Geochemical Study of the WKP Ungaran, Central Java

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Abstract. This study aims to analyze the composition, origin, and characteristics of thermal fluids in the Ungaran geothermal field, Central Java, and to estimate the reservoir temperature using geothermometers. The methods used include geochemical surveys, chemical analysis of water and gas, and interpretation of geoindicators. The results show that the thermal fluids in this field have chloride, bicarbonate, and sulfate water types, with the upflow zone dominated by sulfate water and the outflow zone by bicarbonate water. Stable isotope analysis indicates water-rock interaction in the subsurface. Reservoir temperature estimates based on silica geothermometers range from 110-179°C, while gas geothermometers indicate temperatures between 220-270°C. The conceptual model produced depicts a geothermal system controlled by geological structures such as normal faults and calderas. This study provides significant insights into the Ungaran geothermal system and can serve as a basis for further exploration.

Keywords: *Geothermal fluids, Ungaran geothermal field, geochemical survey, geoindicators, reservoir temperature, silica geothermometer, gas geothermometer, water-rock interaction, geological structures.*

1 Introduction

The utilization of renewable energy sources is a primary focus for PT PLN (Persero) to achieve its energy targets of 23% by 2023 and 31% by 2050. One of the renewable energy sources being developed in Indonesia is geothermal energy. The Ungaran Geothermal Working Area (WKP) as shown in figure 1, is strategically located on the island of Java, Central Java Province. It is situated approximately 40 kilometers southwest of Semarang Regency. The area is accessible by a 2 hour drive from Semarang City, making it relatively easy to reach for field studies and exploration activities. The geographical setting of the Ungaran geothermal field provides a unique opportunity to study and develop geothermal resources in a region with significant geothermal potential. WKP Ungaran is currently in the exploration stage. Initial exploration was conducted by Pertamina between 1983 and 1988, followed by shallow temperature gradient drilling in four wells. To understand the subsurface conditions of geothermal locations, geochemical methods are employed. These methods provide crucial data on the physical and chemical properties of thermal and non-thermal fluids, which are essential for assessing the potential of geothermal resources.

The geochemical exploration study in the Ungaran geothermal field aims to achieve several key objectives. Firstly, to analyze the composition, origin, and

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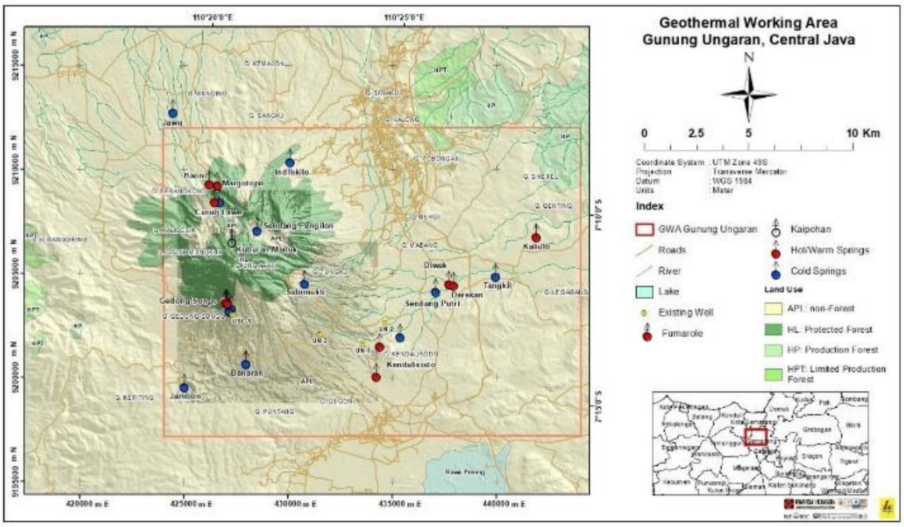

Figure 1 . Ungaran Geothermal Field [1]

characteristics of the thermal fluids present in the field. This involves detailed chemical analysis to identify the various elements and compounds within the fluids. Secondly, the study aims to estimate the reservoir temperatures using fluid & gas geothermometers, which are tools that measure the temperature of geothermal fluids based on their chemical composition. Thirdly, the study involves interpreting the geothermal system of the study area using geo indicators, which are specific chemical markers that provide insights into the geothermal processes occurring underground. And then, the study aims to develop a conceptual model of the Ungaran geothermal system based on geochemical study, which will help in understanding the overall geothermal dynamics as a guide for future exploration and development. At last but not least, this study is purposed to re-evaluation of geochemical analysis with the aim of confirming existing data and refining the interpretation of previous geochemical studies.

2 Geological Review

2.1 Regional Geology

Java Island's geological history is marked by complex formations of basins, faults, folds, and volcanism due to varying stress regimes. The tectonic evolution has resulted in three main structural trends: Northeast-Southwest (NE-SW), North-South (NS), and East-West (EW). The subduction of the Indo-Australian Plate beneath the Eurasian Plate has created rich patterns of igneous and volcanic rocks, divided into four magmatic belts: Eocene to Middle Miocene, Upper Miocene to Pliocene, Quaternary volcanic arc, and Quaternary back-arc volcanic belt. Mount Ungaran, located in Central Java, is part of a near-back-arc magmatic zone with an elevation of approximately 2050 meters[1]. It sits on Tertiary formations in the North Serayu and Kendeng Basins, with geological structures controlled by collapse structures and fault systems. The volcano features varied rock compositions, including basalt, andesite, and gabbro, and has undergone multiple developmental phases [2].

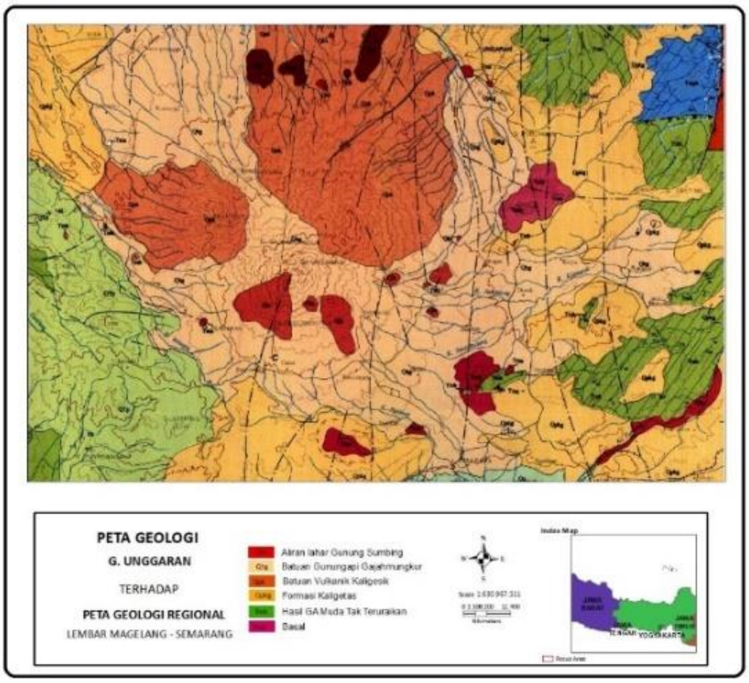

Figure 2 Geological Map of Mt. Ungaran [2]

2.2 Geomorphology of the Study Area

Geomorphological mapping is used to represent relief and understand the dynamics of morphological features. Volcanic morphology is influenced by volcanism, tectonics, and erosion, requiring careful study of growth and erosion processes. Volcanic geomorphological analysis integrates morphographic, morphometric, and morphogenetic variables to understand volcanism characteristics, analyze tectonic factors, and reconstruct the growth stages of volcanic complexes.

As shown in figure 3, PT PLN (Persero) conducted a geomorphological analysis of the Ungaran Volcanic Complex using a Digital Terrain Model (DTM). DTM data, derived from high-resolution LiDAR (0.5 m x 0.5 m) and National DEM (8 m x 8 m), is sufficient to identify volcanic terrain features.[3]

Based on morphographic and morphogenetic criteria, the Ungaran Volcanic Complex can be classified into 7 volcanic geomorphological units as shown in figure 4:

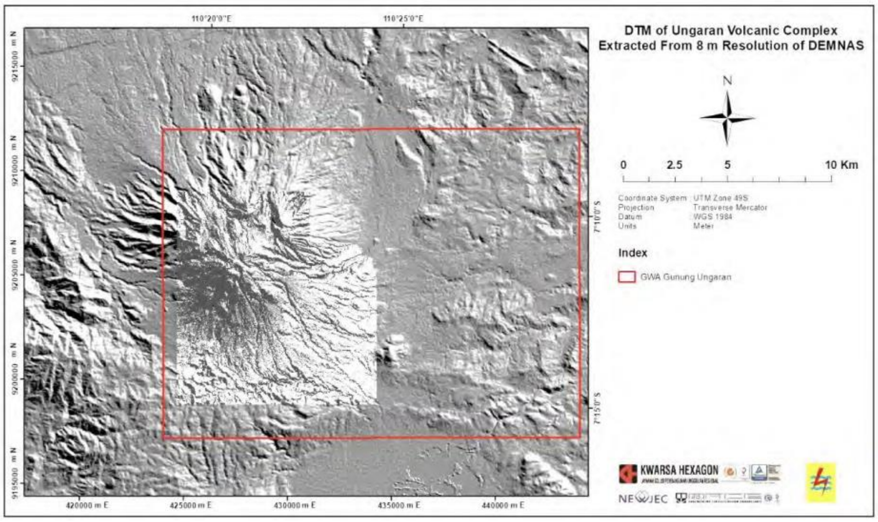

Figure 3 Digital Terrain Model (DTM) of the Ungaran Volcanic Complex [3]

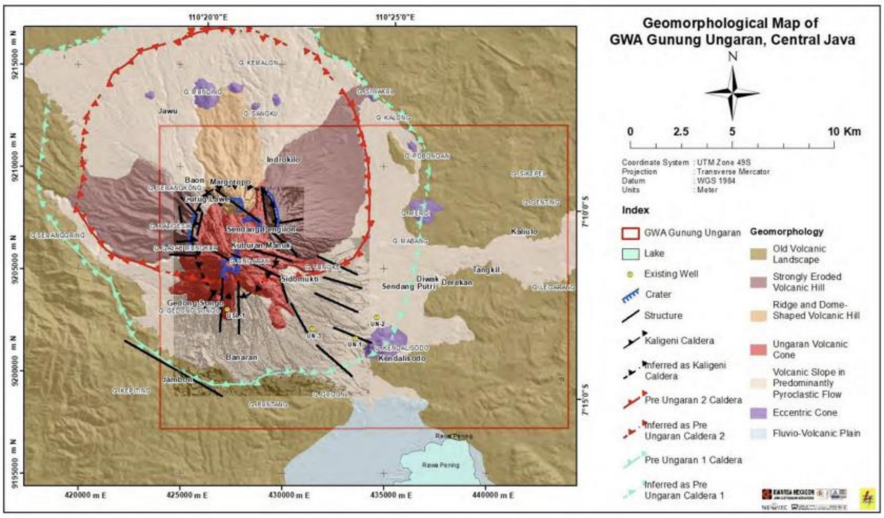

Figure 4 Geomorphological Map of the Ungaran Volcanic Complex [3]

- Ridge and Dome-Shaped Volcanic Hills
- Strongly Eroded Volcanic Hills
- Old Volcanic Landscape
- Ungaran Volcanic Cone
- Volcanic Slopes with Dominant Pyroclastic Flows
- Eccentric Cones
- Fluvio-Volcanic Plains

2.3 Surface Manifestations and Hydrothermal Alteration

The geothermal surface manifestations in the Ungaran Geothermal System as shown in figure 5, are found in Gedongsongo, Kendalisodo, Diwak, Derekan, Kaliulo, Margotopo, Baon, and Curug Lawe. The Gedongsongo geothermal manifestations are located on the southern slopes of the Ungaran Complex. The caldera walls show "volcanic breccia" and auto-brecciated lava, partially altered to clay minerals (mainly kaolinite). The walls near the fumaroles are partially covered by sulfur and anhydrite. The fumaroles have a temperature of 89.7°C, and the hot water pools have a temperature of 58.2°C with a pH of 5.2. The altered steaming ground is a type of thermal manifestation in Gedongsongo [3]. Visual observations conducted by PT. PLN (persero), the fumaroles show thin white smoke blowing at moderate pressure, smelling of H_2S. Gas detection results with a Kitagawa detector (measured 3 times) show SO_2 gas levels of 0.07 – 0.08 ppm and H_2S levels of 50 ppm (beyond scale). These thermal manifestations situated at an elevation of 1.361 – 1.393 meters above sea level [3].

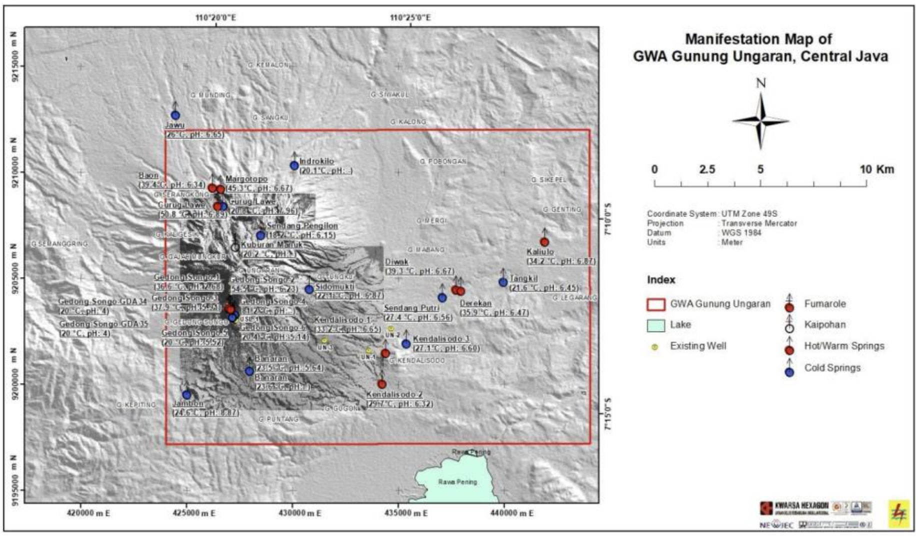

Figure 5 Ungaran Mountain Manifestations[3]

3 Geochemical Data

3.1 Physical Characteristics of Manifestations

PT PLN (Persero) conducted a geochemical survey in the Ungaran Geothermal Field from September 15 to 27, 2019. The survey involved sampling thermal and non-thermal manifestations and measuring physical properties like temperature, pH, and total dissolved solids (TDS). Water samples were analyzed for anions, cations, and stable isotopes [3]

The survey results showed several manifestations around the Ungaran Geothermal Field, as shown in Figure 6, identified several manifestation features grouped into hot/warm springs and cold springs based on temperature measurements at various locations, including Gedongsongo, Kendalisodo, Diwak, Derekan, and Kali Ulo. Fumarole manifestations were found in several locations such as Gedongsongo, Kendalisodo, Diwak, Banaran, and Margotopo. The physical parameter measurements conducted on these features are shown in Tables 1 and 2.

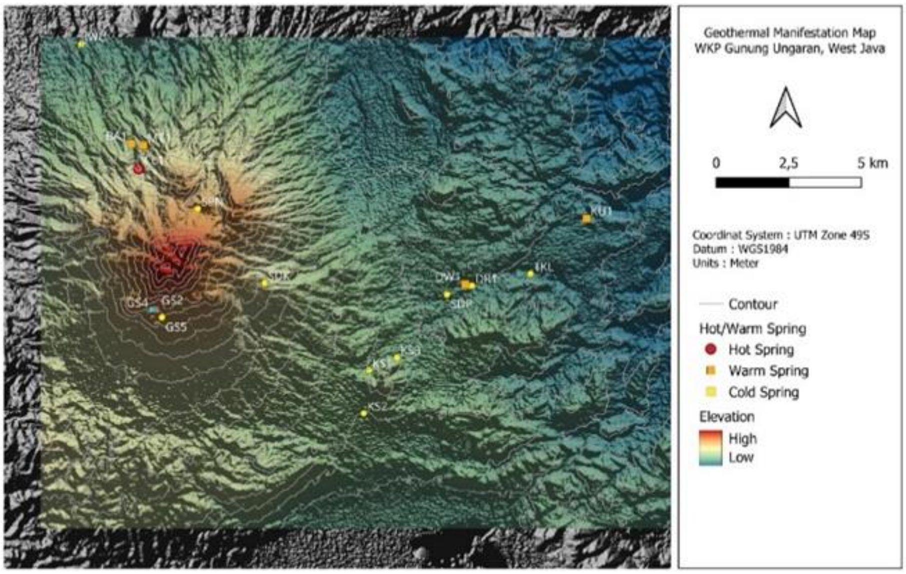

Figure 6 Distribution Map of Thermal and Non-Thermal Manifestations in the Ungaran Geothermal Field and Surroundings

Table 1 Chemical Composition of Water (mg/kg) [3]

No	Lokasi	Code	PH	T	Density	TDS	SiO2	Fe	Ca	Mg	K	Na	Li	As	NH4	B	Al	F	Cl	SO4	HCO3	CO3	IB
1	Gedongsongo	GS1	2,74	36,30	993,54	3056	144,22	100,25	29,72	11,60	5,88	11,26	0,02	-	423,23	0,23	102,04	-	2,01	2225,16	-	-	-18%
2	Gedongsongo	GS2	6,18	54,50	985,91	449	201,87	1,42	18,50	7,41	11,63	32,93	0,02	-	2,57	0,23	0,83	0,02	3,04	149,61	18,41	-	-1%
3	Kendalisodo	KS1	7,23	33,20	994,60	3683	164,85	0,03	358,56	92,13	41,11	616,80	2,51	-	13,98	32,96	-	-	989,40	2,01	1368,79	-	4%
4	Kendalisodo	KS2	7,17	29,70	995,70	1282	146,94	0,09	93,58	44,20	16,35	143,35	0,35	0,02	0,90	5,63	-	-	211,78	2,01	616,41	-	-3%
5	Diwak	DW1	7,22	39,30	992,45	2094	165,03	0,76	167,77	127,19	29,02	142,20	0,18	-	1,40	34,38	-	-	15,11	-	1410,62	-	5%
6	Derekan	DR1	7,35	35,90	993,68	1507	153,19	0,06	22,49	120,37	26,84	138,22	0,18	0,02	0,13	16,72	-	-	212,21	0,20	816,33	-	-4%
7	Kali Ulo	KU1	8,27	43,20	990,92	15297	58,75	0,14	51,97	33,53	191,57	5236,92	2,07	-	36,13	222,03	-	-	6171,24	7,06	2555,62	729,79	0%
8	Margotopo	MT1	7,44	45,30	990,06	1970	187,19	0,48	188,60	96,80	22,87	126,36	0,20	-	2,39	6,12	-	-	71,01	5,05	1262,77	-	2%
9	Baon	BA1	7,20	39,40	992,41	1262	177,13	-	40,53	80,04	19,48	113,54	0,14	-	2,05	27,60	-	-	141,66	2,02	657,33	-	-2%
10	Curug	CL1	7,57	50,80	987,65	1796	65,32	0,10	182,74	94,75	22,77	129,93	0,21	-	2,49	22,73	-	-	142,34	2,03	1130,31	-	2%
11	Gedongsongo	GS3	6,27	20,40	998,08	466	138,41	0,36	35,49	19,04	8,42	15,50	0,02	0,02	2,79	0,23	0,02	0,23	1,00	40,08	204,60	-	2%
12	Gedongsongo	GS5	5,71	20,00	998,16	126	65,04	1,60	3,13	1,95	3,19	4,50	-	-	0,30	0,23	-	-	-	0,50	45,46	-	-6%
13	Kendalisodo	KS3	7,03	27,10	996,45	379	99,64	0,03	27,40	10,91	4,55	24,28	0,08	0,02	0,04	19,60	-	-	20,07	5,02	167,36	-	1%
14	SendangPutri	SDP	7,59	27,40	996,36	802	114,76	0,05	70,18	43,81	11,41	36,36	0,05	-	0,48	16,22	-	-	20,07	0,20	487,97	-	3%
15	Tangkil	TKL	7,19	21,60	997,82	340	95,25	0,21	33,03	8,61	5,36	13,91	0,02	0,02	0,34	0,23	-	-	10,02	7,02	166,00	-	0%
16	Sidomukti	SDK	7,08	22,10	997,71	152	83,17	0,06	6,70	1,74	4,89	6,94	0,01	-	0,35	0,23	-	-	3,01	5,01	40,02	-	5%
17	Jawu	JWU	7,21	23,00	997,50	244	59,63	0,40	21,61	7,60	5,51	11,87	-	0,02	0,28	0,45	-	-	30,08	3,01	103,60	-	-4%
18	Sendang Pengilon	SPN	6,62	18,20	998,51	156	58,38	-	11,18	2,66	4,59	6,71	-	0,02	0,29	3,60	-	-	2,00	-	67,04	-	2%

* IB = ion balance (given in %)
= ion balance ±5%

Hot springs in the Ungaran Geothermal Field have temperatures of 50ºC or higher, while warm and cold springs are below 50ºC. These springs can be turbid

Table 2 Gas Composition (in mmol) of Manifestations in the Ungaran Geothermal Field [3]

No	Location	Sample Code	Gas (mol %) dry gas								Steam
			CO2	H2S	He	H2	N2	Ar	CH4	O2	(mmol)
1	Gedongsongo	GS1	152,00	2,00	0,00	0,81	1,72	0,01	1,17	0,01	190,86
2	Gedongsongo	GS2	172,10	2,20	0,00	0,88	1,80	0,01	1,28	0,01	400,45
3	Gedongsongo	GS3	168,80	2,20	0,00	0,85	1,87	0,01	1,24	0,01	86,25
4	Gedongsongo	GS4	101,10	0,80	0,00	0,42	1,07	0,01	0,63	0,01	174,58

or clear, fresh, and either sulfur-smelling or odorless, with a neutral pH of 5-7 and TDS ranging from 126 to 15,000 ppm.

Fumaroles, found south of Mount Ungaran in the Gedongsongo area, emit gases collected using glass tubes or funnels. These gas samples are then analyzed in the laboratory.

4 Data Analysis

4.1 Water Geochemistry Analysis

4.1.1 Ion Balance

From September 15 to 27, 2019, water samples from 18 locations in the Ungaran Geothermal Field were analyzed for anions, cations, and stable isotopes. The quality of the geochemical data was assessed using ion balance, which should not exceed ±5% for accurate interpretation [4]. Ion balance is calculated using the formula:

$$ion\ balance\ (\%) = \frac{\sum cation - \sum anion}{\sum cation + \sum anion}\ \ x\ 100$$

The ion balance of the samples ranged from 0.02% to 4.7%, with 16 samples are include in acceptable range, making them suitable for further geochemical interpretation. Two samples (GS1 and GS5) were excluded due to their ion balances being outside the acceptable range.

4.1.2 Fluid Types (Cl-SO_4-HCO_3 Ternary Diagram)

The Cl-SO_4-HCO_3 ternary diagram classifies hot/warm spring fluids based on their anion composition. The thermal and non-thermal water samples from the Ungaran geothermal area were plotted on diagram (figure 7), which has revealed three types of water:

- Chloride Water: Only one sample, Kali Ulo (KU1), has high chloride content (6,210.46 mg/kg) and significant bicarbonate (2,555.62 mg/kg). The high chloride indicates a permeable zone controlled by faults, allowing reservoir water to surface. High sodium content, indicates mixing with sedimentary water.

Table 3 Data Quality (Ion Balance) of water samples in the Ungaran Geothermal Field

No	Lokasi	Code	PH	T	Density	TDS	SiO2	Fe	Ca	Mg	K	Na	Li	As	NH4	B	Al	F	Cl	SO4	HCO3	CO3	IB
											mg/kg												
1	Gedongsongo	GS2	6,18	54,50	985,91	449	201,87	1,42	18,50	7,41	11,63	32,93	0,02	-	2,57	0,23	0,83	0,02	3,04	149,61	18,41	-	-0,63%
2	Kendalisodo	KS1	7,23	33,20	994,60	3683	164,85	0,03	358,56	92,13	41,11	616,80	2,51	-	13,98	32,96	-	-	989,40	2,01	1368,79	-	3,91%
3	Kendalisodo	KS2	7,17	29,70	995,70	1282	146,94	0,09	93,58	44,20	16,35	143,35	0,35	0,02	0,90	5,63	-	-	211,78	2,01	616,41	-	-3,39%
4	Diwak	DW1	7,22	39,30	992,45	2094	165,03	0,76	167,77	127,19	29,02	142,20	0,18	-	1,40	34,38	-	-	15,11	-	1410,62	-	4,75%
5	Derekan	DR1	7,35	35,90	993,68	1507	153,19	0,06	22,49	120,37	26,84	138,22	0,18	0,02	0,13	16,72	-	-	212,21	0,20	816,33	-	-4,34%
6	Kali Ulo	KU1	8,27	43,20	990,92	15297	58,75	0,14	51,97	33,53	191,57	5236,92	2,07	-	36,13	222,03	-	-	6171,24	7,06	2555,62	729,79	-0,02%
7	Margotopo	MT1	7,44	45,30	990,06	1970	187,19	0,48	188,60	96,80	22,87	126,36	0,20	-	2,39	6,12	-	-	71,01	5,05	1262,77	-	1,79%
8	Baon	BA1	7,20	39,40	992,41	1262	177,13	-	40,53	80,04	19,48	113,54	0,14	-	2,05	27,60	-	-	141,66	2,02	657,33	-	-2,19%
9	Curug	CL1	7,57	50,80	987,65	1796	65,32	0,10	182,74	94,75	22,77	129,93	0,21	-	2,49	22,73	-	-	142,34	2,03	1130,31	-	1,60%
10	Gedongsongo	GS3	6,27	20,40	998,08	466	138,41	0,36	35,49	19,04	8,42	15,50	0,02	0,02	2,79	0,23	0,02	0,23	1,00	40,08	204,60	-	1,96%
11	Kendalisodo	KS3	7,03	27,10	996,45	379	99,64	0,03	27,40	10,91	4,55	24,28	0,08	0,02	0,04	19,60	-	-	20,07	5,02	167,36	-	0,55%
12	SendangPutri	SDP	7,59	27,40	996,36	802	114,76	0,05	70,18	43,81	11,41	36,36	0,05	-	0,48	16,22	-	-	20,07	0,20	487,97	-	2,54%
13	Tangkil	TKL	7,19	21,60	997,82	340	95,25	0,21	33,03	8,61	5,36	13,91	0,02	0,02	0,34	0,23	-	-	10,02	7,02	166,00	-	-0,34%
14	Sidomukti	SDK	7,08	22,10	997,71	152	83,17	0,06	6,70	1,74	4,89	6,94	0,01	-	0,35	0,23	-	-	3,01	5,01	40,02	-	4,65%
15	Jawu	JWU	7,21	23,00	997,50	244	59,63	0,40	21,61	7,60	5,51	11,87	-	0,02	0,28	0,45	-	-	30,08	3,01	103,60	-	-4,36%
16	Sendang Pengilon	SPN	6,62	18,20	998,51	156	58,38	-	11,18	2,66	4,59	6,71	-	0,02	0,29	3,60	-	-	2,00	-	67,04	-	2,00%

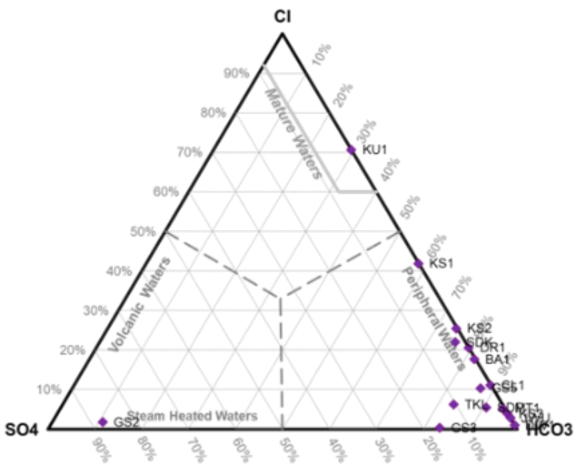

Figure 7 Cl-SO_4-HCO_3 Ternary Diagram

- Bicarbonate Water: Samples KS2, DR1, DW1, BA1, CL1, and MT1 are high in bicarbonate, indicating interaction with carbonate-rich sedimentary rocks. Carbonate rocks are indicated form the basement of the Ungaran geothermal system. These carbonate rocks are estimated to originate from the Tertiary-aged “Kerek” Formation, which consists of interbedded claystone, marl, tuffaceous sandstone, conglomerate, volcanic breccia, and limestone. The claystone, which ranges from light to dark gray and is calcareous, is mostly interbedded with siltstone or sandstone and contains Tertiary-aged fossils of foraminifera, mollusks, and colonial corals compared to the rock formation

[5]. These samples show high magnesium and calcium, suggesting mixing of hot water with meteoric water. All cold springs include in this category.

- Sulfate Water: Geothermal fluid location is part of the Gedongsongo area (GS2), which has the highest SO_4^{2-} concentration and the lowest cation concentrations (Na^+, K^+, Ca^{2+}, and Mg^{2+}). This location is formed from the condensation of steam and gas with high H_2S content. This geothermal fluid is a discharge from the upflow zone in the volcanic geothermal system.

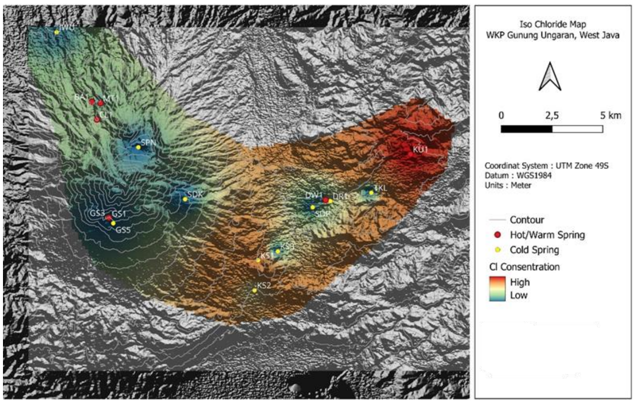

Figure 8 Iso-Chloride Map

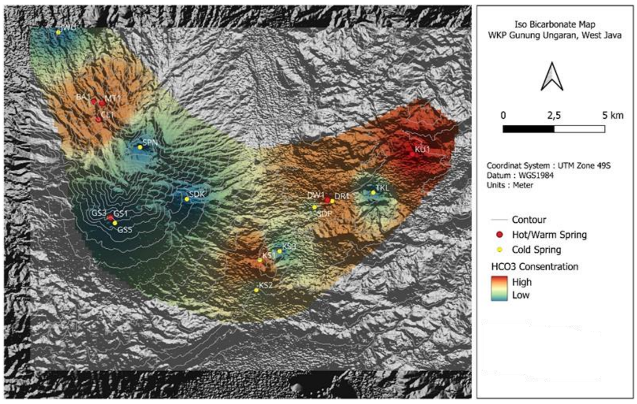

Figure 9 Iso-Bicarbonate Water Map

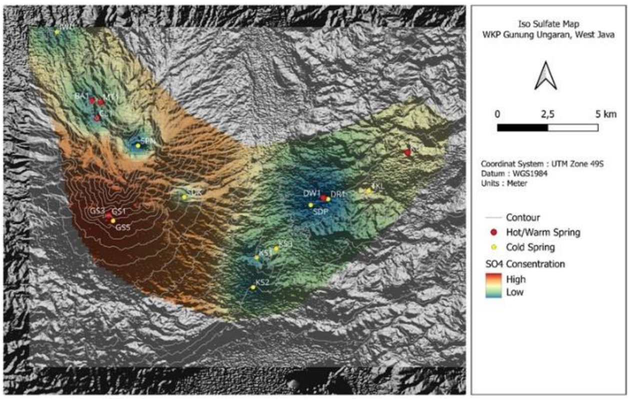

Figure 10 Iso-Sulphate Water Map

The distribution of concentrations was separated using the quantile method to reflect clearer concentration levels at all sampling points as shown in figure 8,9,10. The iso chloride, sulfate, and bicarbonate maps do not include extrapolation, to provide better delineation.

Analysis Results, based on figure 8,9,10:

- Chloride Water: High chloride content in KU1 (6,210.46 mg/kg) indicates a permeable zone controlled by geological structures.
- Bicarbonate Water: High magnesium and calcium content in KS2, DR1, DW1, BA1, CL1, and MT1 indicates mixing with meteoric water.

- Sulfate Water: High SO_4^{2-} content in GS2 indicates condensation of steam and gas with high H_2S content.

4.2 Geoindicators

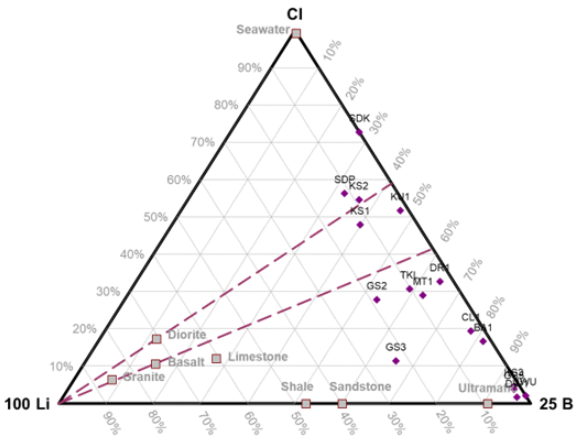

Figure 11 Cl-Li-B Ternary Diagram

Geoindicators help interpret chemical-physical processes in thermal water, reservoir similarities, and fluid flow patterns. The Cl-Li-B diagram and element ratios identify subsurface fluid processes[4]. In the Ungaran geothermal area, thermal water samples plot in the Boron-Chloride zone, indicating similar underground processes and higher B/Cl absorption linked to young volcanic activity. Consistent Cl/B ratios among samples suggest a common reservoir. The sample plots on the Cl-Li-B diagram for the Ungaran geothermal area are shown in Figure 11.

The thermal water samples from Mount Ungaran are plotted in the Boron-Chloride zone. The proximity of several sample plots indicates that the fluids have undergone similar processes underground. The samples tend to show higher B/Cl absorption, suggesting an association with young volcanic activity. This may be influenced by surface water mixing with condensate from near-surface boiling, characterized by boron enrichment. Reservoir similarity is also indicated by consistent Cl/B ratios among several manifestation samples, suggesting a common reservoir in the Ungaran field.

Cl/B Ratio: The Cl/B ratio in table 4, is calculated using the formula [4]:

$$Cl/B\ ratio = \frac{CCl(mg/kg)}{CB(mg/kg)}\ \ x\ \frac{fwB}{fwCl}$$

where C*Cl* and C*B* are the concentrations of chloride and boron, respectively, and *fwB* and *fwC* are their formula weights.

Flow Direction Interpretation: Flow direction is interpreted through Cl/B and B/Li ratios. Upflow, permeability, boiling, and high-temperature zones are mapped using geoindicators such as Na/K, Na/Ca, Mg/Ca, Cl/F, and Cl/Mg ratios [4]. These geoindicators also help determine other physical processes like dilution/mixing with seawater or groundwater.

Table 4 Dissolved Element Ratios from Ungaran Manifestation Fluid Samples:

Interpretasi Rasio		Arah Aliran		Upflow/High Permeability/Boiling/High Temperature				
		Tinggi-Rendah	*Rendah-Tinggi*	*Rasio Rendah*	*Rasio Rendah*	*Rasio Rendah*	*Rasio Tinggi*	*Rasio Tinggi*
Sampel Name	**Number**	**Cl/B**	**B/Li**	**Na/K**	**Na/Ca**	**Mg/Ca**	**Cl/F**	**Cl/Mg**
Gedongsongo	GS2	3,98	7,38	4,82	3,10	0,66	80,35	0,28
Kendalisodo	KS1	9,15	8,42	25,52	3,00	0,42	-	7,36
Kendalisodo	KS2	11,46	10,29	14,91	2,67	0,78	-	3,28
Diwak	DW1	0,13	121,69	8,34	1,48	1,25	-	0,08
Derekan	DR1	3,87	59,24	8,76	10,72	8,82	-	1,21
Kali Ulo	KU1	8,48	68,90	46,50	175,70	1,06	-	126,15
Margotopo	MT1	3,54	19,45	9,40	1,17	0,85	-	0,50
MAP-Baon	BA1	1,57	125,60	9,92	4,89	3,26	-	1,21
Curug	CL1	1,91	68,63	9,71	1,24	0,86	-	1,03
Gedongsongo	GS3	1,33	7,38	3,13	0,76	0,88	2,33	0,04
Kendalisodo	KS3	0,31	156,73	9,08	1,55	0,66	-	1,26
SendangPutri	SDP	0,38	207,49	5,42	0,90	1,03	-	0,31
Tangkil	TKL	13,26	7,38	4,41	0,73	0,43	-	0,80
Sidomukti	SDK	3,98	14,77	2,41	1,81	0,43	-	1,18
Jawu	JWU	20,33	-	3,66	0,96	0,58	-	2,71
Sendang Pengilon	SPN	0,17	-	2,49	1,05	0,39	-	0,52

Result of geoindicator calculations, then plotted in map, using the quantile method to reflect clearer levels at all sampling points as shown in figure 12,13,14

Na/K Ratio : Indicates high permeability and boiling zones.

Na/Ca Ratio : Indicates high-temperature zones.

Mg/Ca Ratio : Indicates upflow zones.

Geoindicator conclusion according to figure 12,13,14: The upflow/high permeability/boiling/high temperature zones are consistently located in Gedongsongo (GS), Sidomukti (SDK), Sendang Pengilon (SPN), and Jawu (JWU).

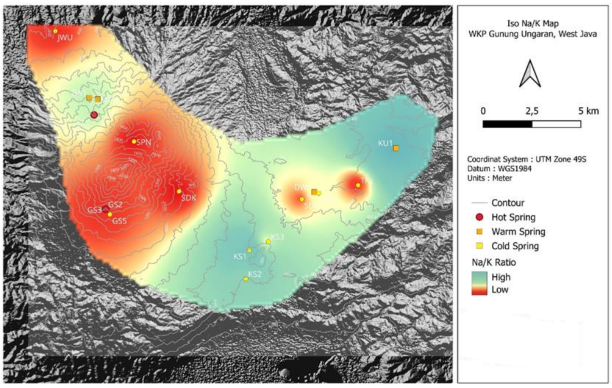

Figure 12 Iso Na/K Map

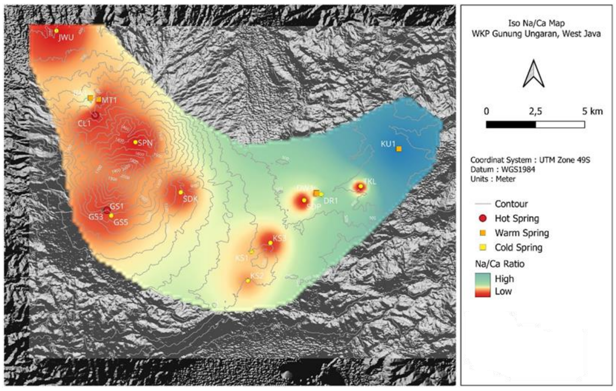

Figure 13 Iso Na/Ca Map

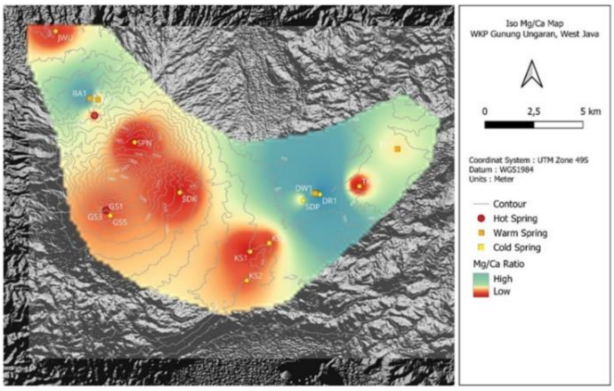

Figure 14 Iso Mg/Ca

4.3 Fluid Equilibrium (Na-K-Mg Ternary Diagram)

The Na-K-Mg diagram is useful for classifying the equilibrium level of thermal water relative to the reservoir. The classification is divided into three categories: full equilibrium, partial equilibrium, and immature water[6]. The plot of thermal and non-thermal water samples from the Ungaran geothermal area on the Na-K-Mg diagram is shown in Figure 15. Generally, the plot results indicate that most thermal and non-thermal water samples fall within the immature water zone.

Analysis Results:
Sample KU1: The plot of sample KU1 falls within the partial equilibrium area, indicating the condition of the reservoir fluid. Sample KU1, in partial equilibrium, can be used to estimate the reservoir temperature, which is approximately 160°C on the Na-K-Mg diagram.

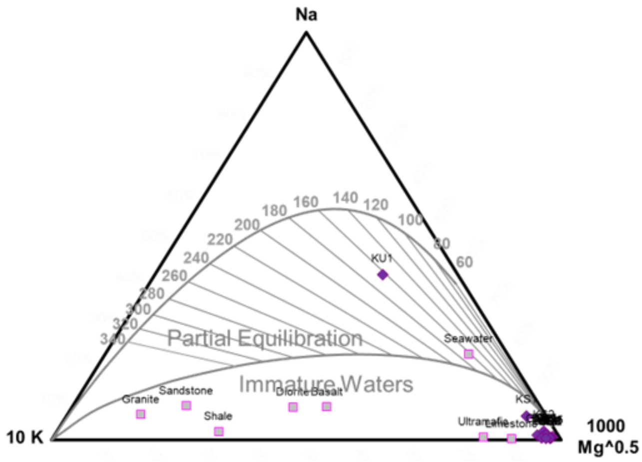

Figure 15 Na-K-Mg Ternary Diagram

Key Findings:

Most thermal water samples are in the immature water zone, suggesting significant mixing with surface water.
Sample KU1, in partial equilibrium, indicates a reservoir temperature of 160°C.

4.4 Water Geothermometers

Geothermometer calculations can use dissolved element geothermometers, such as silica/quartz, Na/K, and Na-K-Ca. These rely on concentrations of SiO_2, Na, K, and Ca, influenced by fluid-rock interactions, mixing, boiling, and rock dissolution[5]. The results for water samples from the Ungaran geothermal area are shown in Tables 5 and 6 helping estimate reservoir temperatures.

Table 1 Silica Geothermometer Temperature Calculations:

Sample Name	Amorphous Silica	Alpha Cristobalite	Beta Cristobalite	Chalcedony conductive	Quartz conductive	Quartz adiabatic	Na-K-Ca	Na-K-Ca Mg corr
Gedongsongo	57	131	81	160	181	169	94	56
Kendalisodo	44	117	67	144	168	158	157	58
Kendalisodo	38	110	60	136	160	152	85	44
Diwak	44	117	68	144	168	158	91	26
Derekan	40	112	63	139	163	154	214	5
Kali Ulo	-7	59	12	80	110	109	179	64
Margotopo	52	126	76	154	176	164	79	42
MAP-Baon	49	122	72	150	172	161	197	3
Curug	-3	64	17	86	115	114	80	41
Gedongsongo	34	106	57	132	156	149	61	51
Kendalisodo	17	86	38	110	137	133	53	53
SendangPutri	24	94	46	119	145	139	65	42
Tangkil	15	84	35	108	135	130	49	49
Sidomukti	8	76	28	99	127	124	70	70
Jawu	-7	60	12	81	111	110	56	56
Sendang Pengilon	-8	59	11	80	110	109	58	58

Table 2 Alkali Geothermometer Temperature Calculations:

Sample Name	Na/K Fournier 1979	Na/K Truesdell 1976	Na/K Giggenbach 1988	Na/K Tonani 1980	Na/K Nieva & Nieva 1987	Na/K Arnorsson 1983	K/Mg Giggenbach 1986
Gedongsongo	356	380	358	444	340	373	74
Kendalisodo	185	148	202	178	172	157	74
Kendalisodo	229	202	243	239	215	209	62
Diwak	287	280	296	327	272	281	63
Derekan	281	272	291	319	267	274	62
Kali Ulo	144	100	163	125	132	111	131
Margotopo	274	262	285	307	259	264	60
MAP-Baon	268	254	279	298	254	257	59
Curug	270	257	281	302	256	260	61
Gedongsongo	423	489	417	572	406	468	56
Kendalisodo	277	267	288	313	263	269	49
SendangPutri	340	356	344	415	324	350	54
Tangkil	368	400	369	466	352	390	55
Sidomukti	471	575	458	675	453	542	71
Jawu	397	446	394	520	380	430	57
Sendang Pengilon	465	564	453	661	447	532	65

Analysis Results:
Fluid Equilibrium: The fluid equilibrium of thermal water samples from the Ungaran geothermal area, based on the Na-K-Mg diagram (Figure 15), shows that almost all water samples fall within the immature water zone. These samples have likely undergone significant mixing with surface water, increasing Mg and decreasing Na and K, making geothermometer results unreliable.

Sample Focus: Geothermometer calculations are focused only on the sample in partial equilibrium, Kali Ulo (KU1), despite geoindicator analysis suggesting higher reservoir temperatures in Gedongsongo (GS), Sidomukti (SDK), and Sendang Pengilon (SPN).

Temperature Estimates: The estimated reservoir temperature based on the silica geothermometer for sample KU1 ranges from 110-179ºC, while the alkali geothermometer estimates a range of 125-163ºC. These results may not fully represent the volcanic geothermal system's, as the Kali Ulo (KU1) manifestation is likely in the outflow zone with a manifestation T of <50ºC (warm spring).

4.5 Stable Isotopes

Stable isotope analysis of δ18O and δ2H was conducted at PAIR, Batan. The results are in Table 7, with δ18O vs δ2H data plotted in Figure 16. The global meteoric water line equation (δ2H = 8 δ18O + 10) by Craig 1961 was used to assess the isotope shift in the water samples[7].

Table 3 Stable Isotopes δ18O and δ2H from Thermal and Non-Thermal Manifestations in the Ungaran Geothermal Area:

No	Sampel	Kode Sampel	δ18O	δ2H
1	Gedongsongo	GS2	0,19	-29,5
2	Kendalisodo	KS1	-3,46	-39,4
3	Kendalisodo	KS2	-5,17	-43,4
4	Diwak	DW1	-6,31	-46,4
5	Derekan	DR1	-5,45	-46,3
6	Kali Ulo	KU1	5,53	-26,1
7	Margotopo	MT1	-6,47	-49
8	MAP-Baon	BA1	-6,77	-52,2
9	Curug	CL1	-6,66	-48,2
10	Gedongsongo	GS3	-4,1	-38,2
11	Kendalisodo	KS3	-	99
12	SendangPutri	SDP	-3,99	-41,3
13	Tangkil	TKL	-5,56	-45
14	Sidomukti	SDK	-6,59	-50,7
15	Jawu	JWU	-5,39	-39,6
16	Sendang Pengilon	SPN	-7,51	-52,6

Analysis Results:

Stable Isotope Values: The stable isotope values of thermal and non-thermal water in the Ungaran geothermal area range from δ18O -6.77‰ to 0.19‰ and δ2H -52.2‰ to -26.1‰. The minimum δ18O and δ2H values are shown by the Sidomukti (SDK) sample, while the maximum values are shown by the Derekan (DR1) sample.

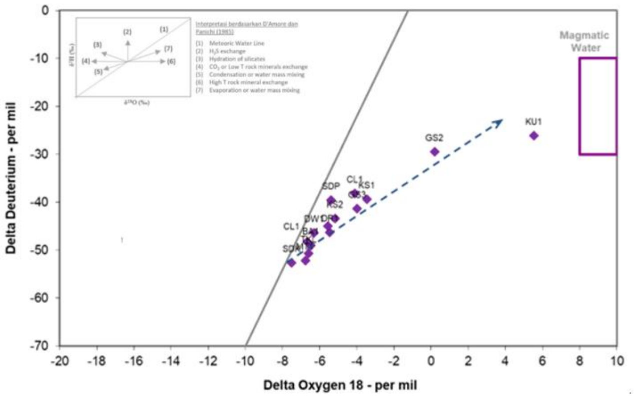

Figure 16 Stable Isotopes Plot

Plot Interpretation: The plot shows that the thermal water samples GS2 and KU1 appear to shift to the right, away from the meteoric water line, indicating water-rock interaction in the Ungaran geothermal area. Other thermal water samples are relatively close to the global meteoric water line, indicating mixing with meteoric water.

4.6 Soil Gas Geochemistry Analysis

4.6.1 Gas Origin

The N_2-CO_2-Ar diagram indicates that the gas samples from Gedongsongo (GS1, GS2, GS3, and GS4) suggest the presence of hydrothermal reservoir fluids with minor magmatic fluid mixing[8]. The N_2-He-Ar diagram supports this, indicating that the gas samples from Gedongsongo originate from a magmatic (volcanic) geothermal system.

Analysis Results:
N_2-CO_2-Ar Diagram: Indicates hydrothermal reservoir fluids with minor magmatic mixing.
N_2-He-Ar Diagram: Confirms magmatic origin of the geothermal system gases.

4.6.2 Gas Geothermometers

Several gas geothermometers are used to determine reservoir temperature, enhancing the interpretation of subsurface conditions [8]. The gas geothermometers include DAP (CO_2-H_2) and CO_2. The calculation results presented in Table 8.

Table 4 Gas Geothermometer Calculations:

Parameter	GS 1	GS 2	GS 3	GS 4
	% mole	% mole	(% mole)	(% mole)
CO2	152	172.1	169	101.1
H2	0.809	0.877	0.847	0.442
Geotermometer Gas				
T1	355.10	360.60	358.87	325.70
T2	227.16	227.21	227.20	226.98

T1 = CO2-H2 (Henley, Truesdell & Barton, 1984)
T2 = CO2 (Giggenbach & Goguel,1989)

4.6.3 Gas Geoindicators

Gas geoindicators, such as CO_2/H_2S and CO_2/H_2 ratios, show that the Gedongsongo area is a permeable or upflow zone. The ratios decrease from GS1 to GS4, indicating higher CO_2 content near GS1, thus closer to the upflow zone.

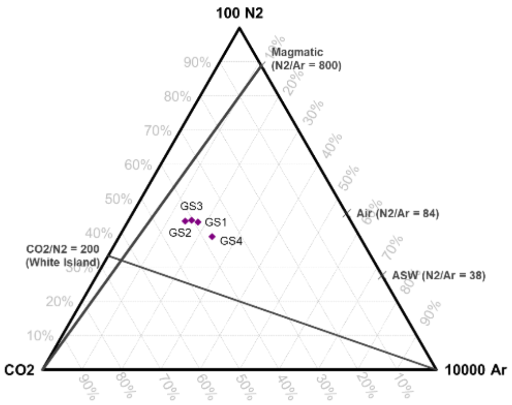

Figure 17 N_2-CO_2-Ar Diagram

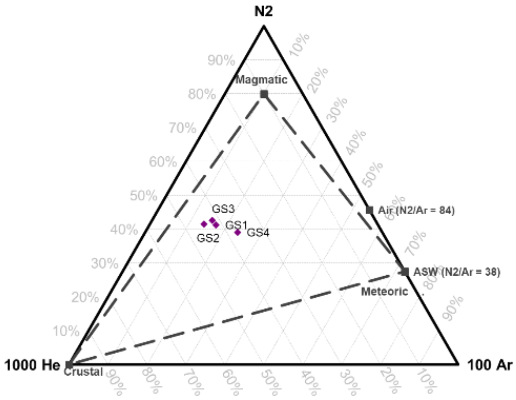

Figure 18 N_2-He-Ar Diagram

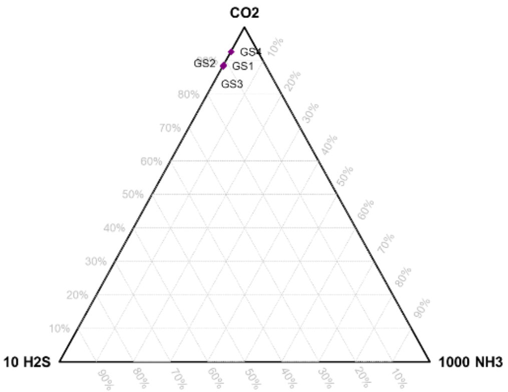

Figure 19 CO_2-H_2S-NH_3 Diagram

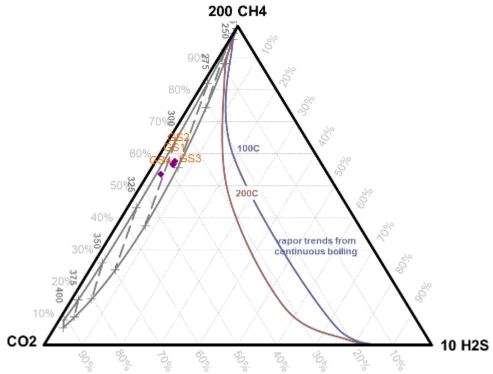

Figure 20 CH_4-CO_2-H_2S Diagram

Analysis Results:
CO_2/H_2S and CO_2/H_2 Ratios: Decrease from GS1 to GS4, indicating higher CO_2 content near GS1 and suggesting a permeable or upflow zone.
Temperature Estimates: The H_2-CO_2-Ar and H_2-Ar-CH_4-CO_2 diagrams estimate the reservoir temperature to be above 275°C, indicating a liquid-dominated reservoir.

4.7 Comprehensive Analysis according to Geochemical Data

Based on the geochemical analysis of water and gas in the Ungaran geothermal area, the following conclusions can be shown in figure 22 (cross section of blue line in figure 21):

1. Upflow Zone: The upflow zone is characterized by sulphate-type water as a result of vapor CO_2 condensation around the Gedongsongo area. This is confirmed by the presence of fumarole manifestations with high CO_2 content,

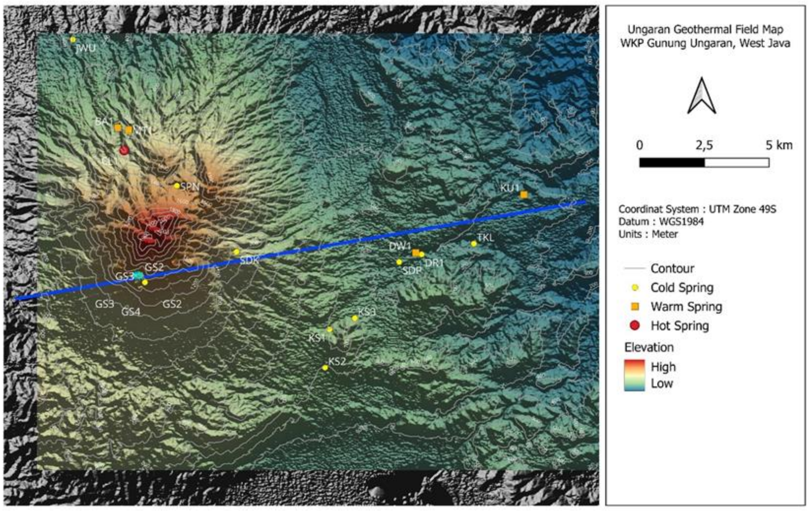

Figure 21 Conceptual Model Cross-section (in blue line)

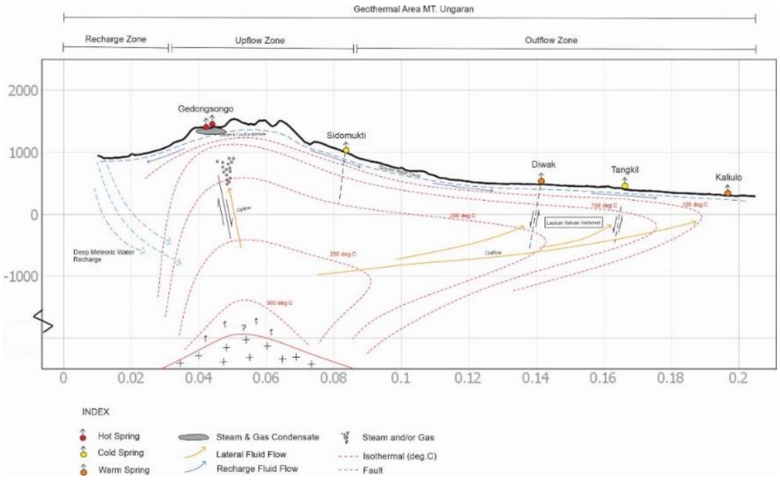

Figure 22 Conceptual Model of Mt. Ungaran

indicating a permeable zone controlled by geological structures such as normal faults, which also contribute to the formation of the Ungaran Caldera.

2. Outflow Zone: The outflow zone is located in Sidomukti-Tangkil, characterized by bicarbonate-type water resulting from the interaction of boiling geothermal fluids with carbonate rocks forming HCO_3. The carbonate rocks are indicated to be the basement of the Ungaran geothermal system, likely originating from the Tertiary-aged Kerek Formation, composed of interbedded claystone, marl, tuffaceous sandstone, conglomerate, volcanic breccia, and limestone.
3. Geoindicators: The Li-Cl-B geoindicators suggest that the water samples tend towards higher B/Cl absorption (high boron composition), indicating an

association with young volcanic activity. This is confirmed by the geological condition of Mount Ungaran, composed of Quaternary volcanic rocks.

4. Temperature Estimates:
   - Water Geothermometer (Silica): Estimated reservoir temperature range of 110-179°C.
   - Gas Geothermometer (CO_2): Estimated reservoir temperature range of 220-270°C.

5 Conclusions

Geochemical analysis of the Ungaran geothermal system identifies distinct upflow and outflow zones. The upflow zone near Gondong Sangu has sulfate-type water from CO_2 steam condensation, confirmed by high CO_2 fumaroles, indicating a permeable zone controlled by normal faults, contributing to the Ungaran Caldera formation.

The outflow zone from Sidomukti to Tangkil features bicarbonate-type water from geothermal fluid boiling with carbonate rocks. These carbonate rocks, likely from the Tertiary-aged Kerek Formation, form the system's basement.

Geoindicator analysis with Li-Cl-B samples shows high boron absorption, indicating younger volcanic activity, confirmed by Quaternary volcanic rocks. Boiling and mixing processes are evident in the geothermal manifestations, with higher chloride content than estimated in the reservoir.

Reservoir temperatures are estimated at 110-179°C (silica geothermometer) and 220-270°C (CO_2 geothermometer), providing essential data for further exploration and development of the Ungaran geothermal system.

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