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Technology Development of 'Steam Spot' Detection for Suitable Location of Production Wells by Integrating Geoscientific Methods

Katsuaki Koike[1], Taiki Kubo[1], Koki Kashiwaya[1], Yohei Tada[1], Tada-nori Goto[1], Shigeki Sakurai[2], Sudarto Notosiswoyo[3], Mohamad Nur Heriawan[3], lrwan lskandar[3], Asep Saepuloh[4], Arie Naftali Hawu Hede[3], Nenny Miryani Saptadji[3] and Sutopo[3]

[1]Graduate School of Engineering, Kyoto University, Katsura C1-2, Kyoto 615-8540, Japan

[2]Graduate School of Advanced Integrated Studies in Human Survivability, Kyoto University, Yoshida, Kyoto 606-8306, Japan

[3]Faculty of Mining and Petroleum Engineering, Bandung Institute of Technology, Bandung, West Java 40132, Indonesia

[4]Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Bandung, West Java 40132, Indonesia

[1]koike.katsuaki.5x@kyoto-u.ac.jp

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ABSTRACT

A five-year collaboration project between Kyoto University and Bandung Institute of Technology as core groups, entitled "Project for technology development of steam-spot detection and sustainable resource use for large enhancement of geothermal power generation in Indonesia" is ongoing under the framework of SATREPS. This project aims to develop the technologies that can reduce drilling costs and increase success rate of production-well location by detecting steam spots through a combination of remote sensing, mathematical geology, geochemistry, geophysics, and mineralogy. In addition to the steam-spot detection, remote sensing-based technologies for environmental monitoring to check the effect of geothermal power plant operation and the optimal operation control system of geothermal power generation for a long-term use of geothermal resource are being developed. Human resource development for the geothermal science and technology is also an important target of this project. Steam spot is a coined word for the permeable fractures with much amount of thermal water and steam that enables large and long-term power generation. By selecting the Wayang Windu geothermal field in West Java, Indonesia for a case study, this paper presents an effectiveness to consider a lineament direction and density extracted from multi-shaded digital elevation model and SAR intensity image, presence of hydrothermal alteration minerals detected from optical sensor imagery, temporal-change pattern in radon concentrations in soil gasses at many borehole points, and water and gas geochemical features for locating steam spots. By integrating all the results, steam spots may be formed by continuous fractures in steam- and upflow-dominated portion in reservoir, which yields high and temporally stable radon concentrations in soil gases and alteration minerals with high temperature of stability near the surface. This project will advance towards the overall goal to reduce the exploratory drilling cost at planned sites of geothermal power plant by developing the application of the technologies.

1. INTRODUCTION

One of the most serious issues that hinders large enhancement of geothermal power generation is the cost of exploration drilling. A large number of exploration wells need to be drilled at great depth, but a small number of wells successfully reach a reservoir in general. For this problem, we aim to reduce the drilling cost and increase the success rate by identifying a 'steam spot' which is suitable for the location of production wells. The 'Steam spot' is a coined word for the permeable fractures with much amount of thermal water and steam that enables large and long-term power generation.

Under five-year collaboration project between Kyoto University and Bandung Institute of Technology as core groups until March 2020 in a framework of Science and Technology Research Partnership for Sustainable Development Program (SATREPS) supported by JICA and JST, steam-spot detection technologies have been studied and developed by a combination of remote sensing, mathematical geology, geochemistry, geophysics, and mineralogy. In addition, remote sensing-based technologies for environmental monitoring to check the effect of geothermal power plant operation and numerical simulation-based optimal operation system of geothermal power generation for a long-term resource use are the targets of development. Satellite imagery and topographic data analyses, field surveys, analyses of water/gas/soil and rock samples, geophysical surveys using transient electromagnetic (TEM) and audio-magnetotelluric (AMT) methods, and reservoir simulation chiefly using TOUGH2 have made a progress for the technology development by selecting the Wayang Windu geothermal field (WWGF) situated as 35 km south from Bandung city and its surrounding three geothermal fields (Patuha, Tampomas, and Tangkuban Perahu) near the Bandung basin, West Java, Indonesia (Fig. 1). A geothermal power plant with 227 MW capacity is operating in WWGF. Our team calls this project, BAGUS (Beneficial and Advanced Geothermal Use System) project, which means "very good" in Indonesian.

Through the four and half-years studies so far, effectiveness of an integration of lineament-based fracture mapping, distribution of hydrothermal alteration minerals, spatial and temporal features of radon concentrations using shallow boreholes, compositions and isotopic features of waters and crustal gases, and reservoir simulation has been clarified to steam-spot detection and hydrothermal flow modelling. Our overall goal is to reduce the exploratory drilling cost at planned sites of a geothermal power plant by applying of the technologies developed. Human resource development for a geothermal use that targets young researchers, engineers, and students in Japan and Indonesia is also an important task of the BAGUS project. A part of the research results of steam-spot detection focusing on WWGF only is presented in this paper.

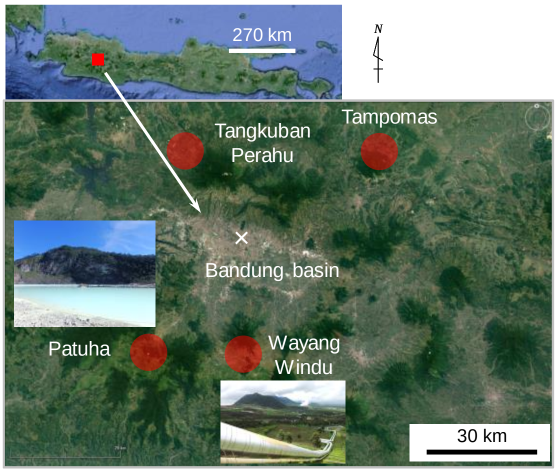

Figure 1: Location of the case study field, Wayang Windu geothermal field (WWGF) and its surrounding three geothermal fields around the Bandung basin, West Java, Indonesia.

2. METHODS AND GEOLOGIC SETTING

2.1 Concept of Steam Spot

We describe that a steam spot is a part of permeable, continuous fractures along which much amount of thermal water and steam ascend from reservoir to the surface, and therefore, a steam spot is the target of setting production well. Identifying accurately the location of steam spot from the ground surface may increase power generation by reducing drilling cost largely. A steam spot of our concept is the place that satisfies the following four factors on chemical and physical properties of a fracture, fluids (thermal water and steam), and a reservoir; i.e. a steam spot is the intersection of these factors (Fig. 2). How each factor can be analyzed, measured, and evaluated is explained subsequently.

- Existences of continuous and permeable fractures and young fluids: Because it is highly possible that fractures with such properties tend to appear on topography, they can be detected through analyses of satellite imagery and digital elevation model (DEM) data. Fluids age is estimable though a chemical analysis.
- Connection between near surface and a reservoir by fractures accompanying large steam amount: Radon and mercury concentrations in soil gas can be used as an indicator of the connection. Larger permeability in the shallow crust is thought to generate higher radon concentration and larger amount of steam.
- High reservoir temperature and dominancy of deep origin crustal gases: Estimation of reservoir temperature is possible through geothermometers by combining several water or gas component concentrations. In addition, ratio of stable isotope gas such as He can be an indicator of identifying gas sources.
- Remarkable presence of hydrothermally altered minerals with proof of gas and fluid ascents to near surface: Stable temperature of hydrothermal alteration mineral differ among minerals. It is highly possible, accordingly, that water and steam with high temperature have continued to ascend from a reservoir to the surface at the place with large ratio of minerals with high stable temperature.

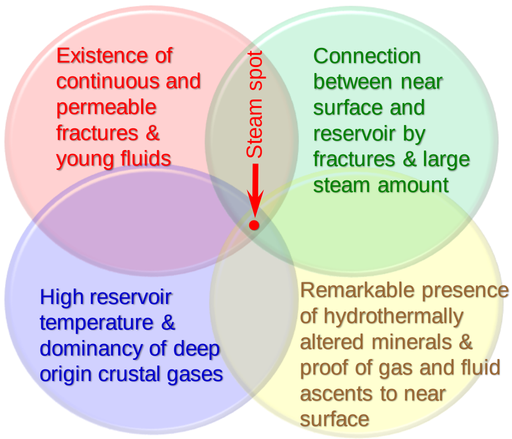

Figure 2: Concept of "Steam Spot" that satisfies four factors on chemical and physical properties of fracture, fluid (water and steam), and reservoir.

2.2 Research Items and Contents

Based on the above concept of steam spot, the following eight research items were set to develop technologies for detecting steam spots. One challenging point of the BAGUS project is how we can obtain information on deeply-seated reservoir from the surface and near-surface geoscientific data. To accomplish this, many shallow drillholes were dug for the sampling and gas monitoring as an outlet of migrated deep information. This idea and each research item are schematically drawn in Figure 3.

(1-1) Extract major and permeable fractures from satellite imagery (optical sensor and SAR imageries) and DEM data, (1-2) Estimate their 3D distribution patter by calculating strike and dip of each fracture plane, (1-3) Detect continuous fractures connected from a reservoir to the near surface by radon and mercury concentrations in soil gases, (1-4) Estimate temperature and pressure in a reservoir by geothermometers using gas components and water chemistry, (1-5) Estimate the original depth of gases using stable isotopes in gases, (1-6) Identify fractures that have acted as paths of hydrothermal fluids from reservoir to the near surface by mineralogical analyses of rock and soil samples, (1-7) Clarify origin and circulation of hydrothermal fluids by chemical and isotopic analyses of water and gas samples, and (1-8) Develop a mathematical method for evaluating potentiality of steam-spot existence by integrating all results of 1-1 to 1-7 items.

For the items (1-3) to (1-7), short holes were drilled by a hand machine to take gas and soil samples. In addition to the steam spot detection, technology development of environmental monitoring to check the effect of geothermal power plant operation is the second purpose by the following two research items.

(2-1) Develop methods for clarifying botanical activity near geothermal power plant from optical sensor satellite imagery, and (2-2) Develop Differential Interferometric Synthetic Aperture Radar (D-InSAR) method for detecting topographic deformation caused by change in temperature and pressure of reservoir with an accuracy of mm order.

The third purpose is establishment of optimal operation control system of geothermal power generation for a long-term use of geothermal resource by the following three items. The items of the second and the third purposes are also included in Figure 3.

(3-1) Simulate temperature and pressure changes in geothermal reservoir for various geologic conditions and resource uses, (3-2) Simulate change in power generation using the result of (3-1) and calculate the lifetime of power generation, and (3-3) Develop a design method for a long-term use of geothermal energy based on the results of (3-1) and (3-2).

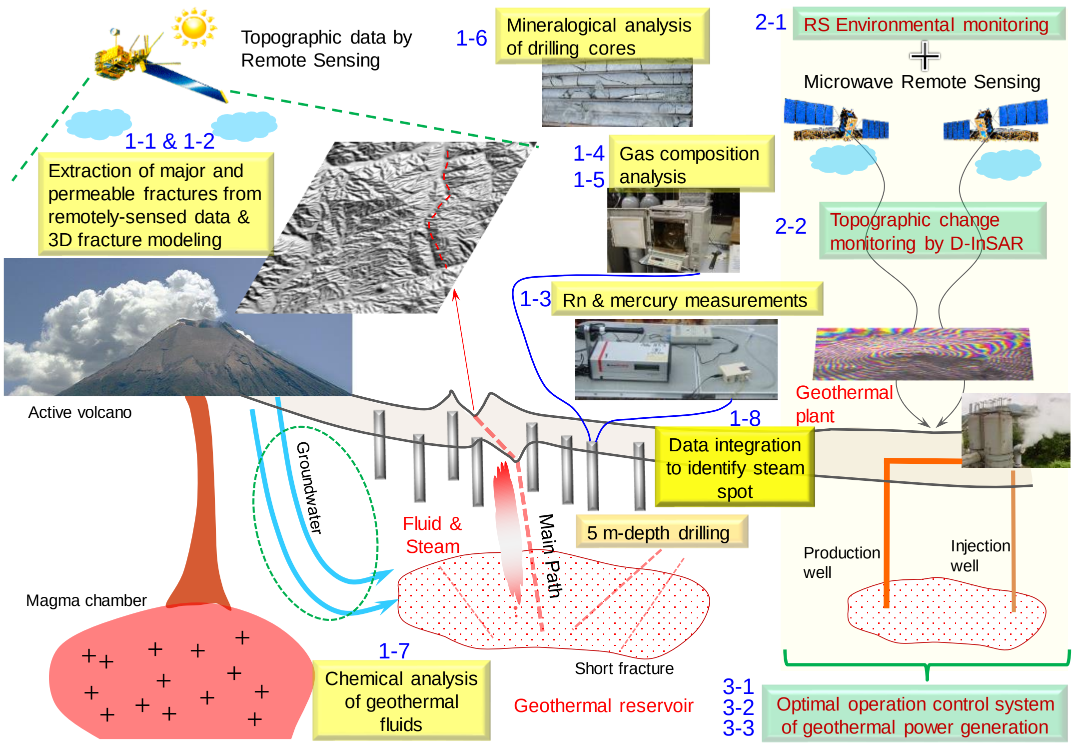

Figure 3: Schematic figure of research contents of the BAGUS project composed of basically three parts. Each number stands for research item in the parts described in the text.

2.3 Geologic Setting of the Study Area

Lithology and geologic structure of WWGF are described in detail by Saepuloh et al. (2018). The following descriptions are summary of them. WWGF is situated in the volcano-magmatic arc and covered mainly by the Quaternary andesite, pyroclastic flows, and tuff. Its geothermal system is characterized as transitional between the southern water- and northern steam-domains. Geothermal manifestations are composed of hydrothermal alteration minerals, mud pools, fumaroles, and hot springs that are located at the slopes of mountain range and crater rims. Major faults strike mainly 40°NE and 20°NW, which were generated by the subduction of the

Indo-Australia Plate beneath the Sunda Plate. Three craters, Burung (north), Wayang (middle), and Windu craters (south) are thought to be situated at the intersection of the major faults, and the springs are also distributed along the faults.

3. RESULTS AND DISCUSSION

3.1 Fracture Characterization through Lineament Extraction

Continuous fractures tend to appear as lineaments, linear or slightly curved topographic features on remotely-sensed imagery and DEM. There are two sources of computer-aided lineament extraction, multi-shaded DEM (Masoud and Koike, 2011) and ALOS-1 PALSAR (Phased Array type L-band SAR) intensity image of dual (ascending and descending) orbits (Saepuloh et al., 2018). For the DEM data, SRTM (Shuttle Radar Topography Mission) DEM with 30-m resolution and highly precise DEM produced by an UAV with 0.5 m resolution were used. Lineament extraction from these data sources was based on the Segment Tracing Algorithm (STA; Koike et al., 1995) and its modified method (Saepuloh et al., 2018). By grouping the lineaments based on similarity of direction and distance between neighborhoods, pseudo-fracture planes were constructed with estimation of their strikes and dips, lengths, and distribution pattern as Koike et al. (1998).

As an example of the lineament analysis, SRTM DEM lineaments were extracted by STA and their distribution density map was drawn by a box counting (Fig. 4). Two dominant directions, NE-SW and NNW-SSE to NW-SE are agreeable with those of the major faults, and most geothermal manifestations such as fumaroles and hot springs are overlapped with the high density zones. Therefore, the high density zone can be used as an indicator for subsequent detailed field surveys to narrow steam-spots locations. Furthermore, most pseudo-fracture planes were revealed to have steep dip angles, and 84 % of the tips of production wells were located on the planes. The directions (dip angles and aspects and strikes) of the planes generally corresponded with those of the actual fractures observed by the drilling. These facts demonstrate effectiveness of the lineament extraction method by this study.

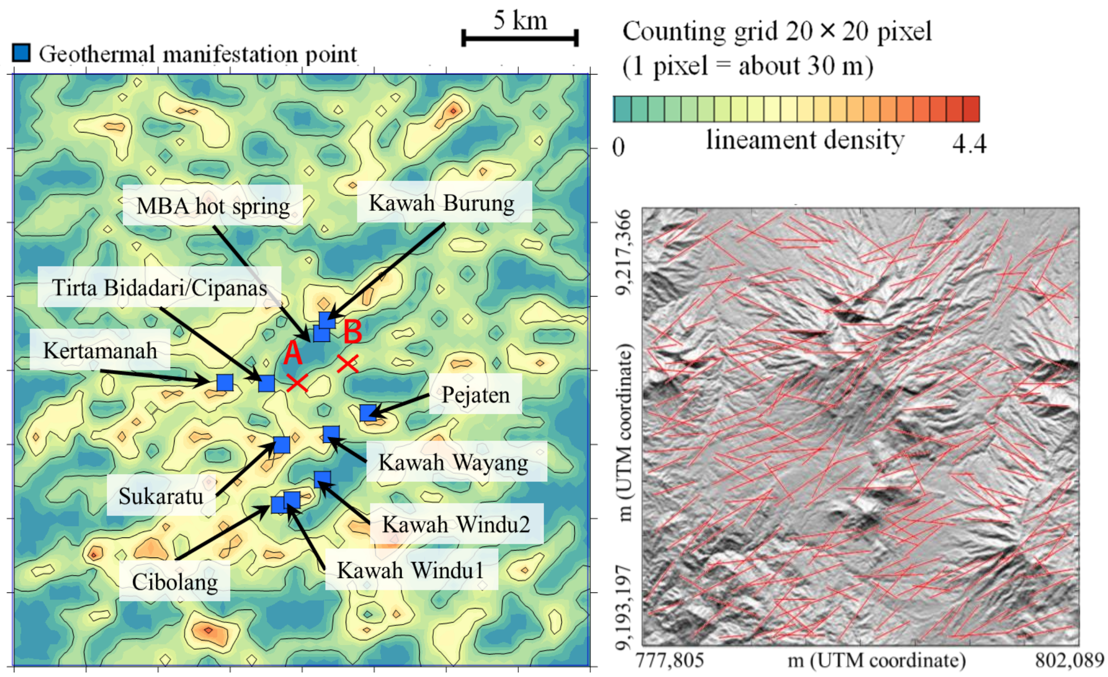

Figure 4: Lineament distribution extracted from multi-shaded SRTM DEM with 30-m resolution using STA (right) and their distribution density map with geothermal manifestations such as fumaroles and hot springs. A and B points in the density map, which are located in a relatively low and high density zones, respectively, are targets of comparing radon concentration feature in Figure 6.

3.2 Detection and Mapping of Hydrothermal Alteration Minerals

To detect hydrothermal alteration minerals, a traditional mineral index analysis and unmixing analyses using Linear Spectral Mixture, Direct Principal Component Analysis, Mixture Tuned Matched Filtering, and Spectral Angle Mapper were adopted to a typical multiband satellite imagery, ASTER image and the sole hyperspectral satellite imagery, Hyperion image. The advantage of ASTER is its five bands (bands 5 to 9) in short-wave infrared region, 2 to 2.5 μm, which is effective to discriminate the minerals containing OH, H_2O, and CO_3 by their absorption patterns of reflectance. Mineral index is to emphasize this absorption pattern that is different with mineral in terms of wavelength, absorption depth, and shape of reflectance curve, by combining two or more band data. The simplest index is a band ratio, reference band data without absorption divided by absorption band data.

Because alunite, kaolinite, and calcite are known to typical alteration minerals related to the geothermal manifestations in WWGF (Bogie et al., 2008), existence possibilities of these minerals were derived by the mineral indices, then color composite image of three mineral indices were produced as shown in Figure 5. In this map, the zones with NDVI (Normalized Difference Vegetation Index) values over 0.8 were masked by gray color to exclude the zones covered thickly by vegetation. Although large index zones are roughly overlapped with the hot springs and fumaroles, there are many large index zones except for such geothermal manifestations. One example is a relatively high density zone of lineaments marked by B in Figure 4. Another remarkable feature is that the large index zones seem to be distributed along an NNW-SSE fault passing through B. There are other several linear features of the large index zone. The zones whose lineament density and mineral indices are both high can be a next target to locate steam spots. Furthermore, surface roughness that can be estimated by HV polarimetric data of ALOS-1 PALSAR (Saepuloh et al., 2015) was revealed to be effective to extract craters and fumaroles composed of outcropped rocks.

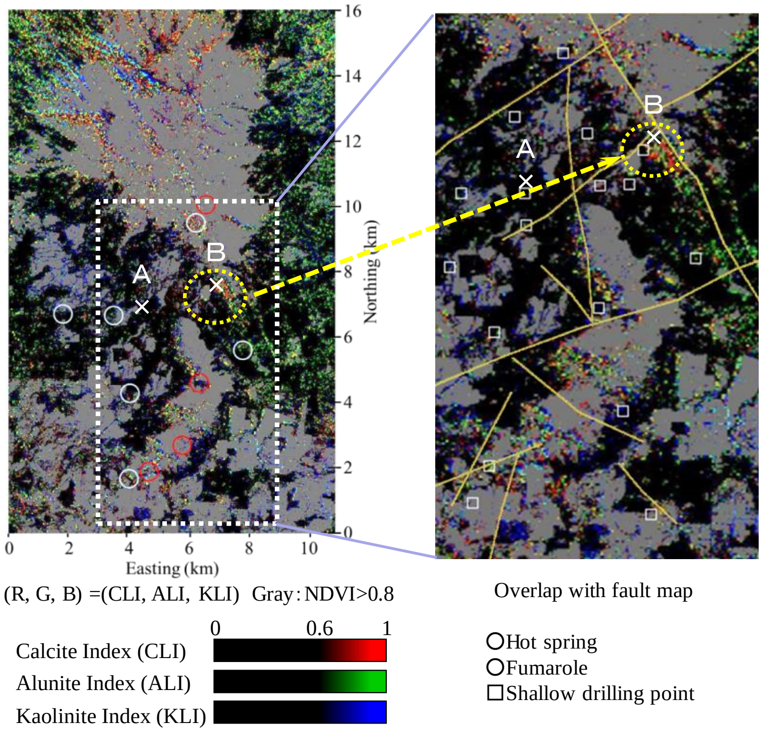

Figure 5: Color composite image of three indices of typical alteration minerals in WWGF (alunite, kaolinite, and calcite) excluding thickly vegetated zones with NDVI over 0.8 (left), and its enlargement for the shallow drilling area overlapped with fault map (right).

3.3 Soil-Gas Radon Measurement for Confirming Steam Ascent

To evaluate the formation of permeable fractures acting hydrothermal fluid paths from a reservoir, radon concentrations in soil gasses were measured at 24 points using an instrument RAD7 (Durridge). Junctions of two or three major faults and estimated high density zones of lineaments were selected for the measurement points, and shallow boreholes were dug down to the 5 m depth. Locations of the points are shown in Figure 5. For the points with shallow groundwater levels, the borehole depths shallower than 5 m were determined by considering the levels. Gasses were pumped up from the boreholes, and the concentrations of two radon isotopes, Rn-222 and Rn-220, were measured repeatedly at each point by setting the unit period to five minutes. Because the half-life of Rn-222 (3.58 d) is 6000 times longer than that of Rn-220 (53.4 s), we used the Rn-222 concentrations for the above purpose. Usefulness of radon was demonstrated for geothermal fields in Japan as a tracer of temperature and pressure changes in a geothermal reservoir (Koike et al., 2014).

We repeated the radon measurements five times in dry seasons from 2016 to 2018, and found that the temporal change pattern of the Rn-222 concentrations could be classified into two types, type I: large increase of concentrations from the start of measurement up to 10 minutes and large decrease after that, and type II: keeping the high concentration with the elapse time after large increase (Fig. 6). The type I is generally distributed in the low lineament density zones with absence of alteration minerals as the A point in Figure 4, whereas the type II appears in the high density zones accompanying alteration minerals as the B point. Rn-222 concentrations of the type II were higher than those of the type I. A numerical simulation based on the radioactive decay law clarified that the type II could be generated by large volume and high ascent velocity of radon carrier gases originated from the degassing of hydrothermal fluids.

Components of the gases sampled from the boreholes were also measured by gas chromatography. Volcanic components, typically shown by H_2S in the type II, were revealed to be higher concentrations than those of the type I. The gas components of the type I were almost equivalent to the atmosphere.

Furthermore, mineral compositions of the dug soils were identified by XRD analysis for all the borehole points. Presence of minerals bearing high temperature of stability such as halloysite, cristobalite, and biotite was confirmed at the B point, whereas the type I points were composed generally of usual weathered soils. Those results suggest that the sites bearing the type II are presumably on fluid-path fractures in which stream spots are formed.

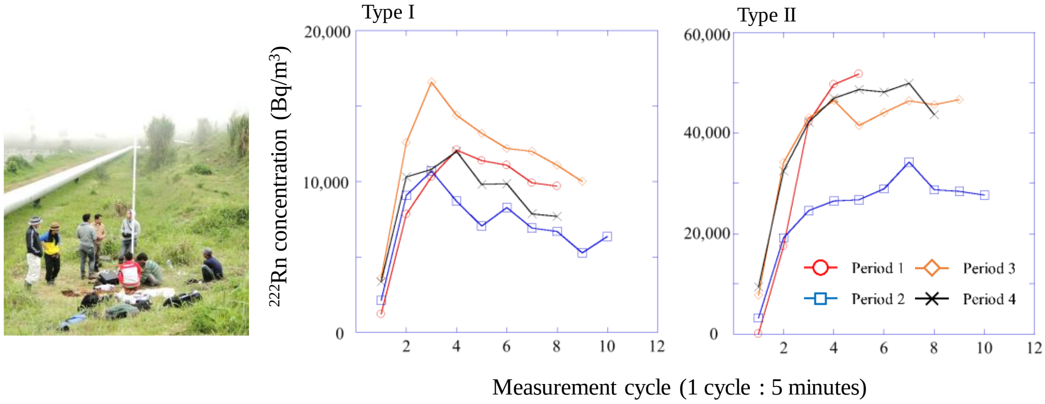

Figure 6: Two general patters of Rn-222 concentrations in WWGF, type I: large increase of concentrations from the start of measurement up to 10 minutes and large decrease after that and type II: keeping the high concentration with the elapse time after large increase. The type I and II are the data of A and B points in Figure 4, respectively in different lineament density zones. Rn-222 concentrations are higher in the type II. Left picture shows scenery of one measurement point and a casing pipe used to protect the borehole.

3.4 Water and Gas Geochemistry for Interpreting Steam Spot Generation and Fluid Flow System

Clarifications of a fluid flow system and reservoir conditions regarding temperature and dominancy of water or steam are also indispensable to identifications of steam spots and their formation mechanisms. For this purpose, samples of water and steam condensate were collected to measure the water isotope ratios (δD and $\delta^{18}O$) and major anion-cation concentrations at the wellhead of 20 production wells in August 2016, and January and August 2017. Targeted ions were Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^- measured by ion chromatography and titration, and additionally, trace elements including B, rare alkali metals Li, Rb, and Cs, and REEs were measured using ICP-MS. Measurement of noble gas isotopes, ^3He, ^4He, and ^{20}Ne, was to estimate depth of gas sources, i.e. shallow or deep crust origin or mantle origin.

As an example of the water and gas analyses, spatial distributions of Cl^- concentrations and $\delta^{18}O$ values in the reservoir are depicted by interpolating those data to discriminate steam and liquid domains (Fig. 7). $\delta^{18}O$ values in the steam composition were corrected by considering fractionation characteristics of ^{18}O in rocks and liquid phases. One remarkable feature is that extremely low Cl^- concentrations extend in the northern area including the B point, colored by black. This concentration feature signifies mixing of the parent fluid with surficial meteoric water and the extent of steam zone (Shoedarto et al., 2018). $\delta^{18}O$ value of the B point is heavier than that of the A point, which may imply that upflow is more dominant at the B point. This feature is concordant with the gas component result that more volcanic gas components are observed at the B point bearing Rn-222 concentration pattern of the type II. By integrating the results of water and gas analyses, a model of fluid flow system in WWGF was constructed, which suggests that the estimated steam spots are formed by continuous fractures in steam- and upflow-dominated portion in a reservoir.

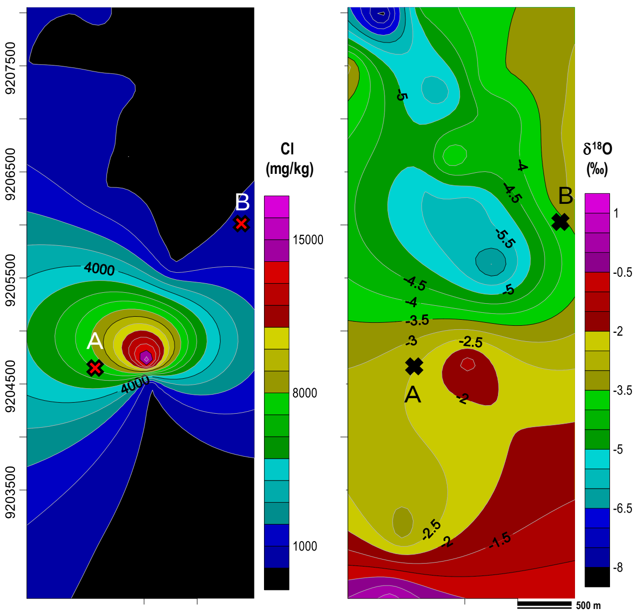

Figure 7: Spatial distributions of Cl^- concentrations (left) and $\delta^{18}O$ values (right) in the subsurface conditions before boiling process.

4. CONCLUSION

This paper presents a part of the results of ongoing BAGUS project that aims large enhancement of geothermal power generation by identifying steam spots suitable for the location of production wells, and therefore, by reducing the drilling cost. Defined steam spot is the location satisfying the four factors: existences of continuous and permeable fractures and young fluids, connection between near surface and a reservoir by fractures accompanying large steam amount, high reservoir temperature and dominancy of deep origin crustal gases, and remarkable presence of hydrothermally altered minerals with proof of gas and fluid ascents to near surface. The Wayang Windu geothermal field (WWGF) in West Java, Indonesia was selected for a case study.

Lineaments extracted from multi-shaded DEM and SAR intensity image of dual (ascending and descending) orbits by STA-based methods were agreeable with the dominant directions of major faults, and the zones satisfying both high lineament density and presence of hydrothermal alteration minerals were the main targets of subsequent detailed field surveys to narrow down the steam-spot locations. To evaluate the formation of permeable fractures acting hydrothermal fluid paths from a reservoir, radon concentrations in soil gasses were measured at 24 points using RAD7. The temporal change pattern of the Rn-222 concentrations could be classified into two types, type I: large increase of concentrations from the start of measurement up to 10 minutes and large decrease after that, and type II: keeping the high concentration with the elapse time after large increase. The type II was generally higher in Rn-222 concentration, located in the above preferable zones, and revealed to generate by large volume and high ascent velocity of radon carrier gases originated from the degassing of hydrothermal fluids. By integrating the results of XRD for mineral compositions and water and gas geochemical analyses, the sites bearing the type II were considered to be presumably on fluid-path fractures containing stream spots.

The resultant conceptual model of the fluid flow system suggested that the estimated steam spots are formed by continuous fractures in steam- and upflow-dominated portion in a reservoir. We continue working on refining the steam-spot locations by obtaining more fracture and geochemical data, TEM and AMT surveys, and developing a method that can integrate all the data for steam-spot potential mapping.

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