

RESEARCH ARTICLE

The Water Chemistry Geothermal of Ranang-Kasimbar Hot Springs, Parigi Moutong Regency, Central Sulawesi, Indonesia

Anna Yushantarti^{1, 2*}, Dudi Hermawan¹, Dwi Fitri Yudiantoro²

¹ Center for Mineral Coal and Geothermal Resources (PSDMBP) Jl Soekarno Hatta 444 Bandung Jawa Barat Indonesia.

² Program Studi Magister Teknik Geologi, Fakultas Teknologi Mineral dan Energi, Universitas Pembangunan Nasional "Veteran" Yogyakarta.

* Corresponding author : untuk.anna@gmail.com, anna.yushantarti@esdm.go.id
Tel.: +81-72-867-1686; fax: +81-72-867-1658 [Tel./fax of the corresponding author]
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Abstract

The Ranang-Kasimbar geothermal system in Central Sulawesi is located within the West Sulawesi Mandala, an area significantly influenced by the active tectonic zone of the Palu-Koro Fault that controls the emergence of surface manifestations. This study aims to characterize the water chemistry of the Ranang-Kasimbar hot springs through surface geological mapping and fluid geochemical analysis, which includes cation-anion analysis, stable ¹⁸O and ²H (D) isotopes, and geothermometer calculations for subsurface temperature estimation. The geological conditions of the study area are composed of Cretaceous-Eocene metamorphic rocks, Tertiary intrusive rocks, and Quaternary sedimentary rocks, with structural controls in the form of north-south trending strike-slip faults and a normal fault system that forms a central depression zone as controls for the emergence of manifestations. Field data identified hot springs with surface temperatures ranging from 55–61°C and alkaline pH (~9). Geochemical analysis results classify the geothermal fluid as a chloride type indicating a deep reservoir origin, with a Cl/B ratio indicating strong interaction with igneous rocks and partial equilibrium conditions. Isotope analysis indicates a dominant mixing with meteoric water with very low oxygen-18 enrichment. Reservoir temperature estimation using a Na-K geothermometer and a silica-enthalpy mixing model indicates a minimum temperature of 130°C, thus categorizing it as a medium enthalpy system. This geothermal system is controlled by secondary permeability from normal and strike-slip fault structures, with the heat source suspected to originate from residual heat from Plio-Pleistocene andesitic intrusions.

Keywords: Geothermal, Hot Springs, Geochemistry, Sulawesi

1. Introduction

Geothermal settings across the Indonesian archipelago are fundamentally split by their heat sources. Volcanic-hosted fields are genetically linked to Quaternary volcanism along the main arc systems (Sumatra, Java, Bali, Nusa Tenggara, Banda, and North Sulawesi), whereas non-volcanic provinces rely on deep structural circulation within magmatically inactive terrains like Kalimantan, Papua, Buru, and most of Sulawesi (Yushantarti and Setiawan, 2015).

Geothermal surface manifestations, particularly hot springs, present significant potential for both power generation and direct use (Fatimah et al., 2025). The distribution and viability of geothermal resources are intimately linked to regional tectonic settings (Tzanis et al., 2020 in (Manyoe and Hutagalung, 2022)). Geothermal fields encompass regions where active subsurface domains manifest at the surface via geysers, fumaroles, or boiling mud ponds, features (Kaasalainen and Stefánsson, 2012) characteristically bound to active volcanic provinces. Alternatively, non-manifesting geothermal systems can be identified by high terrestrial heat flow and steep geothermal gradients, confirming that energy production remains feasible even in hidden or blind reservoirs (Boldizsár, 1943 in (Aditya, 2017)).

However, not all thermal discharges meet the technical criteria required for feasibility assessments regarding geothermal energy extraction. Consequently, geochemical surveys are utilized to analyze discrete hot spring samples, thereby characterizing the subsurface water chemistry and defining the underlying reservoir type (Fatimah et al., 2025; Yushantarti et al., 2024; Yushantarti and Hermawan, 2023, 2022; Yushantarti and Mustofa, 2016; Yushantarti and Setiawan, 2015; Yushantarti and Sulaeman, 2021). Geothermal fluids come from several distinct water sources, including rainwater or surface water (meteoric), water trapped in rock pores (connate), and deeper metamorphic or magmatic (juvenile) waters (Nicholson, 1993 in Iswahyudi et al., 2020). Additionally, early work by Ellis and Mahon (1967 in (Iswahyudi et al., 2020)) notes that these fluids are generated as surface groundwater flows through and chemically reacts with the hot surrounding bedrock.

The Ranang-Kasimbar geothermal area is located in Kasimbar District, Parigi Moutong Regency, Central Sulawesi Province, approximately 140 km north-northeast of Palu. Initial geothermal surveys of Tambu in 2008 identified Ranang hot springs as the primary surface manifestation, with temperatures of 60°C, discharge of 1 liter/second, and conductivity of 430 µS/cm at an elevation of 12 meters. Previous study in the area includes

geological work by Van Bemmelen (Bemmelen, 1949), regional geology of Palu (Sukamto et al., 1973), alteration type of Kasimbar (Salamah et al., 2014) and inventory hot springs of Ranang (Kusnadi and Anna Y., 2008). Despite these studies, no detailed geological and geochemical interpretation of the Ranang-Kasimbar geothermal system existed. So, continuing the 2008 inventory, a more comprehensive study was conducted in 2011 involving expanded surface mapping, sampling, and reanalysis. This article addresses this gap by analyzing the geochemical characteristics to interpret the geothermal system, emphasizes the interpretation of geothermal water in hot springs of Ranang-Kasimbar. It is important to understand the characteristic of hot spring in order to identified the hot springs and could be the foundation for next study (Yushantarti and Hermawan, 2022) and utilization development of Ranang-Kasimbar geothermal area.



Fig. 1. Location map of the study area of Ranang Kasimbar

2. Methods

The methods are using inventory of surface geothermal features, sampling the waters of them, classifying the type of manifestation, and interpreting for thermal water analysis for type of the water and consideration the temperature reservoir with water geothermometer. The characteristics were identified from the type of manifestations and the result of water analysis. Water samples were analyzed at laboratory of Center for Mineral, Coal, and Geothermal Resources. This interpretation also combines secondary data from several literatur

3. The Geological Background

Geothermal systems in typical volcanic arc settings are generally driven by volcanic activity. In contrast, within complex geological terrains like Sulawesi, hydrothermal configurations are influenced by a combination of volcanic activity and regional structural geological features (Draniswari and Hendrawan, 2016).

The Ranang-Kasimbar area is located in West Mandala Sulawesi, which is affected by the tectonic activity of the Palu-Koro Fault. The Ranang-Kasimbar geothermal area is physiographically situated in the neck of Sulawesi Island, which is composed of a complex of Cretaceous-Eocene metamorphic rocks, Tertiary intrusive rocks, and Quaternary sedimentary rocks.

The developing structures consist of strike-slip faults trending north-south and normal faults trending southwest-northeast, northwest-southeast, and west-east, which cause the formation of a depression zone in

the center of the study area and control the emergence of the Ranang hot spring manifestations.

The formation of the geothermal system in the Ranang-Kasimbar area is thought to be related to young magmatic activity along the structural zone in the form of andesitic dikes that still retain heat. The youngest magmatic activity consists of andesitic dikes that formed 1.7 million years ago. The structures that developed in the study area are influenced by the activity of the Palu-Koro Fault, which consists of normal faults and strike-slip faults.

Surface heat loss in the Ranang-Kasimbar area is approximately 123 kWth. The heat source is thought to be residual heat from a magma chamber associated with young magmatic activity in the form of andesitic dikes.

The cap rock is thought to be found in schist and granite, which are believed to have undergone alteration. The rock permeability serving as a reservoir in the Ranang-Kasimbar geothermal system is estimated to occur in fractured and permeable schist and granite.

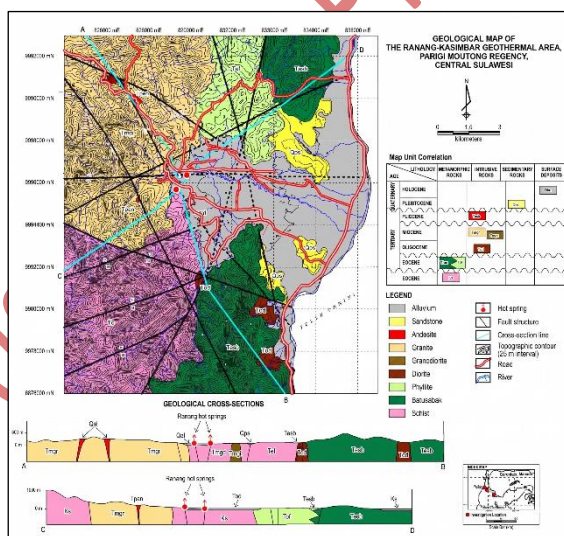


Fig 2. Geological Map of Ranang-Kasimbar Geothermal Area

4. Geothermal Surface Features

Geothermal surface features that appear at the study area consist of a hot spring complex in West Kasimbar Village with temperatures of 55-61°C, pH around 9, discharge <0.5 l/s, tasteless, smell not too sharp, appearing in three point in the adjacent distance range (\pm 50-1000m). The hot springs are Ranang-Kasimbar 1,2, and 3 hot springs. The Physical Characteristics of Hot springs at Ranang-Kasimbar, Central Sulawesi, Indonesia in table-1.

5. Water Analysis Result

As deep aquifer waters ascend, they migrate through various rock layers and experience temperature increases at depth. The resulting concentration of trace elements and dissolved constituents is strictly dictated by the geochemical composition of the subsurface reservoir, alongside fluid temperature, hydrodynamic flow rates, pathway lengths, and rock-water residence times (Erfurt, 2021; Hurwitz et al., 2025; Mahon et al., n.d.; Morales-Arredondo et al., 2018; Pauccara, n.d.).

The results of the chemical analysis of hot springs in the Ranang-Kasimbar geothermal area are shown in table 2 as follows.

5.1 Ranang-1 hot spring

The composition of Ranang-1 (pH 9.42 and electrical conductivity 542 $\mu\text{S}/\text{cm}$) is dominated by Cl (59.58 mg/l), Na (83.90 mg/l), SiO_2 (52.97 mg/l), and HCO_3 (40.46 mg/l), the concentrations of other chemical compounds tend to be lower compared to these components, including: 0.97 mg/l B; 0.75 mg/l Ca; 1.31 mg/l K; 1.49 mg/l Li; 39.50 mg/l SO_4 ; and 0.16 mg/l Mg.

5.2 Ranang-2 hot springs

The composition of Ranang-2 (pH 9.57 and electrical conductivity 436 $\mu\text{S}/\text{cm}$) is also dominated by Cl (63.50 mg/l), Na (72.80 mg/l), SiO_2 (65.95 mg/l), and HCO_3 (40.72 mg/l), the concentration of other chemical compounds tends to be lower compared to these components, including: 0.26 mg/l B; 0.16 mg/l Ca; 1.02 mg/l K; 1.94 mg/l Li; 41.03 mg/l SO_4 ; and 0.04 mg/l Mg.

5.3 Ranang 3 hot springs

The composition of Ranang-3 (pH 9.31 and electrical conductivity 691 $\mu\text{S}/\text{cm}$) is also dominated by Cl (165.77 mg/l), Na (133.80 mg/l), SiO_2 (52.46 mg/l), HCO_3 (32.57 mg/l), and SO_4 (56.79 mg/l), the concentrations of other chemical compounds tend to be lower compared to these components, including: 0.75 mg/l B; 6.70 mg/l Ca; 2.64 mg/l K; 1.70 mg/l Li; and 0.13 mg/l Mg.

5.4 Cold springs Peningka

Two cold spring samples from Peningka showed a neutral pH tending to alkaline (9.27), an electrical conductivity of 463 $\mu\text{S}/\text{cm}$, a concentration of chemical compounds lower than the concentration contained in the hot water sample, and dominated by Na (21.45 mg/l), SiO_2 (44.28 mg/l), HCO_3 (214.31 mg/l), and Ca (69.14 mg/l), the concentrations of other chemical compounds

tend to be lower compared to these components, including: 7.50 mg/l Cl, 0 mg/l B; 2 mg/l SO_4 ; 0.76 mg/l K; 0.03 mg/l Li; and 18.81 mg/l Mg.

5.5 Posona Cold springs, Peningka River Water, and TSM Village River Water

Three cold spring samples originating from Ranang showed neutral pH (7.11-8.02), electrical conductivity of 219-295 $\mu\text{S}/\text{cm}$, concentrations of chemical compounds lower than those contained in hot water samples, and dominated by 136.71-187.89 mg/l HCO_3 ; 29.67-62.12 mg/l SiO_2 ; 7.50-10 mg/l Cl; 7.85-18.49 mg/l Na; and 6.65-12.10 mg/l Mg.

The Laboratory Result of Water Analysis at Ranang-Kasimbar, Central Sulawesi, Indonesia in table-2.



Fig. 3. Field photographs of thermal spring manifestations in the Ranang geothermal area. Top left: Ranang-1 hot springs displaying a surface temperature of 61.0°C. Top right: Natural discharge vent of Ranang-2 at 57.4°C. Bottom: Ranang-3 outflow channel recording 55.7°C. These thermal waters represent surface expressions of the underlying hydrothermal system.

Table 1. Physical Characteristics of Hot springs at Ranang-Kasimbar, Central Sulawesi, Indonesia

No.	Name of Hot Springs	Coordinate (UTM)		Elev (m)	Tempera ture Hot springs (°C)	Tempera ture of Air (°C)	pH	Flow Rate (L/sec)	Conducti vity ($\mu\text{S}/\text{cm}$)	Explanation
		X (m)	Y (m)							
1	Ranang-1, Dusun Lebaksuren, Desa Kasimbar Barat, Kecamatan Kasimbar	829864	9986415	54	61.8	30.5	9.42	0.5	542	Area of approx. 2×2 m, clear color, tasteless, smells of sulfur not too sharp, comes out on alluvium, there are thin travertine deposits on rocks through which hot spring passes, there are air bubbles which are not too strong.
2	Ranang-2, Dusun Lebaksuren, Desa Kasimbar Barat, Kecamatan Kasimbar	829780	9986464	52	57.4	28.7	9.57	0.3	436	Area of about 0.5×0.5 m, clear color, tasteless, odorless, out on the alluvium, located 50 m from the Ranang-1 hot spring location, on the edge of the Tompis river, there are weak air bubbles, no travertine and no silica sinter.
3	Ranang-3, Dusun Mayapo, Desa Kasimbar Barat, Kecamatan Kasimbar	829375	9985724	56	55.7	28.4	9.31	0.2	691	About 0.5×0.5 m wide, clear in color, tasteless, odorless, comes out on the alluvium plain, is about 750 m from the Ranang-1 hot spring location, there are weak air bubbles, no travertine and no silica sinter, out of the rock.

Table 2. Laboratory Result of Water Analysis at Ranang-Kasimbar, Central Sulawesi, Indonesia

Sampel	Unit	hot springs Ranang-1	hot springs Ranang-2	hot springs Ranang-3	Coldsprings Peningka	coldsprings Posona	river water of Peningka	river water of TSM
pH		9.42	8.57	9.27	9.27	7.11	08.02	7.83
EC	($\mu\text{S}/\text{cm}$)	542	426	692	463	290	219	295
SiO ₂	(mg/L)	52.97	65.95	59.46	44.28	62.12	29.67	44.28
B	(mg/L)	0.97	0.26	0.75	0.00	0.00	0.00	0.00
Al ³⁺	(mg/L)	0.07	0.07	0.07	0.08	0.04	0.08	0.04
Fe ³⁺	(mg/L)	0.08	0.07	0.01	0.02	0.27	0.04	0.01
Ca ²⁺	(mg/L)	0.75	0.16	6.70	69.14	24.88	36.38	29.78
Mg ²⁺	(mg/L)	0.16	0.04	0.13	18.81	12.08	6.65	12.10
Na ⁺	(mg/L)	83.90	72.80	133.80	21.45	17.50	7.85	18.49
K ⁺	(mg/L)	1.31	01.02	2.64	0.76	04.05	0.76	2.52
Li ⁺	(mg/L)	1.49	1.94	1.70	0.03	0.49	0.08	0.06
As ³⁺	(mg/L)	0.00	0.00	0.50	0.00	0.00	0.00	0.00
NH ₄ ⁺	(mg/L)	0.66	0.41	0.57	0.07	2.19	0.07	0.09
F ⁻	(mg/L)	0.15	0.31	0.31	0.00	0.00	0.00	0.00
Cl ⁻	(mg/L)	59.58	63.50	165.77	7.50	10.00	7.50	7.50
SO ₄ ²⁻	(mg/L)	39.50	41.03	56.79	2.00	2.00	5.00	2.50
HCO ₃ ⁻	(mg/L)	40.46	40.72	32.57	214.31	180.79	136.71	187.89
CO ₃ ²⁻	(mg/L)	18.50	0.00	0.00	49.38	0.00	0.00	0.00
meq cation		4.00	3.52	6.55	5.97	3.31	2.75	3.37
meq anion		3.79	3.33	6.41	5.41	3.29	2.56	3.34
ion balance		2.65	2.75	1.10	4.89	0.36	3.65	0.38
Cl/B		61.42	244.23	221.03	-	-	-	-

6. Classification of The Fluids

The accuracy of the analysis process for major cations and anions from hot springs, indicated by ion balance (IB) values of less than 5% for hot springs and cold springs samples, this is an indication that the analysis results can be used in further geochemical interpretation, in hot springs samples in Ranang has an ion balance of less than 5% so it can be used for further interpretation.

Based on the results of hot spring and cold springs analysis (figure 4), in the Cl-SO₄-HCO₃ triangle diagram (Giggenbach, 1991), Ranang hot springs is located in the Chloride zone position, while cold water as a comparison is located in the bicarbonate position. Ranang-3 hot springs has a higher concentration of chloride ions than the other 2 hot springs, where in Ranang-1 and Ranang-2 bicarbonate ions are also the major anion after chloride, the presence of bicarbonate is thought to be associated with rising geothermal fluids containing gas, mainly CO₂ then condenses in shallow aquifers,

Based on the Cl-Li-B triangle diagram (Giggenbach, 1991) (figure 4) Ranang hot springs is in the Li to Cl zone, where there are indications of hot springs interacting with igneous rocks at depth before reaching the surface. The Cl/B ratio is generally used to indicate the common reservoir source (Nicholson, 1993) of a fluid. The difference in the value of this ratio depends on the lithology and adsorption of B into the clay layer during the fluid flow process. In table 2, it can be seen that there is a positive correlation between Ranang 1, 2 and 3, which indicates that all three come from the same source.

Based on the Na-K-Mg triangle diagram (Giggenbach, 1991, 1986) (figure 4), the Ranang hot springs are located in Partial equilibrium, as an indication of manifestations

that appear to the surface shortly after reaching equilibrium there are indications of mixing with surface water, and when pulled to Na-K and K-Mg are in a straight line and fall at almost the same point at moderate temperatures (around 120-130°C).

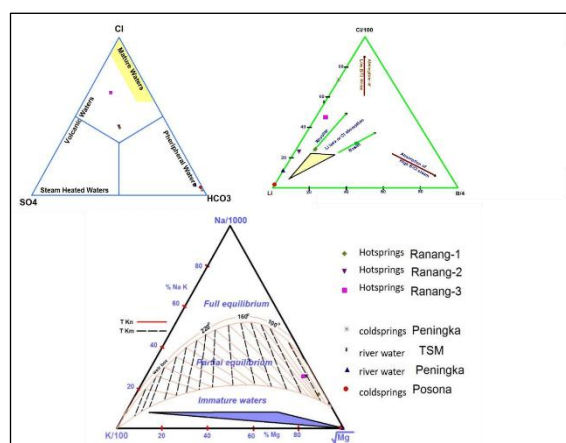


Fig 4. Cl-SO₄-HCO₃, The relative of Cl-Li-B, The relative of Na-K-Mg Ternary Diagram

7. Water Isotope

In general, geothermal fluids will undergo the process of adding the oxygen-18 isotope from water origin, in this case is meteoric water (Craig, 1963 in (Nicholson, 1993)). Thermal waters from discrete geographical areas are characterized by varying levels of oxygen-18 enrichment ($\delta^{18}\text{O}$ shift) when plotted against the GMWL framework

(Hurwitz et al., 2025). Enriched $\delta^{18}\text{O}$ shifts away from the Global Meteoric Water Line (GMWL) serve as an indicator of elevated reservoir temperatures within hydrothermal zones (Hurwitz et al., 2025).

The data is plotted into the diagram relationship between oxygen-18 isotope ($\delta^{18}\text{O}$) versus deuterium ($\delta^2\text{H}$) and compared with the line of Indonesia's local meteoric water (BAFI-BATAN, 1984 in (Sidauruk P. et al., 2000)). The graph of the relationship between the isotope oxygen-18 ($\delta^{18}\text{O}$) to deuterium ($\delta^2\text{H}$) with the equation for local meteoric water in Java (meteoric water line) $\delta^2\text{H} = 8 \delta^{18}\text{O} + 14$. The results of the analysis of the concentrations of ^{18}O and ^2H (D) isotopes from the Ranang-3 hot springs sample tend to stay away from the meteoric water line, this reflects that the hot springs in the Ranang-3 area come from deep water. As a comparison, isotope measurements for cold water were also carried out where the cold springs plotting results were on the meteoric line, while the hot water in Ranang-1 and Ranang-2 had a tendency to approach the meteoric line indicating dominance of mixing with surface water. Isotope values as in the following table:

Table 3: Isotope Analysis Data of Ranang Kasimbar Sulawesi

No.	Sampel	^{18}O (‰)	D (‰)
1	Hot springs Ranang 1	-7.58	-48.9
2	Hot springs Ranang 2	-7.58	-48.1
3	Hot springs Ranang 3	-6.93	-48.2
4	Cold springs Posona	-6.69	-40.9
5	Cold springs Peningka	-7.43	-48.0

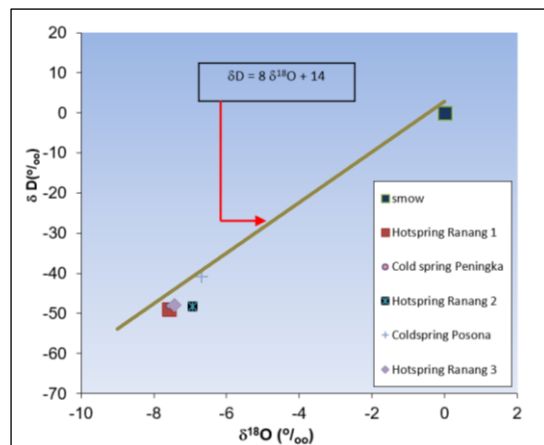


Fig 5. The diagram of water isotope at Ranang Kasimbar, Central Sulawesi

8. Geothermometry

Estimating reservoir temperature is the main objective in the chemical characteristics of hot springs. Some of the approaches used to determine a geothermometer can be through the concentration of solutes in water, isotopes, or a gas geothermometer. The solute geothermometer is based on fluid-mineral equilibrium that depends on temperature with several assumptions (Ellis, 1979; Fournier, 1977; Fournier et al., 1974; Truesdell, 1976; and White, 1970, in (Nicholson, 1993)). In other words, the reaction must be fast enough to maintain the conditions equilibrium that has occurred in the reservoir.

Cation geothermometry estimates geothermal reservoir temperatures based on dissolved ion ratios, assuming deep fluid-rock equilibrium. However, the

accuracy of these solute geothermometers can be compromised. Factors such as cold groundwater mixing or incomplete chemical equilibration at depth frequently yield high levels of uncertainty in the calculated reservoir temperatures (Gan et al., 2019; Zhang et al., 2019).

Silica (SiO_2) geothermometry was utilized to calculate minimum reservoir temperatures, as this method provides reliable estimates for low-temperature systems characterized by fluid-rock silica equilibrium (Arnósson, 1975; Fournier, 1977; Karingithi, 2009 in (Morales-Arredondo et al., 2018)).

Plotting on the $\text{Cl-SO}_4\text{-HCO}_3$ triangle diagram, hot springs generally belongs to the chloride type, on the Na-K-Mg diagram it is located in the partial equilibrium zone, the low concentration is also of Cl-Li-Boron, indicating the formation of hot springs in the investigation area occurred in at low temperatures, a water geothermometer that may be applied is the Na-K geothermometer, (referring to Giggensch, 1988 in (Nicholson, 1993)) through the equation: $T^\circ\text{C} = [1390 / ((\log \text{Na}/\text{K} + 1.75) - 273)]$, a temperature of 130°C is obtained. Based on the geothermometer calculation results this water, to estimate the subsurface temperature with a minimum value that may be related to the reservoir temperature. The subsurface temperature of the Ranang-Kasimbar geothermal area using the Na-K (Giggensch) geothermometer was obtained 130°C .

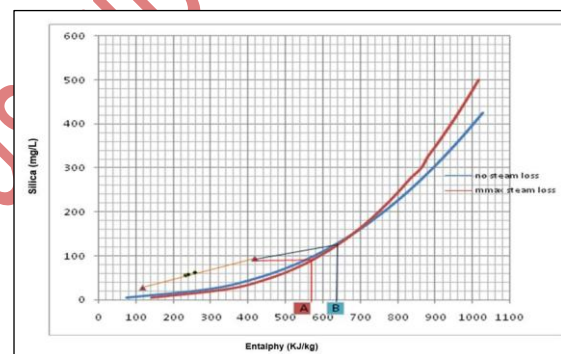


Fig 6. The diagram of water isotope at Ranang-Kasimbar, Central Sulawesi

The Estimation of the subsurface temperature of the Ranang-Kasimbar geothermal area could be also using the silica-enthalpy mixing model as follows:

In some conditions, the concentration of dissolved silica from hot water mixed with surface water can be used to determine the reservoir temperature (Fournier, 1977 in (Nicholson, 1993)). A simple method is to plot the silica concentration versus the enthalpy of the hot water. On the silica-enthalpy diagram, the reservoir temperature is estimated from the intersection of the mixing line (joining the cold-water line to the hot-water line) with the solubility curve of quartz (Fournier, 1977 in (Nicholson, 1993)). From the diagram above, it is obtained: for A: if it is assumed that there is separation of steam before mixing, the enthalpy value is around 560 kJ/kg or equivalent to the reservoir temperature around 133°C . For B: it is assumed that there is no vapor separation before mixing occurs, the enthalpy value is around 640 kJ/kg or equivalent to the reservoir temperature around 148°C .

Thus, the estimated minimum temperature of the Ranang-Kasimbar geothermal reservoir using a Na-K geothermometer and silica-enthalpy diagrams is estimated to be in the range of $129\text{-}133^\circ\text{C}$, so it is

estimated that the minimum temperature of the Ranang-Kasimbar geothermal reservoir is 130°C.

9. Conclusion

The Ranang-Kasimbar geothermal system is a type of magmatic system associated with the presence of igneous rocks in the form of andesite cracks. The residual heat from this magmatic activity supports the geothermal system's activity, thus forming a reservoir in the Ranang-Kasimbar geothermal area.

Geothermal surface features in the Ranang-Kasimbar area are hot springs as a result of the interaction process of geothermal fluids which flow by convection towards the surface with a chloride type (indication of fluids from geothermal reservoirs/from depth), neutral pH tends to be alkaline (around 9), and indicates fluid interactions with igneous rocks at depth. The hot springs generally belongs to the chloride type, on the Na-K-Mg diagram it is located in the partial equilibrium zone. The domination of surface water is also evident in the isotope analysis results, which only slightly enriches oxygen-18. This shows that there is only a partial equilibrium process in the process of interaction of the hot fluid with the surrounding rock. The minimum temperature of the geothermal reservoir in Ranang is estimated to be 130°C.

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