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Initial State Fluid Geochemistry of the Dieng Geothermal Field, Indonesia: New Constraints for Conceptual Model

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ABSTRACT

The Dieng Geothermal Field, Indonesia has a 2-phase reservoir with a current installed capacity of 60 MW. The data used is fluid geochemical data from manifestations taken in the period 1977 - 1997 and well fluid data (brine, gas, and stable isotopes) during production tests in 1980 – 1999. The Dieng Geothermal System is divided into 2 reservoir areas, i.e., the Sileri and Sikidang areas. The Sileri area has a neutral fluid characteristic, even though it has magmatic fluid influx potential. The neutralization process occurs due to the intensive water-rock interaction process in the reservoir. The reservoir has a temperature of around 283-338^oC with a Cl content of 9,600 – 19,000 mg/kg. The source of the fluid is heated meteoric water, mixed with fluids resulting from magmatic degassing, boiling, and experiencing water-rock interaction with sedimentary or meta-sedimentary rocks. Besides being characterized by a high Cl content, interactions with sedimentary rock formations are also supported by a high boron content. The hydrothermal fluid in the Sileri reservoir flows vertically towards the upflow zone in two areas, i.e., Pagerkandang Crater (Well-10 and Well-1) and Merdada Crater (Well-4 and Well-9). There is also a steam cap zone in the Sileri area, which is characterized by excess enthalpy, high NCG, and a temperature profile that exceeds the boiling point depth. The Sikidang reservoir has a more acidic fluid character due to the more dominant influence of magmatic fluid. The Sikidang reservoir has a two-phase fluid, with most wells penetrating the steam cap zone and several wells penetrating the liquid zone, it is estimated that there is a boiling zone between liquid and steam reservoirs. The fluid temperature in the reservoir ranges from 260 to 324^oC with high NCG content (2 – 21 wt%). The fluid flow in the Sikidang Area comes from upflow around Pangonan Crater, Well-V, Sikidang, and Sibanteng manifestations. This upflow zone also correlates with the acid fluid zone, therefore there is the potential for acid fluid to be found deep in the reservoir.

1. INTRODUCTION

The Dieng Geothermal Field is located in Central Java, Indonesia. Pertamina was the first to do exploration in Dieng from 1977 to 1994, drilling 27 exploratory wells. These wells are numbered Well-A to Well-Z, with 24 of them in Sikidang and three in Sileri (Figure 2). Himpurna California Energy has continued the exploring effort after 1995, drilling an additional 17 wells in Sileri and three in Sikidang. The distribution of wells and surface manifestations in the Dieng Geothermal Field is shown in Figure 1. The exploration was put on hold during the 1998 Indonesian financial crisis until Geo Dipa Energi established the first unit with a capacity of 60 MWe in 2002. Geo Dipa Energi has since installed a 10 MWe small-scale unit, which was commissioned in 2021.

Geochemistry data is essential to know the reservoir characteristics, e.g., fluid chemistry, reservoir temperature, reservoir processes, fluid flow pattern, acidic fluid potential, etc. This paper will explain the initial geochemical model of the Dieng Geothermal Field as a baseline to interpret reservoir process changes during production. The data used are well and surface thermal manifestation chemistry, including liquid, gas, and isotope analysis. Ultimately, the initial state geochemistry model will be used as a comparison with monitoring data to identify the changes in reservoir processes during production to better manage the Dieng Geothermal Field.

2. GEOLOGICAL BACKGROUND

Sukhyar et al. (1986) made a geological map of the Dieng area, as in Figure 2. The Dieng volcanic complex was formed as a result of volcanic eruptions of the Quaternary age on sedimentary rocks from the Kalibiuk Formation (Tpb) of the Pliocene age (Sukhyar et al., 1986 in Luthfian, 2014). During the Pleistocene, the Jembangan volcano (Qpjv) was formed which covered West Jembangan and East Jembangan with the remains of the volcanic cone still being observed on Mount Ngesong, Mount Alang, and Mount Kemulan. The formation of Mount Prau (Qppv) and Mount Tlerep (Qptv) marked the subsequent process of volcanism. These two mountains then experienced major eruptions; the empty magma chamber collapsed and formed the Prau Caldera (open to the southwest) and the Tlerep Caldera (open to the south). Volcanic rocks at this time have a basalt to andesite composition (Sukhyar et al., 1986). After the formation of the Prau Caldera, the next volcanic activity was on Mount Bucu (Qpbv), Nagasari (Qpna), Bisma (Qpbl(b)), Sidede (Qpbl(sd)), Sikunang (Qpbl(sku)), Jimat (Qpja), Butak-Petarangan (Qpbp), Menjer (Qpll(m)) and the parasitic cones of Mount Petarangan (Qpll(p)), Igir Binem (Qpit), Pagerkandang (Qppl), Siglagah (Qpsv), Pangonan-Merdada (Qppa) and, finally, Mount Dringo (Qhlr); (Sukhyar et al., 1986 in Luthfian, 2014). The latest volcanic activity produced volcanoes with andesitic to dacitic composition, e.g., Mount Kendil, Watusumbul, Pakuwaja, Prambanan, and Sikunir.

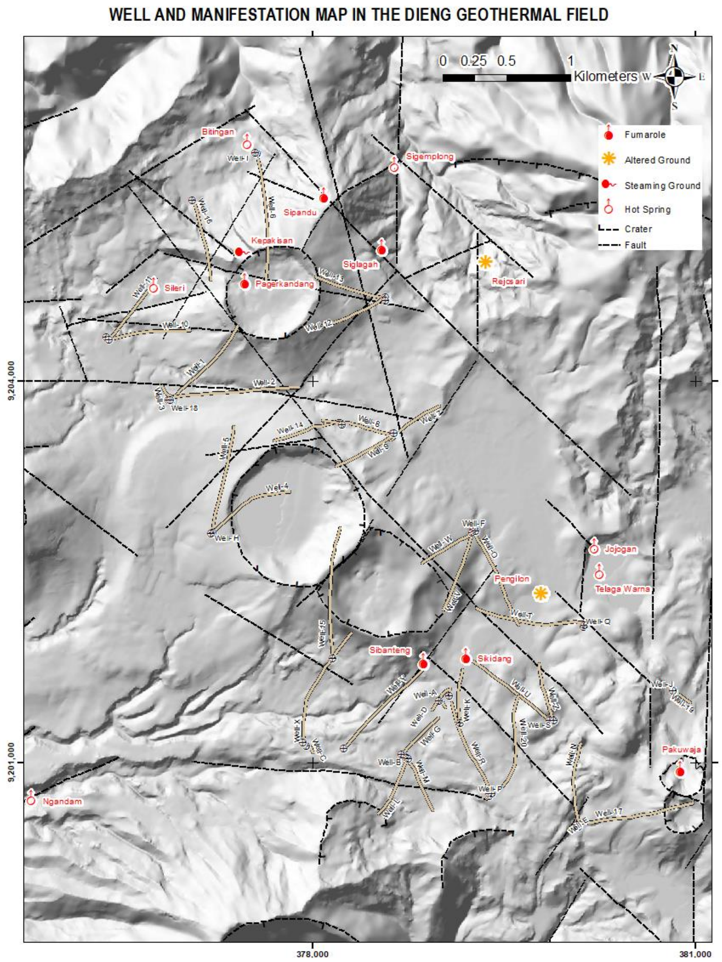

Figure 1: Distribution of well and manifestation in the Dieng Geothermal Field.

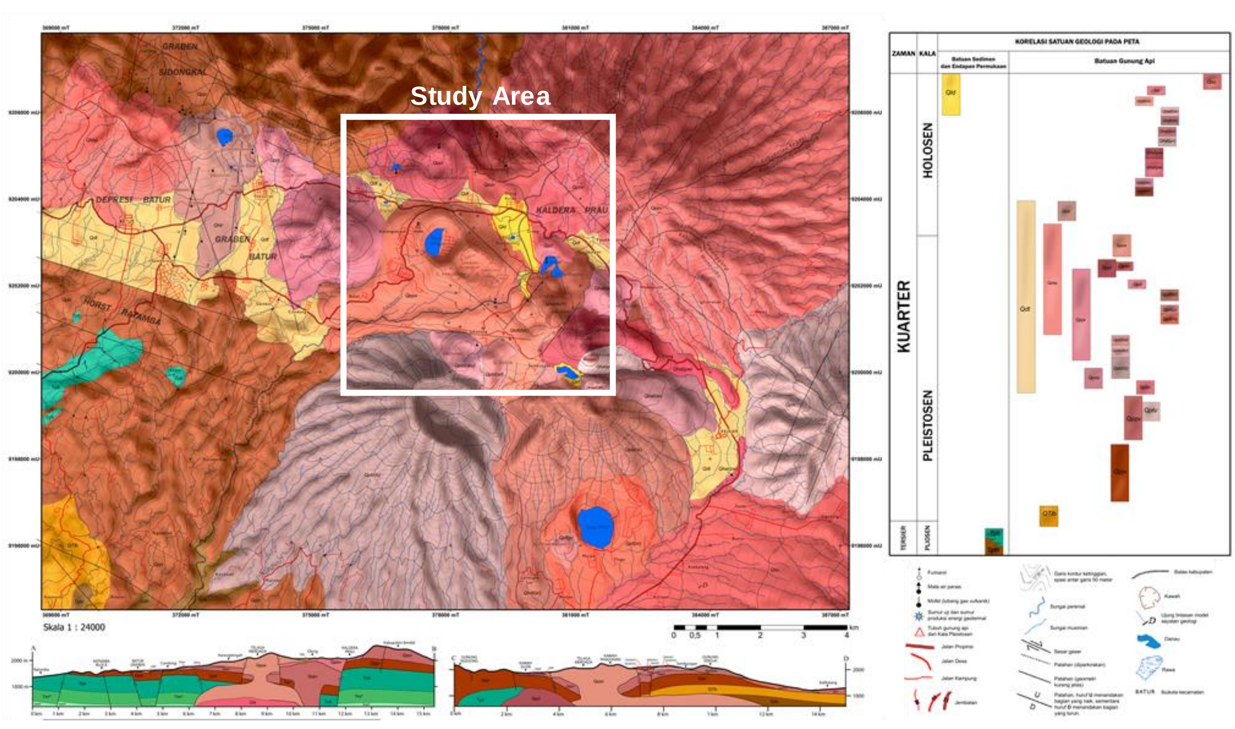

Figure 2: Geological map of the Dieng area (Sukhyar et al., 1986 in Luthfian, 2014).

3. DATA AND METHODS

The data used in this research consists of manifestation geochemical data taken during the exploration period from 1977 to 1997 and well geochemical data which includes brine, gas, and stable isotope chemistry data during production tests from 1980 to 1999. In addition, data on fluid thermodynamics parameters, e.g., enthalpy and vapor fraction, are needed to calculate the chemical composition of the fluid from sampling conditions to reservoir conditions.

Calculations for reservoir conditions assume that the steam separation process occurs adiabatically, that is, no heat is lost to the surroundings and no heat is added to the fluid. This calculation refers to the mass balance equation by Nicholson (1993) which is expressed by:

$$C_{i,res} = y\, C_{i,v} + (1-y)\, C_{i,l}$$

Where

y = steam fraction from production test (division of steam flow by total mass flow)

$C_{i,res}$ = concentration of species "i" in the reservoir

$C_{i,v}$ = concentration of species "i" in the vapor phase

$C_{i,l}$ = concentration of species "i" in the liquid phase

Chemical elements dissolved in the brine, e.g. Cl, can be said to be insoluble in the vapor phase, so the equation can be simplified to:

$$C_{i,res} = (1-y)\, C_{i,l}$$

Meanwhile, to calculate the chemical composition of the gas, a gas distribution coefficient (Bgas) is needed which is the division between the gas concentration in the steam phase and the gas concentration in the liquid phase ($\frac{C_{i,v}}{C_{i,l}}$). The distribution coefficients of several gases are presented in Table 1 which refers to Giggenbach (1980). By entering the gas distribution coefficient, the gas concentration in the reservoir becomes:

$$C_{i,res} = \frac{C_{i,v}}{B}(y\, B + 1 - y)$$

Table 1: Gas distribution coefficients in the temperature range of 100 – 340 deg C (Giggenbach, 1980).

Gas	Equations (t is temperature)
CO_2	log B = 4.7593 – 0.01092t
H_2S	log B = 4.0547 – 0.00981t
CH_4	log B = 6.0783 – 0.01383t
H_2	log B = 6.2283 – 0.01403t
N_2	log B = 6.4426 – 0.01416t
NH_3	log B = 1.4113 – 0.00292t

4. RESULT AND DISCUSSION

3.1 Surface Manifestation

Active geothermal manifestations that appear in the Dieng Geothermal Field are fumaroles, solfatara, steamy soil, mud pools, and hot springs. Manifestations of fumaroles and steamy soil are present in the Pagerkandang, Siglagah, Sipandu, Kepakisan, Sikidang, and Sibanteng areas. Solfatara manifestations only appear in the Pakuwaja area in the southeast area. Mud pools emerge in the Sileri and Sikidang areas. Meanwhile, hot springs are spread across the Sileri, Pagerkandang, Siglagah, Sikidang, Bitingan, Sigemplong, Jojogan, Pulosari and Ngandam areas. Several manifestations, such as Sipandu, Sigemplong, Kepakisan, Sibanteng, Pengilon, Telaga Warna, Jojogan, and Pakuwaja, have not yet collected complete water and gas geochemical data. The three main anions in geothermal fluids are chloride (Cl), bicarbonate (HCO_3), and sulfate (SO_4), as well as the three main cations sodium (Na), potassium (K), and magnesium (Mg) are used to identify the water type of hot spring manifestations. Determining the type of water is done by plotting the main anion and cation components on the Cl-HCO_3-SO_4 and Na-K-Mg diagrams (Figure 3).

The output of Sikidang hot springs shows a sulfate water type (immature water). The pH of the Sikidang hot springs is included in the acid range with a pH value of 2.70. The fluid in this manifestation shows the characteristics of condensate water formed due to condensation or oxidation of hydrogen sulfide gas (H_2S) in shallow groundwater layers. The Sileri hot springs show an immature type of bicarbonate water. The chemical concentration is dominated by bicarbonate anions, which show the characteristics of condensate water from the CO_2 gas condensation process with groundwater. Near the surface, the condensate water mixes with surface water or meteoric water and then comes out as a manifestation of hot springs. This is supported by the high magnesium content (20 – 32 mg/kg) and the neutral pH of the water (6.12 – 6.74). The output of the Pagerkandang hot springs shows an immature sulfate water with a pH of about 3.44 (acid). Pagerkandang hot springs show the characteristics of condensate water which is formed due to condensation or oxidation of hydrogen sulfide gas (H_2S) on the groundwater layer.

Siglagah hot springs are included in the sulfate-bicarbonate water type with immature conditions. Fluids are formed by mixing condensate water and meteoric water, with the proportion of meteoric water being more dominant. This is supported by the fairly high magnesium content, i.e., 26.2 mg/kg, and neutral pH (6.90). The output of the Bitingan hot spring shows an immature sulfate-bicarbonate water type with a neutral pH (6.95). These hot springs show the characteristics of mixing between condensate water and meteoric water with a more dominant proportion of meteoric water. Pulosari hot springs are included in the type of immature chloride water with anions dominated by chloride elements (420 – 497 mg/kg), with a fairly high bicarbonate content (110 – 216 mg/kg). The magnesium content in Pulosari hot springs is 48 – 59 mg/kg. Based on these characteristics, the Pulosari hot springs indicate that they were formed by mixing the reservoir's chloride water with meteoric water. Hot springs with this type of water may come out in the outflow zone from geothermal systems. Ngandam hot springs are immature chloride-sulfate-bicarbonate water. The magnesium content in Pulosari hot springs is 47 mg/kg. Based on these characteristics, it is interpreted that the Ngandam hot springs were formed from the mixing of reservoir chloride water with meteoric water that comes out in the outflow zone.

The isotopic composition of hot and cold springs in the Dieng Geothermal Field is shown in Figure 4. The 18-oxygen isotope ($\delta^{18}O$) and deuterium (δD) are used to determine the origin and processes of the fluid during its flow to the surface. The δD content in hydrothermal fluids has almost the same value as meteoric water, while the $\delta^{18}O$ in hydrothermal fluids has a heavier value than meteoric water. This is due to water-rock interactions (Craig, 1961 in Nicholson, 1993). The stable isotope plot of rainwater taken in the Dieng area coincides with the global meteoric water line. The local meteoric water line (Local Meteoric Water Line/LMWL) in Dieng Geothermal Field was taken from BAFI-BATAN (1990) in Prasetio et al. (2010).

Siglagah hot springs are on the global meteoric water line. This indicates a mixing process with dominant meteoric water. This process is supported by the type of water from the Bitingan and Siglagah hot springs in the form of bicarbonate-sulfate which indicates the contribution of meteoric water or groundwater. The addition of the stable isotope $\delta^{18}O$ and δD is seen in the Sikidang, Sileri, and Pagerkandang hot springs. This isotope shifting indicates the presence of boiling, condensation, or steam-heated processes. The very significant enrichment of the stable isotope in the Sikidang hot spring can also be caused by mixing with magmatic fluids. This is also supported by the low pH of the water in the Sikidang hot springs (1.84 – 2.70) and the wells that lead to this area (Well-V and Well-W). The stable isotope plot shows clearly that the origin of the hydrothermal fluids, both in Sikidang and Sileri, is meteoric water. In the Sikidang area, hydrothermal fluids undergo a process of condensation and mixing with magmatic fluids. Meanwhile, in the Sileri area, hydrothermal fluid experiences a condensation process near the surface with little influence from magmatic fluid.

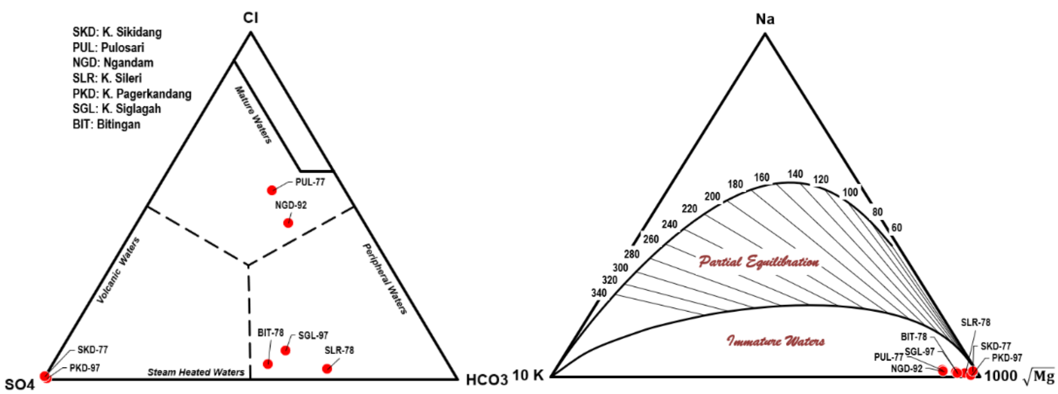

Figure 3: The Cl-HCO$_3$-SO$_4$ (left) and Na-K-Mg (right) diagrams from hot springs.

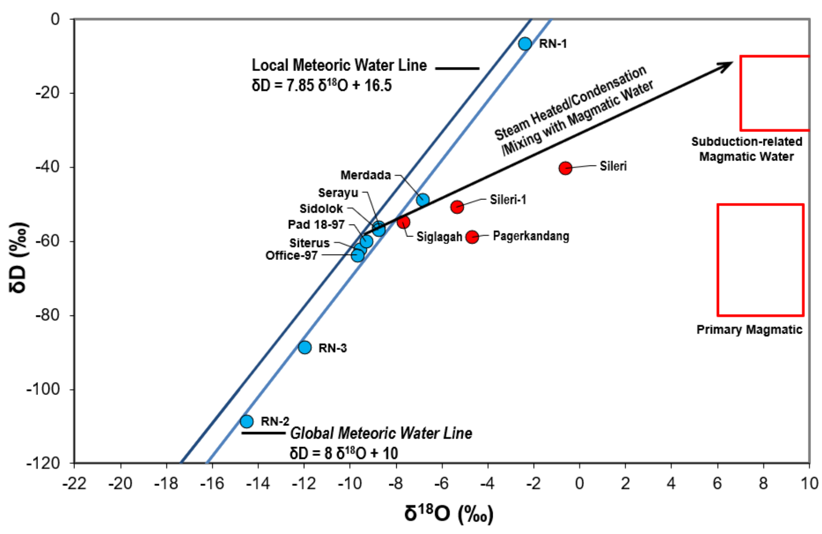

Figure 4: Stable isotope diagram.

3.2 Well Geochemistry

In the process of analyzing data, particularly with the current condition of initial data, it is crucial to be able to sort or carry out data quality control (QC) therefore the analysis or interpretation results have a high confidence level. One way to QC fluid chemistry data is ion balance (IB), which is a calculation method to determine the quality of the analysis results of geothermal fluid samples by calculating the difference between anion and cation. The suitability of the results of water chemical analysis can be said to be good or worthy of further interpretation if the IB value is less than 5%. However, the ion equilibrium value is also controlled by the type and pH of the water. All samples from the Sileri wells show ion equilibrium values of less than ±5%, so these samples are worthy of further interpretation. Several samples from Sikidang wells showed high IB values, e.g., Well-N, Well-O, Well-Q, Well-R, Well-S, Well-X, and Well-17. Some of the causes of high IB values in these wells include the fluid taken being condensate which does not represent reservoir fluid (Well-N, Well-Q, and Well-17), magmatic fluid influx (Well-R which is characterized by a very high Fe content, i.e., 3238 mg/kg), the sample is a downhole sample that experiences contamination by condensate (Well-X), and poor analysis quality (Well-O and Well-S). The sample is not suitable for further analysis or requires notes if it is to be interpreted because there is no other data that can be used apart from the sample. Figure 5 shows the Cl-HCO_3-SO_4 and Na-K-Mg diagrams of the fluid from wells. In general, Sileri wells show mature chloride water which is typical for reservoir fluids. Meanwhile, Sikidang wells have various types of water, e.g., chloride water, chloride-sulfate water, bicarbonate water, and chloride-bicarbonate water.

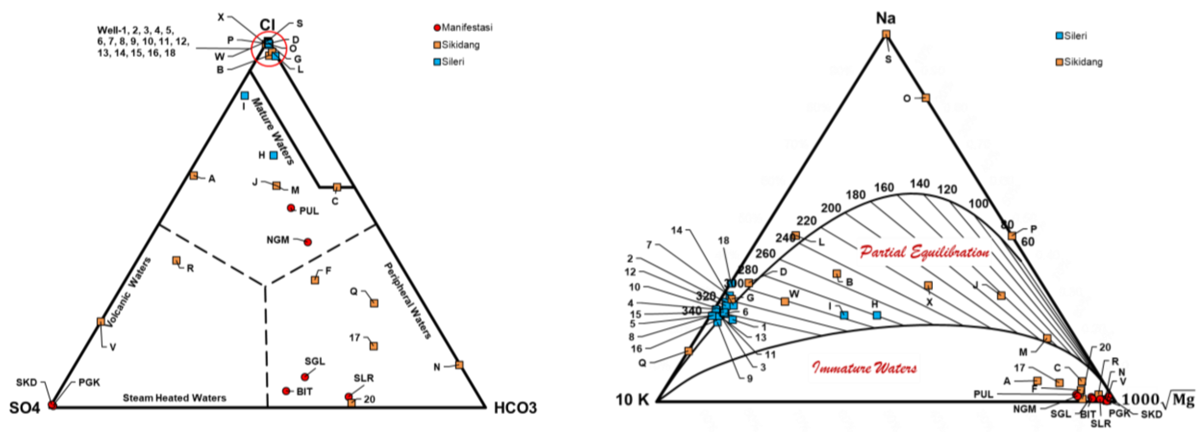

Figure 5: The Cl-HCO_3-SO_4 (left) and Na-K-Mg (right) diagrams from Sileri and Sikidang wells.

In the geochemical analysis of the wells, brine, gas, and stable isotope data were used which were grouped into 2 based on area, i.e., Sileri and Sikidang. The concentration of elements in brine, gas, and stable isotopes is first calculated at reservoir conditions using reservoir temperature data (P-T data) and enthalpy (TFT data). The characteristics of the water that comes out of the wells in the Dieng Geothermal Field are as follows:

1. Sileri

The fluid that comes out of the wells in the Sileri area is chloride water with mature and full equilibrium conditions, except for Well-H and Well-I. Both wells produce chloride-type fluids under partial equilibrium conditions. When compared with other wells, Well-H and Well-I have quite high sulfate contents, i.e., 267 and 732 mg/kg, respectively. This indicates that there is mixing with the condensate fluid in the two wells. This condition is supported by a fairly high Mg concentration, i.e., 1.5 mg/kg in Well-H and 12.6 mg/kg in Well-I. Based on the high Mg content in Well-I, the well fluid may be influenced by the presence of meteoric water which indicates the edge area of the system. Meanwhile, other wells produce fluid from the reservoir. The fluid has experienced equilibrium and reaction with the rock (water-rock interaction) which is quite intensive in the reservoir. This is shown by the plot on the Na-K-Mg diagram which is in the full equilibrium zone. Therefore, all brine chemistry data from the Sileri Wells, except Well-H and Well-I, can be used for further analysis such as geoindicators and geothermometers.

2. Sikidang

The Sikidang Wells show a fairly Well-distributed plot on the Cl-HCO_3-SO_4 and Na-K-Mg diagrams. Well-A, Well-R, and Well-V belong to the immature chloride-sulfate water. The fluid coming out of these Wells does not represent reservoir fluid but indicates mixing between hydrothermal fluid and magmatic fluid, especially in the Well-V (fluid pH 2.47). Some wells that include chloride water include Well-B, Well-C, Well-D, Well-G, Well-J, Well-L, Well-O, Well-P, Well-S, Well-W, and Well-X. All fluids from these wells are included in the mature water, except for the Well-C. Even though it is classified as chloride water, some wells do not represent reservoir fluids. Well-C, Well-O, Well-P, and Well-X showed high Mg contents (199, 13, 4, and 9 mg/kg, respectively). This shows that there is a mixing between hydrothermal fluids and meteoric water or shallow groundwater. The Well-G showed a very high Cl content in the reservoir (32,294 mg/kg), while the Well-W had acidic fluid with a pH of 2.77. Both wells indicate that it exists the influx from magmatic fluids. Likewise, the fluid from Well-B and Well-S does not represent reservoir fluid due to the low Cl content (499 mg/kg) in Well-B and incomplete chemical analysis in Well-S. Meanwhile, fluid from Well-D, Well-J, and Well-L shows the characteristics of water originating from a reservoir with a Cl content in the reservoir ranging from 3,424 – 23,772 mg/kg. Well-F can be classified as non-equilibrium chloride-bicarbonate water (*immature*). The fluid coming out of Well-F shows mixing between hydrothermal fluid and meteoric water or shallow groundwater. Therefore, the fluid from the Well-F does not represent the reservoir fluid. Well-N, Well-Q, Well-17, and Well-20 are included in the immature bicarbonate water, except for the Well-Q. The condition of full equilibrium in the Well-Q due to the absence of Mg analysis results in the well. Because of that, the fluids from these four wells already experienced mixing between hydrothermal fluid and meteoric water. The wells from the Sikidang Area that are likely to show reservoir fluid characteristics are Well-D, Well-J, and Well-L. While other wells show mixing characteristics with meteoric water and magmatic fluids influx.

To determine the origin of the hydrothermal fluid or the similarity of the reservoir in the Dieng Geothermal Field, the Cl-Li-B diagram and Cl-B plot are used (Figure 6). In general, there are two Cl-Li-B ratio clusters, i.e., the Sileri cluster and the Sikidang cluster. Several Sileri wells, such as Well-H, Well-I, and Well-18 show plots outside the Sileri cluster. This is because the Li element was not analyzed in the two Wells. However, the plots of Well-H and Well-I in the Cl vs B diagram are still on the Sileri trend line. Meanwhile, Well-18 shows a plot close to the boron side because it has a low Cl content in reservoir conditions (2243 mg/kg) with relatively high boron (105 mg/kg). Meanwhile, only Well-D and Well-L can be interpreted as representing the Sikidang Area. Correspondingly, a cross plot of Cl vs B shows two trends in the Cl/B ratio, i.e., Sileri and Sikidang trends. The difference in the Cl-Li-B ratio between the Sileri and Sikidang wells indicates that there are two different fluid sources or reservoirs between Sileri and Sikidang. The trend in the Sikidang area shows a higher enrichment of the element boron compared to the Sileri area which is probably caused by the magmatic fluid influx in the Sikidang Area.

The stable isotope composition of wells in the Dieng Geothermal Field is shown in Figure 7. All cold water samples are located on the meteoric water line. Addition of the stable isotope $\delta^{18}O$, with a little shifting of δD, seen in Sileri wells. These characteristics indicate the existence of a water-rock interaction process in the Sileri reservoir zone. This is supported by the water type of the Sileri wells which is classified as full equilibrium chloride water. The addition of the $\delta^{18}O$ in the Sileri wells is quite significant, i.e., 6 – 8 ‰. This shows that the Sileri area is a young hydrothermal system, high temperature, high permeability, high porosity, and water-rock reactions have occurred for quite a long time in the reservoir. Meanwhile, the Sikidang wells showed the addition of the stable isotope $\delta^{18}O$ and δD. This trend indicates a mixing process between meteoric water and magmatic fluid which forms hydrothermal fluid in the Sikidang Area. The proportion of magmatic fluid that is mixed is quite significant, around 51% to 59%. The existence of mixing with magmatic fluid is also supported by chemical analysis of water in several wells in the previous discussion of water types, as well as gas analysis in the following discussion.

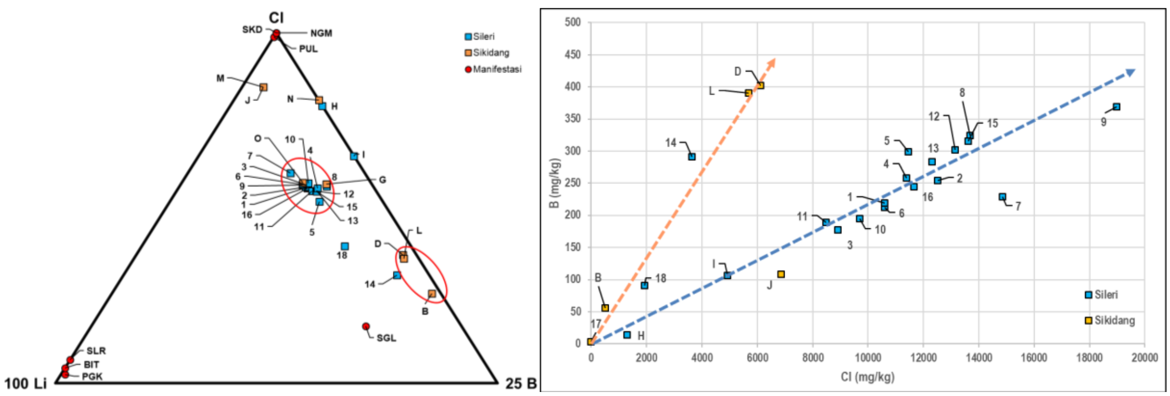

Figure 6: The Cl-Li-B diagram (left) and Cl vs B (right) which shows that there are 2 Cl/B ratio clusters, i.e., the Sileri and Sikidang clusters. The difference in the ratio indicates a difference in the origin of the fluid or reservoir.

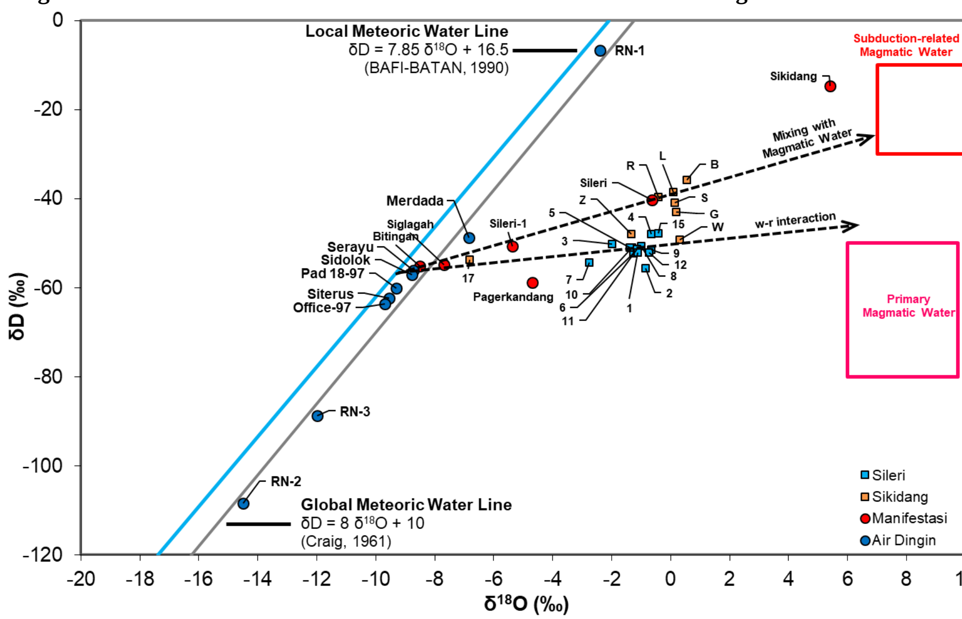

Figure 7: Stable isotope diagram $\delta^{18}O$ and δD. Sileri and Sikidang hydrothermal fluids come from meteoric water and the same liquid source.

Although the Sileri and Sikidang areas have two different trends and processes, both areas probably originate from similar liquid sources. This is indicated by both trend lines meeting at the same point on the meteoric water line. Based on these conditions, it is interpreted that there is the same source of brine below the surface. At shallower depths, hydrothermal fluids experience two different processes and equilibrium conditions, i.e., water-rock interaction in the Sileri area and magmatic fluid influx in the Sikidang Area. Both processes in this area are likely limited by the Merdada Fault.

Lateral distribution of some elements, e.g., Cl, SiO2, B, and As is used to see possible upflow zones, hydrothermal fluid flow patterns, as well as delineation of zones influenced by magmatic fluid in the Sikidang Area. The concentration distribution map of the four element is shown in Figure 8. In general, the Sikidang area is characterized by very high concentrations of the elements Cl, B, and As compared to the Sileri area. The distribution pattern of the Cl element shows a concentration that slowly decreases towards Sileri, it looks like there is a neutralization process from the Sikidang area to Sileri. Meanwhile, the SiO_2 concentration in the Sikidang Area is much lower than Sileri which is probably caused by the fluid phase coming out of the Sikidang Area being steam.

The reservoir fluid in the Sileri area has a Cl content of 9,600 – 19,000 mg/kg and very high boron elements (190 – 370 mg/kg). In geothermal fields associated with volcanoes, the Cl element in the fluid comes from the degassing of the HCl magmatic gas. However, high Cl concentrations in the Dieng Field probably do not only come from magmatic processes but are also influenced by *water-rock interaction* with sedimentary rock. This is supported by the low water-rock ratio which is characterized by the large addition of the $\delta^{18}O$ isotope (6 – 8 ‰) and very high boron concentrations.

Nicholson (1993) stated that fluid from chloride-type wells generally has a boron content of 10 – 50 mg/kg. However, the boron enrichment that occurs in the Dieng Geothermal Field can be caused by the presence of sedimentary rocks. However, no sedimentary rock formations were found in all the wells in the Dieng Field. However, regionally the Dieng volcanic area is located at the top of the North Serayu Physiographic Zone which is composed of sedimentary rocks. Thus, there may be sedimentary rock formations at much deeper depths.

The contribution of sedimentary rock formations is also supported by the results of boron isotope analysis ($\delta^{11}B$) taken from brine Pad-28 (0.26 ‰) and Pad-7 (-0.02 ‰) by Purnomo et al. (2016). The $\delta^{11}B$ is in the range of marine carbonate rocks, i.e., -5.5 to 20 ‰ (Yuan et al., 2014). Meanwhile, the $\delta^{11}B$ in igneous rocks ranges from -17 to -2 ‰. Thus, it is estimated that the water-rock interaction with sedimentary rock occurs at a depth greater than the current well penetration. Several other geothermal fields that have boron content >100 mg/kg, such as Lardarello, The Geysers, Los Azufres, Mofet, and Ngahwa, indicate the existence of water-rock interaction with sedimentary or meta-sedimentary rocks (Bernard et al., 2011). Therefore, the high Cl and B content in the Dieng Geothermal System is thought to come from magmatic fluids, fluid reactions with volcanic rocks, as well as sedimentary or meta-sedimentary rocks below the surface.

To see fluid flow patterns in the Sileri area more specifically, a distribution map was created that only covers the Sileri area (Figure 9). High Cl concentrations (>14,500 mg/kg) were identified in the Well-9 and Well-15 Well areas indicating an upflow zone in the Merdada area. The high Cl content could also be caused by the influence of the influx of Cl-rich magmatic fluid in the Merdada area. Gradually, the Cl concentration decreased towards the Well-12, indicating the presence of hydrothermal fluid flow from the Merdada area to the north. There are two areas with high SiO_2 content, namely the Sileri (Well-10, Well-1, Well-3, and Well-16) and Merdada (Well-9 and Well-15) areas. This anomalous pattern is possibly related to the presence of two upflow zones in the Sileri Area, namely in the Sileri and Merdada Crater areas. High B and As contents are distributed around Well-7, Well-8, Well-9, and Well-15. This indicates that there is an influence of magmatic fluid in the Merdada area, but this process does not make the reservoir fluid in this area acidic like in the Sikidang area.

To delineate areas influenced by magmatic fluids (acid fluid areas) in the Sikidang Area, the lateral distribution of the elements Cl, B, and As is used (Figure 10). In general, the Sikidang area is characterized by very high concentrations of the elements Cl, B, and As compared to the Sileri area. The high anomalous distribution of these elements is estimated to be an area affected by magmatic fluid or an area of acidic fluid with an area of around 1 km^2. This is supported by Well-V and Well-W which have a pH of 2.47 and 2.77 respectively.

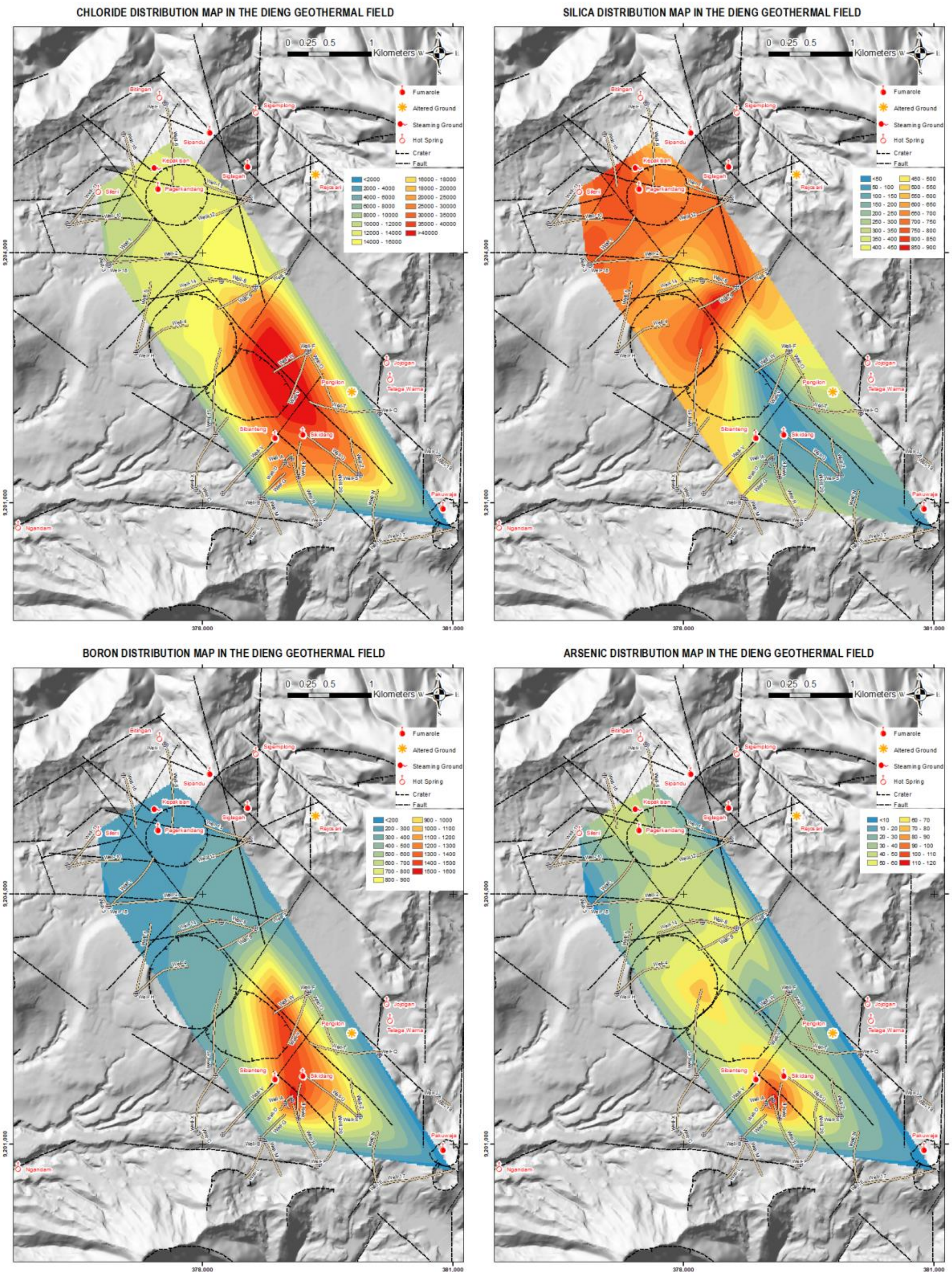

Figure 8: The distribution of chloride, silica, boron, and arsenic (in ppm) at the initial condition in the Dieng Geothermal Field.

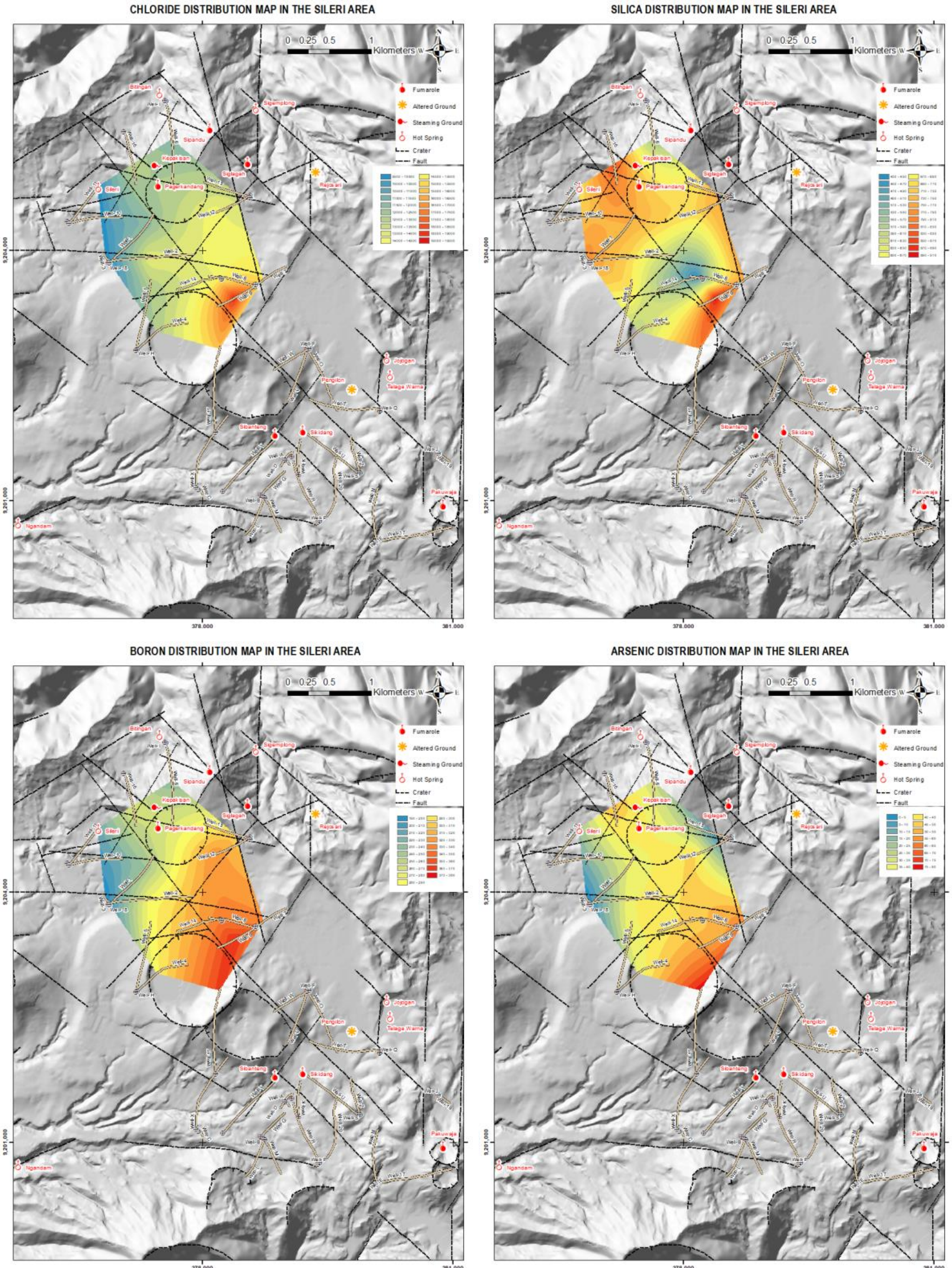

Figure 9: Distribution of chloride, silica, boron, and arsenic (in ppm) in the Sileri area.

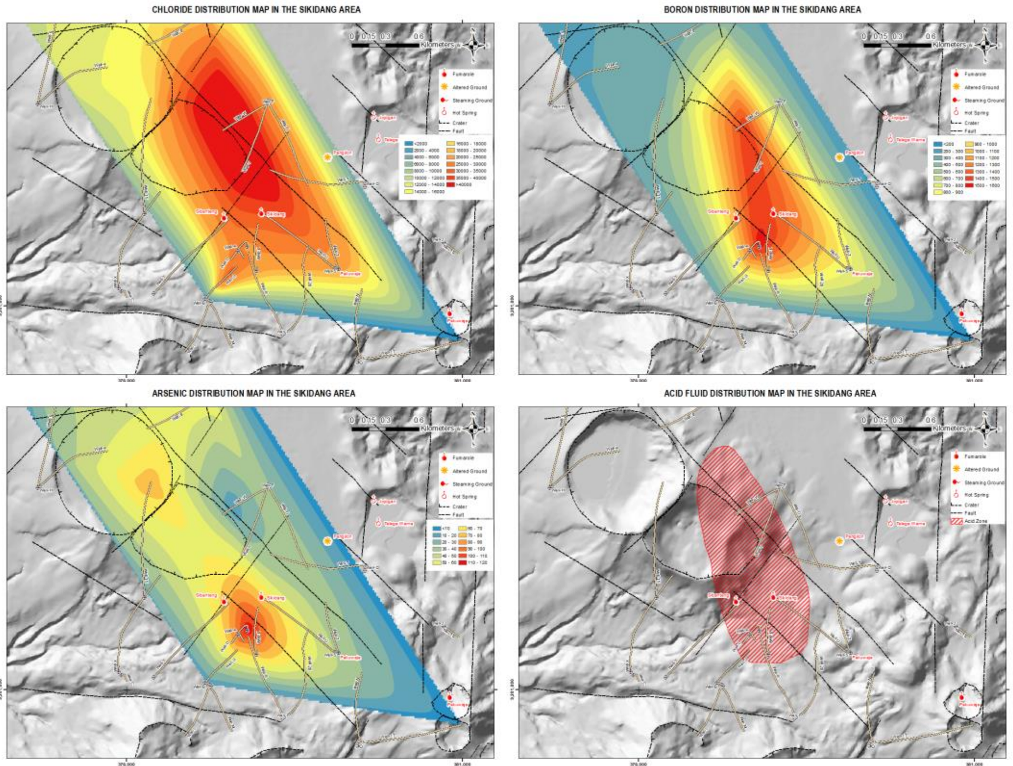

Figure 10: Distribution of Cl, B, and As (in ppm) in the Sikidang Area to delineate the acid fluid area.

The origin of gas and sample contamination from free air and meteoric from wells in the Dieng Field is interpreted from the N_2-CO_2-Ar (Figure 11). Based on this diagram, the gas from the Sileri wells shows the origin of meteoric fluid mixed with magmatic fluid in a not very significant proportion. Meanwhile, gas from Sikidang wells is dominated by magmatic fluid. This was confirmed by cross plot of N_2/Ar and CO_2/CH_4 (Figure 11). In the diagram, the Sileri well is located between the shallow meteoric and magmatic, while the Sikidang well is in the magmatic.

When compared with the results of the H_2-H_2S-CH_4 diagram in Figure 12, most of the wells are plotted in the CH_4 area. Gas from the Sileri wells originates from neutral pH fluids. A few are shifting towards the H_2 corner, e.g., Well-8, Well-9, and Well-15 which shows that there is the influence of magmatic fluid in these wells. Meanwhile, the Sikidang wells show plots in the CH_4 gas zone which indicates the origin of the fluid has a neutral pH, except for Well-V and Well-W. These two wells show quite strong magmatic fluid influence; gas from the Well-V originates from supercritical magmatic and Well-W originates from quenching magmatic gas SO_2. This is supported by fluid (water) from those wells which have an acidic pH.

In geothermal systems, chemical reactivity and gas solubility vary widely. The level of gas solubility from difficult to dissolve to easily dissolved is shown by the following relationship $N_2 < O_2 < H_2 < CH_4 < CO_2 < H_2S < NH_3$ (Nicholson, 1993). By comparing the solubility of these gases, the processes experienced by the reservoir gas/fluid can be estimated. Processes that occur in reservoir fluids including boiling and condensation, can be analyzed using a CO_2-H_2S-NH_3 and CH_4-CO_2-H_2S as in Figure 12.

NH_3 is the most soluble gas, followed by H_2S dan CO_2. In general, the plot results from the Sileri and Sikidang wells show that the gas that comes out is gas that comes from the reservoir and represents the characteristics of the Sileri and Sikidang reservoirs. However, gas from Well-V shows a different plot, namely it is located close to the H_2S. This shows that the fluid from the Well-W has experienced re-boiling on its way to the surface. It also shows that the Well-V was greatly influenced by magmatic fluid influx. In addition, gas from the Well-V and Well-17 is in the re-boiling outflow area which confirmed that both wells were at the edge of the system.

The CH_4-CO_2-H_2S diagram (Figure 12) compares three types of gas to estimate the boiling stages. CH_4 which has an intermediate level of solubility allows it to be an indication of boiling degree. Getting closer to the CH_4 indicates the degree of boiling which is not very significant (early boiling). Vice versa, the further away from the CH_4 or getting closer to area H_2S, the boiling in the reservoir has taken place (late boiling). As for CO_2 can indicate that boiling occurs at great depths below the surface. Plot results of gas samples from the Sileri wells indicate the middle stage of boiling, except for the Well-, Well-9, and Well-12 which are more in the late stage. The Sikidang wells also show the middle stage of boiling, except for Well-V and Well-W which are already in the late stage of boiling.

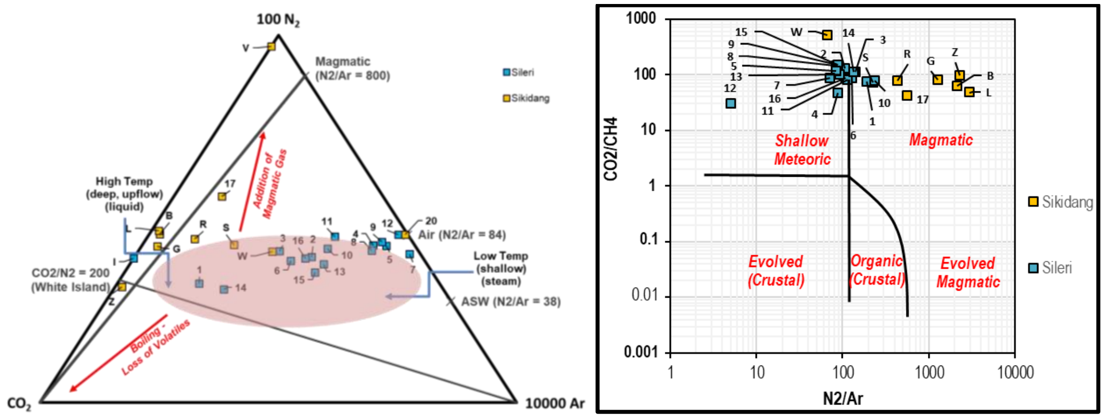

Figure 11: N_2-CO_2-Ar diagram (left) and CO_2/CH_4 vs N_2/Ar cross plot (right).

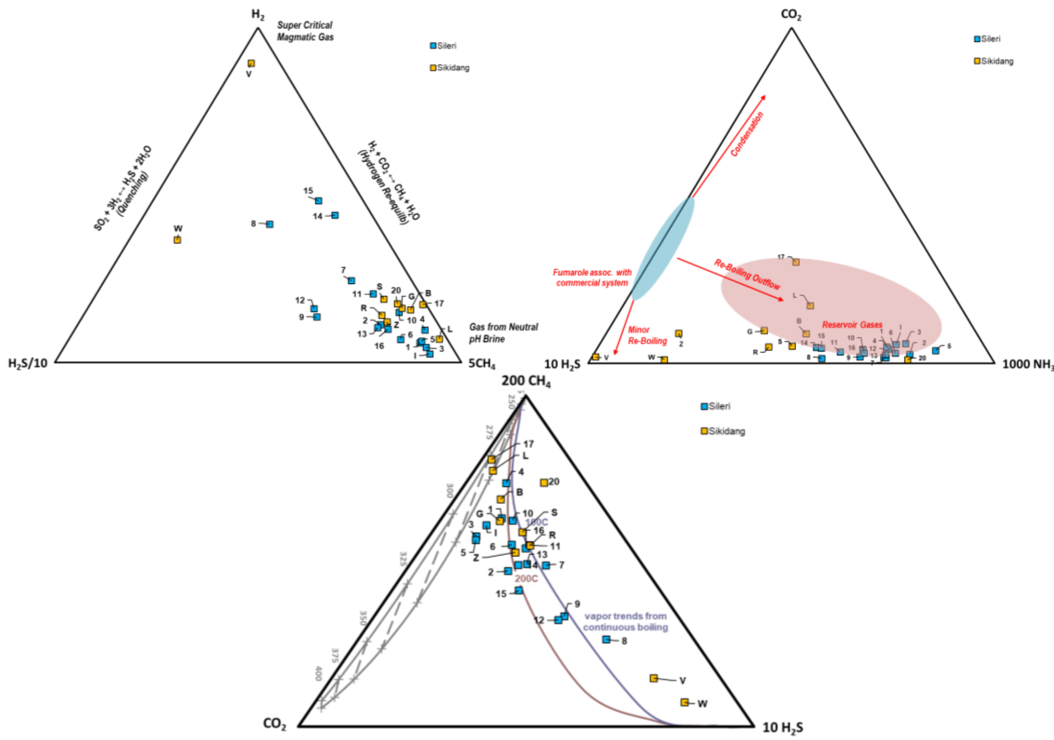

Figure 12: H_2-H_2S-CH_4, CO_2-H_2S-NH_3, and CH_4-CO_2-H_2S diagrams.

The FT – HSH method is used to evaluate the vapor fraction from the reservoir (y) which is based on the Fischer – Tropsch reaction (methane breakdown) and pyrite – pyrrhotite (HSH3). In the Dieng geothermal field, the FT-HSH3 diagram shows the reservoir process better than FT-HSH1 and FT-HSH2 because it shows the suitability of the temperature estimates with the P-T measurement results. Figure 13 shows the plot of the Sileri and Sikidang wells on the FT-HSH3 diagram. The Sileri well shows an estimated temperature of around 300 – 330°C, most of the wells have a value of $y<0$ which indicates the gas comes from the liquid-dominated zone. Meanwhile, other Sileri wells including Well-10, Well-11, Well-4, Well-7, Well-8, Well-14, and Wel-15 have a value of $y>0$ This condition indicates that the gas comes from a two-phase or vapor-dominated zone (or steam cap). The Sikidang Well shows a plot in the $y>0$ area which indicates that the gas comes from the two-phase or vapor zone. The distribution map of NCG content in Dieng Field is shown in Figure 14. In general, the Sikidang reservoir has a fairly high NCG content, namely 2 - 21 wt%, when compared to the Merdada and Sileri areas (<1 wt%). The high NCG content in the Sikidang Area is probably caused by the presence of steam cap and magmatic fluid input. Meanwhile, the condition of the Sileri reservoir is in *liquid* or two-phase causing its NCG content to be lower. In addition, there is a closure of high NCG content in the Sikidang – Sibanteng manifestation area and the Well-V. This may be related to the presence of an upflow zone in the Sikidang Area.

Monitoring reservoir temperature conditions is very important to see changes that occur in the reservoir. If direct temperature measurement (T logging survey) cannot be done every year like, in Dieng Geothermal Field, an approach using a geothermometer can be done. The Well-14 Well was not considered in this analysis because the PT survey and fluid geochemical samples were taken at different timescales. The Dieng Geothermal Field, particularly in the Sileri Area, is included in a liquid-dominated or two-phase system, so a water geothermometer will provide a better estimate compared to a gas geothermometer. In general, the Na-K-Ca geothermometer shows a gap that is still within the geothermometer error range (5 – 10°C) so for the Sileri area, this geothermometer was chosen to then monitor reservoir temperature during production. Apart from the low gap, the brine in the Dieng Geothermal Field has a high Ca content without any carbonate deposits, so the Na-K-Ca geothermometer is suitable for use. Based on the P-T survey, the Sileri reservoir temperature ranges from 283 to 338°C. Meanwhile, referring to several geothermometers, the Sileri sector reservoir is estimated to have a temperature of around 300 – 340°C. In the Sikidang area, it is difficult to compare the appropriate PT and geothermometer data because there are only 2 wells that have good PT quality. Based on the P-T survey, the temperature of the Sikidang reservoir is 260 - 324°C, slightly lower than the Sileri reservoir. Meanwhile, according to several geothermometers, the Sikidang Area reservoir is estimated to have a temperature of around 250 - 316°C. Wells with high temperatures (>300°C) in the Sikidang Area from geothermometer estimation results are Well-A, Well-V, Well-W, and Well-20. These wells may be associated with the upflow zone or the acid fluid area in the Sikidang Area.

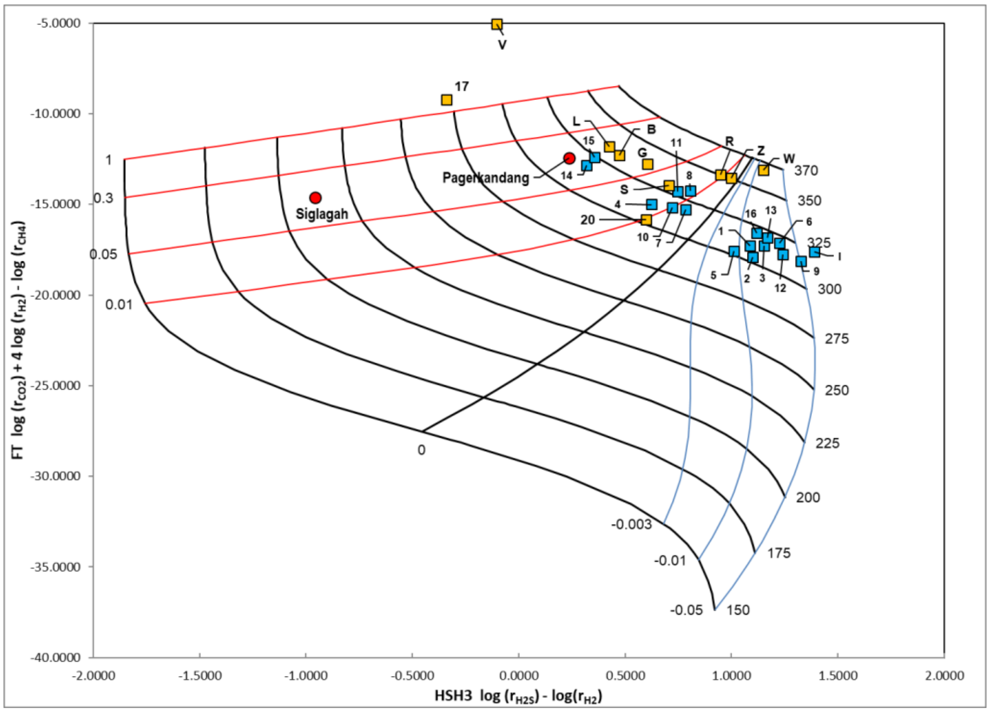

Figure 13: FT-HSH3 diagram showing the Sileri well is in the y<0 and y>0 area, while the Sikidang well is in the y>0 area.

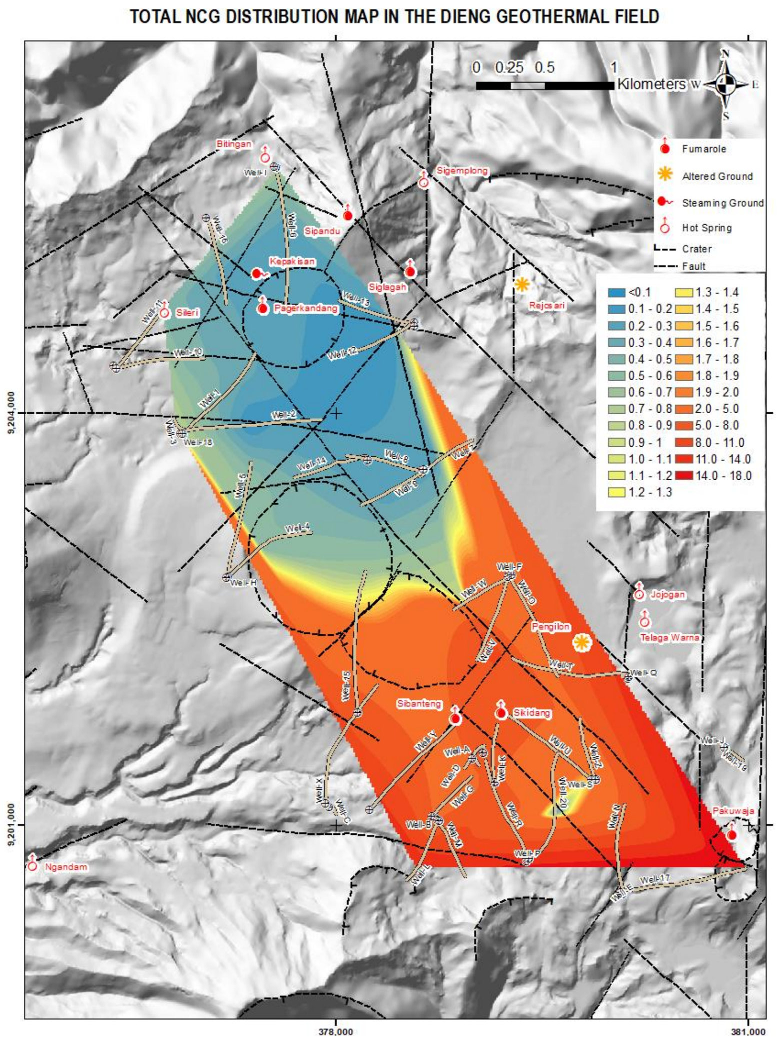

Figure 14: Map of reservoir NCG content distribution in the Dieng Field at the initial conditions.

3.3 Geochemistry Tentative Model

A tentative geochemical model was built by integrating geochemical data from manifestations and well data (Figure 15). Well geochemical data in the Sileri area is of better quality and more complete than data in the Sikidang area. Therefore, there are limitations in analyzing the processes that occur in the Sikidang Area. Table 2 shows a summary of the differences in reservoir characteristics in the Dieng Geothermal Field. Referring to the previous explanation, there are two reservoirs in the Dieng Geothermal Field, i.e., Sileri and Sikidang Areas which are separated by the Merdada Fault. Although separate, both areas likely originate from similar liquid sources, but at shallow depths, the processes that occur in the two areas are quite different. The Sileri area is dominated by intensive *water-rock interaction* with little influence of magmatic fluid, while the Sikidang Area is strongly influenced by magmatic fluid influx.

The Sileri Reservoir has water-dominated fluid to two-phase with a temperature of 283 – 338°C based on the interpretation of P-T and geothermometer data. The fluid in the reservoir has a low NCG content (< 1wt%) and is included in the mature chloride brine with a high Cl content, i.e., 9,600 – 19,000 mg/kg. The source of the fluid is heated meteoric water, mixed with the degassing magmatic fluid, boiling, as well as experienced water-rock interaction with sedimentary or meta-sedimentary rocks. Apart from being characterized by a high Cl content, the presence of interactions with sedimentary rock formations is also supported by a very high boron content (190 – 370 mg/kg). Hydrothermal fluid in the Sileri reservoir flows vertically towards the upflow zone in two areas, i.e., Pagerkandang Crater (Well-10 and Well-1) and Merdada Crater (Well-4 and Well-9). Both areas are characterized by high Cl and SiO_2 contents and low CO_2/H_2S & CO_2/H_2. The fluid then flows laterally in all directions, including towards Well-H, Well-12, Well-3, Well-I, the Siglagah manifestation, and the Bitingan manifestation. The marginal area of the Sileri reservoir is indicated by the appearance of Bitingan (bicarbonate water) manifestation.

In contrast to the Sileri Area, the Sikidang reservoir has a more acidic fluid character due to the more dominant influence of magmatic fluid. The acid fluid area in Sikidang is estimated to have an area of around 1 km^2 which is delineated from the high anomalies of the Cl, B, and As. This area is distributed around the Sikidang Crater, Well-V, dan Well-W which have an acidic pH (2.44 and 2.77, respectively). The Sikidang reservoir has a two-phase fluid, with most wells penetrating the steam cap zone and several wells penetrating the liquid zone, it is estimated that there is a boiling zone between liquid and steam reservoirs. The fluid temperature in the reservoir ranges from 260 to 324^{o}C based on the results of P-T and geothermometer analysis. Hydrothermal fluids have a very high NCG content in the reservoir (2 – 21 wt%). The fluid flow in the Sikidang Area comes from upflow around Pangonan Crater, Well-V, Sikidang manifestation, and Sibanteng manifestation. This upflow zone also correlates with the acid fluid zone, so there is the potential for acid fluid to be found deep in the reservoir. Hydrothermal fluid from the reservoir also flows laterally towards the Pakuwaja Crater area to the southeast, the Pulosari manifestation to the southwest, the Well-L, and Well-M areas to the south, and the Jojogan manifestation to the northeast. The recharge zone of the Dieng Geothermal Field cannot yet be mapped in detail. However, in a volcanic geothermal system such as Dieng, the absorption zone is likely to be at a high elevation morphology such as the cone of Mount Prau, Mount Gajahmungkur, Mount Nagasari, and Mount Bisma.

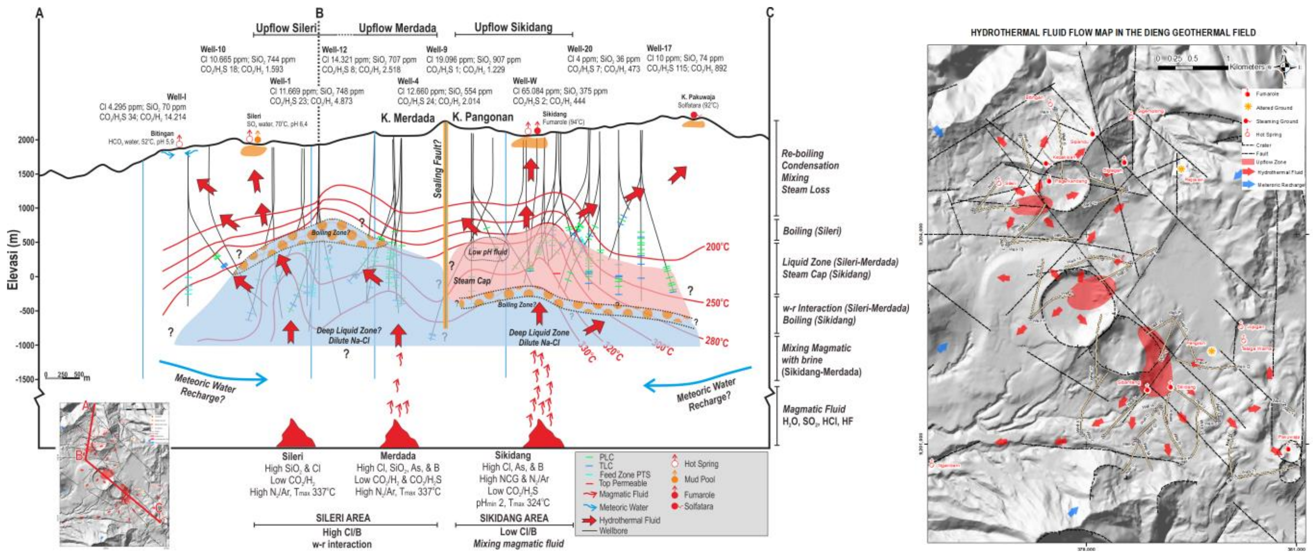

Figure 15: Tentative geochemical model of the Dieng geothermal system. In the Dieng Geothermal Field, there are two reservoir zones, i.e., Sileri and Sikidang reservoirs. Both areas are thought to originate from the same liquid source, but have different near-surface processes. The Sileri Area is dominated by water-rock interaction processes, while the Sikidang Area is dominated by boiling and mixing processes with magmatic fluids. The two areas are separated by the Merdada Fault.

Table 2: Summary of differences in reservoir characteristics in the Dieng Geothermal Field.

Characteristics	Area	
	Sileri	**Sikidang**
Reservoir Temperature	283- 338^{o}C	260 - 324^{o}C
Reservoir Fluid Phase	Liquid-dominated / two-phase	Two-phase
Reservoir Fluid pH	Neutral	Acid (Well-V, Well-W, Sikidang, and Sibanteng)
Cl Concentration	9.600 - 19.000 mg/kg	3.400 – 23.800 mg/kg
NCG Concentration	< 1 wt%	2 - 21 wt%
Cl/B Ratio	High	Low
Magmatic Fluid Input	Minor	Major
Water-rock Interaction	Major	Minor
Steam Cap	Minor (Well-3, Well-8, Well-9, Well-10, Well-14)	Major
Upflow Zone	Sileri and Merdada	Sikidang
Outflow Zone	Well-H, Well-12, Well-3, Well-I, Siglagah, and Bitingan	Well-L, Well-M, Pulosari, Pakuwaja, and Jojogan

4. CONCLUSION

The Dieng Geothermal System is divided into two reservoir areas, i.e., Sileri and Sikidang. Both have similar liquid sources but have different processes at shallow depths; water-rock interaction in the Sileri Area and magmatic fluid influx in the Sikidang Area. The fluid in the Sileri reservoir is a two-phase fluid with a temperature of around 283 – 338^{o}C, neutral pH, high Cl content (9,600 – 19,000 mg/kg), and low NCG (<1 wt%). The origin of the fluid is meteoric water which experiences slight mixing with magmatic fluid, water-rock interaction with sedimentary or meta-sedimentary rocks, and intensive boiling. The fluid in the Sikidang reservoir is a two-phase fluid, with some wells penetrating the steam cap zone and several wells penetrating the liquid zone. Fluid with acidic pH is distributed around the Sikidang Crater, Well-V, and Well-W covering an area of 1 km^2. The fluid temperature in the Sikidang reservoir ranges from 260 – 324OC, low – high Cl (3,424 – 23,772 mg/kg), and high NCG (2 – 21 wt%). The upflow zone in the Sileri area is around the Pagerkandang Crater (Well-1 and Well-10) and the Merdada Crater (Well-4 and Well-9). The upflow zone in the Sikidang area is around the Pangonan Crater, the Well-V, the Sikidang manifestation, and the Sibanteng manifestation which also correlates with the acid area.

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