the Late Triassic Period, the Ootoritanisawa formation composed of tuff and tuffaceous sand, and Mt. Takamatsu volcanic rocks composed of dacite or pyroxene andesite lava in the Quaternary. The granitic rocks which form geothermal reservoir under developing is located in mylonite zone so-called Onikobe mylonite zone shown in Figure 2 defined by Sasada (1984), which is distributed from Miyagi prefecture to Akita prefecture through the power station site. This evidence can be confirmed as “undulatory extinction” of quartz phenocrysts in the granite collected by our drilling under polarization microscope. The granite is covered with upper layer, and its distribution on the surface is limited in bottom of the river, whereas its wildly distribution in underground of the power station site has been confirmed in NEDO’s survey and the wells drilled in this construction. Doroyu-formation distributed on the granite, which is composed of basal gravel, sandstone, mudstone, tuff, andesite lavas and pyroclastic rocks. Mizugaki (1991) reported existence of planktonic foraminifera in the formation in her geo-structural study in the caldera distributed around the Yuzawa-Ogachi area. Therefore, there is possibility that Doroyu formation is marine deposit. However, existence of the formation could not be confirmed in the samples obtained by the newly drilled wells in the area, and then accordingly, it can be assumed that, when this formation was formed to a certain extent, the upper surface of the granite had already had irregularities. Ootoritanisawa formation is distributed in west of the power station construction site, and the formation consists of decide, rhyolite and tuff accompanied with dolerite dike. Originally, Ootoritanisawa formation had been defined as a part of Doroyu formation in NEDO (1990). However, Ootoritanisawa formation mainly consists of felsic rocks, and it differs from characteristics of Doroyu formation.

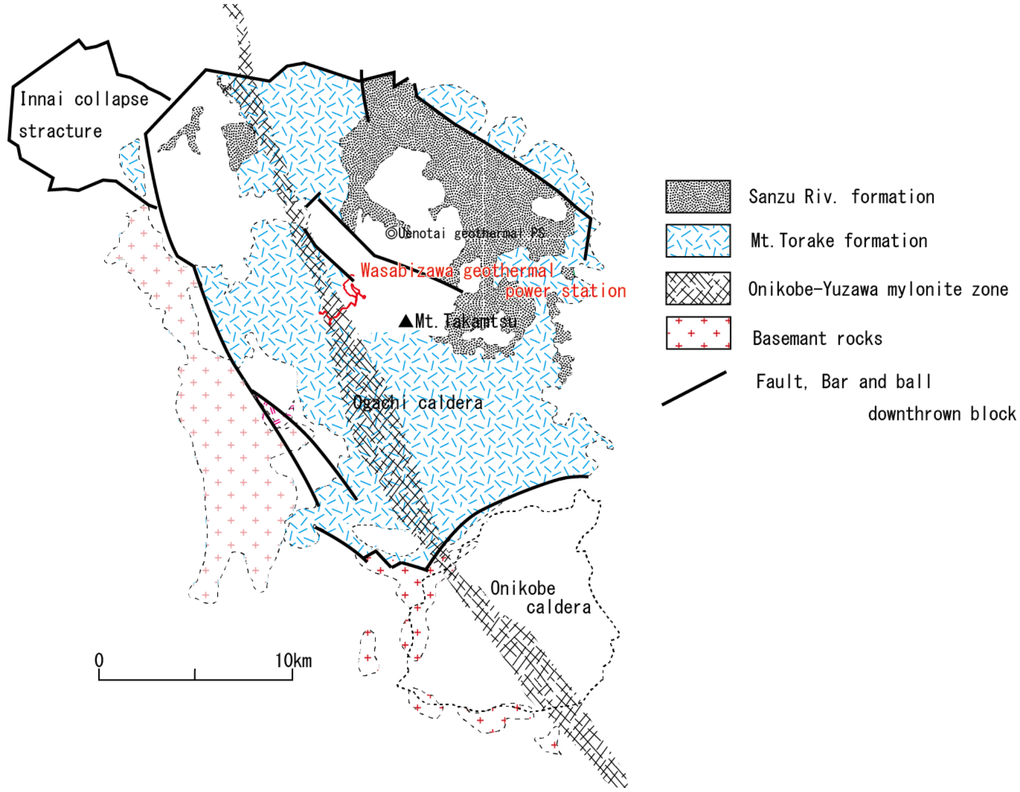


Figure 2 Relationship between the caldera structure and the geology around Yuzawa Ogachi area. (This figure was modified Sasada (1984) and Takeno (1989).)

Therefore, in our study, we divided the Doroyu formation into two members, Doroyu formation and Ootoritanisawa formation based on the lithofacies. The Ootoritanisawa formation was recognized in only the wells which were located in southeast side of the site. Mt. Torake formation and the Minase river formation are the most commonly observed strata in the Yuzawa - Ogachi area. Mt. Torake formation is consisted of dacitic tuff breccia, widely distributed on the southwest side of the site. The Sanzu river formation mainly consists of alternated sandstone and mudstone layers, which is distributed surrounding the construction site. As mentioned earlier, the distribution of the alternation tuffaceous sandstone and mudstone was also confirmed in Mt. Torake / Minase river formation in boring core of civil work in the construction, the authors handled as consecutively formation formed by continuous volcanic activity in this construction project. Sanzu River formation is consisted of alternation sand and mud which was lake deposit. However, Sanzu river formation is not distributed in the site, and the distribution is limited in north part of the site (as shown in Figure 2). Mt. Takamatsu volcanic rocks are lava-like pyroxene andesite, the highest formation in the site. This formation was formed by the activity of Mt. Takamatsu volcano and it is a heat source of the Wasabizawa geothermal system.

The basement rocks forming the reservoir of the power station was formed in Paleogene, and it have been influenced in many geological events occurred in the area. Especially, the Yuzawa-Ogachi area is located in Tohoku mountainous backbone, which is special tectonic setting in northeastern Japan island arc, and it is considered that the area had been more influenced by the tectonics and the volcanic activities. For these backgrounds, many studies about the characteristics of the fault system and geostructure of basement rocks have been examined for long time. NEDO (1998), NEDO (2001) performed gravity survey and magneto telluric survey, those revealed horst and graben structure around the power station construction site. In this construction, the authors interpreted that sharp changes in gravimetric basement altitude imply large fault displacement, and delineated the fault system as shown in Figures 3 and 4 by taking into account stratigraphic correlation of the wells drilled in the Yuzawa-Ogachi area.

4. WELL DRILLING AND PERMEABIRYTY

In this construction project, six production wells and five reinjection wells were drilled. Before start the construction, the authors interpreted that the high permeable zone may be developed along the fault system within granite, and designed targets of the wells to be the fault distributed around the site (as shown in Figures 3 and 4). The drilling trajectories are shown in the Figure 5. The wells indicated colored name in blue in the figure indicate the wells encountered total lost circulation zones, and black one shows dry hole. We could confirm that the lost circulation occurred during drilling around the assumed fault zone shown in Figure 3 in most wells. On the other hand, well AA-3, AB-2 and WC-3 had been completed without any major lost circulations.

Furthermore, in order to confirm the productivity / injectivity of wells, we performed water injection / falloff test for well completion test. Tables 2 and 3 show the results for the Akinomiya and the Wasabizawa areas respectively. Due to effect of changes in thermal condition in the well, the good quality data for analysis could not be acquired for well WA-4 and WB-1. The fall off test was not performed for WZ-9 in NEDO's survey. Therefore, the authors employed hydraulic parameters calculated from buildup test performed in production test for these three wells; WZ-9, WA-4 and WB-1. We employed k-h [Darcy-m] and $\varphi c_t h$ [m/Pa] derived from pressure translation analysis, and inversion in pressure was taken as the objective function. Injectivity index (II) is not taken account in this evaluation. The Tables 2 and 3 indicate that, on the whole, permeability of the wells drilled in production pads tends to be higher than permeability of the wells in reinjection pads.

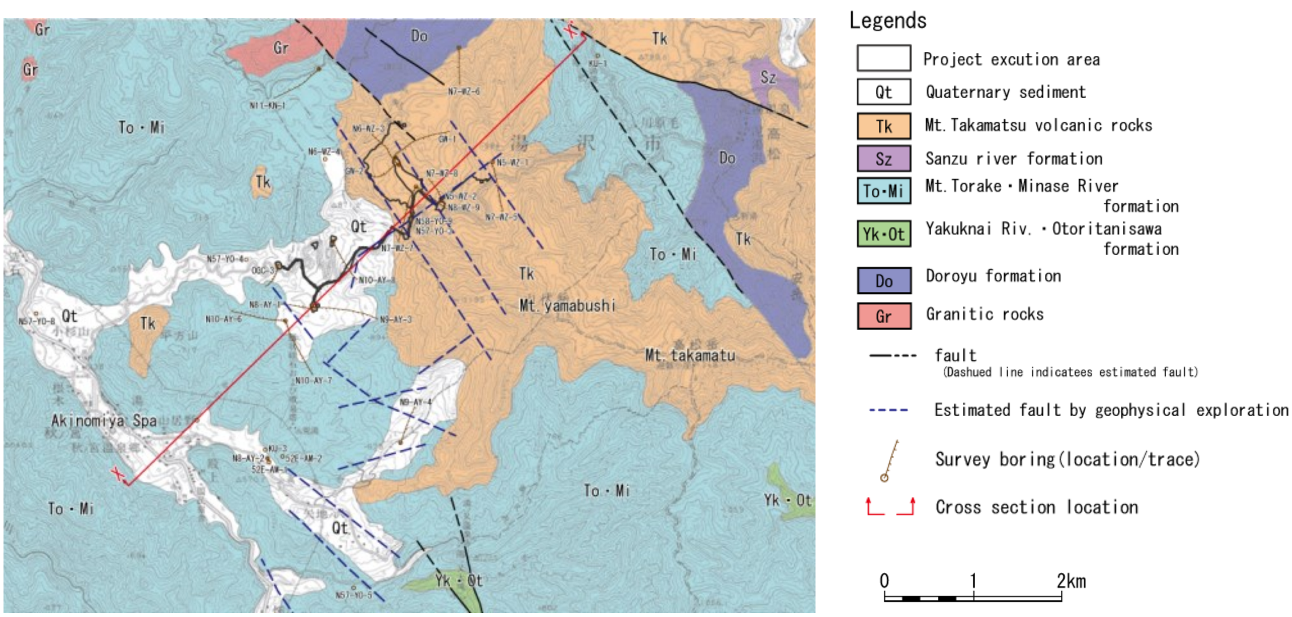


Figure 3 Geology at the Wasabizawa geothermal area (Modified from NEDO (1998) and NEDO (2001). The geology in the Wasabizawa side, northwest of the site, was from NEDO (1998), and it in the Akinomiya side, southwest of the site, was from NEDO (2001))

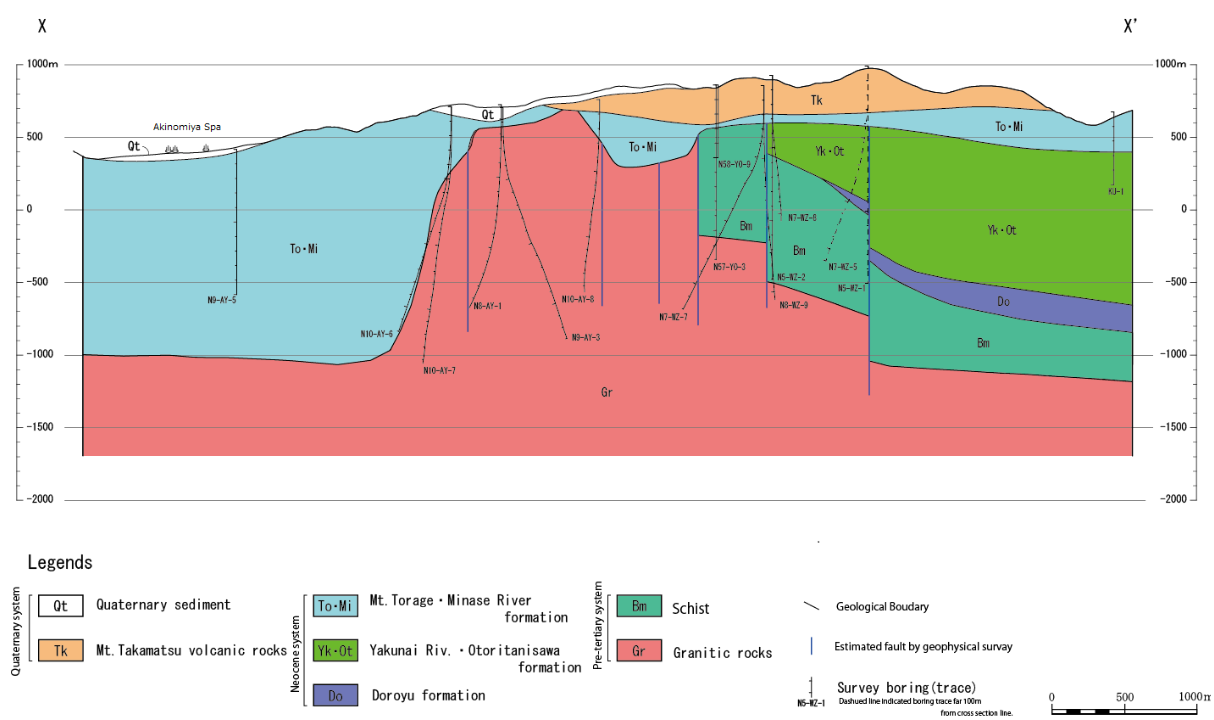


Figure 4 Geological Cross section along X-X' line in Figure 3

Table 2 Result of pressure transient analysis (The wells named 'AY' from NEDO (1998))

Well name	WZ-2	WZ-3	WZ-4	WZ-7	WZ-8	WZ-9	GW-1	GW-2
kh[darcy ·m]	0.01	0.02	-	5.4	0.2	(5.0)	1.8	5.0
φ ch[m/Pa]	6.21×10^{-8}	8.01×10^{-10}	-	1.3×10^{-11}	2.42×10^{-9}	(8.77×10^{-8})	6.5×10^{-6}	5.4×10^{-3}
skin factor[-]	0.0	0.0	-	0.0	0.0	(20.0)	-2.5	2.5
remarks	NEDO work. Type curve	NEDO work. Type vurve	NEDO work. Not complied	NEDO work. Type curve	NEDO work. Type curve	NEDO work. Type curve	This work. Invertion	This work. Invertion

Well name	WA-3	WA-4	WB-1	WB-2	WC-2	WC-3
kh[darcy ·m]	6.7	(30.3)	(25.7)	2.3	43.3	-
φ ch[m/Pa]	2.0×10^{-9}	(5.4×10^{-8})	(1.4×10^{-7})	3.2×10^{-7}	5.3×10^{-9}	-
skin factor[-]	0.4	(20.4)	(-4.8)	5.7	-6.26	-
remarks	This work. Ivertion	This work. Invertion	This work. Invertion	This work. Invertion	This work. Invertion	This work. Not complied

( ):clculated from resuts of buildup test in well production test.

Table 3 Result of pressure transient analysis (The wells named 'WZ' from NEDO (2001))

Well name	AY-1	AY-3	AY-6	AY-7	AY-8	AB-1	AB-2	AB-2 side track
kh[darcy ·m]	1.2	4.8	0.6	-	0.7	16.7	-	-
φ c_th[m/Pa]	2.6×10^{-7}	1.9×10^{-8}	2.4×10^{-8}	-	1.5×10^{-7}	1.0×10^{-7}	-	-
skin factor[-]	-5.0	-2.9	-8.1	-	2.0	9.6	-	-
remarks	This work. Invertion	This work. Invertion	Nedo work. Type curve	NEDO work. Not complied	NEDO work. Type curve	This work. Invertion	This work. Not complied	This work. Not complied

Well name	AA-3	AA-3 side track	AA-4	AA-5
kh[darcy ·m]	-	2.3	2.3	16.7
φ c_th[m/Pa]	-	2.1×10^{-7}	1.0×10^{-6}	1.0×10^{-7}
skin factor[-]	-	14.8	2.6	9.6
remarks	This work. Not complied	This work. Invertion	This work. Invertion	This work. Invertion

5. XRD ANALYSIS AND MINERAL DISTRIBUTIONS

In this construction, a cuttings obtained by the drilling was collected every 5 meter. Then, the cuttings were analyzed by X-ray diffraction analysis (XRD) and observed by polarizing microscope. At the time of XRD, in order to accurately identify the clay minerals, we conducted whole rock analysis with 'ethylene glycol solution treatment' and 'hydrochloric acid solution treatment'. Total numbers of the sample for XRD were 200 samples. Ito et al. (1989) attempted alteration zoning for geology inside Ogachi caldera depending on distribution of zeolites, and they summarized the characteristics of the caldera type alteration, which have characteristics combined both diagenesis and hydrothermal alteration. NEDO (1998), NEDO (2001) and Zhang et al. (1999) extended the research area to depth of basement rocks, and attempted alternation zoning based on distributions of chlorite, sericite and epidote. Especially, Zhang et al. (1999) focused on existence of the amphibole, and modified the NEDO (2001)'s alteration zoning by adding Epidote -

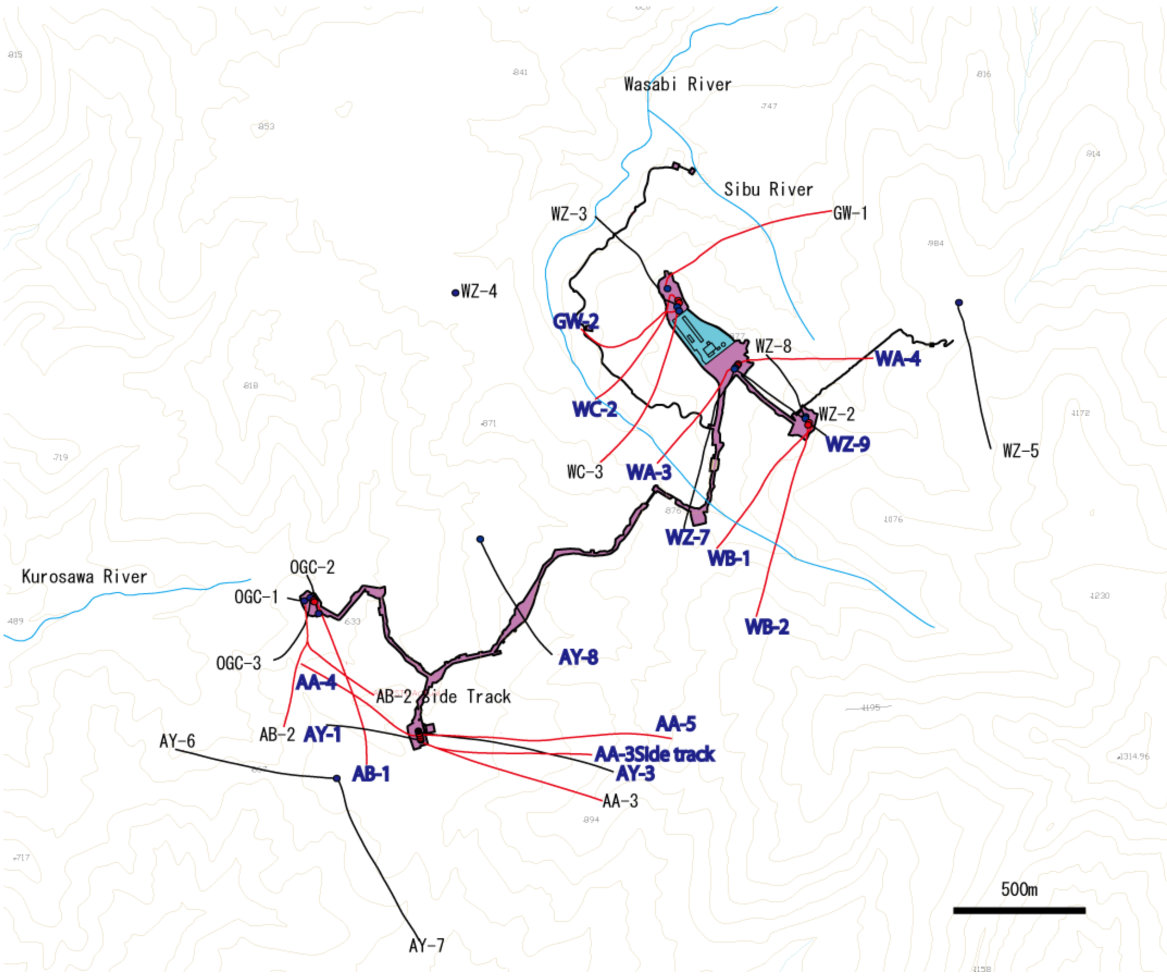


Figure 5 Drilling trajectory and situation of lost circulation of the wells in the Wasabizawa geothermal power station project area. (The characters in the figure indicate well name; black characters mean no or less lost circulation wells, and blue colors mean total lost circulation wells. The lines indicate well trajectory, red colors mean well trajectory drilled in the Wasabizawa project, black colors mean the wells drilled in NEDO's survey)

Amphibole alteration zone. Furthermore, they found a tendency that the Epidote - Amphibole alteration zone tends to be match with a lost circulation zone. Similarly, the authors also confirmed amphibole in the cuttings obtained by the drilling.

We deduced 'Kaolinite zone', 'Montmorillonite zone', 'Chlorite zone' and 'Epidote–Sericite zone' based on the result of XRD. The alteration zoning are shown in Table 4. Amphibole was not employed for the alteration zoning. Because we interpreted the amphibole was a part of the metamorphic rocks involved within the granite, so we found that these mineral showed characteristic of schistosity formation. The alteration zoning diagrams are shown in Figures 6 and 7 for production and reinjection areas respectively. In order to describe the alteration situation throughout the Wasabizawa geothermal project area, all of the wells were used for this consideration arranged side by side. In general, hydrothermal alteration is affected by not only the properties of hot water but also host rocks, so we describe the characteristics of alteration separately for the basement rock and the upper layer.

Chlorite and sericite were distributed in cuttings of basement rocks. Almost of the minerals were rarely observed as vein type mineral, also, mica and plagioclase were confirmed as source mineral with the chlorite and the sericite under stereomicroscope. Therefore, the authors interpreted that chlorite and sericite transformed from mica and plagioclase involved in the granite under hydrothermal condition. In the deep part, the distribution of the epidote becomes prominent. Because of these epidote tends to be vein and rarely euhedral, the epidote is likely formed to fill clack in the granite. Furthermore, the minerals are distributed in deeper places more than temperature 200 °C, which is probably the result of reflecting the underground temperature structure. Also, as Zhang et al. (1999) pointed out, there is a tendency that a lost circulation tends to occur at the depth of distribution of epidote, but this is not necessarily the case. However, the idea of Zhang et al. (1999) indicating relationship between alternation and lost circulations is deeply interesting, thus, we also stand in the point, and attempted alteration zoning by taking into account the prehnite. Prehnite is the typical mineral caused by neutrality hot water, and it is crystalized at 200 to 300 °C, and we considered that it can be used as indicator. Even at this site, the prehnite was confirmed as vein filling mineral, and occasionally accompanied with wairakite. Figure 8 (a) shows polarization microscope photograph of thin section obtained from drilling of a production well which occurred total lost circulation, In particular, it can be confirmed that prehnite fills with the crack. Figure 8 (b) and (c) are the photographs of sample obtained from reinjection well which did not occurred total lost circulation. These photographs show that epidote completely filled with veins. Hence, these facts imply the possibility that the age in which the epidote and the prehnite crystalized was different each other.

Table 4 Alteration zoning by XRD for cuttings sample from the wells in the site.

Alternation Mineral	Kaolinite zone	Montmorillonite zone	Chlorite-Sericite zone	Epidote-Sericite zone
Cristobalite	━━━━			
Tridymite	━━━━			
Kaolinite	━━━━━	- - - - -		
Quartz	━━━━━	━━━━━	━━━━━	━━━━━
Montmorillonite	- - - - -	━━━━		
Calcite	━━	━━━━━	━━━━	
Chlorite		- - - - -	━━━━━	- - - - -
Sericite		- - - - -	━━━━━	━━━━━
Epidote			- - - - -	━━━━━
Prehnite			- - - - -	- - - - -
Wairakite			- - - - -	- - - - -

A distinctive distribution of montmorillonite and kaolinite was observed corresponding to the distribution of volcanic rocks. Regarding the genesis of a montmorillonite, in general, there are two theories; one is caused by the groundwater near the ground surface and the other is caused by neutral to alkaline hydrothermal fluid. Since montmorillonite was observed in some part of the granite which is the basement rocks (for example, well WZ-2 etc.), part of this mineral is interpreted as being caused by hydrothermal alteration and a montmorillonite zone was provided. In addition, acidic alteration zone consisting of kaolinite with tridymite and alunite was found inside the montmorillonite zone, and such sites were classified as kaolinite zone.

For simplicity, we call each alteration zonings as; 'Kaolinite zone': zone 4, 'montmorillonite zone': zone 3, 'chlorite zone': zone 2, and 'epidote–sericite zone': zone 1.

6. GEOSTRUCTURE AND DISCUSSION

We studied the characteristics of alteration condition and hydraulic property of the construction site by taking into account geological structural development around the site, also, considered the genesis of it. The results are shown in Figure 9.

Sasada (1984) reported that the granites distributed around the Yuzawa-Ogachi area intruded and consolidated before 100 Ma, and later the granites were affected by the mylonitization. As mentioned earlier, undulatory extinction of quartz and plagioclase was also observed in our drilling. Based on general recrystallization temperature of quartz, it is estimated that the temperature in this area was around 300 - 400 °C at the end of the mylonitization. According to Sasada (1984), the mylonite zone in this area is said to have been formed from the late Cretaceous to the Paleogene. Consequently, it is assumed that chlorite and sericite distributed in Zone 1 and Zone 2 were crystalized after mylonitization. In particular, the cause of the widely distribution of chlorite in granite is probably due to the wide high temperature structure of the Yuzawa-Ogachi area, rather than due to the rise of hot water. Thus, the authors interpreted this stage as the beginning of volcanic activity around the area (as shown in Figure 9 (c)).

Next, we discuss about Zone 1, which is distributed in lower part of the site. The epidote in Zone 1 showed characteristics of vein mineral, and also, several idiomorphic was confirmed. These facts imply that the formation of Zone 1 was affected by structural motion of basement rocks with forming fractures and the up-welling of hot water along the fracture. Hence, it means beginning of Ogachi caldera which was erupted with a large amount volcanic product (as shown in Figure 9 (d)).

In general, prehnites are produced by alkaline alteration at temperature of 200 to 300 °C, thus, it can be considered that they crystallized simultaneously with epidote. However, it is tendency to show that the permeability of wells which confirmed the prehnite exists is higher than the permeability of well that not to be observed it. Therefore, the authors interpreted that this reason is due to the different age of formation of the fractures filled with each mineral. As Ito et al. (1989) and Takeno (1989) argued, Ogachi caldera was considered to be formed by two big volcanic events. The first event corresponds to the formation of Mt. Torake / Minase River formation, and the epidote was crystalized to be filled with the fracture formed by first event. Further, there is the possibility that the second event corresponds to Sanzu river formation formed new fracture in where prehnite crystalized (Figure 9 (e)).

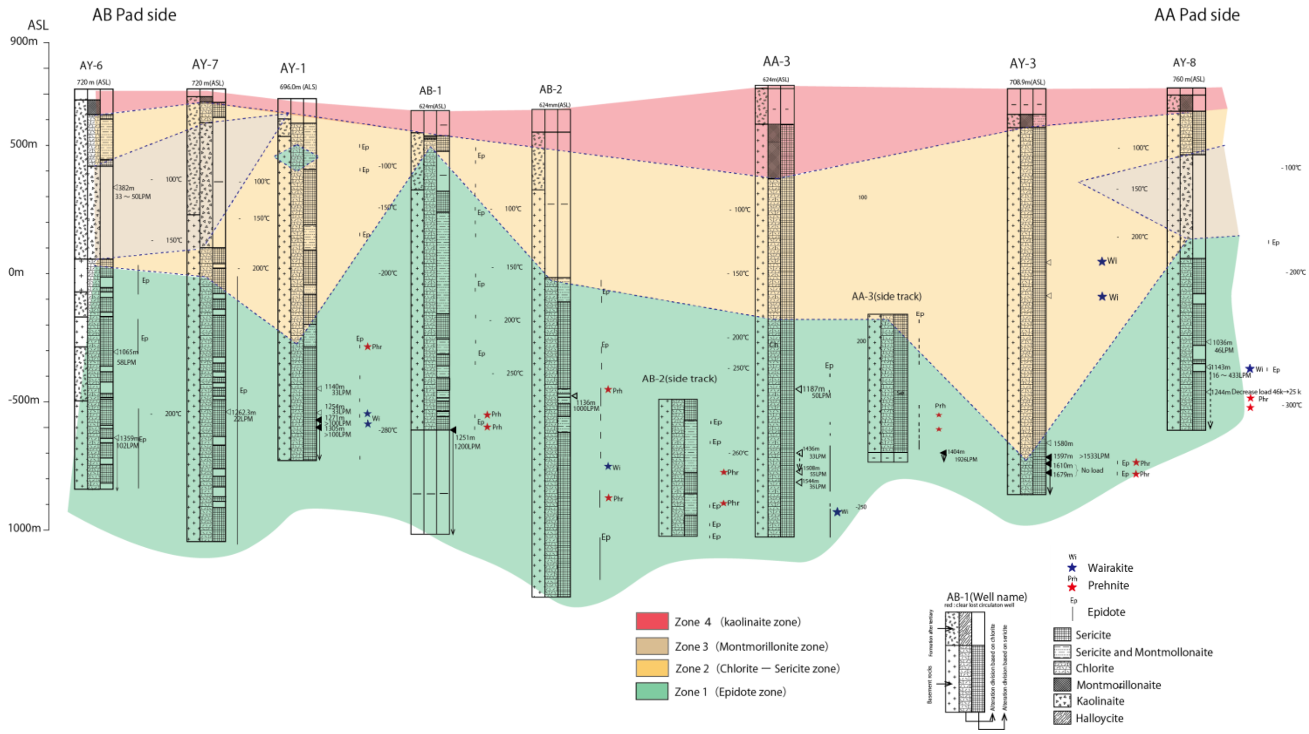


Figure 6 Cross section of alteration zones at reinjection area in the construction site. The XRD data of well AY-6, AY-7, AY-1 and AY-8 were cited from NEDO (2001).

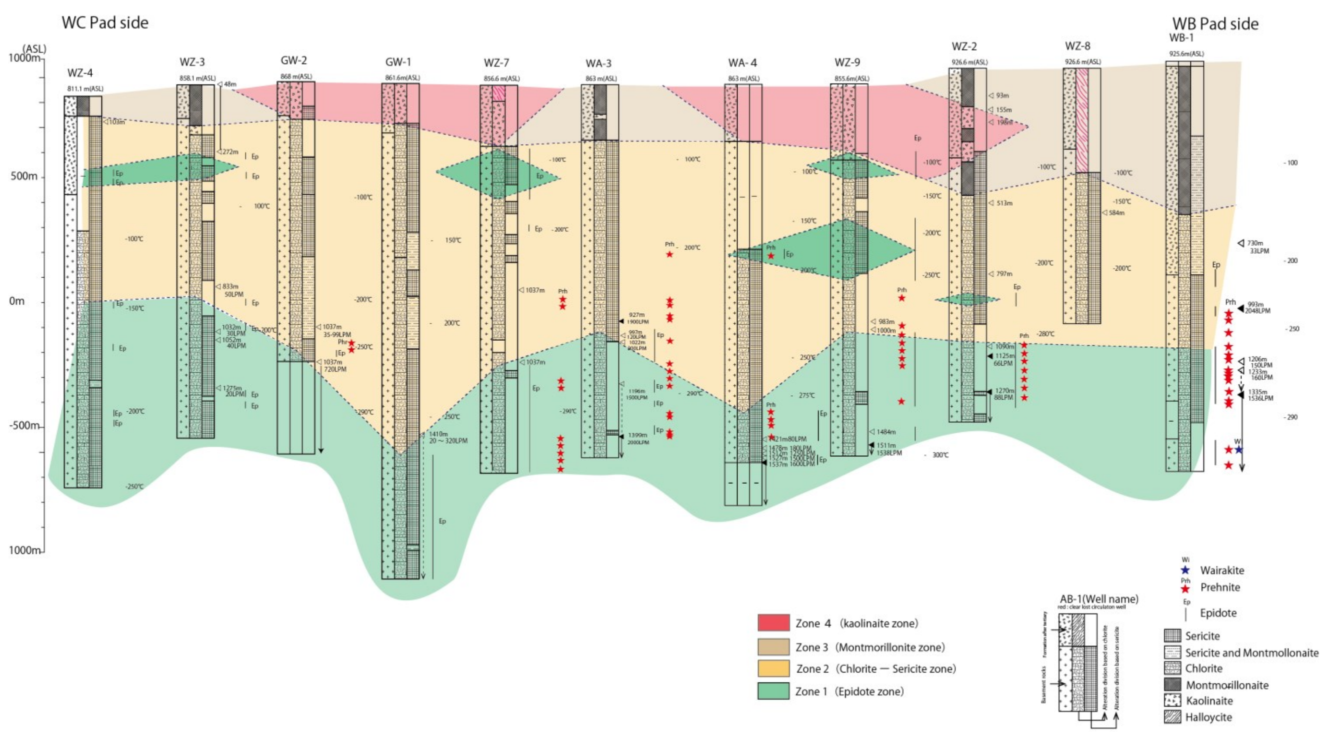
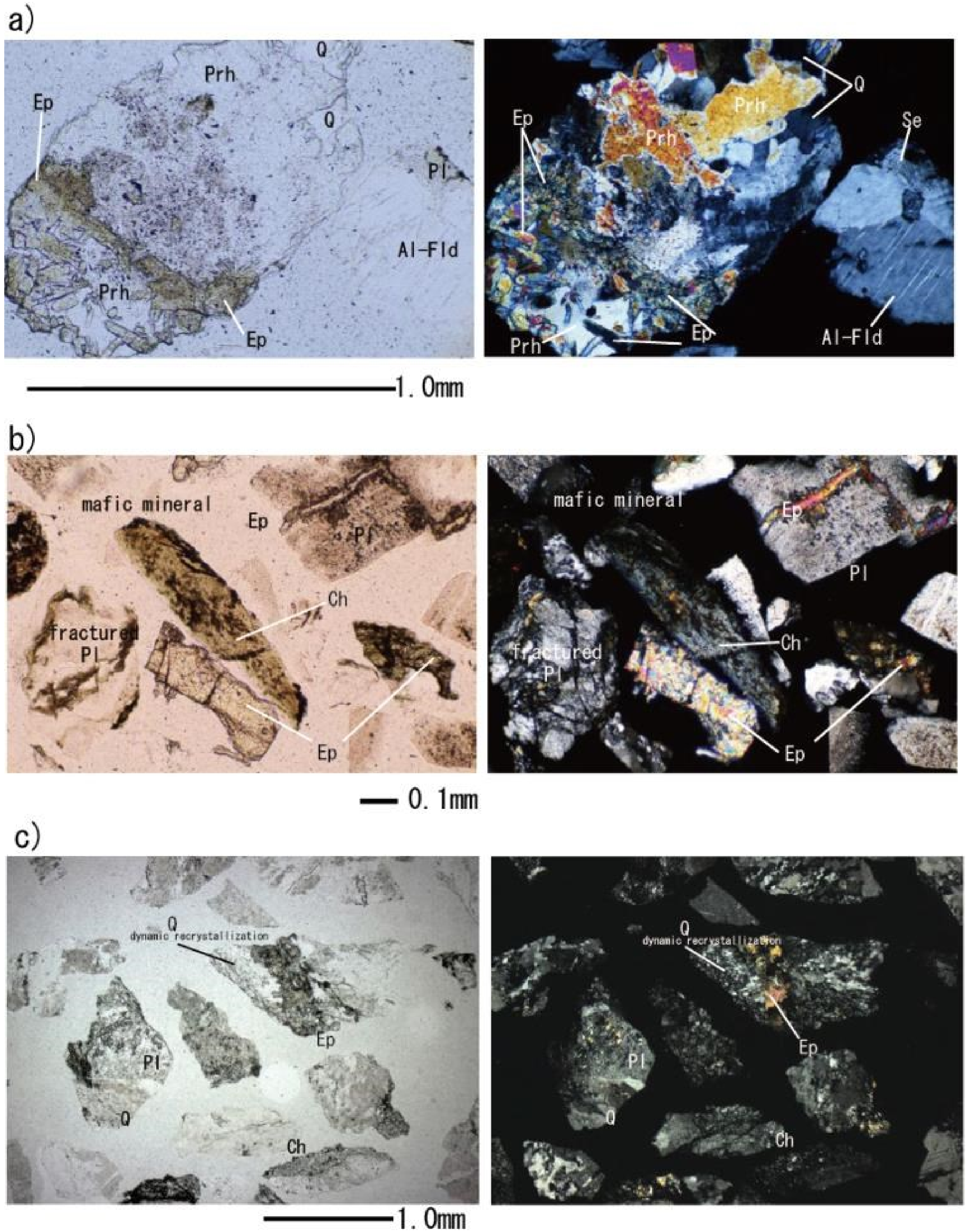


Figure 7 Cross section of alteration zones at production area in the construction site. The XRD data of well WZ-4, WZ-3, WZ-4, WZ-9 and WZ-8 were cited from NEDO (1998).



Al-Fl:Aluminium-Feldspar,Ch:Chlorite,Ep:Epidote,Q:Quartz,Pl:Plagioclase,Prh:Prehnite

Figure 8 Photograph of cuttings samples a)1160-1165m in WB-1, b)1845-1850m in AB-2, c)1160-1665m in AA-3

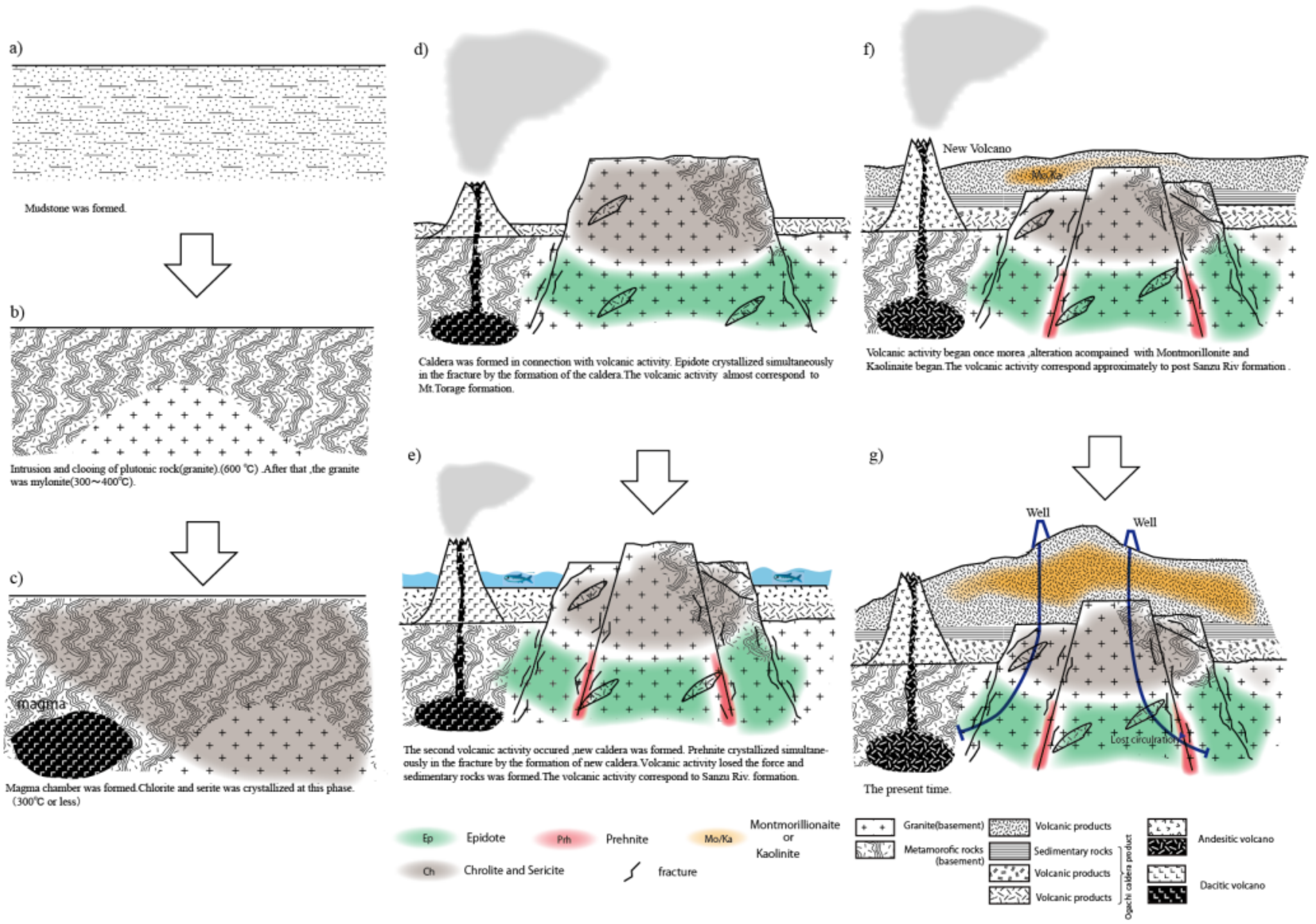


Figure 9 Geological development around Wasabizawa geothermal construction site.

7. CONCLUSIONS

We reveal the possibilities that Ogachi caldera was formed by two major volcanic activities and high permeable zone was influenced by the events, based on organizing of the stratigraphy and geological map.

Geological structure at the Wasabizawa geothermal power station site can be classified into four alteration zones (Zone 1 to 4), by the alteration study focusing on "epidote", "sericite", "chlorite", "montmorillonite" and "kaolinite". Furthermore, the result of the study suggests that formation of altered zones from Zone 1 to 4 may be closely related to the geological formation process of Ogachi caldera. Especially, the upper surface of Zone 1 is corresponded to the depth where lost circulation began to occur during well drilling, and more specifically Zone 1 represents the inferred geothermal reservoir for the power station.

It is highly possible that Zone 1 was formed in the early stage of the caldera formation phase, which corresponds to the first volcanic activity, and the fault was formed in this age. After that, the cracks and fractures developed as a result of formation of fault system would be filled with the epidote because the permeability of Zone 1 is not necessarily good.

On the other hand, a lot of prehnite were found in the high permeable well in Zone 1, and occurrence of the prehnite was characterized by vein filling mineral under polarization microscope. This fact implies that the second volcanic activity corresponding Sanzu River caldera was related to formation of high permeable zone in the reservoir.

It is highly likely that the prehnite can be used as an indicator for permeable zone during well drillings in the Wasabizawa geothermal power station.

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