

Geothermal system boundary at the northern edge of Patuha Geothermal Field based on integrated study of volcanostratigraphy, geological field mapping, and cool springs contamination by thermal fluids

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Abstract. Patuha Geothermal System is a volcanic hydrothermal system. In this type of system, the boundary of the system is often determined by low resistivity (10 ohm.m) anomaly from Magnetotelluric (MT) or DC-Resistivity survey. On the contrary, during geothermal exploration, the system boundary often need to be determined as early as possible even prior of resistivity data available. Thus, a method that use early stage survey data must be developed properly to reduce the uncertainty of the geothermal area extent delineation at the time the geophysical data unavailable. Geological field mapping, volcanostratigraphy analysis and fluid chemistry of thermal water and cold water are the data available at the early stage of exploration. This study integrates this data to delineate the geothermal system boundary. The geological mapping and volcanostratigraphy are constructed to limit the extent of thermal and cold springs. It results that springs in the study area are controlled hydrologically by topography of Patuha Volcanic Crown (complex) or so called PVC, the current geothermal field and Masigit Volcanic Crown (complex) or so called MVC, the dormant volcano not associated with active geothermal system. Some of the cold springs at PVC are contaminated by subsurface steam heated outflow while others are not contaminated. The contaminated cold springs have several characteristics such as higher water temperature than ambient temperature at the time it was measured, higher total dissolved solid (TDS), and lower pH. The soluble elements analysis support the early contamination indication by showing higher cation and anion, and positive oxygen shifting of stable isotope of these cool springs. Where as the uncontaminated spring shows similar characteristic with cool springs occur at MVC. The boundary of the system is delineated by an arbitrary line drawn between distal thermal springs from the upflow or contaminated cool springs with the cool uncontaminated springs. This boundary is more or less in agreement with low resistivity boundary derived from MT and DC resistivity survey. The area defined as part of geothermal area from this method is also validate with drilling data that give high temperature gradient. It suggests that the method use in this study is applicable and reliable.



1. Introduction

Study area is located in Patengan Village, Rancabali District, Bandung Regency, West Java Province, adjacent to Patuha Geothermal Field, with an area of 16 km² (figure 1). Patuha Geothermal System is a volcanic hydrothermal system. Boundary of this system is characterized by a lateral outflow, characterized by the occurrence of acidic to neutral bicarbonate-chloride or chloride thermal springs manifestation.

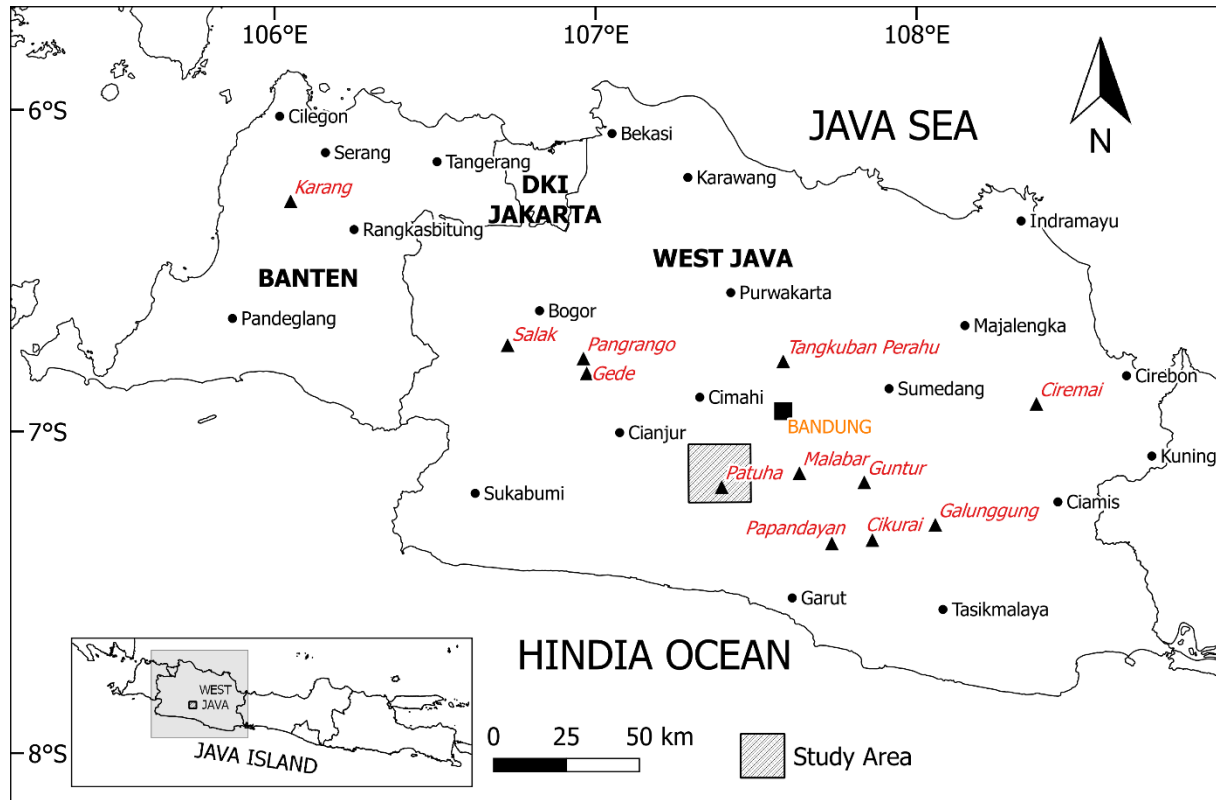


Figure 1. Study area located at Ciwidey Geothermal field about 46 km Southwest from Bandung.

The absence of this thermal spring will be a difficulty in determining the geothermal system boundary. In other side, its occurrence is predicted to contaminate shallow groundwater. Contaminated cold spring will be enriched with cations and anions, as well as the anomaly of pH and temperature from its common trend. The boundary of a geothermal system is expected to be found by examining cold water springs that are not contaminated by the steam heated thermal water.

The objective of this study is to determine the geothermal system boundary at the northern edge of Patuha geothermal field from integrating geological field mapping, volcanostratigraphy analysis and fluid chemistry of thermal water and cold water. The water samples are obtained from several springs in study area, in the early stage of geothermal exploration.

2. Materials and Method

Geological field mapping, volcanostratigraphy analysis and fluid chemistry of thermal water and cold water are the method used in the study. This study integrates these data to delineate the geothermal system boundary.

This study is conducted by classifying cold springs and thermal spring associated with geological analysis, including volcanostratigraphy, geological units, geological structure, from field data and literature. The geological mapping, including volcanostratigraphy are constructed to limit the extent of

thermal and cool springs. It was done to determine their relation with the occurrence of cold springs and thermal springs in the research area and its association with Patuha geothermal system.

Chemical analysis, taken from one hot spring, six warm springs, and nine cold springs, is done to determine which cold water springs has been contaminated with thermal fluid. The location of springs samples is shown in Figure 2. This fluid chemistry analysis was completed by using temperature, pH, TDS, anions, cations, and isotopes data. Laboratory data that consists of anions, cations, and isotopes, are further evaluated by Schoeller Diagram and isotope graph. Geothermal system boundary is determined and validated low resistivity boundary derived from MT and DC resistivity survey and also drilling data that give high temperature gradient.

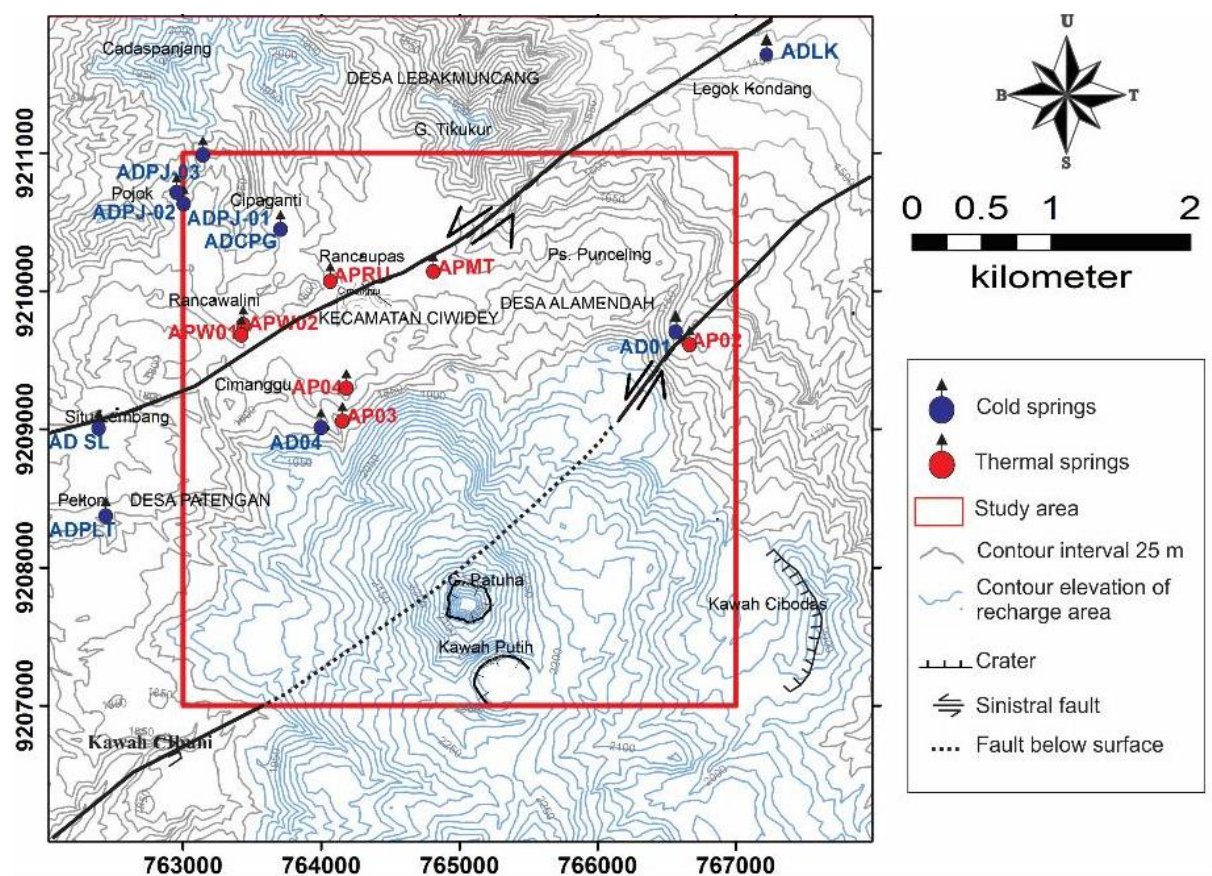


Figure 2. Location of springs sample and countour elevation of recharge area based on [1].

3. Geology

Geology in research area was based on identifying satellite imagery and topography map as well as observing field of study. The analysis includes volcanostratigraphy, geological unit and geological structure. Those analysis were then associated with the springs occurrence.

3.1. Volcanostratigraphy

Volcanostratigraphy analysis was constructed to limit the occurrence of thermal and cold springs. Identifying satellite imagery and topographic map was done to determine the ceruption center, classify the volcanic complex and define the relative age of the geological units. From satellite imagery (Figure 3), eruption center can be determined by identifying circular features that form a cone or depression with the distribution of its surrounding volcanic product, which build the volcanic body. Identifying

topographic map in the scale of 1:100.000 was done to classify study area into several volcanic crown (complex) or khuluk (Figure 4). It is a whole body of volcanic that was produced by one or more eruption center [2].

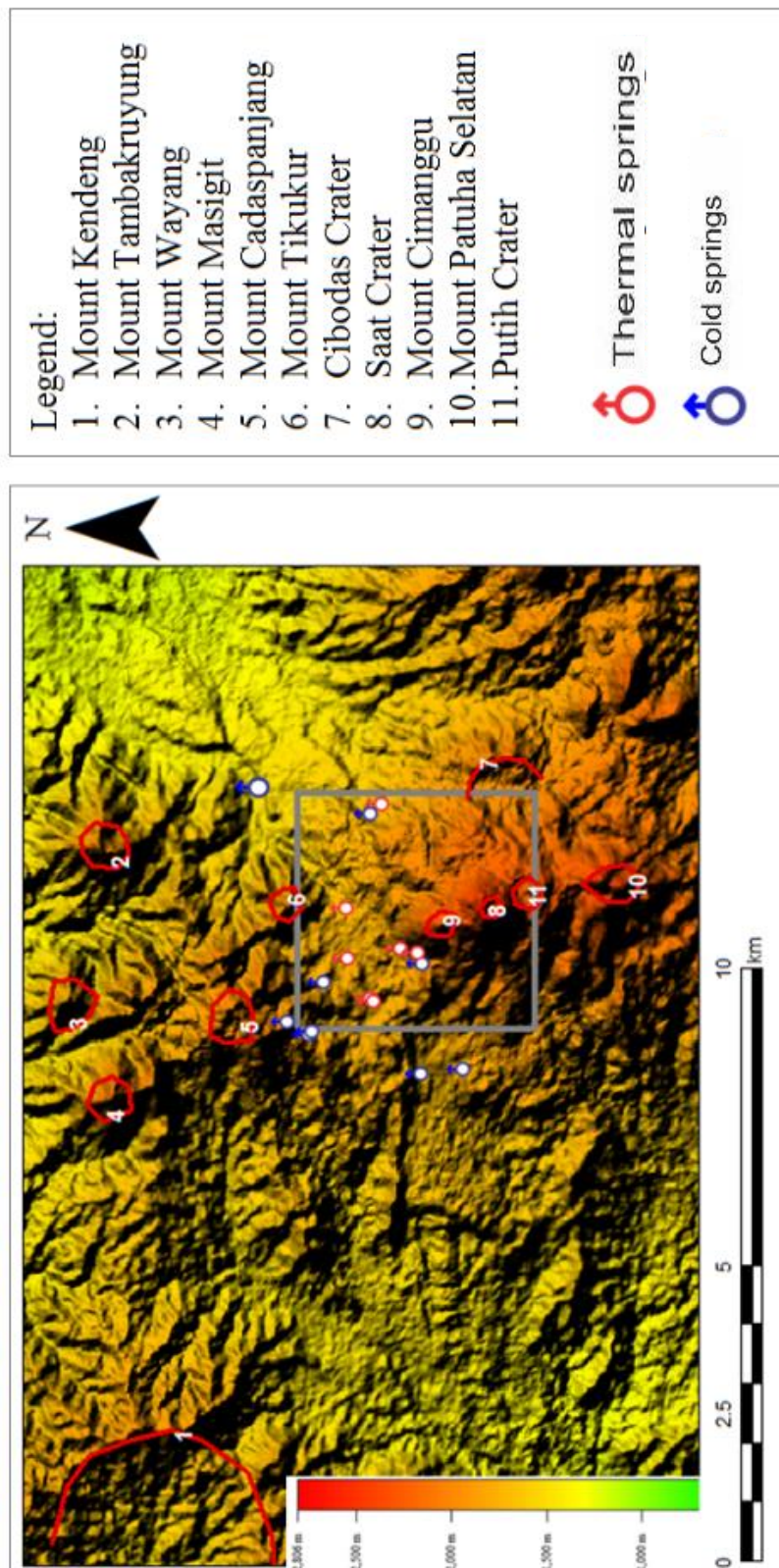


Figure 3. Eruption center from satellite imagery identification.

It results, as seen in the picture 4 that springs in the study area are controlled hydrologically by topography of Patuha Volcanic Crown (complex) or so called PVC, the current geothermal field and Masigit Volcanic Crown (complex) or so called MVC, the dormant volcano not associated with active geothermal system. The occurrence of the springs was associated with a closest volcanic summit that usually become its recharge area. Springs in Pojok, Cipaganti and Legok Kondang came from MVC recharge area, while the rest of them came from PVC recharge area.

Identifying topographic map in the scale of 1:50.000 was done to classify volcanic complex in study area into more detailed volcanic body from each eruption center or gumuk. This classification will lead to further observation of geological units in geological field mapping.

3.2. Geological Units

Names of the unit were related to its eruption center, type of rocks, and relative age, as given in Sandi Stratigrafi Indonesia [2]. Study area consists of 11 geological, which are (from the oldest) Tikukur Tuf-Breccia Pyroclastics Flow (Ta), Cadaspanjang Tuf-Breccia Pyroclastics Flow (Ca), Patuha 1 Breccia Pyroclastics Flow (Pa1), Patuha 1 Andesitic Lava Flow (Pl1), Patuha 2 Andesitic Lava Flow (Pl2), Patuha 3 Andesitic Lava Flow (Pl3), Patuha 4 Andesitic Lava Flow (Pl4), Patuha Andesitic Lava – Tuf-Breccia Pyroclastics Flow (Pa2), Cimanggu Andesitic Lava Flow (Cil), Patuha Selatan Tuf-Breccia Pyroclastics Flow (Psa), dan Kawah Putih Breccia Pyroclastics Flow (Ka). Geological maps and volcanostratigraphy column is given below Figure 5 and Table 1.

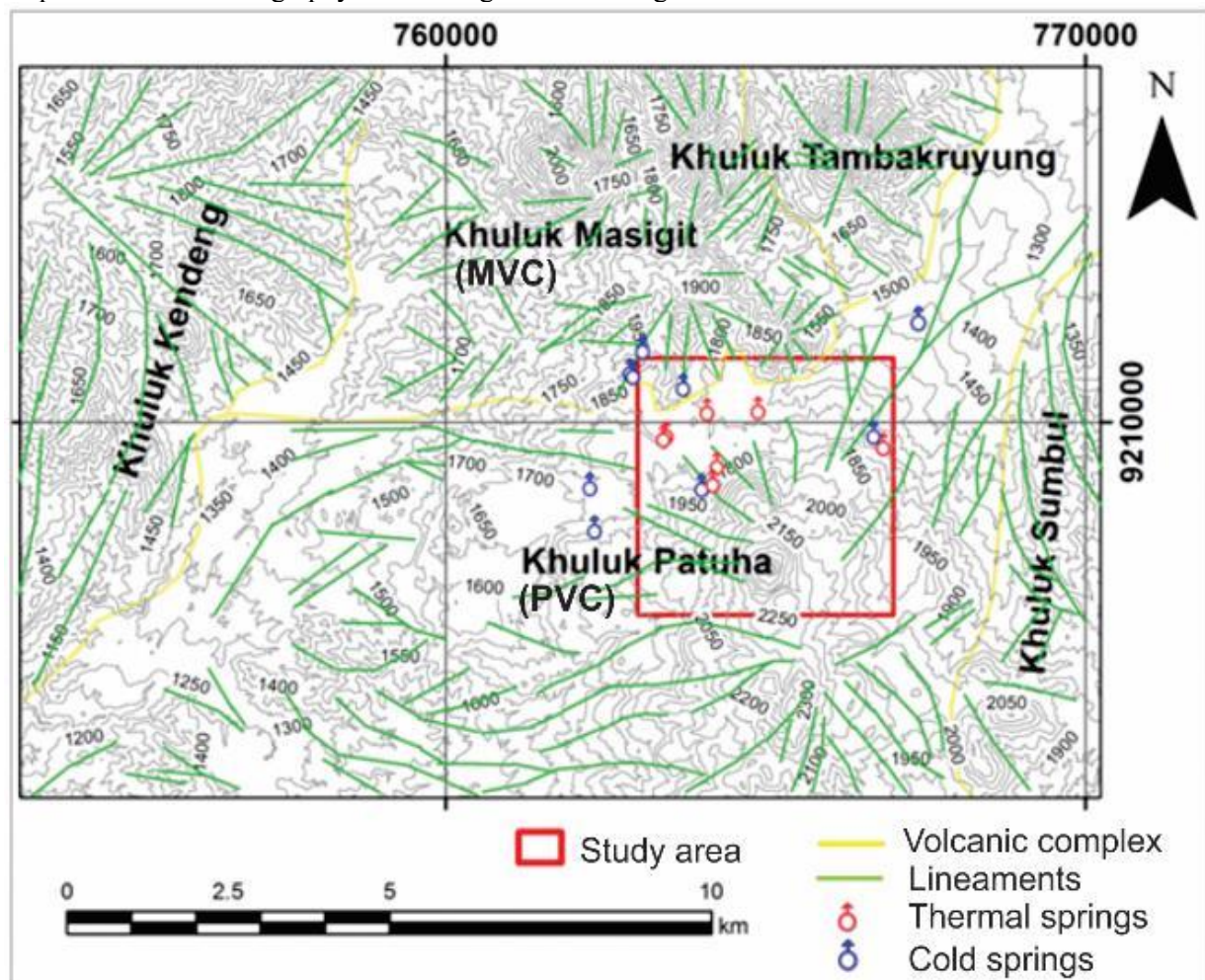


Figure 4. Volcanic complex classification

3.3. Geological Structure

Geological structure in study area consist of craters, which are Saat Crater and Putih Crater, and also faults, which are Punceling Sinistral Fault and Cimanggu Sinistral Fault. These faults were identified from lineaments, occurrence of thermal springs and altered outcrop (Figure 6). Punceling Sinistral Fault is proved by the manifestations occurred in Cibuni Crater and Punceling area. There are also some anomalies in air ground temperature data, ground pH, Hg and CO₂ near Punceling thermal spring and Cibuni Crater along the lineaments [3]. Cimanggu Sinistral Fault is also supported by the thermal springs occurred in Walini, Ranca Upas and EMTE area. There are also some anomalies in air ground temperature data near Walini thermal springs [3].

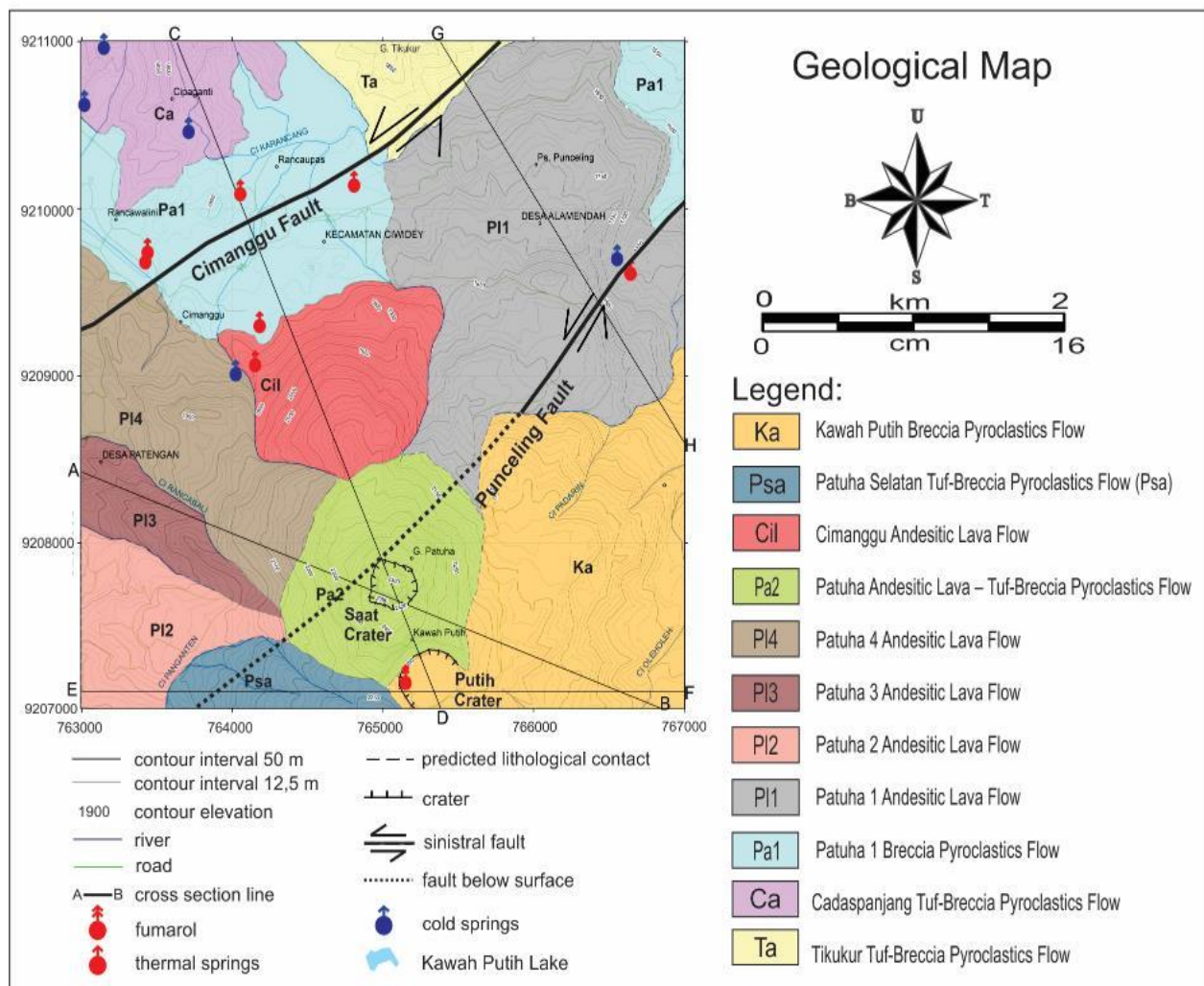


Figure 5. Geological map of study area.

Table 1. Volcanostratigraphy column of research area.

Period	Epoch	Volcanic complex	Eruption center	Primary volcanic deposits	
				Lava	Pyroclastics flow
Quaternary	Holocene	Patuha	Kawah Putih		Ka
			Patuha Selatan		Psa
			Cimanggu	Cil	
			Patuha		Pa2
				PI4	
				PI3	
				PI2	
				PI1	
					Pa1
					Ca
Pleistocene	Masigit		Cadaspanjang		Ta
			Tikukur		

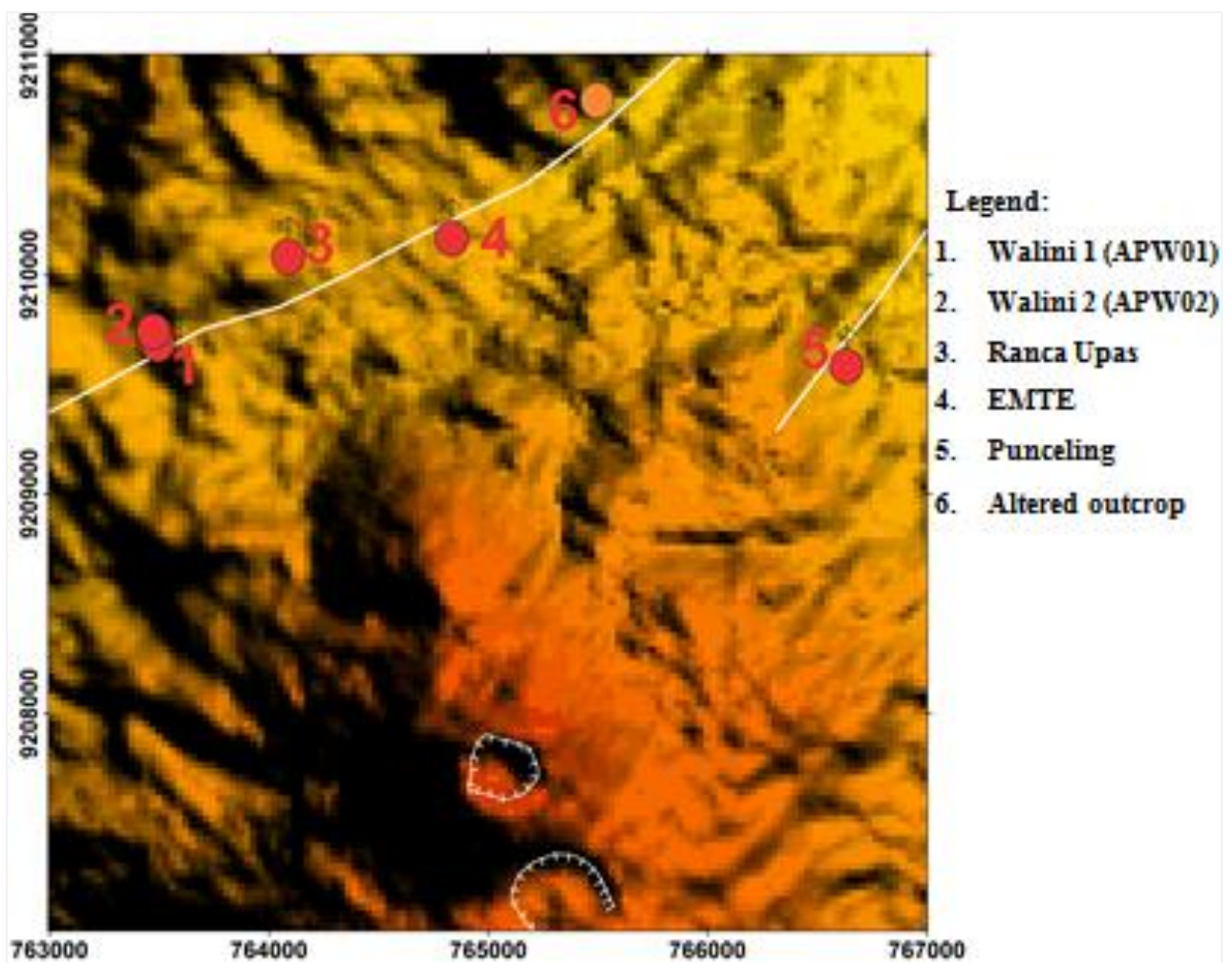


Figure 6. Structural linaments.

4. Fluid Chemistry

Water chemistry analysis was done to determine the contaminated and uncontaminated cold springs by thermal water, which is then integrated with the results of the springs classified from the geological analysis. Collecting of water data in study area started with the measurement of ambient or surrounding air temperature, water temperature, the amount of dissolved solids or Total Dissolve Solid (TDS), as well as pH, followed by water sampling anions, cations and isotope analysis in laboratory. Water samples were taken with the procedures described in [4], consisting of samples for analysis of dissolved elements and isotopes for analysis.

Data were taken from a hot springs ($T > 50^{\circ}\text{C}$), six hot springs ($T \leq 50^{\circ}\text{C}$), and nine cold springs as shown in Figure 2 and Table 2. Sampling was conducted in June - July 2016, with sunny to cloudy weather conditions.

4.1. Temperature, pH, and TDS Data Analysis

The purpose of this field data analysis is to find contaminated cold springs by the indication of higher water temperature than the surface temperature, lower value of pH than the average cold water pH in study area and high amount of dissolved solids ($\text{TDS} > 100$). These values were determined using several assumptions. The first assumption is that the temperature of cold springs uncontaminated with thermal water, equal to the outdoor air temperature when the measurements were taken. Second, the uncontaminated cold springs would have $\text{TDS} < 100$ ppm [5]. Third, water with a very low pH value or below the average is assumed to be contaminated by lateral flow of geothermal fluid. Springs data in the form of temperature, pH, and TDS as the primary data is shown in Table 2.

Table 2. Temperature, pH, and TDS of springs samples

Location	Code	Coordinate		Elevation (m)	Temperatur			pH	TDS (ppm)
		mE	mN		Air	Water	ΔT		
Thermal springs									
Punceling	AP02	766647	9209614	1698,53	22.0	41.3	19.3	5.94	123
Cimanggu	AP03	764153	9209067	1837,50	22.7	72.9	50.2	6.33	438
	AP04	764185	9209301	1777,53	24.9	47.9	23.0	5.93	380
Walini	APW01	763428	9209697	1760,28	23.4	45.5	22.1	6.27	608
	APW02	763441	9209736	1756,53	22.1	39.6	17.5	6.57	540
EMTE	APMT	764810	9210143	1678,00	19.1	41.3	22.2	6.22	746
Ranca Upas	APRU	764057	9210088	1774,91	19.5	36.3	16.8	6.43	406
Cold springs									
Punceling	AD01	766560	9209700	1664,53	23.3	18.6	4.7	7.25	167
Pelton	ADPLT	762442	9208373	1759,53	19.5	17.9	1.6	7.87	66
Cipaganti	ADCPG	763710	9210465	1764,00	19.3	18.1	1.2	6.96	23
Pojok	ADPJ-01	763003	9210623	1768,53	18.9	20.1	-1.2	8.11	72
	ADPJ-02	762974	9210676	1771,53	21.8	17.8	4.0	6.04	17
	ADPJ-03	763150	9210965	1848,52	19.8	16.3	3.5	5.98	19
Cimanggu	AD04	764030	9209008	1818,53	19.2	19.6	-0.4	5.45	115
Legok Kondang	AD LK	767222	9211691	1712,00	23.0	20.9	2.1	6.32	156
Situ Lembang	AD SL	762390	9209011	1448,53	22.6	25.7	-3.1	6.42	252

4.1.1. Temperature

Springs can be classified by its temperature. Thermal springs, according to Bery et al [6], consists of hot springs with temperature above 50°C and warm springs with temperature less than or equal to 50°C. Cold springs naturally will follow the surrounding air temperature. The temperature of cold springs, in ideal conditions should not be higher than the surrounding air temperature, even should be lower. This can happen if the occurrence of these springs are covered by something, such as trees, houses, and others. The temperature of cold springs, if contaminated by thermal fluid, is expected to increase.

Hot springs manifestation was found only in Cimanggu with temperatures reaching 72,9oC. The temperature of the warm springs in the study area ranged between 36.3 – 47,9oC. Cold springs temperatures ranged between 16.3 - 25,7oC. In Table 2, it can be seen that there are three samples that have higher water temperature than surrounding air temperature, as in the sample ADPJ-01, AD04, and ADSL. In Pojok, only springs ADPJ-01 which has a temperature showed an anomaly value. Cold springs ADPJ-01 is located at an elevation of the lowest compared with the other cold springs in Pojok, and their water temperature increases as the elevation is lower (Table 2). The air temperature at ADPJ-01 was supposed to demonstrate the value that is higher than the air temperature at ADPJ-02 and ADPJ-03 which located at a higher elevation. However, existing data showed that air temperature of ADPJ-01 is lower, whereas the value of air temperature ADPJ-02 is much higher than the value of the temperature of cold springs ADPJ-01. Thus, the temperature anomaly at the point ADPJ-01 is estimated to be due to an error in measurement of air temperature data at the moment in ADPJ-01 location. Cold springs in Cimanggu (AD04) and Situ Lembang (ADSL) higher temperature are expected to be caused by contamination of the geothermal fluid lateral flow below the surface.

4.1.2. pH

Level of acidity of the water is indicated by pH value. The pH value can be influenced by the chemical constituents present in the water, so that the pH became one of the important indicators that could indicate changes in water chemistry. The groundwater will generally have pH values ranging from 6.5 to 8.5 [5], whereas the thermal water outflow zone will have a pH that is slightly acidic or almost near neutral [4]. Eyes cold water contaminated expected to have a pH lower than the pH value of the reference [5]. However, lower pH values can also occur due to the influence of agricultural fertilizers containing sulfate, thereby making the water more acidic and increasing pH.

Water samples in study area in general have pH value relatively close to neutral. The hot springs Cimanggu has a pH of 6.33. Warm springs have a pH ranging from 5.93 to 6.57. Meanwhile, cold springs have a slightly wider pH range, 5.45 to 8.11. Cold springs in Pojok (ADPJ-02 and ADPJ-03), Cimanggu (AD04), Legok Kondang (ADLK), and Situ Lembang (ADSL) has a relatively more acidic pH compared to the reference. Decreasing value of pH in the Pojok and Legok Kondang cold springs was thought to be influenced by agricultural fertilizer, as it is located on a plantation area resident. Whilst, decreasing value of pH in Cimanggu and Situ Lembang cold springs was expected due to contamination by lateral flow of geothermal fluid below the surface (Figure 7). The other cold water pH values showed no significant changes and therefore were not used as indicator to determine the conditions of uncontaminated cold springs.

4.1.3. Total Dissolved Solids (TDS)

TDS is a value that indicates the amount of solids or dissolved solids in the water. Most of the natural springs contain relatively small dissolved components (Piper, 1944). Fresh cold springs will have a value of TDS <100 ppm [5], so cold springs with TDS values > 100 ppm are expected to have been contaminated by thermal water.

The hot springs (AP03) in the study area has 438 ppm TDS. Warm springs in the study area has TDS value ranged from 123-746 ppm. The high value of TDS at warm springs in EMTE (APMT) was due to human activities, because this springs is used directly for pools. Cold springs in the study area has a TDS value is relatively low, ranging from 17 – 252 ppm. The lowest TDS value is located in

Pojok, Pelton and Cipaganti cold springs with a value of <100 ppm. Those cold springs is expected to be uncontaminated by thermal water, based on the analysis of the value of TDS. Cold springs in Punceling (AD01) and Cimanggu (AD04), which is very close to the manifestation of thermal springs, have a relatively high TDS values, which exceeds 100 ppm. Cold springs Situ Lembang (ADSL) and Legok Kondang (ADLK) also have relatively high TDS value. TDS value analysis showed that cold springs Punceling, Cimanggu, Situ Lembang, and Legok Kondang suspected to have been contaminated by a thermal fluid (Figure 7).

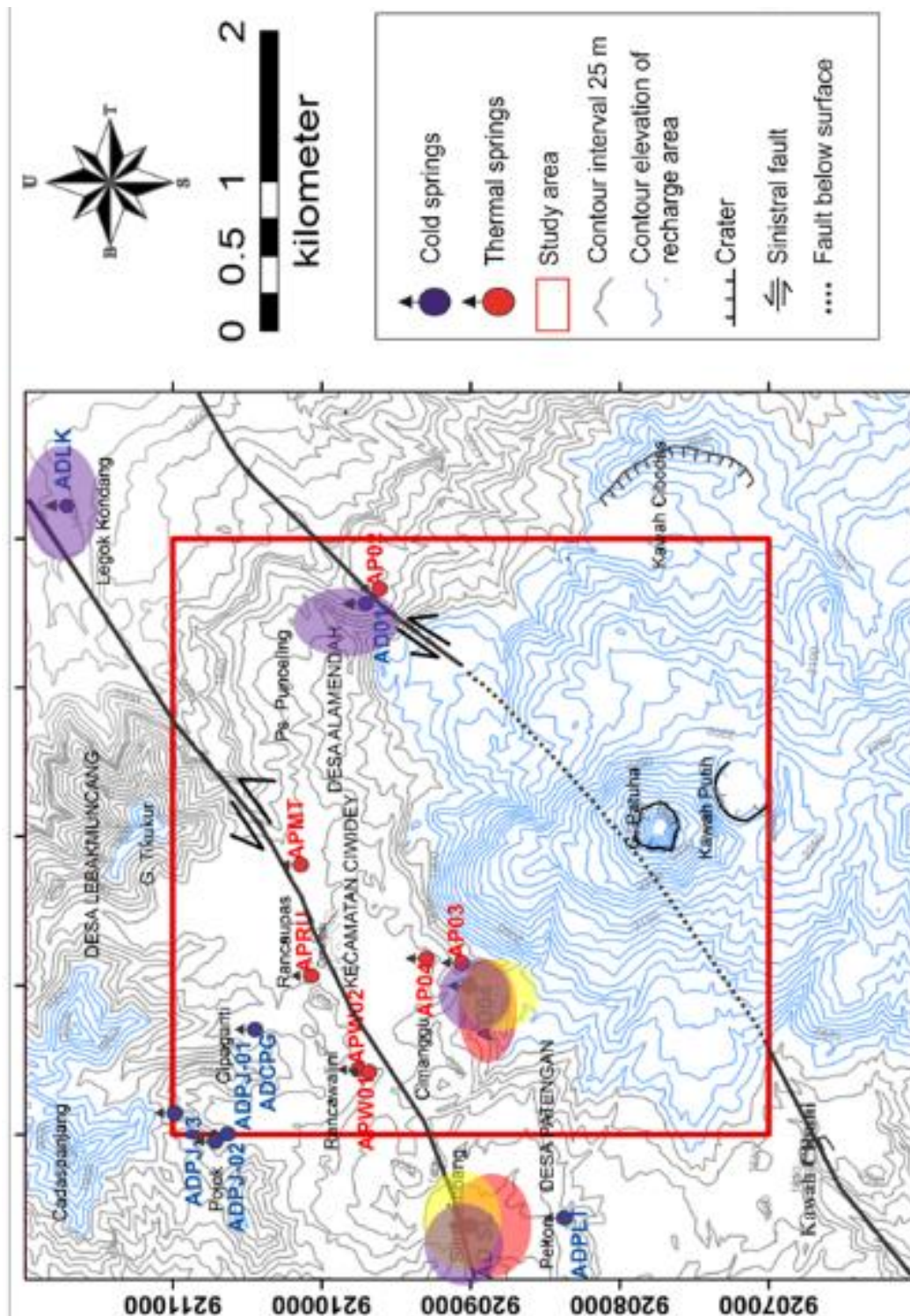


Figure 7. Contaminated cold springs based on temperature data (red circle), pH (yellow circle) and TDS (purple circle).

Based on the review of the water characteristics of above, cold springs that were expected to have been contaminated by thermal water are located in Punceling (AD01), Cimanggu (AD04), Situ Lembang (ADSL), and Legok Kondang (ADLK). Punceling cold springs and Legok Kondang have TDS values greater than 100 ppm. Cimanggu cold springs and Situ Lembang has a higher temperature than the air temperature, the pH is relatively low, and the value of TDS is more than 100 ppm.

4.2. Laboratory Data Analysis

The purpose of analyzing dissolved chemical elements are to identify cold springs that have a relatively high value of cations and anions compared to those of vicinity cold springs. Moreover, this analysis was also done to identify cold springs that have isotope ^{18}O shifting values from the local meteoric line. Some assumptions are used in this analysis. First, cold springs that located quite far away from the geothermal system and have no anomalies in the data of temperature, pH, and TDS, are assumed as uncontaminated cold springs as well as a baseline reference. Second, uncontaminated cold springs from the same volcanic complex or khuluk that associated with geothermal systems will contain relatively similar cations and anions to those in baseline reference. Third, the enrichment of isotope ^{18}O value in cold springs was caused by contamination of the thermal fluid.

Ions data from chemistry laboratory test results are presented in Table 3, while the isotope primary data from study area is shown in Table 4.

4.2.1. Schoeller Diagram

Examination of the Schoeller diagram that shows similar slope of lines connecting solute concentrations is an indication of groundwater from a similar source [7]. If the waters have different concentrations, they will appear on the graph one above the other, thus indicating relative movement of the groundwater between the points of origin of these analyses; the flow being from a lower concentration to a higher concentration [7]. Based on the increasing composition of meteoric water, it can be concluded that the total dissolved solids and dissolved ions concentration can be an indication of contaminated water by thermal springs below the surface. However, this must be supported with other evidence, especially the location of the springs.

Table 3. Ions concentrations of springs sample.

Location	Code	Fe	Ca	Mg	Na	K	NH ₄	Cl	SO ₄	HCO ₃	Σ Cations (meq/L)	Σ Anions (meq/L)
Thermal springs		mg/L										
Punceling	AP02	2.18	250.60	50.58	136.10	37.80	1.00	401.76	480.47	294.36	23.71	26.17
Cimanggu	AP03	0.65	43.07	16.66	84.66	18.12	0.83	50.29	59.34	306.19	7.74	7.68
	AP04	2.54	49.74	15.38	59.34	15.39	0.73	32.43	49.61	292.44	6.86	6.75
Walini	APW01	0.08	70.84	45.69	60.09	20.33	0.08	114.96	172.00	239.24	10.45	10.75
Ranca Upas	APRU	0.08	46.89	30.70	49.29	16.85	0.41	87.42	109.80	161.41	7.48	7.41
Cold springs		mg/L										
Punceling	AD01	0.08	27.71	15.06	13.37	4.42	0.49	63.13	46.28	62.41	3.35	3.77
Pelton	ADPLT	0.24	10.40	2.31	6.24	2.15	1.09	3.47	16.00	37.42	1.10	1.04
Cipaganti	ADCPG	0.64	3.00	1.00	1.56	1.25	2.00	2.00	6.50	14.88	0.47	0.44
Pojok	ADPJ-02	0.18	2.00	0.71	2.00	1.02	1.50	0.61	4.40	14.00	0.36	0.34
	ADPJ-03	0.26	2.38	0.94	1.70	1.25	2.00	0.44	4.20	14.91	0.42	0.34
Cimanggu	AD04	0.13	29.06	3.95	10.06	3.68	0.73	0.92	13.96	117.65	2.36	2.24
Legok Kondang	AD LK	0.02	27.67	10.91	13.94	6.10	0.29	51.44	40.06	50.93	3.06	3.14
Situ Lembang	AD SL	0.29	39.35	22.97	26.26	8.47	0.33	68.59	64.55	122.31	5.24	5.30

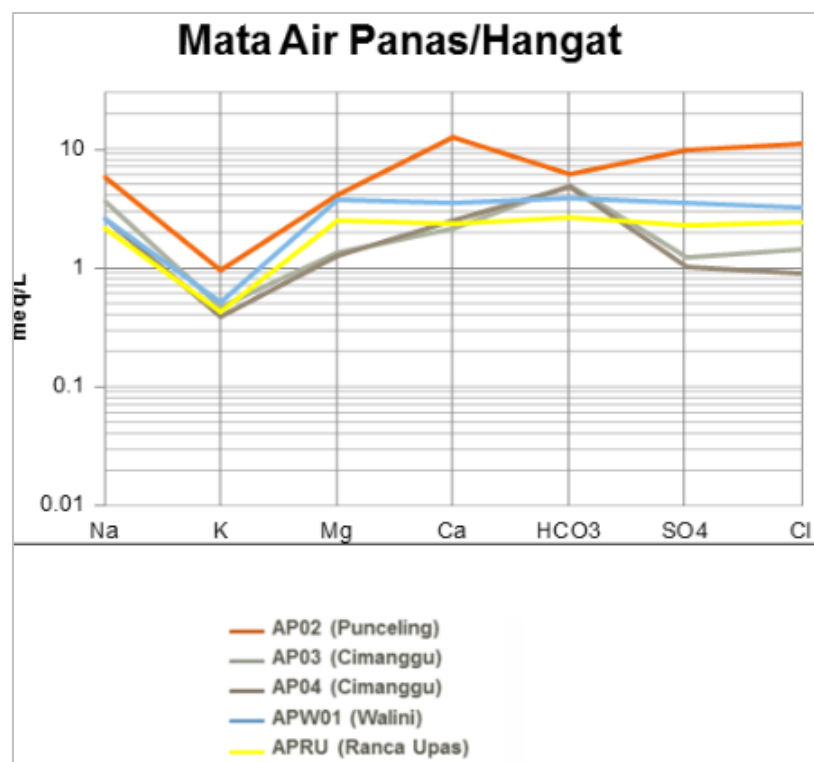
Plot results on Schoeller Diagram shows the difference of ions concentration in general between cold and thermal springs (Figure 8). Thermal springs have relatively higher ions concentration than cold

springs. Cold springs with the lowest ions concentration is located in Pojok (ADPJ-02 and ADPJ-03) and Cipaganti (ADCPG). Those springs have a relatively similar trend and close location, and therefore expected to come from the same source, recharge area in MVC. Relatively low ion concentration is also an indication that the springs is not contaminated by the fluid geothermal systems.

Other cold springs contain relatively higher ions concentration. This enrichment of the dissolved ions with a similar trend line in Schoeller Diagram is an indication of contamination occurred by the geothermal fluid. Cold springs in PVC are also from the recharge area in PVC. The only cold springs in the study area that are located in PVC, but from recharge area in MVC is Legok Kondang cold springs (ADLK), which is marked by a green circle in Figure 9. Legok Kondang springs are cold springs are not contaminated.

4.2.2. Isotope

Rain water isotope data [1] was used to determine the local meteoric water line. The line is used as a reference in determining the value of isotope shifting in the cold springs. Isotope values of springs in the study area are shown in Table 4. Plot of oxygen and deuterium isotope values as well as the meteoric line is shown in Figure 10. Cold springs that originated from meteoric water that is not contaminated by thermal water will have a value of isotopes that are still along the local meteoric water line. Plot results of hot and warm springs showed an ^{18}O isotope shifting due to evaporation or steam heated.



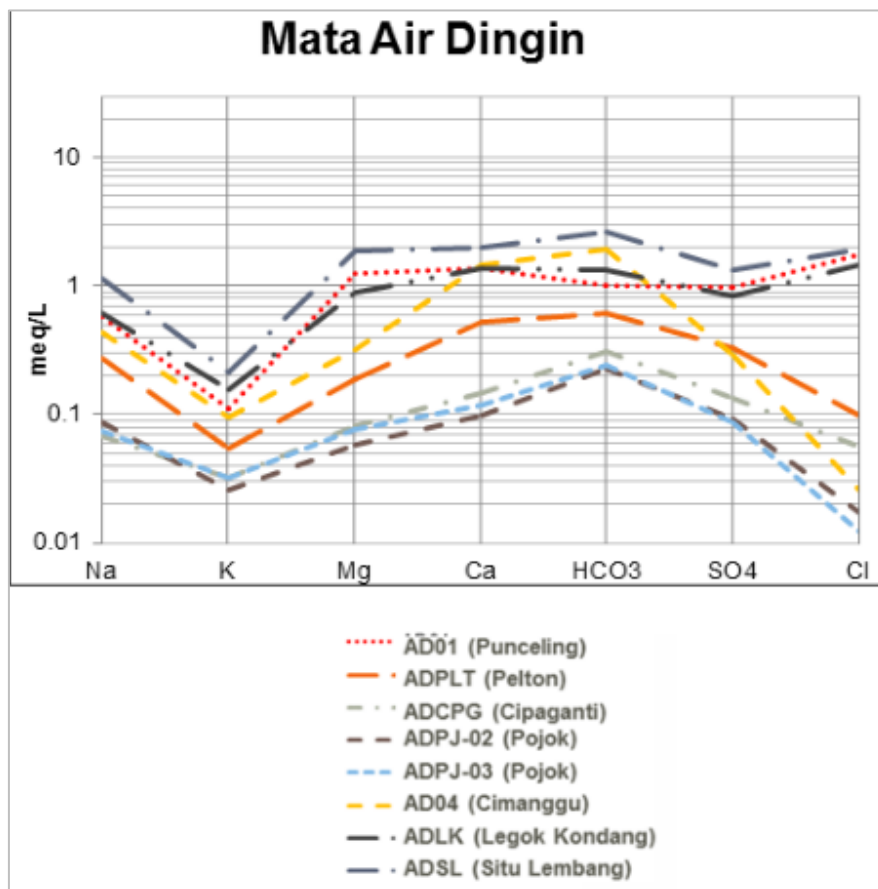


Figure 8. Ions concentrations plot results in Schoeller Diagram

Table 4. ¹⁸O dan ²H isotope data.

Location	Code	d ¹⁸ O	δD
Thermal springs		‰	
Punceling	AP02	-8.50	-55.44
Cimanggu	AP03	-8.96	-56.32
	AP04	-8.95	-57.08
Walini	APW01	-8.69	-55.42
Ranca Upas	APRU	-8.76	-55.65
Cold springs			
Punceling	AD01	-8.66	-54.94
Pelton	ADPLT	-9.25	-58.04
Cipaganti	ADCPG	-9.07	-55.44
Pojoy	ADPJ-02	-9.00	-55.62
	ADPJ-03	-9.23	-56.75
Cimanggu	AD04	-9.47	-58.21
Legok Kondang	AD LK	-8.56	-52.02
Situ Lembang	AD SL	-8.89	-54.68

In Figure 10, we can see that cold springs in Legok Kondang (ADLK), Pojoy (PJ02 and PJ03), Cipaganti (ADCPG) and Cimanggu (AD04) are plotted along the local meteoric water line. Legok

Kondang, Cipaganti and Pojok area are not located adjacent to manifestations of geothermal system, so the cold springs in these areas are not expected to be contaminated by the fluid thermal. The presence of spring water that is not contaminated is indicated by green circle in Figure 8 Cimanggu cold springs (AD04) is located along the local meteoric water line, but the location of cold springs are located very close to the manifestation of Cimanggu thermal springs, the AP03 and AP04, therefore this cold springs is expected to be contaminated by the thermal springs. Cimanggu thermal springs AP03 and AP04 have a value of $\delta^{18}\text{O}$ isotope shifting about 0.5 – 0.6 ‰ from local meteoric water line. Unshifting value of $\delta^{18}\text{O}$ isotope in AD04 can be due to the short residence time of meteoric water below the surface. Therefore, the relatively short local ground water flow will result in no significant change of isotope values when cold springs occur at the surface.

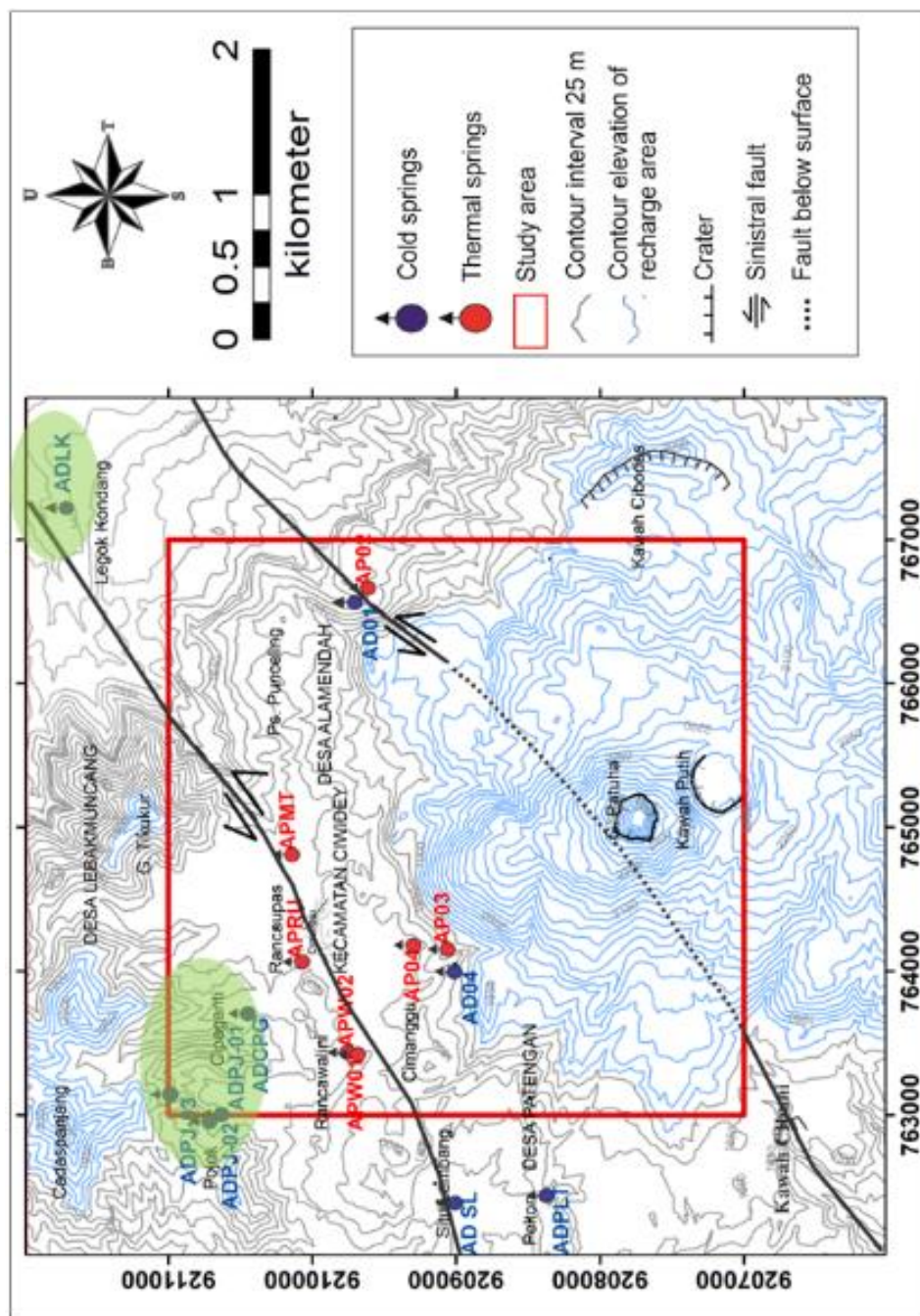


Figure 9. Uncontaminated cold springs based on Schoeller Diagram and isotope analysis (green circle).

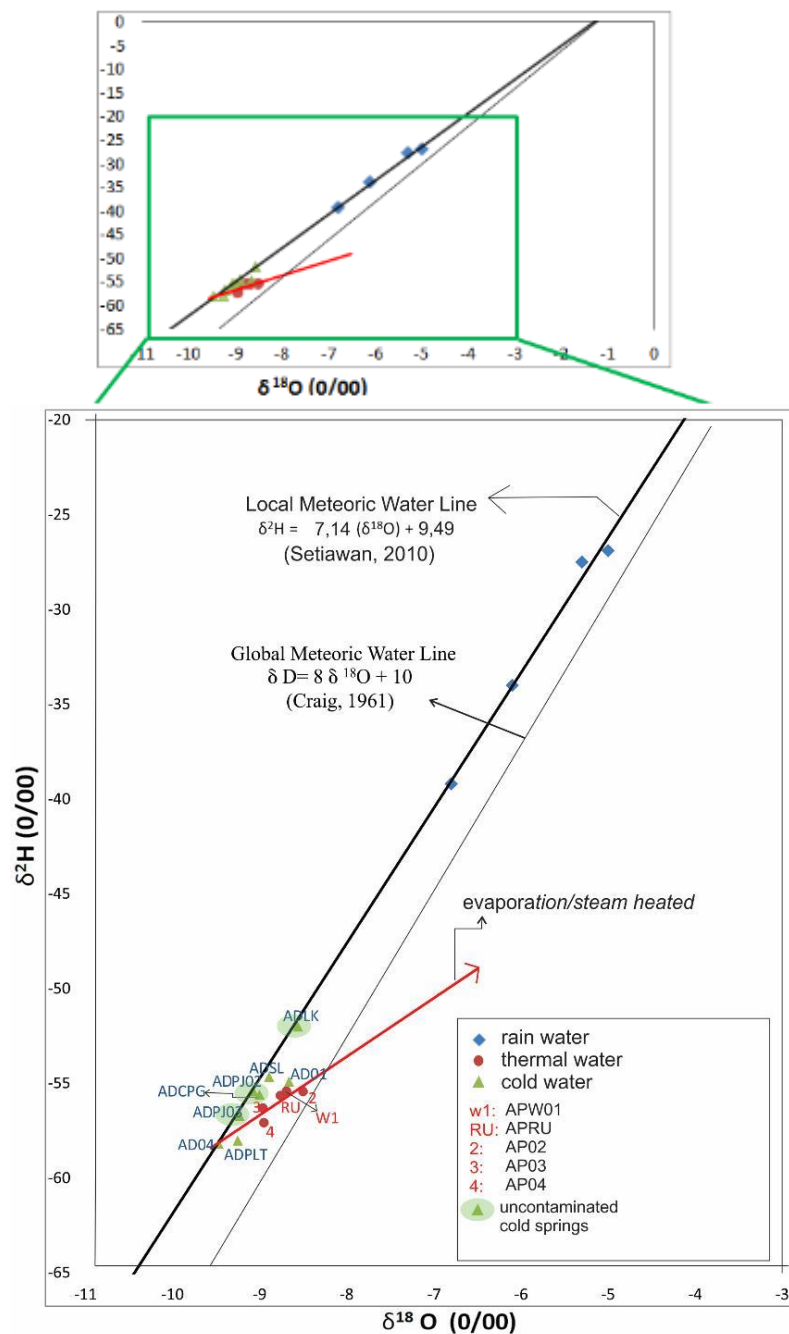


Figure 10. ^{18}O and ^2H Stable Isotope Plot

The other cold springs in Pelton (ADPLT), Situ Lembang (ADSL) and Punceling (AD01) showed a shifting value towards the local meteoric line approaching the line of evaporation / steam heated. Shifting to more positive value can occur due to isotope exchange between water with rocks at a higher temperature [4]. Cold springs in the area Punceling, Pelton and Situ Lembang are expected to be contaminated by a thermal fluid. This is also supported by their location which are quite closed with the surrounding thermal springs manifestation in PVC.

5. Boundary Results

Based on the geological analysis, springs in the study area are grouped into springs PVC, which are springs in Cimanggu, Punceling, Situ Lembang, Pelton and Legok Kondang, and springs in MVC, which are springs in Pojok and Cipaganti. The occurrence of these springs are also controlled by permeable zones in Cimanggu Fault and Punceling Fault, as well as the depression zone in the form of intersection spring soil to the slopes.

Fluid chemistry analysis indicates that cold springs Punceling (AD01), Pelton (ADPLT), Cimanggu (AD04), and Situ Lembang (ADSL) located in PVC have increased in TDS, higher temperature than the surrounding air or ambient temperature, decreased in pH, increased in ions concentration, and isotope ^{18}O shifting due to contamination of the Patuha geothermal system. Those contaminated springs are also located relatively close to the thermal spring manifestations. On the other hand, springs in Legok Kondang (ADLK), Cipaganti (ADCPG), and Pojok (ADPJ-02 and ADPJ-03) are not contaminated by the thermal fluid. The boundary of the system is delineated by an arbitrary line drawn between distal thermal springs from the contaminated cold springs with the uncontaminated cold springs (Figure 11).

This boundary is validated afterward with low resistivity boundary derived from DC and MT resistivity survey (Figure 12 and Figure 13, respectively). Low resistivity values ($<20 \text{ ohm.m}$) represents the cap rocks in the system. Reservoir of geothermal systems is expected to correlate with those cap rocks. This boundary is also validating with drilling data that give high temperature gradient. Figure 12 shows temperature gradient that ranges between $100 - 200^\circ\text{C/km}$. In the normal area, a temperature gradient is typically $\pm 25^\circ\text{C}$ [8]. It shows that the temperature anomaly beneath the surface has a high value and could be an indication of an active geothermal systems. Those validations suggest that the method use in this study is applicable and reliable.

6. Conclusions

Based on geological studies, springs in the study area are controlled hydrologically by topography of Patuha Volcanic Crown (complex) or so called PVC, which consist of springs in Cimanggu, Punceling, Situ Lembang, Pelton, and Legok Kondang, and of Masigit Volcanic Crown (complex) or so called MVC, which consist of springs in Pojok and Cipaganti. Thermal springs manifestations in study area are present as an outflow zone in Patuha geothermal systems.

Some of the cold springs in PVC are contaminated by subsurface steam heated outflow while others are not contaminated. The contaminated cold springs have several characteristics such as higher water temperature than ambient temperature at the time it was measured, higher total dissolved solid (TDS), and lower pH. The soluble elements analysis support the early contamination indication by showing higher cation and anion, and positive oxygen shifting of stable isotope of these cool springs. Whereas the uncontaminated spring shows similar characteristic with cool springs occur at MVC.

The geothermal system boundary location is estimated to be in between uncontaminated cold springs and the farthest thermal springs from upflow zone or the closest contaminated cold springs to outflow zone. This boundary is validated by using low resistivity value ($\leq 20 \text{ ohm.m}$) and temperature gradient data that shows similarity in the boundary location, and it can be concluded that the method used is valid

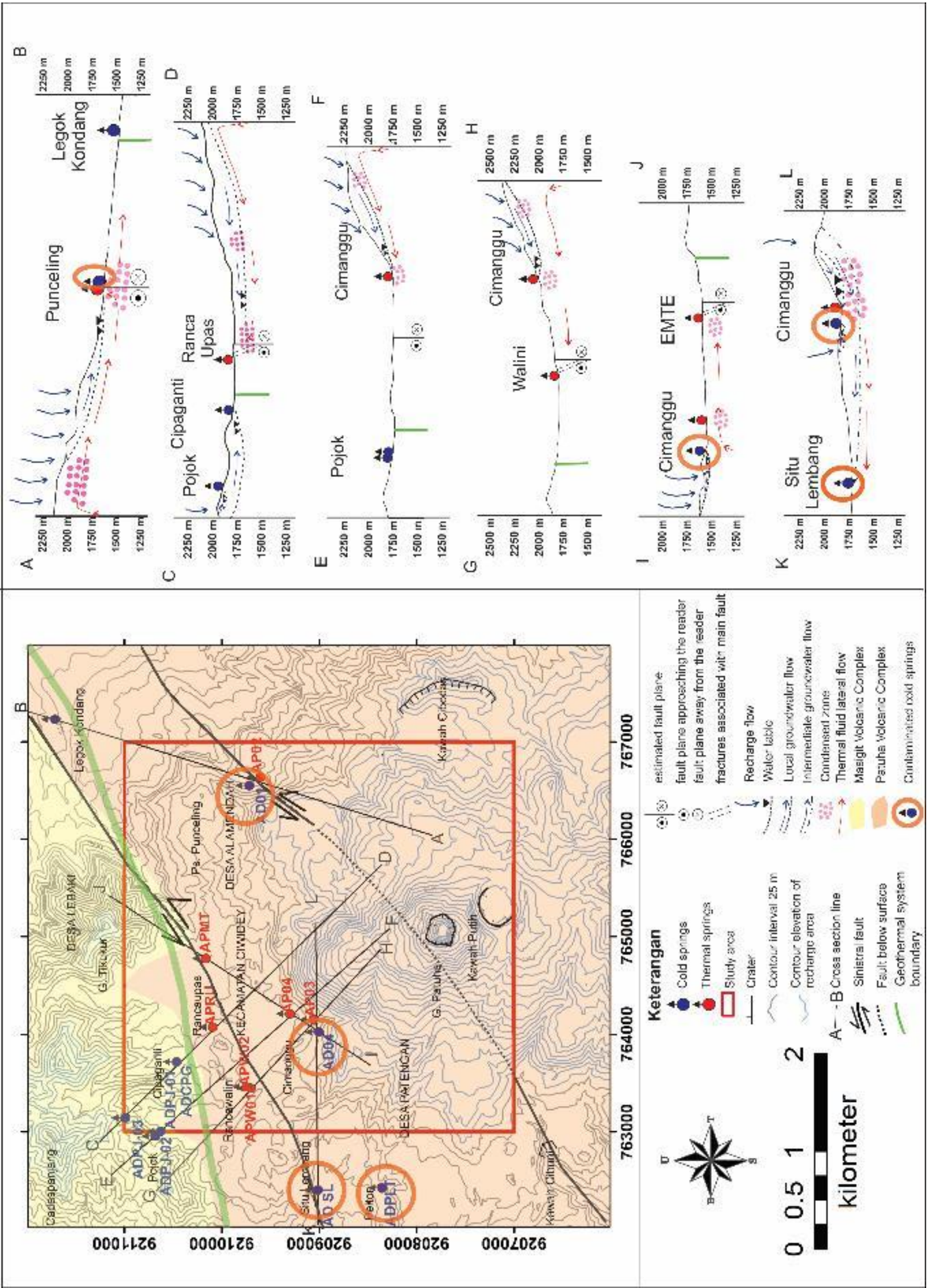


Figure 11. Groundwater flow and thermal water flow model in study area.

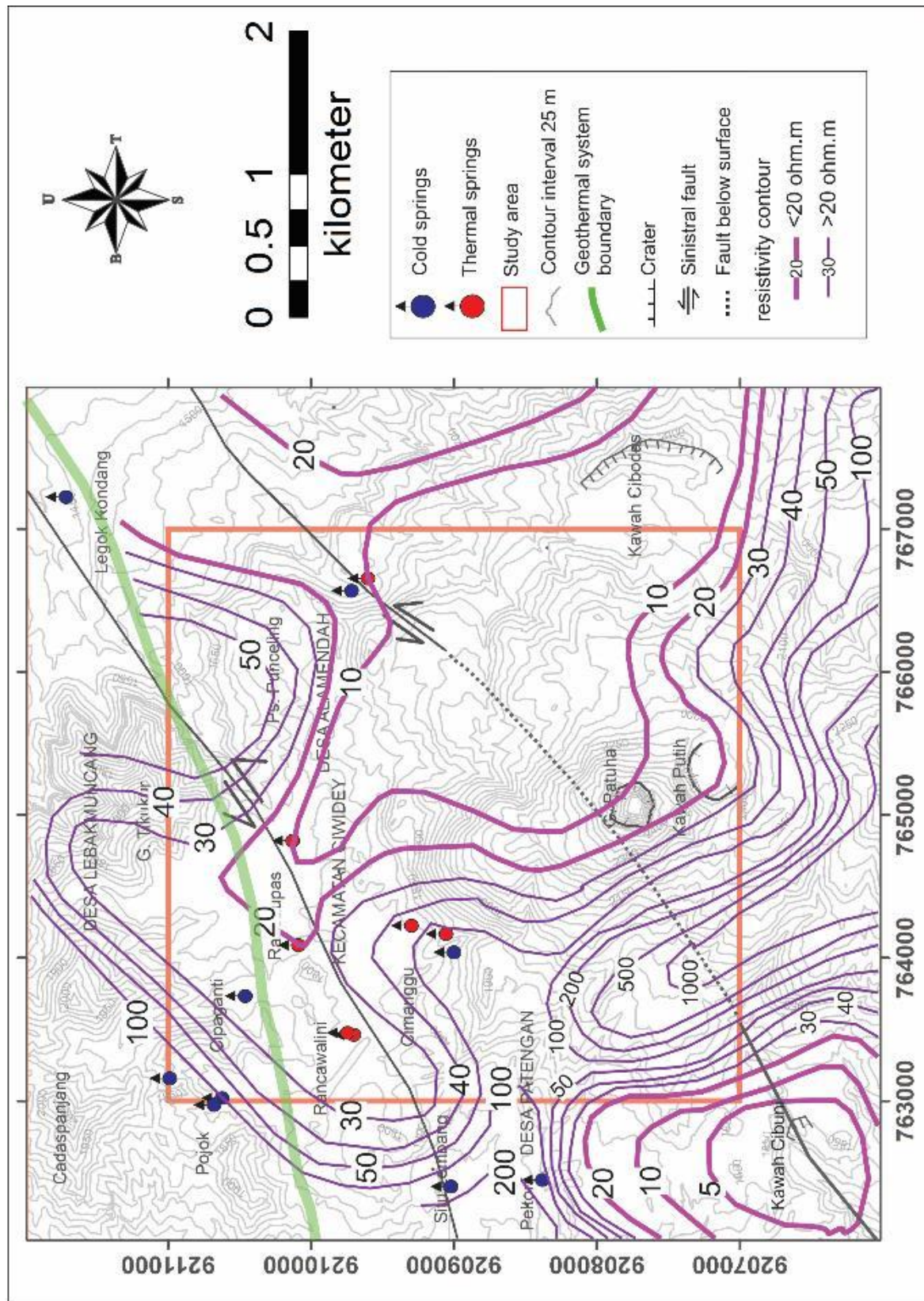


Figure 12. Geothermal system boundary validation with DC-Resistivity, Schlumberger, AB/2 = 500 meter [9].

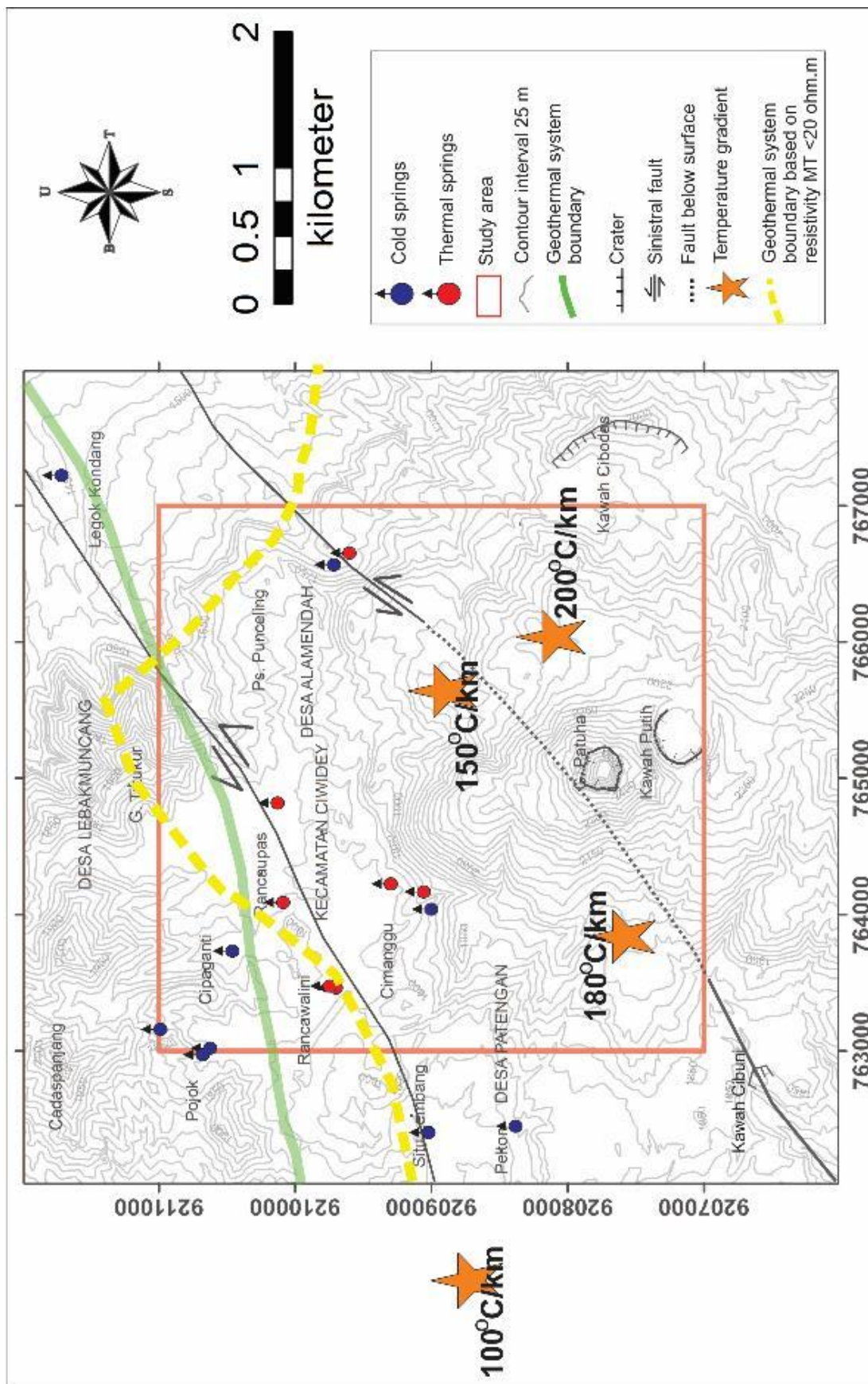


Figure 13. Geothermal system boundary validation with resistivity MT and gradient temperature [10].

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