

RESEARCH ARTICLE

## Geochemical Analysis of Geothermal Manifestations in Buton Island, Southeast Sulawesi, Indonesia

Citra Aulian Chalik<sup>1,\*</sup>, Muhammad Hardin Wakila<sup>2</sup>, Firdaus<sup>3</sup>, Rafli Maulana<sup>4</sup>, Andi Fahdli Heriansyah<sup>5</sup>

<sup>1</sup> Mining Engineering Program Study, Industrial Technology Faculty, Indonesian Muslim University, Makassar, Indonesia

\* Corresponding author : citraaulian@umi.ac.id  
Tel.: +6285399000330  
Received: Dec 7, 2025; Accepted: Sep 21, 2026.  
DOI: 10.25299/jgeet.2026.11.3.25952

### Abstract

The geochemical characteristics of non-volcanic geothermal energy in Buton Island are still rarely studied despite its location in an active tectonic zone. This study explores the geochemical features of geothermal manifestations in Buton Island, Indonesia, with the aim of identifying fluid characteristics and predicting subsurface temperatures from geothermal manifestations in the study area. Water samples collected from five manifestation locations were analyzed for major cations ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) and anions ( $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ) using atomic absorption spectrophotometry,  $\text{HCO}_3^-$  concentration through titrimetric analysis, and  $\text{SiO}_2$  content through spectrophotometry. The ternary diagram of  $\text{Cl-SO}_4\text{-HCO}_3$  indicates the type of bicarbonate fluid, while the ternary diagram of  $\text{Na-K-Mg}$  indicates the characteristics of immature geothermal water in the reservoir. Interpretation is clarified through specific findings in the Gonda Baru and Karede samples that show characteristics of a chloride-bicarbonate mixture type due to the influence of seawater intrusion or intensive rock-water interaction during long residence times in the reservoir. Geothermometers such as  $\text{Na-K-Ca}$  and  $\text{K-Mg}$  are used to estimate reservoir temperatures. The estimated reservoir temperature indicates a relatively low-temperature system, ranging from  $70^\circ\text{C}$  to  $120^\circ\text{C}$ . The implications of identifying this low-temperature system indicate that geothermal resources on Buton Island are ideal for direct use, such as in the agro-system sector (drying agricultural products), tourism/therapeutic hot springs, or small-scale binary cycle power plants. This research provides an important scientific contribution as a basic reference in the strategy for developing non-volcanic renewable energy potential in Eastern Indonesia.

**Keywords:** Geochemical Analysis, Geothermal Manifestations, Buton Island, Fluid Type, Reservoir Temperature.

### 1. Introduction

The move toward renewable energy sources in Indonesia has become a pressing concern in recent years. Indonesia is home to vast geothermal resources that could play a key role in the country's energy transition (Sahdarani et al., 2020). Geothermal energy is used in many ways, including electricity production and various non-electric uses like heating spaces, drying agricultural and livestock products, operating greenhouses, warming water pools, powering geothermal spas, and applications with medicinal benefits (Al-Shareef et al., 2018; Lund, 2010). The effective utilization of these resources requires a comprehensive understanding of the fluid characteristics and geochemistry of geothermal systems (Arnósson et al., 2006; Finster et al., 2015; Lakroun et al., 2022). Regions with geothermal potential routinely exhibit surface geothermal manifestations, such as warm springs, hot springs, fumaroles, and solfataras (Adams et al., 2015; Arifin et al., 2023). These surface features can deliver valuable insights to the underlying geothermal system (Febrianto et al., 2019).

Sulawesi lies at the western end of the active Pacific Plate, within the collision zone between the Eurasian, Indian-Australian, and Pacific Plates. (Abdullah et al., 2020; Idris, 2010). The dynamic tectonic activities in this region has led to the formation of numerous active volcanoes, which in turn have given rise to an abundance of geothermal resources across the island (Radja, 1970). Previous geological and geochemical investigations have identified the geothermal

system in Sulawesi as being associated with the regional fault system (Abdullah et al., 2020). The geothermal energy potential in Sulawesi is mainly concentrated in developed resources. The Quaternary volcanic system in the North Arm dominates with a capacity of 875 MWe, or approximately 41% of the island's total resources (Idris, 2010). In contrast, the remaining resources of 1,299 MWe are distributed across the non-volcanic arms, where individual capacities are relatively small; for example, the southeastern arm accounts for only 14% of the total potential (Arrofi et al., 2022). Geothermal potential of 14% of the total potential or around 10–80 MWe compared to volcanic which reaches 600 MWe can be a direct geothermal utilization or as a small-scale binary cycle power plant, this is the basis for why geochemical research on Buton Island (as part of this non-volcanic system) is very crucial to be carried out. There are three locations of geothermal manifestations in this region: Kaongkeongkea, Gonda Baru, Kabungka, Hangka, and Karede. Geothermal systems are complex, active environments that commonly display diverse geochemical characteristics. These traits can provide useful insights into the source, development, and behavior of geothermal reservoirs beneath the surface. (Millayanti et al., 2019; Shah et al., 2021; Sulistyanto et al., 2019).

This study examined the geochemical composition of geothermal water, focusing on cation and anion concentrations, from geothermal manifestations in Buton, Indonesia. The objective of this analysis is to ascertain the fluid type and the potential origin of the geothermal fluids.

The cations (K, Na, Ca, and Mg) and anions (Cl, HCO<sub>3</sub>, and SO<sub>4</sub>) are critical chemical species that facilitate the measurement of geothermal temperatures and improve understanding of geothermal fluid properties (Lala et al., 2024). The type of geothermal fluid in the manifestations will be determined by analysing the relative concentrations of chloride, bicarbonate, and sulphate ions, as illustrated in a ternary diagram (Arifin et al., 2023). The fluid can provide information on reservoir temperature, fluid origin, and chemical reactions within the geothermal system. Understanding the fluid type and its geochemistry is important for the effective exploration, development, and utilization of geothermal resources (Finster et al., 2015).

The purpose of this research paper is to provide an analysis of geothermal fluid types and characteristics based on geochemical analyses of surface geothermal manifestations in Buton, Indonesia. The objectives of this research are to provide information on the physical and chemical characteristics, fluid types, origin of the source water, and to estimate the reservoir temperature using geothermometers.

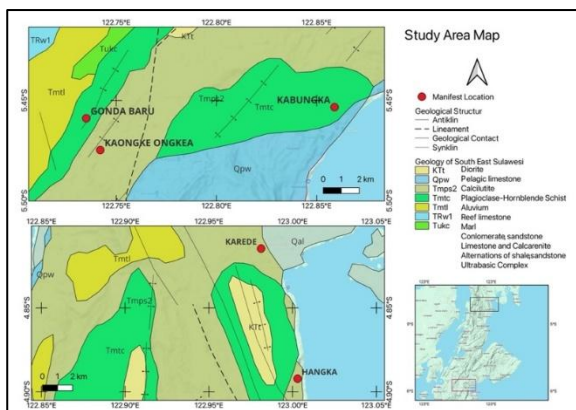


Fig 1. Geology Map of Study area (Modified from Sikumbang) (Sikumbang, 1995)

## 1.1 Geological of the study area

The study area is located in the Buton region of Southeast Sulawesi province, Indonesia. Buton is located at the south-eastern end of the island of Sulawesi, within the active tectonic collision zone between the Eurasian, Indo-Australian, and Pacific plates. This region is characterized by a complex geological setting, with numerous active volcanoes and a well-developed regional fault system (Ningrum et al., 2019; Sulistyanto et al., 2019).

The Kabungka manifestation is located directly within the Tmtc (Tondo Formation) rock region. The presence of hot seepage in this zone indicates that geothermal fluids have successfully ascended from the subsurface reservoir towards or near the upper boundary of the Tondo Formation. The Gonda Baru and Kaongkeongkea manifestations are located near the geological contact boundary between Tmtl (Alluvium), Tmtc, and Tmps2. The contraction of formation boundaries with different physical properties (geological contacts) often becomes a secondary weak plane that facilitates fluid escape to the surface. The geology of Buton is dominated by Tertiary volcanic and sedimentary rocks. The geology of the mapping area refers to the geological map of the Buton Sheet, Southeast Sulawesi (Polii et al., 2021). The geology map of the study area is shown in Figure 1. The stratigraphic sequence of Buton Island from old to young is as follows:

Tondo Formation (Tmtc)

The Tondo Formation, of Pliocene age, covers the southern half of Buton Island from west to east. This rock unit consists of alternating layers of gray shale, sandstone, and volcanic material. The Tondo Formation is interpreted as having been deposited in a rapidly subsiding foreland basin (Fortuin et al., 1990). Tondo Formation (Tmtc), a formation composed of reef limestone and calcarenite lithology. Mixing of sediments, namely destructive shallow-marine sediments rich in foraminifera, with deep-marine sediments, is a characteristic feature of this formation (Chaerul et al., 2017).

Sampolakosa Formation (Tmps)

The Sampolakosa Formation, of Pleistocene age, covers the southern part of Buton Island from west to east and is the youngest Tertiary sedimentary rock unit in the study area. This formation is composed of consolidated reef limestone and calcarenite deposits, interbedded with layers of calcareous sandstone and conglomerate (Ali et al., 1996). The rock units are marl in nature, rarely contain sandstone inserts, and lie aligned above the Tondo Formation. In this unit, many planktonic foraminiferal fossils of the Globigerinidae type were found, along with molluscan fossils, both typical of deep-sea environments. The widest distribution of this unit is on Buton Island (Arifin and Naibaho, 2016).

The Gonda Baru, Kaongkeongkea, and Kabungka manifestations all lie very close to or parallel to these structural/fault alignments. These joints, faults, and fractures affect both the Tmtc Formation and the Tmps2 limestone, creating high secondary permeability (Haerudin et al., 2019). Geothermal fluids utilize this fault damage zone as a "natural pipe" (vertical conduction path) to migrate upwards through the cap rock (Tmps2) towards the surface, which then triggers the emergence of geothermal manifestations in Gonda Baru and Kabungka (Iswahyudi et al., 2026).

## 2.1 Tools and Sampling Method

The data for this study were obtained from field observations and laboratory work on geothermal fluid samples collected from surface features in the area. We collected geochemical water samples from warm springs in Kabungka, Kaongkeongkea, Gonda Baru, Hangka, and Karede (see Figure 1). Water samples from geothermal manifestations (hot springs) were collected at the outlet points exhibiting the highest fluid temperature using an integrated sampling method for cation and anion analyses. The in situ parameters were measured using a portable pH meter and a digital thermocouple. The sampling equipment consisted of 0.45 µm pore-size cellulose acetate syringe filters, sterile 50 mL syringes, and new high-density polyethylene (HDPE) bottles with capacities of 100 mL and 250 mL. The preservatives used were nitric acid and hydrochloric acid.

At each manifestation site (Kabungka, Gonda Baru, and Kaongkeongkea), samples were collected in triplicate, with a minimum of three samples per location, to assess sampling consistency. The sampling procedures were as follows:

- Cation samples (K, Na, Mg, and Ca): The fluids were filtered through a 0.45 µm filter into 100 mL HDPE bottles and subsequently acidified with concentrated nitric acid to achieve a pH < 2. Acidification was performed to prevent metal precipitation and ion adsorption onto the bottle walls.
- Anion samples (Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, and HCO<sub>3</sub><sup>-</sup>): The fluids were filtered through a 0.45 µm filter into 250 mL HDPE bottles without the addition of acid. The bottles were completely filled, leaving no headspace, to minimize oxidation.

- In situ parameters: Temperature and pH were measured directly in the field immediately during sample collection.

## 2.2 Geochemistry Analysis

The geochemical analysis of the water samples involved the determination of major ions, including cations ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) and anions ( $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ ). The geothermal fluid samples collected from surface manifestations were first filtered using Whatman filter paper. The filtered samples were then split into two portions, each stored in a separate container. The first container was labeled "acidified," indicating that the filtrate had been treated with a diluted nitric acid solution to reach a pH of approximately  $\pm 2$ , as confirmed with universal pH meter paper. This acidified water sample was designated for analysis of cation content. The second container was labeled "non-acidified," signifying that the filtrate was untreated. This non-acidified water sample was intended for anion content analysis.

The analysis was conducted at the water quality laboratory of the Makassar Public Health Laboratory Centre I. The concentrations of the major cations, such as  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ , and  $\text{Mg}^{2+}$ , were determined through atomic absorption spectrophotometry analysis. The anions  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  were analysed using Standard Methods for the Examination of Water and Wastewater (SM APHA 23rd edition), while the  $\text{HCO}_3^-$  concentration was measured using titrimetric analysis, and the  $\text{SiO}_2$  content was quantified using spectrophotometric techniques.

## 2.3 Data Analysis

The geochemical data from the laboratory analysis helped us understand the type of fluid and estimate the temperature of the geothermal reservoir. First, by measuring Ion Balance, we compare the total positive charges with the total negative charges of all major ions in the water sample, recognizing that charge balance must naturally be maintained (Lala et al., 2024). We calculated the ionic balance of the geothermal fluid samples to ensure that the positive and negative charges were in harmony. The ionic balance was determined using the following formula (1).

$$\text{Ionic Balance} = \frac{(\Sigma(\text{cations}) - \Sigma(\text{anions}))}{(\Sigma(\text{cations}) + \Sigma(\text{anions}))} \times 100\% \quad (1)$$

Table 1. Manifestation Characteristics in the study area

| Location      | Id Sampel | X        | Y      | Elevation | T air (° C) | T water (° C) | pH   |
|---------------|-----------|----------|--------|-----------|-------------|---------------|------|
| Kaongkeongkea | KK        | 122,7420 | -5,475 | 255       | 28          | 33,8          | 6,86 |
| kabungka      | KB        | 122,8590 | -5,453 | 146       | 28          | 28,7          | 6,2  |
| Gonda Baru    | GB        | 122,7350 | -5,459 | 294       | 34          | 26            | 5,82 |
| Hangka        | HK        | 123,0029 | -4,892 | 37        | 33          | 26,5          | 6,86 |
| Karede        | KR        | 122,9812 | -4,815 | 30        | 25          | 42,2          | 5,68 |

The Kaongkeongkea, Kabungka, and Gonda Baru springs are located in the southern part of Buton, while Hangka and Karede springs are found in the north. Based on temperature readings, Kaongkeongkea (KK) and Karede (KR) springs are warm, and both emit gas bubbles, adding a lively touch to their features. In contrast, Gonda Baru (GB), Kabungka (KB), and Hangka (HK) springs are cooler, with no gas bubbles present. The water samples from all five springs do not show any sulfur smell, which is usually associated with such features. The pH levels are below 6 in Gonda Baru and Karede springs, making them slightly more acidic, while the others are closer to neutral, with pH values between 6 and 7. These temperature differences reflect varying levels of geothermal activity and heat output, as noted by Arifin et al. (2023). The slight variations in pH levels tell us about the water's chemical makeup and its acidity or alkalinity. Overall, these physical and chemical traits give us a

Here,  $\Sigma^+$  denotes the total cation concentration, and  $\Sigma^-$  denotes the total anion concentration. Next, the type of geothermal fluid was identified using a  $\text{Cl-HCO}_3\text{-SO}_4$  ternary diagram (Juliarka and Niasari, 2016; Tassi et al., 2018). The location of a sample on this diagram reveals the dominant anion type, giving us clues about the origin and evolution of the geothermal fluid (Polii et al., 2021; Utami and Putra, 2018). Additionally, the characteristics of immature geothermal waters within the reservoir were examined using a Na-K-Mg ternary diagram, which indicates an immature water condition (Syah et al., 2023). This method combines two distinct geothermometer equations: the Na-K equation, reflecting slow equilibrium reactions in the reservoir, and the K-Mg equation, which relates to faster reactions closer to the surface (Arifin et al., 2023). Finally, the reservoir temperature was estimated using geothermometer equations based on the chemical makeup of the geothermal fluid. The geothermometers employed—Na-K-Ca and K-Mg (Giggenbach)—help us estimate this temperature, and their results were compared to identify the most reliable estimate of the geothermal reservoir's temperature.

## 3. Result and Discussion

This report presents the results of geochemical analysis and data interpretation for geothermal fluid samples collected from the study area section:

### 3.1 Characteristic of Surface Manifestation

The geothermal surface manifestations observed in the study area include warm springs and cold springs. In situ measurements and sampling of surface manifestations in the research area were carried out in December 2023. The geothermal manifestation locations comprise 5 sites: Kaongkeongkea (KK), Kabungka (KB), Gonda Baru (GB), Hangka (HK), and Karede (KR). Surface characteristic measurements include pH and surface temperature (C). Measurements were carried out in situ, with each measurement lasting 30-50 seconds. Additionally, the air temperature, coordinates, and altitude around the manifestation are measured. The results of the measurements of manifestation characteristics in the research area are presented in Table 1.

fascinating glimpse into the unique qualities of each spring in the area. Understanding these aspects helps us appreciate the geological and hydrological processes that shape these remarkable hot springs, as discussed by Herzhegovina et al. (2020).

The spatial variations in temperature ( $26^\circ\text{C} - 42.2^\circ\text{C}$ ) and pH (5.68-6.86) among the five manifestations strongly reflect distinct degrees of fluid mixing and heat dissipation within the non-volcanic geothermal system of Buton Island (Sidqi & Utami, 2018). The highest temperature recorded at Karede (KR:  $42.2^\circ\text{C}$ ) at the lowest elevation (30 m) implies a relatively rapid convective ascent of deep-seated fluid via permeable fault pathways, minimizing conductive heat loss. Conversely, the high-elevation manifestation at Gonda Baru (GB: 294 m) exhibits near-ambient water temperature ( $26^\circ\text{C}$ ), serving as a clear indicator of intense shallow groundwater

dilution. The slightly acidic to neutral pH range suggests that the deep reservoir fluids, hosted within the Tondo Formation (Tmtc), undergo moderate carbon dioxide (CO<sub>2</sub>) dissolution derived from the surrounding carbonate sequences (Tmps2), which buffers the fluid and prevents extreme acidification typical of volcanic-hydrothermal systems.

3.2 Geochemical Characteristics of Surface Fluid

Table 2 presents the chemical composition of geothermal surface-fluid samples from the study area. The total dissolved solids (TDS) range from 163.8 mg/L to 1,966 mg/L, with Gonda Baru (GB) and Karede (KR) showing the highest dissolved load. Both GB and KR contain high bicarbonate concentrations, 776.138 mg/L and 1019.14 mg/L respectively, together with elevated chloride concentrations of 404.96 mg/L and 324.91 mg/L. This combined HCO<sub>3</sub><sup>-</sup>-Cl<sup>-</sup> enrichment indicates that these waters should not be interpreted simply as meteoric bicarbonate waters or as direct evidence of seawater intrusion without additional constraints. The ion-balance values range from 5.06% to 24.82%; therefore, only KK and KB fall within the commonly accepted ±10% analytical threshold, whereas GB, HK, and KR require cautious interpretation or analytical verification before strong geochemical conclusions are drawn. Based on

the hydrochemical analysis, the Charge Balance Error (CBE) values for the KK and KB samples fall within the acceptable standard threshold (< 10%). Conversely, samples GB (24.82%), HK (15.02%), and KR (13.51%) exhibit highly positive electro-neutrality values. This elevated ion imbalance is strongly attributed to the local geological constraints of Buton Island, which is heavily dominated by carbonate sequences (Sampolakosa Formation). The presence of dissolved limestone cementation matrices and suspended colloidal calcite (HCO<sub>3</sub><sup>-</sup>) micro-particles within the thermal spring fluids led to an overestimation of dissolved calcium (Ca<sup>2+</sup>) during laboratory analysis (ICP-OES/AAS) upon sample acidification. Concurrently, these suspended carbonaceous matrices interfered with the endpoint sharpness and precision of the field-based volumetric titration used for bicarbonate (HCO<sub>3</sub><sup>-</sup>) determination, leading to underestimated total anion charges. Despite these high CBE values, the data points were retained for the hydrogeochemical discussion as their spatial chloride and magnesium trends yield highly consistent and coherent interpretations regarding sub-surface fluid mixing and water-rock interaction processes.

Table 2. Geochemical analysis of all samples in study area

| Pharameter                    | Units | Samples |        |         |        |         |
|-------------------------------|-------|---------|--------|---------|--------|---------|
|                               |       | KK      | KB     | GB      | HK     | KR      |
| Fe <sup>2+</sup>              | mg/l  | 0,01    | 0,01   | 0,01    | 0,01   | 0,01    |
| F <sup>-</sup>                | mg/l  | 0,69    | 0,1    | 0,29    | 0,1    | 1,32    |
| AL <sup>3+</sup>              | mg/l  | 0,01    | 0,01   | 0,01    | 0,01   | 0,01    |
| N                             | mg/l  | 0,02    | 0,03   | 1,45    | 0,3    | 3,33    |
| SO <sub>4</sub> <sup>2-</sup> | mg/l  | 4,64    | 4,77   | 7,82    | 10,5   | 21,3    |
| Cl <sup>-</sup>               | mg/l  | 76,66   | 6,49   | 404,96  | 5,83   | 324,91  |
| K <sup>+</sup>                | mg/l  | 10,69   | 1,41   | 20,85   | 0,61   | 21,74   |
| Ca <sup>2+</sup>              | mg/l  | 69,25   | 110,01 | 79,46   | 47,75  | 133,02  |
| Mg <sup>2+</sup>              | mg/l  | 29,18   | 16,11  | 48,27   | 4,15   | 42,96   |
| Na <sup>+</sup>               | mg/l  | 87,24   | 24,08  | 144,19  | 40,35  | 217,28  |
| SiO <sub>2</sub>              | mg/l  | 7,36    | 0,4    | 6,24    | 0,1    | 3,59    |
| HCO <sub>3</sub> <sup>-</sup> | mg/l  | 530,65  | 394,26 | 776,138 | 347,15 | 1019,14 |
| TDS                           | mg/l  | 542,1   | 348,8  | 1966    | 163,8  | 1619    |
| pH                            |       | 6,86    | 6,2    | 5,82    | 6,86   | 5,68    |
| Temperature                   | °C    | 33,8    | 28,7   | 26      | 26,5   | 42,2    |
| Ion Balance                   | %     | 5,06    | 7,91   | 24,82   | 15,02  | 13,51   |

A critical review of the hydrochemical data reveals a distinct evolutionary pathway for the GB and KR manifestations. Table 2 highlights that GB and KR exhibit the highest chloride concentrations (404.96 mg/L) and (324.91mg/L), respectively) paired with elevated (HCO<sub>3</sub><sup>-</sup>) levels. This co-enrichment of chloride and bicarbonate rules out simple modern seawater intrusion. Instead, it indicates a complex dual-mechanism driven by geological host rocks and structural pathways. The high (Cl<sup>-</sup>) and (Na<sup>+</sup>) signatures are genetically linked to deep fluid circulation within the marine-derived clastic sequences of the Tondo Formation (Tmtc), where the fluid leaches fossil connate water or trapped salts (Brehme et al., 2016). As this deep chloride-rich fluid ascends along permeable fault zones, it encounters the carbonate-rich calcilitute of the Sampolakosa Formation (Tmps2), triggering intense carbonate dissolution that superimposes a high HCO<sub>3</sub> concentration onto the fluid. Furthermore, the significant magnesium (Mg<sup>2+</sup>) concentrations in GB (48.27 mg/L) and KR (16.11mg/L) provide definitive hydrochemical evidence of shallow meteoric water mixing. The high-elevation manifestation at Gonda Baru (GB) represents a more advanced dilution stage where the deep thermal ascent is partially quenched by cold, oxygenated near-surface groundwater, lowering its surface temperature while upgrading its Mg<sup>2+</sup> content. This pervasive water-rock

interaction and subsequent mixing mask the pristine deep reservoir properties, positioning the fluids within the immature zone of the Na-K-Mg diagram and stabilizing the surface pH via carbonate buffering.

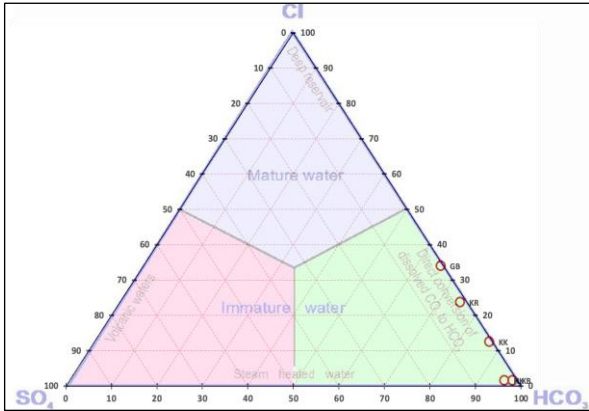


Fig 2. Cl-SO<sub>4</sub>-HCO<sub>3</sub> Ternary Diagram

3.3 Determination of Fluid Type

To determine the type of geothermal fluid in the study area, a series of geochemical diagrams was utilized, including

the Cl-SO<sub>4</sub>-HCO<sub>3</sub> ternary Diagram and the Na-K-Mg Ternary Diagram. These diagrams classify geothermal water types by analyzing dominant anion concentrations, as illustrated by the Cl-SO<sub>4</sub>-HCO<sub>3</sub> ternary diagram (Figure 2). This diagram illustrates that the water at all points of manifestation is bicarbonate-type. Based on the plot results, 3 springs (GB, KR, and KK) fall into the mixed chloride-bicarbonate type, indicating the possibility of mixing with groundwater. It is important to determine whether the water is diluted chloride or non-bicarbonate, as these are genetically very different. This is important because the term "carbonate water" (bicarbonate water) is often used to denote any water that comes out of a spring, without considering its origin from steam-heating or the dissolution of carbonates. Low chloride/bicarbonate ratios indicate a greater influence of shallow-water interactions (Juliarka and Niasari, 2016). Bicarbonate HCO<sub>3</sub><sup>-</sup> acts as a buffer, helping stabilize the pH of water. The relatively high bicarbonate concentration can cause the water to tend to be neutral, even though there is input from geothermal water, which is more acidic (Arifin et al., 2023)

The anion analysis results suggest that the geothermal fluid manifestations in the study area are predominantly bicarbonate-type. This indicates that the geothermal fluid originates from a shallow reservoir, where it has interacted with surrounding rocks or other fluids. This variety of geothermal fluid, identified as neutral bicarbonate, is typically present in outflow regions where the reservoir is shallow, temperatures are elevated, and the pH is nearly neutral. This occurs due to the interaction between the fluids and rocks as the fluid ascends to the surface (Struhsacker et al., 1983).

GB and KR show the clearest mixed chloride-bicarbonate signatures, as indicated by high chloride concentrations in GB (404.96 mg/L) and KR (324.91 mg/L), elevated sodium, and very high bicarbonate concentrations. Therefore, KR should not be described as a low-chloride sample. The chloride enrichment may indicate saline or marine influence, but confirmation of seawater intrusion requires additional ionic ratios or isotopic evidence. The high HCO<sub>3</sub><sup>-</sup> concentrations, especially in KR, are more consistent with intensive water-rock interaction involving carbonate-bearing units such as the Sampolakosa Formation, while the near-neutral to slightly acidic pH range suggests buffering through carbonate dissolution and mixing with shallow groundwater during ascent. The spatial hydrochemical evolution in the study area is clearly illustrated by the positioning of the samples within the ternary diagrams. In the diagram Cl-SO<sub>4</sub>-HCO<sub>3</sub>, the heavy grouping of samples toward the HCO<sub>3</sub><sup>-</sup> apex underscores distal outflow system characteristics. However, unlike volcanic settings where bicarbonate waters originate from steam-heating, the high HCO<sub>3</sub><sup>-</sup> concentration here is genetically driven by intensive carbonate dissolution of the calcilitite units within the Sampolakosa Formation (Tmps2). The evolutionary shift of GB and KR toward the mixed chloride-bicarbonate zone reveals an active hydrothermal mixing process; deep-seated chloride-rich fluids ascending via permeable faults of the Tondo Formation (Tmtc) interact with trapped connate marine salts and subsequently merge with shallow meteoric waters. Furthermore, the assignment of all fluid samples to the 'immature water' region of the Na-K-Mg diagram highlights a significant limitation for sub-surface reservoir evaluation. This immature state indicates that the fluids have not attained chemical water-rock equilibrium, largely due to high Mg ingestion from near-surface water-rock interactions and extensive meteoric dilution during fluid ascent. Consequently, standard cation geothermometers (e.g., Na/K) are highly restricted and

inapplicable as they yield unreliable reservoir temperatures under non-equilibrium conditions. To address this limitation, solute geothermometers with magnesium corrections or silica SiO<sub>2</sub> geothermometers must be employed to provide a realistic assessment of this low-to-medium enthalpy non-volcanic system.

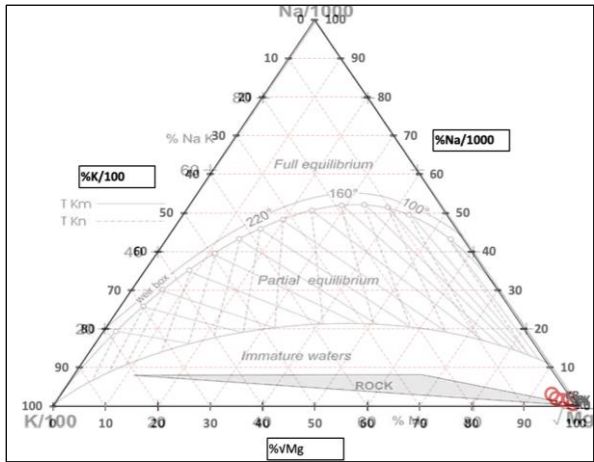


Fig 3. Na-K-Mg Ternary Diagram

The Giggenbach Ternary Diagram, which plots the relative concentrations of sodium, potassium (K), and magnesium, can be utilized to evaluate the extent of water-rock equilibrium and estimate the temperature of the geothermal reservoir (Giggenbach, 1988). Based on the ternary diagram Na-K-Mg on figure 3, the samples in this study are in immature water.

### 3.4 Determination of Reservoir Temperature

To estimate the reservoir temperature, several geochemical geothermometers were applied, including the K-Mg and Na-K-Ca geothermometers. The geothermometers formula used are

$$\text{K-Mg: } T = 4410 / (14 - \log(K^2/Mg)) - 273.15 \quad (2)$$

$$\text{Na-K-Ca: } T = [\log Ca / Na + 2.06] > 0, \text{ use } \beta = 4/3 \quad (3)$$

Table 3. Estimated temperature of reservoir

| Geothermometer | Estimated Temperature (°C) |      |       |       |       |
|----------------|----------------------------|------|-------|-------|-------|
|                | KK                         | KB   | GB    | HK    | KR    |
| Na-Ka-Ca       | 112,2                      | 89,8 | 117,1 | 141,3 | 115,9 |
| K-Mg           | 104,3                      | 78,6 | 118,4 | 61,4  | 120,1 |

The application of solute geothermometers (such as K-Mg), Na-K-Ca, and silica) to estimate the deep sub-surface temperatures yields high uncertainties and misleading results for the study area. Although the mathematical calculations of the K-Mg) and Na-K-Ca equations formally indicate a low-temperature system ranging from 70°C to 120°C, these values cannot be considered representation of actual reservoir temperatures. This major limitation is strongly forced by the hydrothermal non-equilibrium state of the fluids. The extremely low dissolved silica (SiO<sub>2</sub>) concentrations across all samples (< 7.4mg/L), which fall well below the standard baseline for hydro-silicate equilibrium (< 10 mg/L), combined with excessive Mg<sup>2+</sup> and highly positive Charge Balance Errors (CBE), demonstrate that the manifestations are heavily governed by shallow meteoric dilution and intense carbonate leaching of the Sampolakosa Formation (Tmps2). Consequently, standard solute chemical geothermometers are inapplicable in this non-volcanic system of Buton Island, as the original deep chemical signatures have been completely

masked before reaching the surface. Therefore, the geothermal resource can only be qualitatively classified as a low-enthalpy system 150°C, and alternative exploration methods such as gas geothermometry or direct thermal gradient drilling are strictly required for accurate reservoir evaluation.

#### 4. Conclusion

The hydrogeochemical evaluation of thermal springs on Buton Island confirms a low-enthalpy, structurally controlled non-volcanic geothermal system. The thermal fluids exhibit a spatial evolution from distal bicarbonate ( $\text{HCO}_3^-$ ) to mixed chloride-bicarbonate ( $\text{Cl-HCO}_3^-$ ) water types. Bicarbonate enrichment is highly driven by intensive dissolution of the Sampolakosa calcilutite (Tmps2), which buffers the system to near-neutral or slightly acidic pH. Concurrently, high Cl and  $\text{Na}^+$  contents in GB and KR sample reflect deep circulation leaching trapped marine connate waters within the Tondo Formation (Tmtc). Elevated  $\text{Mg}^{2+}$  concentrations and the 'immature water' classification on the Na-K-Mg diagram provide definitive evidence of profound shallow groundwater mixing, which also accounts for the high Charge Balance Errors due to suspended carbonaceous matrices. Crucially, due to this non-equilibrium state and extremely low dissolved silica levels ( $< 7.4 \text{ mg/L}$ ), standard solute chemical geothermometers are mathematically invalid and inapplicable for predicting deep reservoir temperatures in this specific geological setting. Consequently, the geothermal system can only be qualitatively designated as low-temperature ( $< 150^\circ\text{C}$ ), and future sub-surface temperature validation must rely on alternative tools such as gas geothermometry or shallow thermal gradient drilling.

#### Acknowledgements

The authors highly appreciate the financial support from the UMI Research and Resource Development Institute (LP2S). We also thank to the research team who contributed to this research.

#### References

- Abdullah, C.I., Rampisela, D.A. and others (2020) 'Regional tectonic control of geothermal systems in Sulawesi, Indonesia'.
- Adams, M.C., Moore, J.N., Bjornstad, S. and Norman, D.I. (2015) 'Geologic and geochemical indicators of geothermal systems'.
- Al-Shareef, A.J., Al-Dabbas, M.A. and others (2018) 'Direct uses of geothermal energy and its applications'.
- Ali, J.R., Hall, R. and others (1996) 'Geological evolution and stratigraphy of Buton Island, Southeast Sulawesi'.
- Arifin, M.H. and Naibaho, A. (2016) 'Stratigraphy and sedimentary characteristics of the Sampolakosa Formation, Buton Island'.
- Arifin, M.H., Putra, A. and others (2023) 'Hydrogeochemical interpretation of geothermal manifestations using ternary diagrams'.
- Arnórsson, S., Bjarnason, J.Ö., Giroud, N., Gunnarsson, I. and Stefánsson, A. (2006) 'Sampling and analysis of geothermal fluids', *Geofluids*, 6, pp. 203–216.
- Arrofi, A., Setiawan, A. and others (2022) 'Distribution and potential of non-volcanic geothermal resources in Sulawesi'.
- Brehme, M. and others (2016) 'Fluid flow and geochemical reactions controlled by permeability in fault-related fractures', *Journal of Geoscience, Engineering, Environment, and Technology*.
- Chaerul, M. and others (2017) 'Sedimentary characteristics of the Tondo Formation, Buton Island, Southeast Sulawesi'.
- Febrianto, R., Setiawan, B. and others (2019) 'Surface geothermal manifestations as indicators of geothermal systems'.
- Finster, M., Clark, C., Schroeder, J. and Martino, L. (2015) 'Geothermal produced fluids: characteristics, treatment technologies, and management options'.
- Fortuin, A.R., de Smet, M.E.M. and others (1990) 'Stratigraphy and basin development of Buton Island, eastern Indonesia'.
- Fournier, R.O. and Truesdell, A.H. (1973) 'An empirical Na-K-Ca geothermometer for natural waters', *Geochimica et Cosmochimica Acta*, 37(5), pp. 1255–1275.
- Gafoer, S., Sikumbang, N., Sanyoto, P. and Supandjono, R.J.B. (1995) Geological Map of the Buton Sheet, Southeast Sulawesi. Bandung: Geological Research and Development Centre.
- Giggenbach, W.F. (1988) 'Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geothermometers', *Geochimica et Cosmochimica Acta*, 52(12), pp. 2749–2765.
- Haerudin, N., Alami, F. and Rustadi, R. (2019) 'Hydrogeochemistry of Natar and Cisarua hot springs in South Lampung Regencies', *Journal of Geoscience, Engineering, Environment, and Technology*, 4(3), pp. 184–189.
- Herzegovina, D. and others (2020) 'Physical and chemical characteristics of geothermal spring waters'.
- Idral, A. (2010) 'Geothermal energy resources and development in Sulawesi, Indonesia'.
- Iswahyudi, S. and others (2026) 'The water chemistry geothermal of Ranang-Kasimbar hot springs, Central Sulawesi', *Journal of Geoscience, Engineering, Environment, and Technology*, 11.
- Juliarka, B.R. and Niasari, S.W. (2016) 'Interpretation of geothermal fluid type using  $\text{Cl-SO}_4\text{-HCO}_3$  ternary diagram'.
- Lakrou, H., Bouri, S. and others (2022) 'Hydrogeochemical characterization and geothermometry of geothermal waters'.
- Lala, A.M., Putra, A. and others (2024) 'Major-ion chemistry and geothermometry of geothermal fluids'.
- Lund, J.W. (2010) 'Direct utilization of geothermal energy', *Energies*, 3(8), pp. 1443–1471.
- Millayanti, S. and others (2019) 'Geochemical characteristics of geothermal manifestations in Sulawesi'.
- Ningrum, S.A. and others (2019) 'Tectonic and geological setting of Buton Island, Southeast Sulawesi'.
- Polii, J. and others (2021) 'Geological and hydrogeochemical study of geothermal manifestations in Buton Island'.
- Radja, V.T. (1970) 'Geothermal manifestations and volcanic activity in Sulawesi'.
- Sahdarani, D.N. and others (2020) 'Geothermal energy potential and renewable energy transition in Indonesia'.
- Shah, M. and others (2021) 'Geochemical assessment of geothermal fluids and reservoir characteristics'.
- Sidqi, M. and Utami, P. (2018) 'Modeling and interpretation of geothermal system characteristics based on surface geochemistry and alteration', *Journal of Geoscience, Engineering, Environment, and Technology*.
- Struhsacker, E.M., Smith, C. and others (1983) 'Geochemical classification of geothermal waters and outflow systems'.
- Sulistiyanto, D. and others (2019) 'Structural control and geochemical characteristics of geothermal systems in Sulawesi'.
- Syah, F.A.T. and others (2023) 'Hydrogeochemistry and

isotope characteristics of the hot springs in the Wapsalit Area, Buru Island', Journal of Geoscience, Engineering, Environment, and Technology, 8(4).  
Tassi, F., Venturi, S., Vaselli, O. and others (2018) 'Hydrochemical and isotopic features of geothermal fluids and ternary-diagram interpretation'.  
Utami, P. and Putra, A. (2018) 'Application of

hydrogeochemical diagrams for geothermal-fluid classification'.



© 2026 Journal of Geoscience, Engineering, Environment and Technology. All rights reserved.  
This is an open access article distributed under the terms of the CC BY-SA License (<http://creativecommons.org/licenses/by-sa/4.0/>).

---