CONCEPTUAL MODEL OF OUTFLOW ZONE IN MOUNT UNGARAN GEOTHERMAL SYSTEM, SEMARANG, CENTRAL JAVA USING GEOLOGY AND GEOCHEMISTRY OF MANIFESTATION ANALYSIS

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ABSTRACT

This research is conducted in the outflow zone of Mount Ungaran geothermal system, Semarang, Central Java, Indonesia, i.e. Kendalisodo and surrounding which is located in the eastern and southeastern part of Mount Ungaran. The purpose of the study is to build the conceptual model of the Kendalisodo geothermal system. Methods used comprise of literature study, geological traverse mapping, water sampling, and geochemical study for anions, cations, gas, and stable isotopes $\delta^{18}O$, $\delta^{2}H$, and $\delta^{13}C$ analysis. Geothermal surface manifestation in the study area includes Kendalisodo, Diwak, Derekan, and Kaliulo warm springs; with travertine and salt deposits in some areas. Fumarole and hot springs appear in the upflow zone of Gedongsongo. In the study area, there are two geothermal systems, i.e. Kendalisodo and Diwak system. These two systems are separated by the Old Ungaran Caldera. Both systems are non-volcanic and medium enthalpy systems. The Kendalisodo reservoir has a temperature of 170 ± 10°C. The hydrothermal fluid of the Kendalisodo system originates from meteoric water catchment on the southeast slope of Mount Ungaran; the meteoric water is heated up by the remaining heat of Mount Kendalisodo intrusion. The fluid has experienced mixing with cold water before discharge in the upflow zone at the Kendalisodo area. The Kendalisodo geothermal system, geologically and geochemically, is different from the main geothermal system of Mount Ungaran (Gedongsongo). The Diwak geothermal system has a reservoir with a temperature of 160 ± 10°C. The hydrothermal fluid of the Diwak system is also from meteoric water, which is heated up by high heat-flow and/or overpressure system. The fluid then flows upward through the Derekan Fault and discharges in the upflow zone as the Diwak and Derekan warm springs. The fluid also flows laterally through the Derekan Fault and mixed with formation water to form Kaliulo warm spring in the outflow zone.

1. INTRODUCTION

Mount Ungaran is a Quarternary stratovolcano in the caldera setting, called Ungaran Caldera. Mount Ungaran is growth in Tertiary sedimentary rock formation. This sedimentary rock is outcropped surround Mount Ungaran. According to Claproth (1989), there are three volcanic cycles of Mount Ungaran, namely Mount Ungaran, the Oldest, Old, and Young. The oldest Ungaran Mountain period occurs in Late Pliocene - Middle Pleistocene, Old Ungaran Mountain in Middle-Late Pleistocene, and Ungaran Muda Mountain in Late Pleistocene - Early Holocene (Claproth, 1989). There are two calderas on Mount Ungaran, the Oldest Ungaran Caldera which is buried by younger volcanic products (Saibi et al., 2012) and Old Ungaran Caldera whose morphology can be observed (Claproth, 1989).

The existence of a geothermal system in Mount Ungaran is manifested by geothermal manifestation, i.e. fumaroles, thermal springs, steaming ground, travertine, and altered rocks (Rezky, et al., 2012). Based on Phuong, et al. (2005), the upflow zone of Mount Ungaran geothermal system is located in the Geodongsongo area (southern flank, near the peak of Mount Ungaran). This upflow zone is characterized by the discharge of fumaroles and sulfate thermal springs. Meanwhile, the outflow zone is located in the north area (Nglimut) and east area (Kendalisodo) which characterized by the discharge of bicarbonate and chloride thermal springs.

In the northeast to the south of Mount Ungaran, precisely on the Ungaran Caldera wall, there are parasitic cones that form Mount Kendalisodo, Puntang, Mergi, Pobongan, and Siwakul. The parasitic cone is in the form of intrusion resulting from the volcanism period of Old Ungaran Volcano (Claproth, 1989). According to Thanden, et al. (1996), the parasitic cone is composed of andesite rocks.

The Kendalisodo area (Figure 1) is one of the outflow zones of the Mount Ungaran geothermal system. The area is on the Ungaran Caldera wall and is associated with sedimentary rocks. Meanwhile, the presence of intrusive rocks on Mount Kendalisodo can be a potential source of heat for a geothermal system. This raises the possibility that the Kendalisodo area could form a different geothermal system from Gedongsongo (Mount Ungaran); according to Wohletz and Heiken (1992), a normal fault of the caldera can be a barrier to the geothermal system.

The geology of Mount Ungaran has been discussed by several researchers, including van Bemmelen (1949), Hadisantono and Sumpena (1993), Thanden, et al. (1996), and Claproth (1989). In general, the research discusses the geology and petrogenesis of Mount Ungaran. Also, Rezky et al. (2012) and Phuong, et al. (2005) have discussed the aspects of geoscience and the geothermal prospect zone of the Mount Ungaran area. The research and scientific writings are more focused on the discussion of the geothermal system in Gedongsongo, an area on the southern slope of Mount Ungaran. While in the Kendalisodo region, in the southeastern part of Mount Ungaran, there are only studies of gravity and geomagnetic characteristics by Susilo, et al. (2016). Research on geological and geochemical aspects that specifically addresses the Kendalisodo area has never been conducted before.

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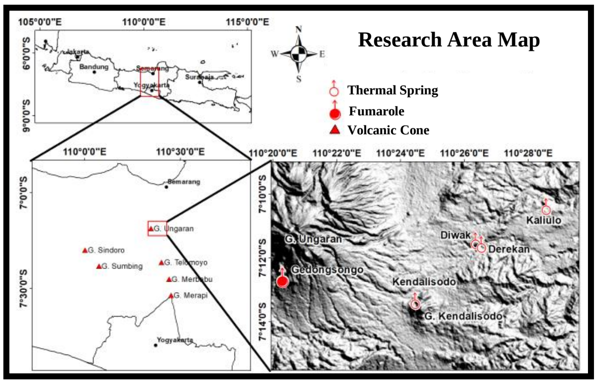

Figure 1: Research area map. The research is conducted in the eastern part of Mount Ungaran, precisely on 4 geothermal manifestations; Kendalisodo, Diwak, Derekan, and Kaliulo.

2. GEOLOGY

2.1 Stratigraphy

The Geological Map of Mount Ungaran is shown in Figure 2. Mount Ungaran grows on Tertiary age sedimentary rocks in the form of Kerek, Penyatan, and Kaligetas Formations. The bedrock is exposed and scattered around Mount Ungaran. The sequence of rock stratigraphy in the area of Mount Ungaran from old to young according to Hadisantono and Sumpena (1993) is Kerek Formation, Penyatan Formation, Payung Formation, Kaligetas Formation, Merangkang Volcanic Unit, Munding Lava, Suroloyo Volcanic Unit, Andesite Intrusion, Ungaran Volcanic Unit, and Alluvial deposits.

In the Kendalisodo research area (to the east of Mount Ungaran), geothermal manifestations emerge out of the Kerek Formation, Merangkang Volcanic Unit, and Andesite Intrusion. The Kerek Formation found in the Kaliulo area is composed of lithology ooids packstone. The Merangkang Volcanic units that are exposed in Kaliulo, Diwak, Derekan, and Kendalisodo are composed of pyroclastic breccias and glass tuffs. While the Andesite Intrusion in the Kendalisodo area is composed of andesite which according to Claproth (1989) is in the Late Pleistocene age.

Based on the geological cross-section in Figure 2, the depth of sedimentary rocks from the summit of Mount Ungaran is around 2000 m (Thanden, et al., 1996), while in the Kendalisodo area it is about 300 meters from the surface (Claproth, 1989). So the possibility of sedimentary rocks become reservoir rocks for geothermal systems.

2.2 Geological Structures

Based on the geological map in Figure 2, in general, there are several structural patterns associated with faults. These faults are as follows.

- Oldest Ungaran Caldera

  The presence of the Oldest Ungaran Caldera structure was obtained from a gravity study by Saibi et al. (2012). The study shows that there are structural patterns below the surface associated with the presence of the Oldest Ungaran Caldera. The structure is covered by younger volcanic products. The Oldest Ungaran Caldera structure is on the southeast side to the south and northwest of Mount Ungaran. The existence of the Oldest Ungaran Caldera on the southeast side of Mount Ungaran might be a barrier between the Gedongsongo geothermal system (Mount Ungaran) and Kendalisodo.

- Derekan Fault

  The presence of the Derekan Fault was interpreted from the results of the lineaments analysis, the appearance of breccias in the field, and the appearance of the lineament of warm springs. Brecciaation is found around the output of the manifestation of Derekan with a trend in the N25^{o}E direction.

- Kaliulo Fault

  The Kaliulo Fault was interpreted from the results of the lineament analysis and appearance of brecciation in the field in the direction of N103^{o}E. The Kaliulo Fault is interpreted as a structure controlling the Kaliulo warm springs discharge. The Kaliulo Fault is also the contact boundary between ooids packstone lithology (Kerek Formation) and pyroclastic breccias (Volcanic Merangkang units) in the Kaliulo area.

- Old Ungaran Caldera

  Geomorphologically, there is a circular feature that is distributed around Mount Ungaran. According to Claproth (1989), circular feature morphology is related to the presence of Old Ungaran Caldera. The Old Ungaran Caldera was formed as the end of the Old Ungaran volcanic period which is in the Late Pleistocene (Claproth, 1989).

  Old Ungaran Caldera can act as a barrier to a geothermal system. In the study area, it appears that the discharge of the Kendalisodo warm springs (UN-5) is inside the Old Ungaran Caldera, while the Kaliulo (UN-1), Diwak (UN-2), and Derekan (UN-3) warm springs are on the outside of the caldera. The role of the caldera structure for the geothermal system in the study area will be discussed later in the section on fluid geochemistry.

- Wringin Fault

  The Wringin Fault is located southwest of Mount Ungaran. This fault forms a northwest-southeast trending pattern. According to van Bemmelen (1949), the Wringin Fault was formed in conjunction with the Old Ungaran Caldera through a volcano-tectonic mechanism. Both structures were formed in the Late Pleistocene age as the end of the volcanism period of Mount Ungaran Tua (van Bemmelen, 1949).

2.3 Geothermal Manifestation

There are several manifestations in the study area, namely Gedongsongo fumaroles, Gedongsongo hot springs (GS-1), Kaliulo warm springs (UN-1), Diwak (UN-2), Derekan (UN-3), and Kendalisodo (UN- 5); (Figure 2). The following is a description of the location and physical appearance of each hot and warm spring.

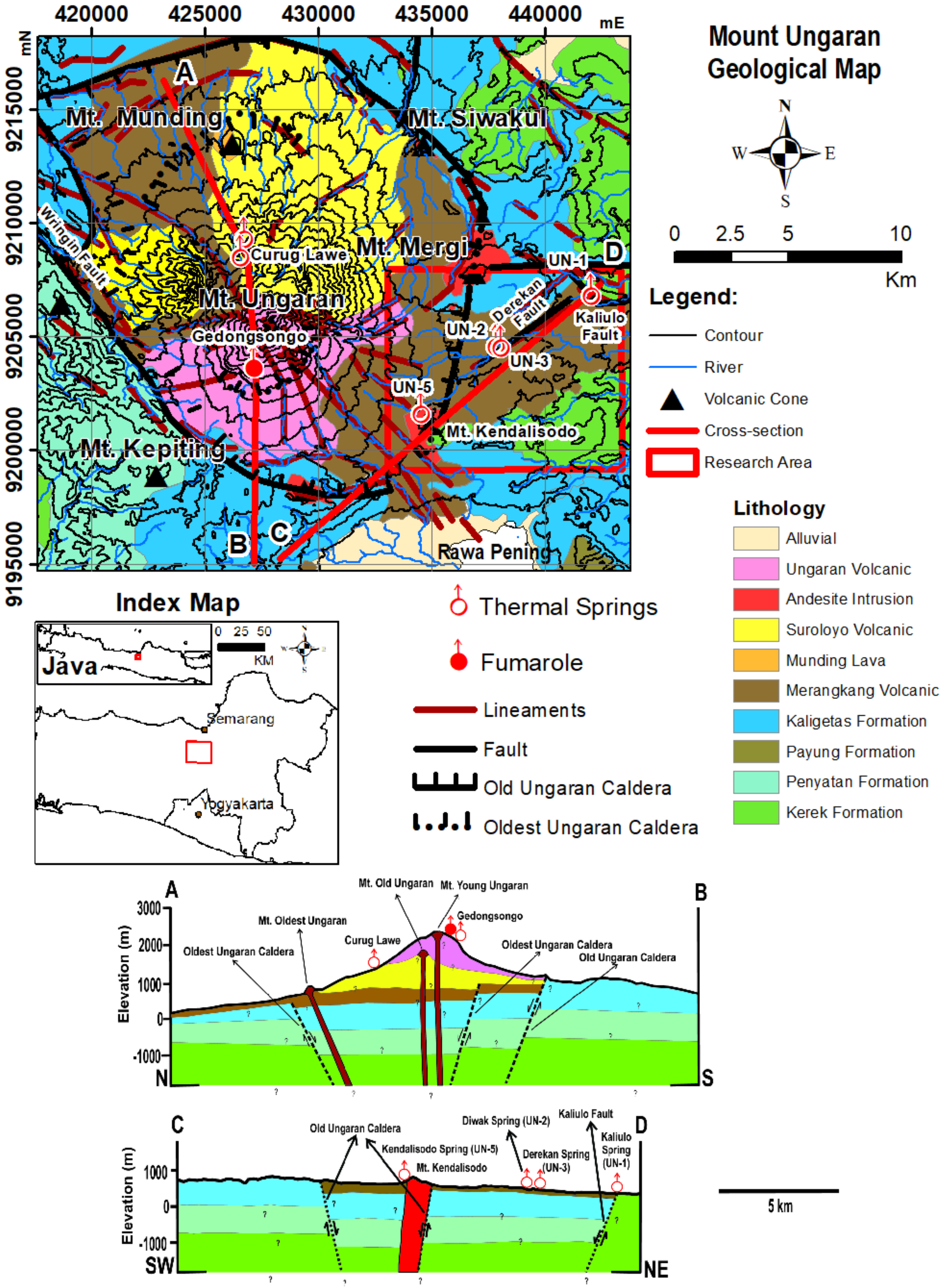

Figure 2: Geological Map of Mount Ungaran (modified from Hadisantono and Sumpena, 1993)

- Gedongsongo (GS-1). The Gedongsongo area is a major manifestation of a geothermal system in Mount Ungaran; consists of fumaroles with a temperature of 88.5°C with roaring characteristics, a hot spring with a temperature of 54.5°C, and altered rocks. Hot springs have an acidic pH (2.68) in the presence of gas bubbles.

- Kaliulo (UN-1). Kaliulo spring has a temperature of 34.9°C, a pH of 6.68, and a TDS (Total Dissolved Solids) measured of 14,000 mg/kg. The physical condition of the spring is brown, quite foamy, and bubbling. From the appearance of this warm spring also formed deposits of travertine and salt. Travertine outcrops are spread over approximately 10 x 5 m^2 with a thickness of each layer of about 5-20 cm. The travertine is composed of crystalline micromorphology, isopachous sparitic pore cement, and pustular.

- Diwak (UN-2). Diwak spring is discharged on the banks of a river in a valley and has been used directly as a bathing pool. This spring has a measured temperature in the field of 39.1°C, pH 6.25, and TDS 1,560 mg/kg with the appearance of gas bubbles. Also, there are also iron oxide deposits along the walls of the pond.

- Derekan (UN-3). Derekan spring discharged on the river bank. This spring is approximately 250 meters from the represented spring. This spring has also been used as a submerged pool (Figure 2.24). However, some warm water seepage out in the river flow. Derekan spring temperature measured in the field is 38.1°C, with a pH of 6.33, and TDS 1,410 mg/kg. The physical condition of the spring is brown, gas bubbles (bubbling) appear, and iron oxide deposits are formed.

- Kendalisodo (UN-5). In this area, there are warm yellowish-brown springs with a temperature of 35.6°C, a pH of 6.36, and TDS 3,280 mg/kg, which is called the Kendalisodo spring. The spring comes out in a pool measuring about 1.0 x 1.5 m^2 with travertine deposits around it. The travertine has a thickness of about 20 cm and has a micromorphology in the form of dendritic.

3. GEOCHEMISTRY

3.1 Water Type

The determination of water type is done by plotting the relative content of anion and cation elements in the triangle diagram Cl-HCO_3-SO_4 and Na-K-Mg (Figures 4 and 5). The types of water that appear in the study area are as follows.

- Chloride water

  Kaliulo Spring (UN-1) belongs to the type of chloride water. This spring has a TDS value of 14,000 mg/kg which shows the characteristics of saltwater or seawater. Meanwhile, the content of boron (B) and ammonium (NH_4^+) which is also high in Kaliulo springs (233.66 and 31.50 mg / L respectively) shows the influence of sedimentary rocks (Nicholson, 1993). The Kaliulo spring (UN-1) in the Na-K-Mg diagram (Figure 4) shows a plot in a partial equilibrium zone. This shows that the Kaliulo spring is a spring that is affected by formation water from sedimentary rocks.

- Chloride – Bicarbonate water

  This water type is indicated by the Kendalisodo spring (UN-5). The high bicarbonate content (1392.48 mg/L) in the spring indicates the mixing process with meteoric water. This is supported by the Kendalisodo spring (UN-5) plot on the Na-K-Mg diagram (Figure 4) which is in the immature waters zone. Thus, it is interpreted that the Kendalisodo spring is produced from the process of mixing hydrothermal fluid with meteoric water.

- Bicarbonate water

  Springs which are bicarbonate water types are Diwak (UN-2) and Derekan (UN-3). In addition to bicarbonate ions, the spring has a high magnesium content, which is 135.55 mg/L (Diwak spring) and 136.70 mg/L (Derekan spring). This can be seen in the Na-K-Mg diagram (Figure 4) which shows the plot of the Diwak and Derekan springs which are in the immature waters zone. Thus, those springs are interpreted as hydrothermal fluids which are influenced by the process of mixing with meteoric water (groundwater) as they rise to the surface.

- Sulphate

  Gedongsongo hot springs (GS-1) belong to the sulfate water type. In the Na-K-Mg diagram (Figure 4), the Gedongsongo spring is in the immature waters zone. This shows that the Gedongsongo spring is formed from a secondary process, namely condensation of steam rich in H_2S gas into groundwater. In high terrain geothermal systems such as Mount Ungaran, sulfate springs together with fumaroles will be found in the upflow zone.

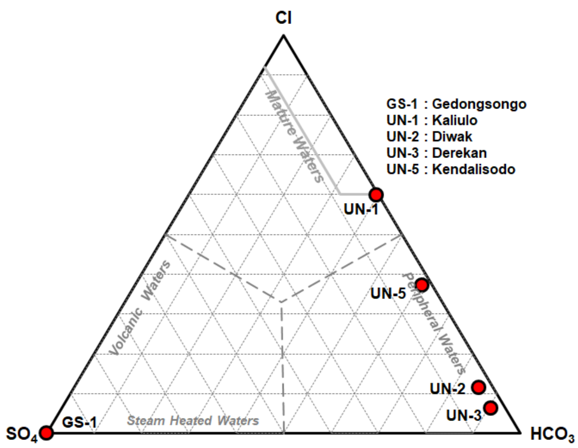

Figure 3: Cl-HCO_3-SO_4 plot diagram. There are three types of water in the Kendalisodo area: chloride water (UN-1), chloride-bicarbonate water (UN-5), and bicarbonate water (UN-2 and UN-3). While the type of water in the Gedongsongo area (GS-1) is a sulfate.

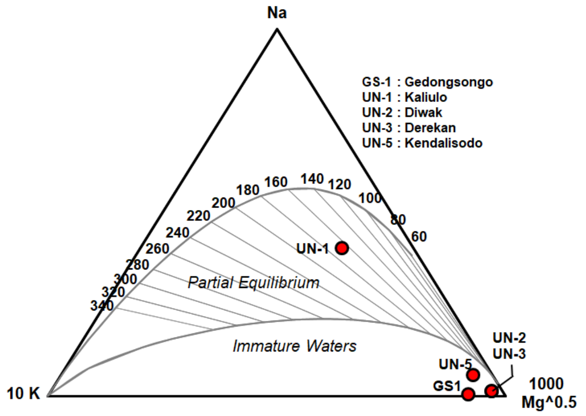

Figure 4: Na-K-Mg diagram showing that UN-1 is in a partial equilibrium zone. UN-2, UN-3, and UN-5 springs are in an immature zone which shows the mixing process with meteoric water. While GS-1 springs show a process of steam condensation.

3.2 Geoindicator

Based on the Cl-Li-B diagram in Figure 5, Kaliulo (UN-1), Represented (UN-2), and Kendalisodo (UN-5) springs have relatively similar Cl / B ratios, which are 25 (UN-1), 26 (UN-2), and 25 (UN-5). While the Derekan spring (UN-3) has a Cl / B ratio of 15. The Gedongsongo spring (GS-1) has a Cl/B ratio that is different from other springs, which is 9.

The difference in the Cl/B ratio at the Gedongsongo spring with other springs shows that the hydrothermal fluid of the Gedongsongo system (Mount Ungaran) is different from the Kendalisodo system (to the east of Mount Ungaran). This is supported by geological data in the presence of the Oldest Ungaran Caldera between the two systems, considering that the caldera structure can be a separator for the geothermal system. Meanwhile, the difference in the Cl/B ratio at the Derekan and other springs does not show a reservoir difference. This is because the two springs come out at close distances and are in the same geological structure, the Derekan Fault (based on the Geological Map of Mount Ungaran in Figure 2).

Hydrogeological patterns of subsurface fluids in geothermal systems can be analyzed using geoindicators of dissolved elements, such as the ratio of Na/K, Na/Mg, Na/Ca, and HCO_3/SO_4. The Kendalisodo spring (UN-5) has a low Na/K ratio value, which is 21. While the Na/K ratio values for Diwak and Derekan springs also show low values, which are 8 and 9. This shows that the Kendalisodo, Diwak, and Derekan springs are discharged in the upflow zone. Thus, in the study area, there are two upflow zones, namely in the Kendalisodo area and in the Diwak and Derekan areas.

Besides, based on the geological map in Figure 2, there is the Old Ungaran Caldera that separates the Kendalisodo spring discharge area with the Kaliulo, Diwak, and Derekan springs. This supports the interpretation that the Kendalisodo spring comes from a different reservoir (Kendalisodo system) compared to the Kaliulo, Diwak, and Derekan springs (Diwak system).

Lateral flow in the Diwak system is indicated by the value of the HCO_3/SO_4 ratio. Consequently, the HCO_3/SO_4 ratio at the Diwak, Derekan, and Kaliulo springs shows an increasingly high value, namely 45, 47, and 123. Thus, the hydrothermal fluid in the Diwak system is interpreted to flow laterally to the outflow zone in the northeast towards Kaliulo.

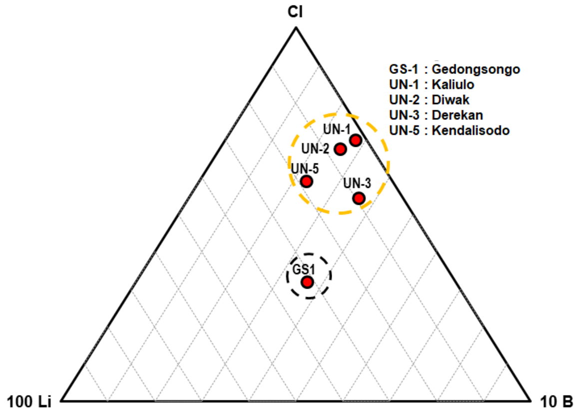

Figure 5: Cl-Li-B diagram. There are two groups of Cl/B ratios shown by yellow circles (Kaliulo, Diwak, Derekan, and Kendalisodo) and black circles (Gedongsongo).

3.3 Geothermometer

In the Kendalisodo system, estimation of the reservoir temperature is carried out using a conductive quartz geothermometer which shows a reservoir temperature of 170±10°C. In the Diwak system, the reservoir temperature estimation is also performed using a conductive quartz geothermometer in the Diwak and Derekan springs which shows a reservoir temperature of 160±10°C. Based on the classification of Hochstein (1990), the Kendalisodo and Diwak systems belong to a medium enthalpy geothermal system.

3.4 Gas Analysis

According to Nicholson (1993), the origin of gas in geothermal systems is generally analyzed using the N_2-He-Ar diagram (Figure 6). Based on the diagram, it is known that the Gedongsongo fumarole has an N_2/Ar ratio of 182 which designates magmatic origin. This interpretation is further supported by the characterisation of GS-1 as sulfate water in Figure 3 suggesting influence from magmatic water. While the Kendalisodo springs (UN-5) and Diwak (UN-2) have N_2/Ar ratios of 42 and 35 which designate the origin of meteoric water, respectively. From above, it is fair to conclude that the Gedongsongo geothermal system has magmatic fluid contribution while the Kendalisodo and Diwak systems are heavily influenced by meteoric water.

Reservoir temperature can also be estimated with gas geothermometers. There are several types of gas geothermometers, including DAP or CO_2-H_2S-H_2-CH_4 (D'AAmore and Panichi, 1980) and CO_2-H_2 geothermometers (Arnórsson and Gunnlaugsson, 1985). The reservoir temperature estimation of the Gedongsongo system was obtained from the Gedongsongo fumarole sample which showed reservoir temperatures of 210°C (DAP geothermometer) and 270°C (CO_2-H_2 geothermometer). While the Kendalisodo system reservoir temperature estimation is obtained from the Kendalisodo spring gas sample which shows an estimated reservoir temperature of30°C (DAP geothermometer) and 170°C (CO_2-H_2 geothermometer). The reservoir temperature estimation of

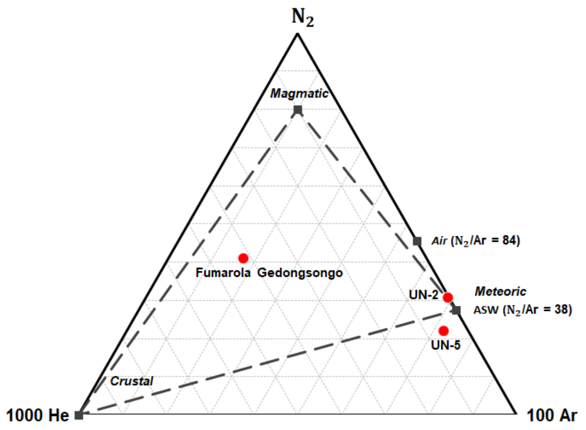

Figure 6: N_2-He-Ar diagram. The N_2/Ar ratio in the Gedongsongo fumarole designates the origin of the gas, which is magmatic, while the Kendalisodo springs (UN-5) and Diwak (UN-2) designate meteoric water.

the Diwak system was obtained from the Diwak spring samples which showed values of 20°C (DAP geothermometer) and 150°C (CO_2-H_2 geothermometer). The temperature estimates from the CO_2-H_2 geothermometer are similar to that derived from the quartz conductive geothermometer.

3.5 Stable Isotope

Analysis of stable isotopes is carried out by plotting δ^2H and δ^{18}O isotope contents from hot, warm, and cold springs (Figure 7). The isotope content of δ^2H and δ^{18}O from cold springs is used to obtain the Local Meteoric Water Line (LMWL). The stable isotope plots in the Gedongsongo hot spring (GS-1) are close to the range of magmatic/andesitic water isotopes. The addition of isotopes δ^2H and δ^{18}O became heavier in the Gedongsongo hot spring (GS-1) due to the mixing process with magmatic water. The process produces a type of water from the Gedongsongo hot spring to sulfate with an acidic pH (pH 2.68). This interpretation is consistent with the information derived from the N_2/Ar gas ratio in Figure 6 suggesting presence of magmatic water.

The isotopic compositions of δ^2H and δ^{18}O in the Kendalisodo (UN-5), Diwak (UN-2), and Derekan (UN-3) springs show plots close to the local meteoric water line. These conditions indicate the presence of the mixing process with meteoric water. Interpretation of the Kendalisodo spring is strengthened by the isotope value δ^{13}C which shows the value of -5.77 ‰. The isotope value of δ^{13}C indicates the origin of meteoric or freshwater based on Trumbore and Druffel (1995). This is consistent with the characterization of the Kendalisodo, Diwak, and Derekan springs in Figures 4 and 5 indicating Cl-HCO_3 and HCO_3 type of waters as a result of mixing process with meteoric water.

The Kaliulo spring (UN-1) shows the δ^2H and δ^{18}O isotope plots close to the range of isotopes of limestone formation water. This shows that there is an influence of formation water on the Kaliulo spring. This condition is supported by the very high TDS and EC values, as well as the chloride water type (with high Na, Cl, B, and NH_4 content). Thus, in the Diwak geothermal system, hydrothermal fluid is influenced not only by meteoric water and mixing with surface water, but it is also influenced by formation water (increasingly dominant towards the east).

3.6 Recharge Area

According to Poage and Chamberlain (2001), the stable isotope content (δ^2H and δ^{18}O) in meteoric water (cold water) will decrease or become lighter with increasing elevation and latitude. This relationship will later be used to determine the recharge area or geothermal fluid catchment area. The relationship between stable isotopes of δ^2H and δ^{18}O in cold springs with elevation and latitude on Mount Ungaran is in Table 1.

The determination of the geothermal system infiltration area is done by entering the isotope composition δ^2H and δ^{18}O reservoir fluid in the equation. To obtain the range of latitude and elevation value of the infiltration area. The intersection between elevation and latitude values can be interpreted as a geothermal system catchment area.

Recharge area analysis is only done for the Kendalisodo system, assuming that the reservoir fluid is a water phase. To calculate the condition of reservoir fluids from surface manifestations, it is necessary to understand several processes that occur below the surface, namely:

- The Kendalisodo spring comes out as an upflow that comes out directly from the reservoir.
- Reservoir fluid has a temperature of 170°C (based on a conductive quartz geothermometer) and is expected to undergo conductive cooling to a temperature of 80°C (based on the K-Mg geothermometer). Conductive cooling does not change the composition of the dissolved elements in the fluid (Nicholson, 1993) so that at a temperature of 80°C the chemical composition of the hydrothermal fluid is still the same as the reservoir fluid.
- The conductive cooling fluid (the same as the reservoir fluid) is then mixed with meteoric (cold) water, in this case, represented mixed with Sidomukti or AD-8 cold springs with a temperature of 22°C. The Sidomukti spring (AD-8) was chosen because geographically the Sidomukti spring is a spring that comes out in the Old Ungaran Caldera and has the closest distance to the Kendalisodo spring compared to other cold springs. The results of mixing reservoir fluid (which has undergone conductive cooling) and cold water produce warm springs Kendalisodo (UN-5) which is a bicarbonate chloride water type and has a temperature of 36°C.

Calculations are performed using the heat equilibrium equation, to obtain the stable isotope composition of the Kendalisodo system reservoir fluid which is δ^2H = -31.5 ‰ and δ^{18}O = -4.79 ‰. This value is then entered into the equation of the stable isotope relationship with elevation and latitude to get the elevation and latitude values (Table 1).

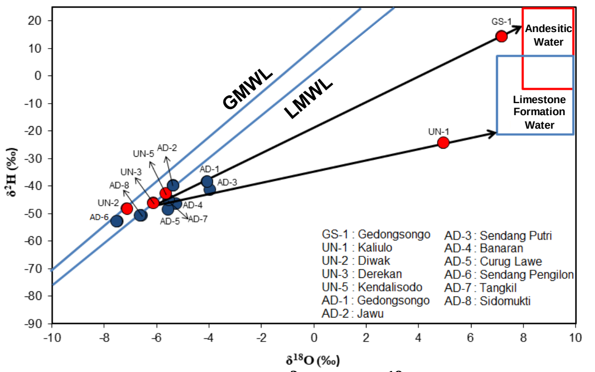

Figure 7: Relationship of δ^2H and $\delta^{18}O$ isotopes in hot, warm, and cold springs (local meteoric water line).

Table 1: Calculation of latitude and elevation of recharge areas.

Isotope δ^2H reservoir	-31,5 ‰	
Isotope $\delta^{18}O$ reservoir	-4,79 ‰	
Latitude (mU)	Latitude (mU) = -171 δ^2H + 9.196.713	9.202.099 mU
	Latitude (mU) = -802 $\delta^{18}O$ + 9.200.233	9.204.075 mU
Elevation (m)	Elevation (m) = -30 δ^2H - 440	505 m
	Elevation (m) = -149 $\delta^{18}O$ + 136	850 m

Based on the calculations tabulated in Table 1, the meteoric water catchment area is in the elevation range 505 - 850 m and latitude 9,202,099 - 9,204,075 mU (UTM coordinates of the 49S zone). The Kendalisodo geothermal system catchment area is the intersection between the elevation and latitude ranges, which shows the area on the southeast slope of Mount Ungaran.

4. CONCEPTUAL MODEL

There are two geothermal conceptual models, the first model that describes the relationship of the Gedongsongo system (Mount Ungaran) and Kendalisodo (Figure 8), and the second model that illustrates the main systems of Kendalisodo and Diwak (Figure 9).

The first conceptual model in Figure 8 was modified from Phuong et al. (2005) which is a northwest-southeast trending cross-section, from Mount Ungaran to Kendalisodo. Based on the geochemical analysis, it is indicated that the Kendalisodo geothermal system is different from the Gedongsongo geothermal system. The presence of the Oldest Ungaran Caldera on the southeast side of Mount Ungaran is thought to act as a barrier to the two geothermal systems.

Hydrothermal fluid from the Gedongsongo system flows upwards in the upflow zone in the Gedongsongo area which is characterized by the presence of fumaroles and sulfate hot springs. The heat source for the Gedongsongo system, according to Rezky, et al. (2012) derived from the remaining magma of Young Ungaran Volcano. Thus, the Gedongsongo geothermal system can be classified as a volcanic system. The presence of fumaroles in Gedongsongo also shows that the geothermal system here is a high enthalpy system with reservoir temperatures reaching 270°C (CO_2-H_2 geothermometer). The top of the Gedongsongo reservoir is estimated to be at an elevation of about 300 meters above sea level (Rezky, et al., 2012).

The conceptual model in Figure 9 (directed southwest-northeast or from Kendalisodo to Diwak, Derekan, and Kaliulo) shows that the Kendalisodo geothermal system is different from the Diwak system. The two systems are separated by Old Ungaran Caldera. The origin of the hydrothermal fluid in the Kendalisodo system is meteoric water that is absorbed from the southeast slope of Mount Ungaran. Below the surface, the meteoric water is then heated by a heat source in the form of intrusion rocks of Mount Kendalisodo which is in the Late Pleistocene age. The hydrothermal fluid then collects in the reservoir.

The Kendalisodo geothermal reservoir has a temperature of 170 ± 10°C based on a conductive quartz geothermometer. The top of the reservoir is estimated to be at a depth of about 1,000 meters from the surface or elevation of 400 meters below sea level, according to calculations using the geothermal gradient of the UN-1 well (15°C / 100m). At that depth, the Kendalisodo reservoir lithology is likely to be the Penyatan and Kerek Formation, with permeability types in the form of lithological boundaries, fractures due to intrusion, and geological structures (Old Ungaran Caldera and northwest-southeast alignment in the southeastern slopes of Mount Ungaran). Hydrothermal fluid from the Kendalisodo system reservoir then flows in the upflow zone in the Kendalisodo region and then undergoes conductive cooling (to a temperature of 80°C based on the K-Mg geothermometer). The fluid is mixed with meteoric water near the surface and then comes out as a warm Kendalisodo spring (UN-5) with a temperature of 36°C.

Reservoir fluid in the Diwak system has a temperature of 160±10°C, based on a conductive quartz geothermometer. The top of the reservoir is estimated to be at a depth of about 950 m from the surface or elevation of 520 meters below sea level, based on calculations with a 15°C / 100m geothermal gradient in the UN-1 well. Reservoir lithology of the Diwak system possibly in the form of Penyatan and Kerek Formation, with the type of reservoir permeability likely in the form of lithology boundaries, Derekan Faults, and Kaliulo Faults.

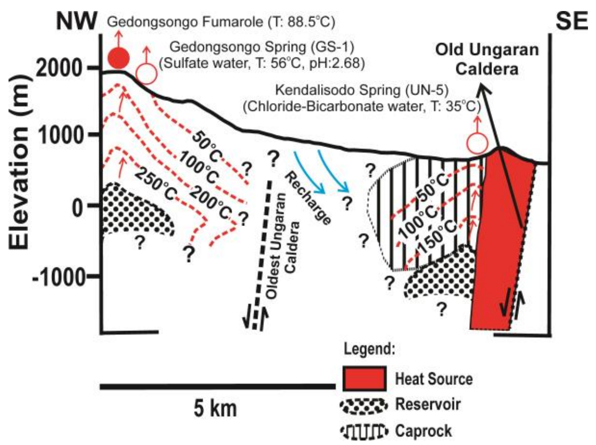

Figure 8: Conceptual model of Gedongsongo (Mount Ungaran) – Kendalisodo geothermal system.

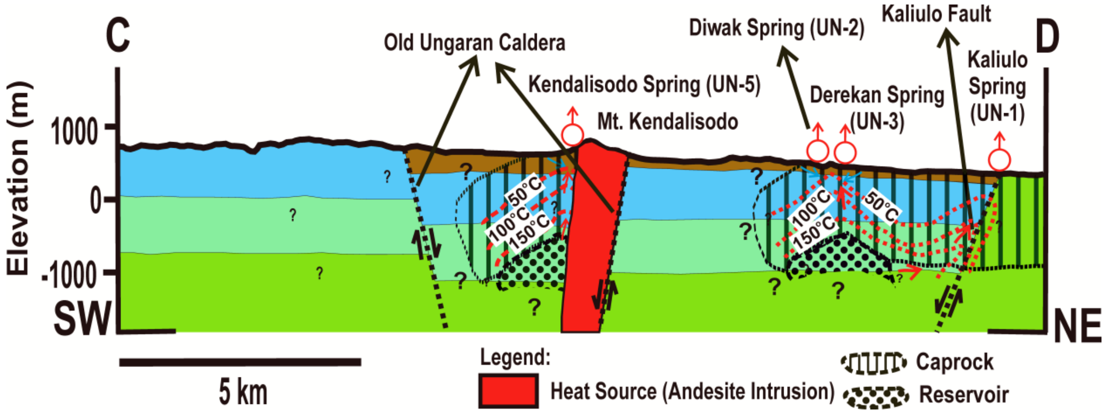

Figure 9: Conceptual model of Kendalisodo and Diwak geothermal system.

The hydrothermal fluid of the Diwak system is from meteoric water and is influenced by formation water. The presence of meteoric water in the Diwak system is indicated from the N_2/Ar indicator gas ratio of the Diwak spring which designates the origin of the gas in the form of meteoric water. While the contribution of formation water to this system is indicated by the water type and isotopes δ^2H and δ^{18}O Kaliulo springs which indicate mixing with formation water.

The upflow zone of the Diwak system is at the discharge of Diwak (UN-2) and Derekan (UN-3) springs. Near the surface, the Diwak reservoir fluid is mixed with cold meteoric water. The hydrothermal fluid then flows laterally through the Derekan Fault into the outflow zone and mixes with formation water. Further east, the hydrothermal fluid is mixed with formation water and comes out as a Kaliulo spring (UN-1). Diwak geothermal systems are non-volcanic systems with an estimated heat source in the form of high heat flow and/or high pressure (overpressure) in sedimentary basins.

5. CONCLUSION

The Kendalisodo geothermal system is a geothermal system that is different from the Mount Ungaran geothermal system (Gedongsongo). The two systems are separated by the Oldest Ungaran Caldera. In the Kendalisodo research area, there are two geothermal systems namely the Kendalisodo and Diwak systems which are separated by Old Ungaran Caldera. Both systems are non-volcanic geothermal systems. The heat source of the Kendalisodo system comes from andesitic intrusions in the Late Pleistocene age, while the Represented system is heated by heat flow and/or high pressure. The Kendalisodo reservoir system has a temperature of 170±10^{o}C, while the reservoir system is represented at a temperature of 160±10^{o}C. Both systems are classified into the medium enthalpy geothermal system. The hydrothermal fluid of the Kendalisodo system originates from the meteoric water catchment on the southeast slope of Mount Ungaran. Fluid in the Diwak system comes from meteoric water and is influenced by formation water.

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