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Geochemical Evidence from Major and Trace Elements in Geothermal Waters of Empat Lawang, Southern Sumatra: Clues to Mineralization and Hydrothermal Sources

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Abstract

This study explores the major and trace element geochemistry of geothermal waters from Empat Lawang, Southern Sumatra, Indonesia, to assess hydrothermal origins and mineral prospecting potential. Five water samples were analyzed using ternary plots, ion correlation diagrams, and geothermometric equations. A strong Na–Cl correlation (R^2 = 0.9694) suggests evaporite dissolution or mixing with connate water, while the Ca–SO_4 relationship (R^2 = 0.9555) indicates gypsum or anhydrite dissolution. The Ca + Mg vs. HCO_3 pattern reflects carbonate and silicate weathering influenced by lithological variability. Diagnostic ion plots reveal active ion exchange and halite dissolution across sample sites. Reservoir temperatures estimated using Giggenbach and Fournier Truesdell equations range from 190°C to 404°C, with an outlier of 1593.75°C in PN3, likely due to fluid disequilibrium. Depths span 4.22 to 16.39 km, indicating deep-seated hydrothermal systems with intense fluid–rock interaction. The Cl/Li vs. B plot identifies hydrothermal signatures, with most samples below the Cl/Li < 1000 threshold and elevated boron levels, suggesting active leaching and mineral transport. These findings highlight the potential for borate and metal mineralization. By integrating classical geochemical approaches with modern trace element indicators, this study provides a novel framework for geothermal exploration in Indonesia's volcanic regions. These findings suggest potential for borate and metal mineralization and offer a geochemical framework for geothermal exploration in Indonesia's volcanic regions.

1. Introduction

Indonesia, situated along the Pacific Ring of Fire, hosts one of the world's largest geothermal potentials due to its active tectonic and volcanic framework. This dynamic geological setting has produced numerous hydrothermal systems across the archipelago, particularly in volcanic belts such as those in southern Sumatra [1]. Geothermal energy is increasingly recognized as a sustainable solution to meet Indonesia's growing energy demands while reducing carbon emissions [2]. However, many geothermal prospects remain underexplored, especially in regions like Empat Lawang, South Sumatra, where surface manifestations are evident but scientific characterization is limited.

The geochemistry of major and trace elements in geothermal water serves as a crucial tool for understanding the origin and evolution of hydrothermal systems. These elements provide insights into rock leaching processes, fluid mixing, and water-rock interactions occurring beneath the surface [3–5]. By analyzing the concentrations and distribution patterns of these elements, researchers can identify heat sources, fluid pathways, and the nature of geothermal reservoirs.

Previous studies have demonstrated that geochemical analysis of geothermal fluids especially major and trace element concentrations provides critical insights into subsurface processes such as water–rock interaction, fluid mixing, and reservoir characteristics [4, 5]. Geothermometric techniques and ion correlation diagrams have been widely applied to estimate reservoir temperatures and identify mineral dissolution pathways in geothermal systems across Indonesia and globally [6]. Despite these advances, there is a notable lack of geochemical data for Empat Lawang, hindering its integration into national geothermal development strategies and limiting comparative assessments with other hydrothermal systems.

A geochemical study of geothermal water in Empat Lawang is particularly important given the lack of large-scale geothermal exploration in the area. This research aims to fill the data gap and offer a scientific foundation for sustainable geothermal energy development in the region. Furthermore, the findings can be used to compare the Empat Lawang hydrothermal system with other geothermal systems in Indonesia and globally [6–8].

In this study, geothermal water samples were collected from several hot springs scattered throughout Empat Lawang. Laboratory analyses were conducted to determine the concentrations of major elements such as Na, K, Ca, Mg, and Cl, as well as trace elements including Li, B, Sr, and As. The geochemical data were then examined using statistical and geochemical approaches to identify patterns and relationships among the elements, and to interpret the subsurface processes involved [9–13].

Data interpretation was carried out in the context of local geological factors, including lithology, structural geology, and volcanic history. This approach enables a more comprehensive understanding of the hydrothermal water origin and the mechanisms driving the geothermal system in Empat Lawang. The results were also compared with conceptual models of hydrothermal systems developed in other regions to assess both similarities and unique features.

Through this study, new insights into the dynamics of the Empat Lawang hydrothermal system and its potential for geothermal energy utilization are expected [14, 15]. The research contributes to the advancement of hydrothermal geochemistry in Indonesia and supports responsible and sustainable exploration and exploitation of geothermal resources.

2. Materials and Methods

2.1. Geological setting

The Empat Lawang region is situated within the Bukit Barisan mountain range, which stretches along the western margin of Sumatra Island [16]. This area is part of the active Sunda Arc, a tectonic zone formed by the subduction of the Indo-Australian Plate beneath the Eurasian Plate (Figure 1). The geological framework of Empat Lawang is characterized by complex interactions between volcanic, sedimentary, and metamorphic units, shaped by intense tectonic activity and crustal deformation over geological time [17].

Lithologically, the region comprises a mixture of Tertiary volcanic rocks, including andesitic to basaltic lava flows, pyroclastic deposits, and volcanic breccias. These volcanic units are interbedded with sedimentary formations such as sandstones, shales, and limestones, which were deposited in both marine and terrestrial environments [18–21]. In addition, older basement rocks, including schists and gneisses of pre-Tertiary age, are exposed in certain parts of the region, particularly in uplifted zones and fault blocks [22–24].

Structurally, Empat Lawang is influenced by a series of northwest-southeast trending faults and fractures, which play a significant role in controlling the circulation of geothermal fluids. The presence of these faults facilitates deep fluid migration and enhances permeability within the subsurface, creating favorable conditions for hydrothermal activity. Several hot springs in the area are aligned along fault zones, suggesting a strong structural control on geothermal manifestations [25–27].

The volcanic history of the region is closely linked to the development of geothermal systems. Episodic volcanic eruptions during the Miocene to Quaternary periods have contributed to the emplacement of heat sources and the formation of hydrothermal reservoirs. The alteration of volcanic rocks due to prolonged water-rock interaction has resulted in the development of clay-rich

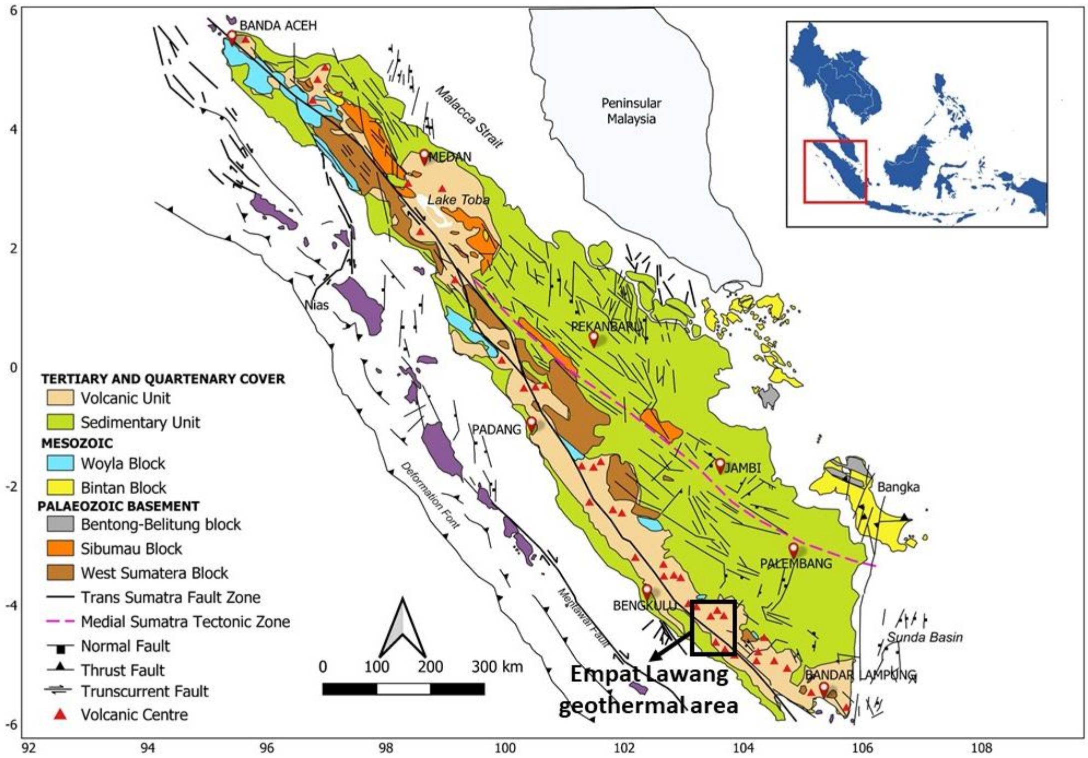

Figure 1. The geological and tectonic setting in Sumatra Island, Indonesia.

zones and secondary mineral assemblages, which are commonly observed in geothermal fields [18, 28, 29].

Overall, the geological setting of Empat Lawang provides a conducive environment for the formation of geothermal systems. The combination of active tectonics, diverse lithology, and volcanic heat sources supports the existence of hydrothermal circulation and mineralization processes. Understanding this geological framework is essential for interpreting the geochemical signatures of geothermal water and assessing the potential for geothermal energy development in the region.

2.2. Sampling Site and Data

A geochemical investigation was conducted at five thermal spring sites located in the Empat Lawang geothermal area, Southern Sumatra, Indonesia (Figure 2). This study employed a hydrogeochemical approach utilizing secondary data derived from previous research conducted by [14] and [15]. The selected sampling sites included four springs from the Penantian area (PN, PN1, PN2, and PN3) and one spring from the Airklinsar area (AK), representing the main geothermal manifestations in the region (n = 5; see Table 1 and Table 2).

Water samples were collected during a dedicated field campaign in June 2012. Sampling was conducted at the natural discharge points of each spring to ensure that the collected water reflected the in-situ geochemical conditions of the geothermal fluids. Each sample was collected in pre-cleaned, acid-washed polyethylene bottles. Prior to final collection, bottles were rinsed three times with the spring water to minimize contamination. Immediately after collection, a portion of each sample was acidified with ultrapure nitric acid (HNO_3) at a concentration of 1 mL per 100 mL of sample to preserve cation integrity. No filtration or other pretreatment was applied, allowing for the retention of suspended particulates and colloids that may influence geochemical signatures. Field documentation included GPS coordinates, site photographs, ambient temperature, and visual observations of spring morphology and discharge characteristics.

Chemical analyses focused on both major and trace elements commonly used to assess water–rock interaction, fluid origin, and reservoir temperature in geothermal systems. Acidified samples were analyzed at the onsite laboratory of Lampung University in Bandar Lampung. Sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) concentrations were determined using atomic absorption spectrophotometry (AAS), while boron (B) and lithium (Li) were quantified using inductively coupled plasma optical emission spectrometry (ICP-OES). Sulfate (SO_4^{2-}) concentrations were measured using spectrophotometric methods, typically involving turbidimetric or colorimetric techniques depending on the concentration range.

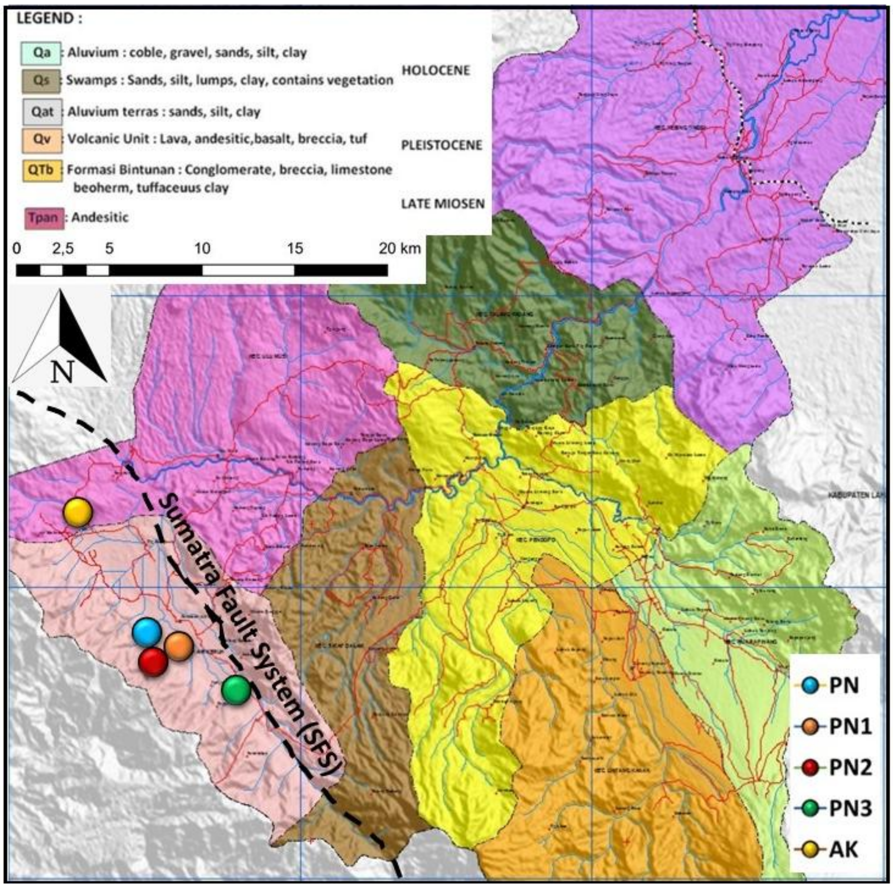

Figure 2. Geological map of the study area with the location of collected samples.

Table 1. Measured trace elements data of thermal springs in the Empat Lawang geothermal area, Southern Sumatra, Indonesia.

Sample Number	Name of thermal springs	Thermal spring codes	pH	B	Li
				(mg/L)	
1	Penantian	PN	6.0	15.15	8.49
2	Penantian 1	PN1	6.5	14.92	8.81
3	Penantian 2	PN2	7.0	14.86	8.85
4	Penantian 3	PN3	6.5	0.95	9.62
5	Airklinsar	AK	6.2	32.00	9.10

*Penantian: PN, PN1, PN2, PN3 from [14]
**Airklinsar: AK from [15]

Table 2. Measured major elements data of thermal springs in the Empat Lawang geothermal area, Southern Sumatra, Indonesia.

Sample Number	Thermal spring codes	Na	K	Mg	Ca	Cl	HCO_3	SO_4
		(mg/L)						
1	PN	15.15	8.49	0.29	30.37	127.00	114.20	140.00
2	PN1	14.92	8.81	0.35	30.77	120.00	190.30	228.00
3	PN2	14.86	8.85	0.36	30.74	117.00	114.20	228.00
4	PN3	0.95	9.62	8.00	42.54	13.40	197.90	24.20
5	AK	32.00	9.10	1.50	133.00	664.00	61.00	50.00

*Penantian: PN, PN1, PN2, PN3 from [14]
**Airklinsar: AK from [15]

Additional analyses for chloride (Cl^-) and bicarbonate (HCO_3^-) were conducted at the laboratory of Sriwijaya University in Palembang. Chloride was determined using ion chromatography or alternatively via Mohr's titration method with silver nitrate, depending on equipment availability and sample matrix. Bicarbonate was quantified using acid-base titration with methyl orange or phenolphthalein indicators to determine the endpoint. All measurements were performed in duplicate or triplicate to ensure reproducibility, and calibration standards, blanks, and certified reference materials were included in each batch of analysis to maintain analytical accuracy and precision.

Data were systematically logged using spreadsheet software, with metadata including sample ID, location, collection date, preservation method, and analytical technique. Remaining samples were stored at 4°C in the dark to prevent degradation and allow for potential reanalysis. This methodological framework was designed to ensure transparency, reproducibility, and scientific rigor, enabling other researchers to replicate the study and assess the validity of its findings in the context of geothermal exploration and hydrogeochemical modeling.

2.3. Chemical Geothermometry

A geothermometric approach was employed to estimate subsurface reservoir temperatures. The main methods utilized cation concentration ratios, specifically the Na–K (in mg/L; Equation 1) [30] and Na–K–Ca (in mg/L; Equation 2) [31] geothermometers, which provided estimates of reservoir temperatures in the Empat Lawang geothermal area, Southern Sumatra, Indonesia (*n* = 5). These temperature interpretations were combined with structural geological data and the location of active faults to understand fluid migration pathways and their relationship to magmatic heat sources.

$$T_{Na-K} = \frac{1390}{1750 + \log\left(\frac{Na}{K}\right)} - 273.15 \quad (1)$$

$$T_{Na-K-Ca} = \frac{1647}{\log\left(\frac{Na}{K}\right) + \beta\left[\log\left(\frac{Ca}{Na}\right)^{1/2} + 2.06\right] + 2.47} - 273.15 \quad (2)$$

where $\beta = \frac{4}{3}$ for T<100 $^\circ\mathrm{C}$, $\beta = \frac{1}{3}$ for T>100 $^\circ\mathrm{C}$. β is an empirical correction coefficient used to adjust for the effects of reaction kinetics and non-equilibrium conditions in geothermal systems. Physically, β reflects the sensitivity of the system to mineral dissolution and precipitation processes during water–rock interaction, and can be influenced by temperature, pressure, and the mineralogical composition of the host rock [31].

2.4 Reservoir Depth Estimation

The reservoir depth can be estimated using Equation 3 [32], where is the reservoir circulation depth (Km), T_R is an average reservoir temperature from Na-K and Na-K-Ca geothermometers (°C), T_S is the average surface temperature in the Empat Lawang geothermal area, Southern Sumatra, Indonesia, k is the thermal conductivity with the assigned value is 1.98 W/Km.°C for the average value of andesite to basaltic volcanic rock, Q is the surface heat flow (120 W/Km^2, and h is the water sampling elevation (Km) [26].

$$H = \frac{(T_R - T_S) \times k}{Q} + h \quad (3)$$

3. Results and Discussion

3.1. Major and Trace Elements

Based on the results, Figure 3A illustrates a positive exponential relationship between sodium (Na) and chloride (Cl) concentrations across the five geothermal water samples from Empat Lawang. The regression equation, y = $15.875e^{0.1269x}$, with a high coefficient of determination (R^2 = 0.9694), indicates a strong correlation between these two ions. This suggests that Na and Cl likely originate from a common source, such as the dissolution of halite (NaCl) or mixing with connate water. The strong correlation also implies that evaporitic mineral dissolution plays a significant role in shaping the chemical composition of the geothermal fluids in this region. Figure 3B shows a linear relationship between calcium (Ca) and sulfate (SO_4), with the regression equation y = 2.2852x + 12.067 and R^2 = 0.9555, indicating a robust correlation. This pattern suggests that the dissolution of gypsum ($CaSO_4{\cdot}2H_2O$) or anhydrite ($CaSO_4$) is a major contributor to the concentrations of both ions. Additionally, the relationship may reflect the influence of sulfide oxidation and the leaching of sedimentary rocks rich in calcium. The consistency across samples implies that these processes are widespread and relatively uniform throughout the geothermal system. Figure 3C presents the relationship between the sum of calcium and magnesium (Ca + Mg) and bicarbonate (HCO_3) concentrations.

Although no regression line is provided, the scatter pattern suggests that elevated HCO_3 levels are associated with the dissolution of carbonate minerals such as calcite and dolomite, as well as potential contributions from silicate weathering. The variability among samples indicates heterogeneity in the lithology of the reservoir rocks and differences in water–rock interaction intensity, which influence the bicarbonate content locally. Figure 3D is a diagnostic plot that compares Na + K – Cl with Ca + Mg – HCO_3 – SO_4, divided into four interpretive quadrants: ion exchange, reverse ion exchange, carbonate and silicate weathering, and dissolution of halite. The position of each sample within these quadrants provides insight into the dominant geochemical processes affecting water chemistry. Samples located in the ion exchange quadrant suggest active cation exchange between geothermal fluids and clay minerals (e.g., $Na^+ \leftrightarrow Ca^{2+}$), while those in the dissolution of halite quadrant indicate significant contributions from evaporite dissolution.

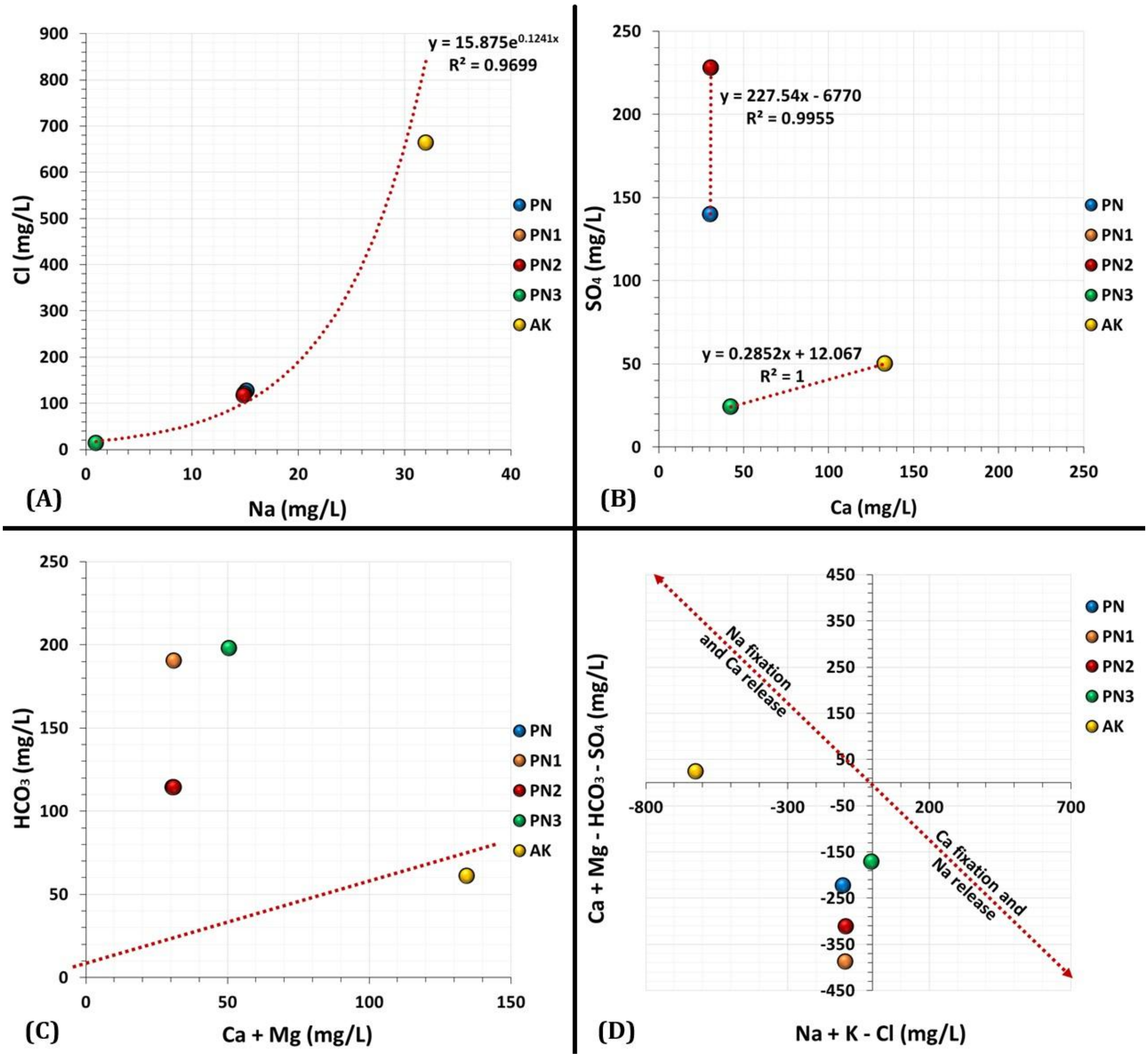

Figure 3. Geochemical relationships of major elements and diagnostic indicators of hydrothermal processes in geothermal waters from Empat Lawang.

Taken together, these four plots reveal that the Empat Lawang geothermal system is influenced by a combination of geochemical processes, including evaporite dissolution, carbonate and silicate weathering, and ion exchange [33–35]. The strong correlations between specific ions support the hypothesis that meteoric water interacts intensively with mineral-rich reservoir rocks, resulting in distinct chemical signatures. The interpretive diagram further reinforces the complexity and variability of subsurface processes across different spring locations.

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The graph shown in Figure 4 contributes significantly to the understanding of the geochemistry of hot springs in the Empat Lawang region of South Sumatra. By plotting the Cl/Li ratio (chloride to lithium) against boron (B) concentration, researchers can identify the hydrothermal characteristics of each water sample. The Cl/Li ratio is a commonly used indicator to distinguish between water originating from active hydrothermal systems and water that has undergone mixing or dilution. In this graph, the Cl/Li < 1000 limit is used as a marker for hydrothermal water, based on a study by [36].

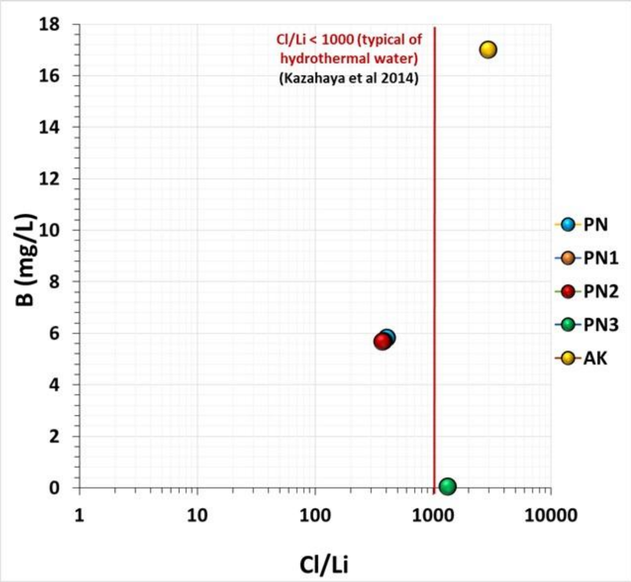

Figure 4. Interpretation of B concentration against Cl/Li ratio.

Most samples, such as PN, PN1, and PN2, are below or exactly at the Cl/Li < 1000 threshold, with relatively high boron concentrations (between 10 and 16 mg/L). This indicates that the water most likely originates from an active hydrothermal system, where the leaching of elements from rocks by hot fluids is still ongoing. In contrast, samples such as PN3 and AK show a much higher Cl/Li ratio (up to 8000) and lower boron concentrations, indicating possible mixing with meteoric water or dilution processes that reduce hydrothermal characteristics [37, 38].

High boron content in hydrothermal water can be an indicator of borate mineralization or other metals carried by geothermal fluids. Therefore, sampling points such as PN and PN1 are promising locations for further mineral exploration. By combining major and trace element analyses such as boron and lithium, this study not only strengthens the understanding of the origin of geothermal water in Empat Lawang, but also opens up opportunities for mineral prospecting. High boron content, for example, can be an indicator of borate mineralization or other metals carried by hydrothermal fluids. By integrating local data from Empat Lawang with global geochemical models, this study broadens our understanding of hydrothermal systems in Indonesia. The use of Cl/Li and boron ratios as key parameters demonstrates a relevant and up-to-date scientific approach [7].

The geochemical investigation of five thermal springs in the Empat Lawang geothermal area revealed several key discoveries. The most prominent finding was the strong exponential correlation between sodium (Na) and chloride (Cl) concentrations (R^2 = 0.9694), suggesting a common origin through halite dissolution or mixing with connate water. Similarly, a robust linear relationship between calcium (Ca) and sulfate (SO_4) (R^2 = 0.9555) indicated significant contributions from gypsum or anhydrite dissolution, potentially coupled with sulfide oxidation and sedimentary rock leaching. These consistent patterns across samples support the hypothesis that evaporitic mineral dissolution and water–rock interaction are dominant processes shaping the geothermal fluid chemistry. In contrast, the scatter relationship between Ca + Mg and bicarbonate (HCO_3) revealed greater variability, pointing to heterogeneous lithology and localized carbonate or silicate weathering. The diagnostic plot (Figure 3D) further confirmed the influence of ion exchange and evaporite dissolution, with samples distributed across interpretive quadrants that reflect diverse subsurface geochemical processes [37, 38].

When comparing results, samples PN, PN1, and PN2 exhibited hydrothermal characteristics with Cl/Li ratios below 1000 and elevated boron concentrations (10–16 mg/L), while PN3 and AK showed higher Cl/Li ratios (up to 8000) and lower boron levels, indicating dilution or mixing with meteoric water. These contrasting patterns highlight spatial variability in hydrothermal activity and fluid evolution. The findings are supported by established geochemical models and align with previous studies on geothermal systems, although the unexpectedly high Cl/Li ratios in PN3 and AK suggest localized deviations that may reflect structural controls or recharge dynamics not captured in earlier research.

Limitations of the study include reliance on secondary data for site selection, limited temporal sampling (single campaign in June 2012), and absence of isotopic or gas analyses that could further constrain fluid sources and processes. Despite these constraints, the study provides valuable insights into the geochemical behavior of geothermal fluids in a relatively understudied region. The integration of Cl/Li ratios and boron concentrations as diagnostic tools represents a novel application in the Indonesian context, enhancing the resolution of hydrothermal system characterization and offering a promising approach for mineral prospecting. The identification of PN and PN1 as potential targets for borate mineralization underscores the economic relevance of the findings.

To build on this work, future research should incorporate multi-seasonal sampling, isotopic tracers, and geophysical surveys to refine the understanding of subsurface flow paths and reservoir structure. Expanding the dataset to include additional springs and integrating regional tectonic and lithological data will further elucidate the controls on geothermal fluid chemistry and

Table 3. Estimated reservoir temperature and depth of each thermal spring in the Empat Lawang geothermal, Southern Sumatra, Indonesia.

Sample Number	Thermal spring codes	Elevation average (masl)	Chemical geothermometry (°C)		Reservoir depth (km)
			(Fournier & Truesdell) [30]	(Giggenbach) [31]	(Arrofi) [32]
1	PN	398	421.32	231.78	5.29
2	PN1	398	429.29	234.83	5.38
3	PN2	398	430.62	235.33	5.41
4	PN3	398	1593.75	404.59	16.39
5	AK	398	332.22	190.13	4.22

support sustainable resource development in Empat Lawang and similar geothermal provinces.

3.2. Estimated Reservoir Temperature

The estimated reservoir temperature and depth information (Table 3) obtained from the geothermometric equations of [30] and [31] contributes significantly to the novelty and depth of analysis in this journal. This data not only strengthens the geochemical interpretation of hot springs in Empat Lawang, but also opens up new insights into the potential of hydrothermal systems and mineralization prospects in the region.

From the calculation results, it can be seen that the reservoir temperature estimate based on the Giggenbach equation shows a very high value, especially in the PN3 sample, which reaches 1593.75°C. Although this figure appears extreme and may be influenced by unbalanced chemical conditions or fluid mixing, it still indicates very intense geothermal activity. Meanwhile, estimates from the Fournier & Truesdell equation provide more conservative and realistic values, ranging from 190°C to 404°C. This difference reflects different methodological approaches, and the use of both methods simultaneously shows that this journal adopts a comprehensive approach to interpreting geothermal systems.

The estimated reservoir depth ranges from 4.22 km to 16.39 km, with PN3 being the deepest point. This depth is highly relevant in the context of geothermal and mineral resource exploration, as it indicates that the hydrothermal system in Empat Lawang potentially originates from a very deep zone, where rock and fluid interactions occur under high pressure and temperature. This supports the hypothesis that geothermal water in this region carries trace and major elements originating from deep rock leaching processes, including boron, lithium, and chloride, as shown in the Cl/Li vs B graph (Figure 4).

The main discoveries of this study reveal that the Empat Lawang geothermal system is shaped by a combination of evaporite dissolution, carbonate and silicate weathering, and ion exchange processes, as evidenced by strong correlations between Na–Cl (R^2 = 0.9694) and Ca–SO_4 (R^2 = 0.9555), and diagnostic plots that classify geochemical behavior across spring sites. These findings are further supported by the Cl/Li vs B diagram, which distinguishes hydrothermal waters (PN, PN1, PN2) from those affected by meteoric dilution (PN3, AK), highlighting spatial variability in fluid evolution. The use of geothermometric equations adds depth to the interpretation, with reservoir temperature estimates ranging from 190°C to 404°C (Fournier & Truesdell) [30] and an anomalously high value of 1593.75°C (Giggenbach) [31] in PN3, likely influenced by chemical disequilibrium or mixing. Estimated reservoir depths span 4.22 to 16.39 km, suggesting that geothermal fluids originate from deep, high-pressure zones where intense rock–fluid interactions mobilize trace elements such as boron, lithium, and chloride. These results collectively support the hypothesis that meteoric water interacts with mineral-rich reservoir rocks, producing distinct chemical signatures and potential mineralization zones.

While most findings align with global geothermal models, the extreme temperature estimate in PN3 and its high Cl/Li ratio present conflicting results that may reflect localized mixing, structural anomalies, or limitations in applying equilibrium-based geothermometers to dynamic systems. The study's limitations include reliance on secondary data for site selection, single-season sampling, and absence of isotopic or gas analyses, which constrain the resolution of fluid source identification and temporal variability. Nonetheless, the integration of major and trace element chemistry with geothermometric modeling establishes the novelty of this work, especially in the context of Indonesian geothermal research. The identification of PN and PN1 as promising sites for borate mineralization underscores the economic importance of the findings, while the methodological approach combining regression analysis, interpretive diagrams, and reservoir modeling demonstrates a robust and replicable framework. Future research should incorporate multi-seasonal sampling, isotopic tracers, and geophysical surveys to refine subsurface models and validate mineral prospecting targets, thereby advancing both scientific understanding

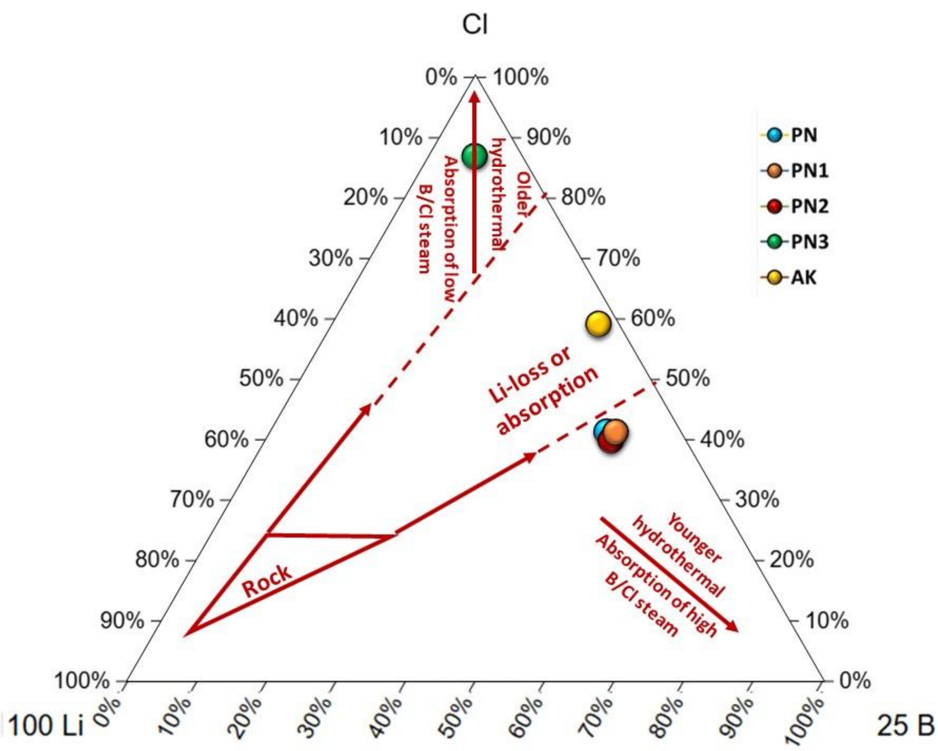

Figure 5. Cl-Li-B diagram for the thermal springs in the Empat Lawang geothermal, Southern Sumatra, Indonesia.

and resource development in Empat Lawang and similar geothermal provinces.

3.3. Water Sample Origin

Analysis of major and trace element composition in geothermal water from Empat Lawang, South Sumatra, shows significant geochemical variation between samples, as illustrated in the Cl–Li–B ternary plot (Figure 5). Samples PN and PN1, located near the chlorine (Cl) corner, indicate enrichment of this element, which generally reflects the strong influence of hydrothermal alteration flows. Meanwhile, the AK sample shows a dominance of boron (B), which is often associated with volcanic hydrothermal systems and potential borate mineralization such as tourmaline. The position of PN2 and PN3 between the Cl and B corners indicates a mixture of alteration processes and possible interaction with the host rock. The high lithium (Li) content in the 'Rock' zone points to the potential for lithium mineralization, which is important in the context of strategic mineral prospecting. The direction of the arrows in the plot illustrates geochemical processes such as hydrothermal fluid flow, elemental absorption by clay minerals, and contributions from volcanic systems [39–41]. Overall, the distribution of Cl, Li, and B elements in these geothermal water samples supports the hypothesis that the Empat Lawang geothermal system is a mixture of meteoritic and magmatic water, with a dominant influence from volcanic activity and hydrothermal alteration processes [42, 43]. These findings have important implications for mineral exploration and understanding the origin of geothermal fluids in the region.

Comparatively, the geothermometric estimates provide a deeper understanding of subsurface conditions. The Fournier & Truesdell equation yields realistic reservoir temperatures (190–404 °C), while the Giggenbach equation produces an anomalously high value (1593.75°C for PN3), likely due to disequilibrium or fluid mixing. Estimated reservoir depths range from 4.22 to 16.39 km, with PN3 again representing the deepest and most geochemically intense zone. These findings support the hypothesis that geothermal fluids originate from deep, high-pressure environments where meteoric and magmatic waters interact with mineral-rich rocks.

While most results align with global geothermal models, the extreme temperature and Cl/Li ratio in PN3 present conflicting signals that may reflect structural anomalies, sampling limitations, or the inadequacy of equilibrium-based geothermometers in dynamic systems. Limitations of the study include reliance on secondary data for site selection, single-season sampling, and the absence of isotopic or gas analyses, which restrict the resolution of fluid source identification and temporal variability.

Despite these constraints, the findings are significant. They establish the Empat Lawang geothermal system as a complex, volcanically influenced hydrothermal environment with promising mineralization potential. The integration of major and trace element chemistry, geothermometry, and ternary plotting techniques demonstrates methodological novelty and provides a replicable framework for future geothermal studies in Indonesia. These insights not only enhance scientific understanding but also inform strategic resource exploration. Further research should include multi-seasonal sampling, isotopic tracing, and geophysical surveys to validate mineral targets and refine subsurface models, advancing both academic knowledge and sustainable development in geothermal provinces.

4. Conclusions

This study provides a comprehensive geochemical assessment of geothermal waters from Empat Lawang, Southern Sumatra, revealing a complex interplay of evaporite dissolution, ion exchange, and carbonate–silicate weathering. Strong correlations between Na–Cl and Ca–SO_4 suggest halite and gypsum dissolution as dominant processes, while bicarbonate variability reflects lithological heterogeneity and water–rock interaction intensity. The Cl/Li vs. B plot further distinguishes hydrothermal signatures, with most samples falling below the Cl/Li < 1000 threshold, indicating active leaching and mineral transport. High boron concentrations in select samples point to promising prospects for borate and metal mineralization. By integrating classical ion relationships with modern geothermometric and trace element indicators, this study advances the understanding of hydrothermal systems in Indonesia and offers a novel framework for mineral exploration in volcanic geothermal settings.

A comprehensive geochemical characterization of geothermal waters from Empat Lawang, Southern Sumatra, highlighting significant enrichment in Cl, B, and Li linked to deep hydrothermal alteration processes. The integration of ternary element analysis with reservoir temperature and depth estimates derived from geothermometers adds more information. The estimated temperature and depth values observed in sample PN3 suggest intense geothermal activity, deep fluid-rock interaction and more evolved, reinforcing the potential for strategic mineral prospecting. These findings offer new insights into the origin and evolution of hydrothermal systems in the region.

Variations in major and trace element compositions reflect hydrothermal alteration processes and the influence of volcanic activity. The Cl–Li–B ternary plot shows that most samples are enriched in chlorine and boron, indicating the involvement of active hydrothermal fluid flows and potential borate mineralization. The lithium content detected in several samples also opens up opportunities for exploration of strategic minerals such as lithium, especially in rock interaction zones. The distribution of these elements supports the interpretation that geothermal water in the area originates from a mixture of meteoritic and magmatic water, with a predominance of volcanic hydrothermal alteration processes. These findings not only strengthen our understanding of the origin of geothermal fluids, but also provide an important scientific basis for mineral prospecting and geothermal resource management in Southern Sumatra, Indonesia.

An unexpected finding in this study was the extremely high reservoir temperature estimate for sample PN3, reaching 1593.75°C based on the Giggenbach geothermometer. This value far exceeds typical geothermal system temperatures and likely reflects disequilibrium conditions, fluid mixing, or limitations in applying equilibrium-based models to dynamic hydrothermal environments. Such anomalies underscore the need for cautious interpretation and highlight the complexity of subsurface processes in Empat Lawang. The discrepancy between the Giggenbach and Fournier & Truesdell temperature estimates where the latter yielded more conservative values between 190°C and 404°C demonstrates methodological divergence and reinforces the importance of using multiple geothermometers to triangulate realistic subsurface conditions. Additionally, the Cl/Li vs B and Cl–Li–B ternary plots revealed geochemical signatures that diverge from expectations in PN3 and AK, suggesting dilution by meteoric water or structural influences that alter fluid pathways and elemental concentrations.

The newness of this study lies in its integration of classical ion correlations with advanced geothermometric modeling and trace element diagnostics, offering a multidimensional framework for interpreting geothermal systems in volcanic settings. The use of Cl/Li ratios and ternary plots involving boron and lithium provides a novel approach to distinguishing hydrothermal fluid origins and assessing mineralization potential particularly for strategic elements like borate and lithium. This methodological synthesis is especially valuable in the Indonesian context, where such integrated geochemical assessments remain limited.

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