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Geochemical Investigation of Thermal Water Wells in Tebing Tinggi, North Sumatra, Indonesia: Geology and Preliminary Insights into Their Sources

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Original scientific paper

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Abstract

This study investigates the hydrogeochemical and isotopic characteristics of thermal waters from artesian wells in Tebing Tinggi, North Sumatra, Indonesia, to determine their origin, reservoir temperature, and structural controls influencing fluid circulation. Water samples from four thermal wells and one cold artesian well were collected and analysed for major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-), trace elements (Li, B, SiO_2), and stable isotopes ($\delta^{18}O$ and δ^2H) using titrimetry, atomic absorption spectrophotometry, ion chromatography, and cavity ring-down spectrometry. The $\delta^{18}O$–δ^2H relationship confirms a meteoric origin for the thermal waters. Hydrochemical analysis classifies the waters as sodium-bicarbonate type, with characteristics of immature waters due to elevated Mg content, indicating mixing with shallow groundwater. Geothermometry using quartz and Na-K-Ca methods estimates reservoir temperatures between 73°C and 123°C, corresponding to a low-enthalpy geothermal system. Reservoir depth is estimated at 1.26–2.67 km based on regional geothermal gradients. Fault and fracture density (FFD) modelling reveals high fracture concentrations in central Tebing Tinggi, aligned with the interpreted NE-SW trending Tebing Tinggi Fault, suggesting structural control on thermal fluid upwelling. These findings indicate that thermal water circulation in Tebing Tinggi is governed by both tectonic fracturing and residual heat from the Toba volcanic complex, providing baseline data for future geothermal resource assessment in the North Sumatra back-arc region.

Keywords:
thermal water hydrogeochemistry; geothermometry; low-enthalpy geothermal system; fault fracture density; North Sumatra

1. Introduction

Indonesia hosts more than 200 hydrothermal systems distributed along its active volcanic arcs, with an average of four hydrothermal systems per 100 km (**Hochstein and Sudarman, 1993**). In Sumatra, the convergence of the Indo-Australian Plate beneath the Eurasian continental crust has created favourable conditions for geothermal activity, with heat sources ranging from active volcanic systems to deep-seated magmatic intrusions in back-arc settings (**Carvalho et al., 1980**). Whilst high-enthalpy geothermal resources associated with active volcanic centres have been extensively studied, low-enthalpy systems in back-arc regions remain largely underexplored despite their potential for direct-use applications (**Hochstein, 1990; Rybach, 2022**).

Geothermal resources are commonly classified based on reservoir temperature into low-enthalpy (<125°C), intermediate-enthalpy (125–225°C), and high-enthalpy (>225°C) categories (**Hochstein, 1990; Nicholson, 1993; Axelsson and Gunnlaugsson, 2000**). Low-temperature geothermal resources in Sumatra have been recognised since 1993, yet systematic mapping of this potential remains incomplete (**Hochstein and Sudarman, 1993**). Recent hydrogeochemical studies in the Toba Caldera region have provided new insight into groundwater characteristics and recharge mechanisms in volcanic terrains (**Hendrayana et al., 2024**). The characterisation of these resources requires comprehensive hydrogeochemical and isotopic investigations to determine thermal water origin, reservoir temperature, and fluid circulation pathways (**Giggenbach, 1988; Fournier, 1977**).

Tebing Tinggi, a small town located approximately 80 km southwest of the Toba Caldera in North Sumatra, represents an intriguing case of thermal water occurrence in a back-arc basin setting. Unlike typical geothermal manifestations characterised by natural hot springs, thermal waters in Tebing Tinggi are exclusively accessed through artesian wells, some of which were drilled during the Dutch colonial period and remain operational today (**Ananda, 2019; Sumarno et al., 2022**). Despite over a

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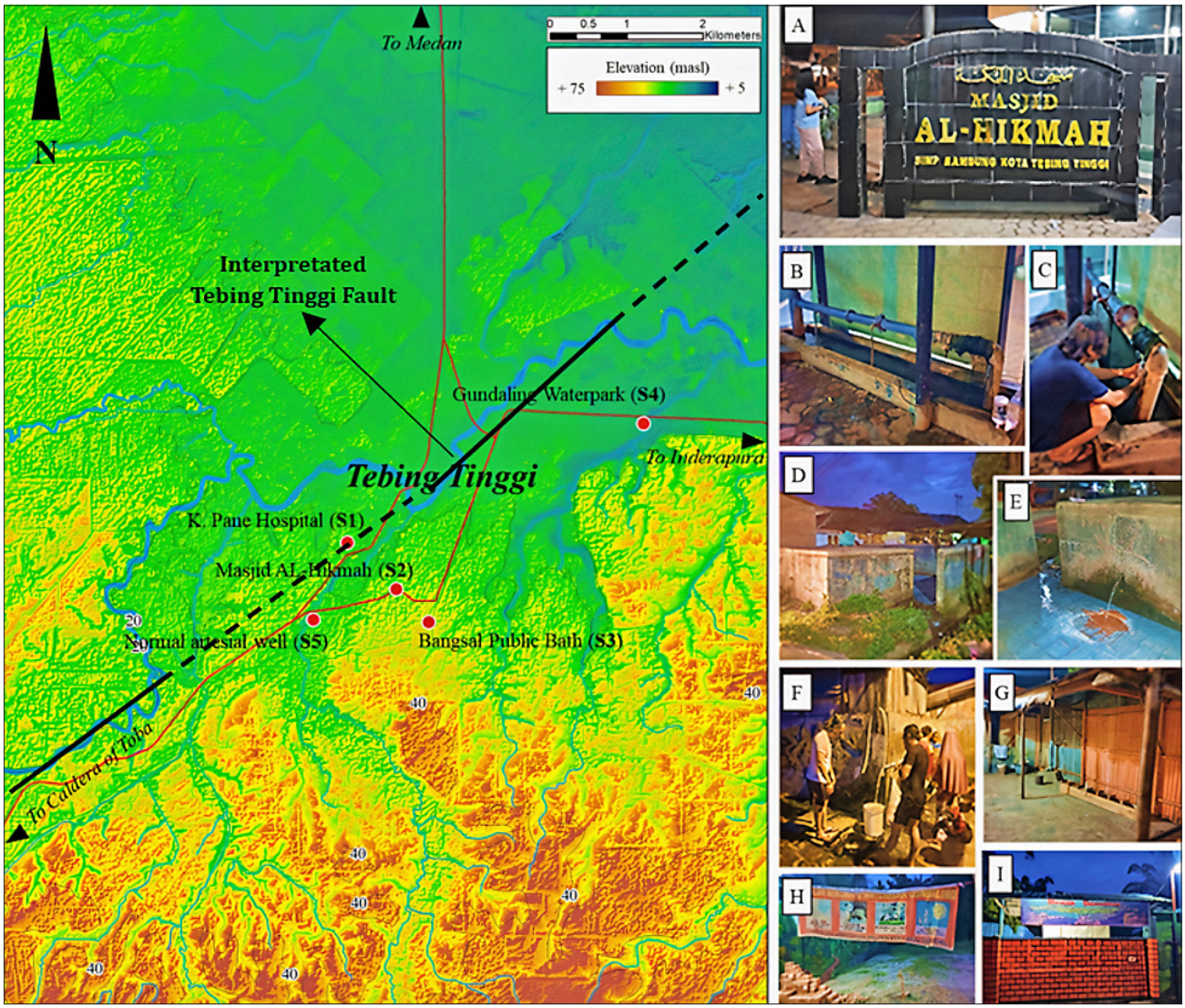


Figure 1: Thermal water sampling locations in Tebing Tinggi: Al-Hikmah Mosque (A, B, C), Bangsal Public Baths (D, E), Kumpulan Pane Hospital Public Baths (F, G), and Gundaling Waterpark (H, I). Contour lines indicate elevation in metres above sea level.

century of utilisation for public bathing and domestic purposes, no comprehensive geochemical investigation has been conducted to characterise these thermal waters or to assess the geothermal potential of the area.

The absence of systematic hydrogeochemical data represents a significant knowledge gap that limits understanding of the origin, reservoir characteristics, and structural controls of thermal water circulation in Tebing Tinggi. Heat from radioactive decay in thick granites can locally increase basement temperatures in the region (**Hochstein and Sudarman, 1993**), and the proximity to the Toba volcanic complex suggests potential volcanic influence on the geothermal system. Similar integrated approaches combining geochemistry and isotope analysis have successfully characterised geothermal systems elsewhere in Sumatra (**Prabowo et al., 2024**).

This study aims to fill this gap by conducting a comprehensive hydrogeochemical and isotopic characterisation of thermal waters from artesian wells in Tebing Tinggi. The specific objectives are: (1) to determine the origin of thermal waters using stable isotope analysis ($\delta^{18}O$ and $\delta^{2}H$); (2) to classify the hydrochemical facies and assess water-rock interaction processes; (3) to estimate reservoir temperatures using geothermometric methods; (4) to evaluate structural controls on thermal fluid circulation through fault and fracture density (FFD) modelling; and (5) to develop a preliminary conceptual model for the geothermal system. This integrated approach provides baseline data for future geothermal resource assessment in the North Sumatra back-arc region.

2. Materials and Methods

2.1. Study area

Tebing Tinggi is located in the North Sumatra Province, Indonesia, approximately 78 km southeast of Med-

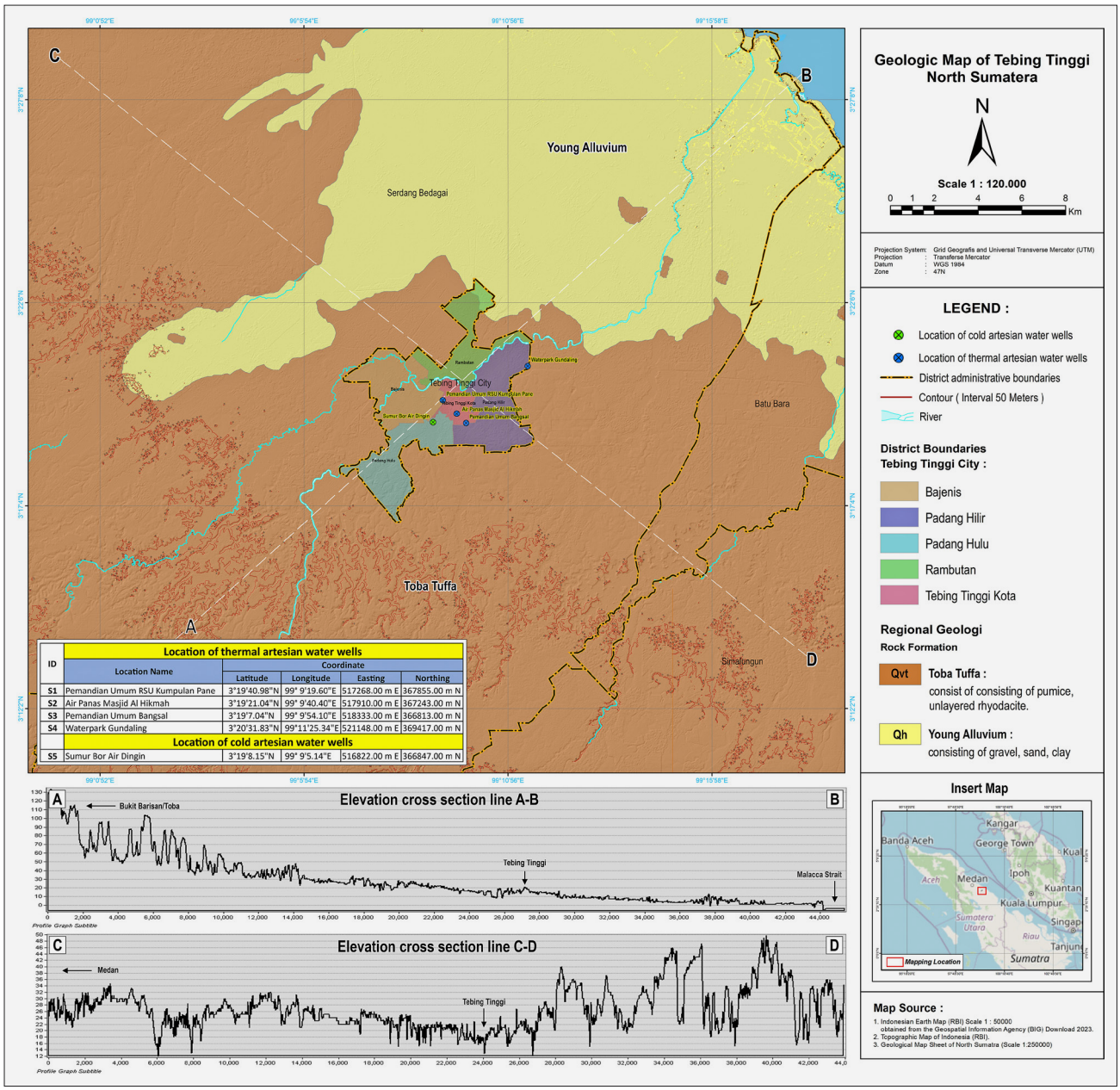


Figure 2: Lithological map of Tebing Tinggi showing the distribution of Toba Tuff (Qvt) and Young Alluvium (Qh), sampling locations, and the interpreted Tebing Tinggi Fault.

an City, 80 km southwest of the Toba Caldera, and 20 km east of the Malacca Strait coast (see **Figure 1**). The town is situated within a back-arc basin system formed by the subduction of the Indo-Australian Plate beneath the Sumatra region, as part of the North Sumatra Basin.

The presence of thermal groundwater in Tebing Tinggi was first discovered during the Dutch colonial era between 1917 and 1924 (**Ananda, 2019; Sumarno et al., 2022**). At least three artesian wells were drilled during this period, coinciding with the establishment of Tebing Tinggi as a municipality on July 1, 1917. The thermal water was distributed through pipelines to European residences in central Tebing Tinggi for domestic water supply. Some of these colonial-era wells, which are over 100 years old, remain operational today. Based on verbal communication with local informants, the drilling depths of the colonial-era thermal wells are approximately 100 m; however, official drilling records from that period are no longer available. Recent drilling activities in the area have reached depths of approximately 260 m to tap into the thermal aquifer.

Geologically, the region is primarily composed of Toba Tuff, a volcanic deposit formed during the Toba supereruption approximately 74,000 years ago (**Rampino and Self, 1993**). This tuff is characterised by non-laminated pumice layers interbedded with rhyodacite. In the northern area, particularly within the Rambutan subdistrict, the lithology consists of Toba Tuff overlain by

younger alluvial deposits (see **Figure 2**). The Toba eruption, with a volcanic explosivity index (VEI) exceeding eight, released approximately 2,800 km³ of material, blanketing an area of roughly 4 million km² (**Satyana et al., 2013**). The tuff deposits cover approximately 20,000 km² around the caldera with thicknesses ranging from 100 to 400 m (**Knight et al., 1986**). The thermal aquifer is interpreted as semi-confined to unconfined, based on the artesian behaviour observed in several wells and information from recent drilling activities in the area.

Although natural hot springs are absent in Tebing Tinggi, geothermal potential was revealed through groundwater drilling, which tapped into a thermal aquifer. The closest natural hot spring is Kawah Putih Tinggi Raja in Simalungun, approximately 50 km to the southwest. The geothermal potential of Tebing Tinggi is likely linked to the ongoing activity of the Toba volcanic complex.

Currently, thermal water locations in Tebing Tinggi include the Kumpulan Pane Hospital Public Bath (S1), Al Hikmah Mosque (S2), Bangsal Public Baths (S3), and Gundaling Waterpark (S4). These thermal waters are utilised primarily for public bathing and recreational purposes. A large hot water pipe at the Al Hikmah Mosque site is believed to be of Dutch origin, indicating the historical significance of thermal water utilisation in the area.

2.2. Methods

Water sampling was conducted in April 2023 at five locations: four thermal water sites (S1–S4) and one cold artesian well (S5) serving as a comparative reference. Temperature and pH were measured in the field at each sampling location. Water samples were collected following standard procedures for geothermal water analysis and transported to the Central Laboratory for Coal and Geothermal Mineral Resources, Bandung, Indonesia.

Laboratory analyses encompassed 21 parameters and dissolved elements, including major anions (Cl^-, SO_4^{2-}, CO_3^{2-}, and HCO_3^-), cations (Ca^{2+}, Na^+, K^+, F^-, Fe^{3+}, Mg^{2+}, and Li^+), and neutral compounds (SiO_2, NH_4, and B). These were analysed using titrimetry, colorimetry, gravimetry, atomic absorption spectrophotometry (AAS), spectrophotometry, and ion chromatography. All analyses were performed under controlled room temperature and humidity using standardised procedures. Anion concentrations (F^-, Cl^-, SO_4^{2-}) were measured using a Dionex ICS-1600 ion chromatograph (Thermo Fisher Scientific, USA). Cation concentrations (Ca^{2+}, Mg^{2+}, K^+, Na^+, Fe^{3+}, Li^+) and SiO_2 and Al^{3+} were determined by atomic absorption spectrophotometry using a Varian AA-280FS spectrometer (Agilent Technologies, Australia). NH_4^+ was measured using an Agilent Cary 300 UV-Vis spectrophotometer (Agilent Technologies, USA). Field parameters (pH and electrical conductivity) were measured using pH indicator paper and a portable conductivity meter, respectively. The methodological workflow of this study is illustrated in **Figure 3**.

Stable isotope contents of oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) were determined using cavity ring-down spectrometry (CRDS) with a Picarro L2130-i analyser (Picarro Inc., USA). The isotopic compositions were used to assess the origin of thermal waters by comparison with the Global Meteoric Water Line (GMWL).

Analytical quality was assessed through multiple procedures. All laboratory analyses were conducted at the Centre for Mineral, Coal and Geothermal Resources Laboratory (PSDMBP), Bandung, Indonesia, an accredited facility certified under KAN (Komite Akreditasi Nasional) accreditation LP-326-IDN, ensuring compliance with internationally recognised precision and accuracy standards. Instrument calibration was performed using certified reference standards in accordance with the applicable national standard methods (SNI) and internal laboratory procedures (IK-NP) specified for each parameter. Method blanks were routinely processed alongside samples to monitor potential contamination throughout the analytical process. Ionic charge balance error (CBE) was calculated as CBE (%) = [(Σ cations − Σ anions) / (Σ cations + Σ anions)] × 100, where ion concentrations are expressed in milliequivalents per litre (meq/L). The CBE values for all five samples ranged from −5.48% to +3.40% (see **Table 2**), with four samples within the generally accepted threshold of ±5% and one sample (S2) at −5.48%, which remains within the acceptable range of ±10% for natural waters with low ionic strength (**Appelo and Postma, 2005**).

Hydrochemical data interpretation was conducted using cross-plot and ternary diagram analyses following the spreadsheet approach proposed by **Powell and Cumming (2010)**. Water type classification was performed using Piper diagrams, whilst water-rock interaction processes were evaluated using Gibbs diagrams. Reservoir temperature estimation was performed using a quartz geothermometer (**Fournier, 1977**) and a Na-K-Ca geothermometer (**Fournier and Truesdell, 1973**). These geothermometers were selected based on their applicability to low-enthalpy systems and the hydrochemical characteristics of the samples. The equilibrium state of thermal waters was assessed using the Na-K-Mg ternary diagram (**Giggenbach, 1988**). Reservoir depth was estimated by combining geothermometer results with regional geothermal gradient data from nearby wells (Diski Well, Tanjung Morawa-1 Well, and NSO-2S Well) available from **Siringoringo et al. (2024)**.

Fault and fracture density (FFD) modelling was performed to evaluate structural controls on thermal fluid circulation. Lineaments were manually extracted from satellite imagery to avoid non-structural features (roads, buildings, shading effects) and classified into major (>1.61 km) and minor (<1.61 km) categories following **Baioumy et al. (2015)** and **Arrofi et al. (2022)**. FFD values were calculated and categorised into five classes: very high (2.81–4.54 km/km²), high (1.91–2.81 km/km²), moderate (1.61–1.91 km/km²), low (0.46–1.61 km/km²), and very low (0–0.46 km/km²).

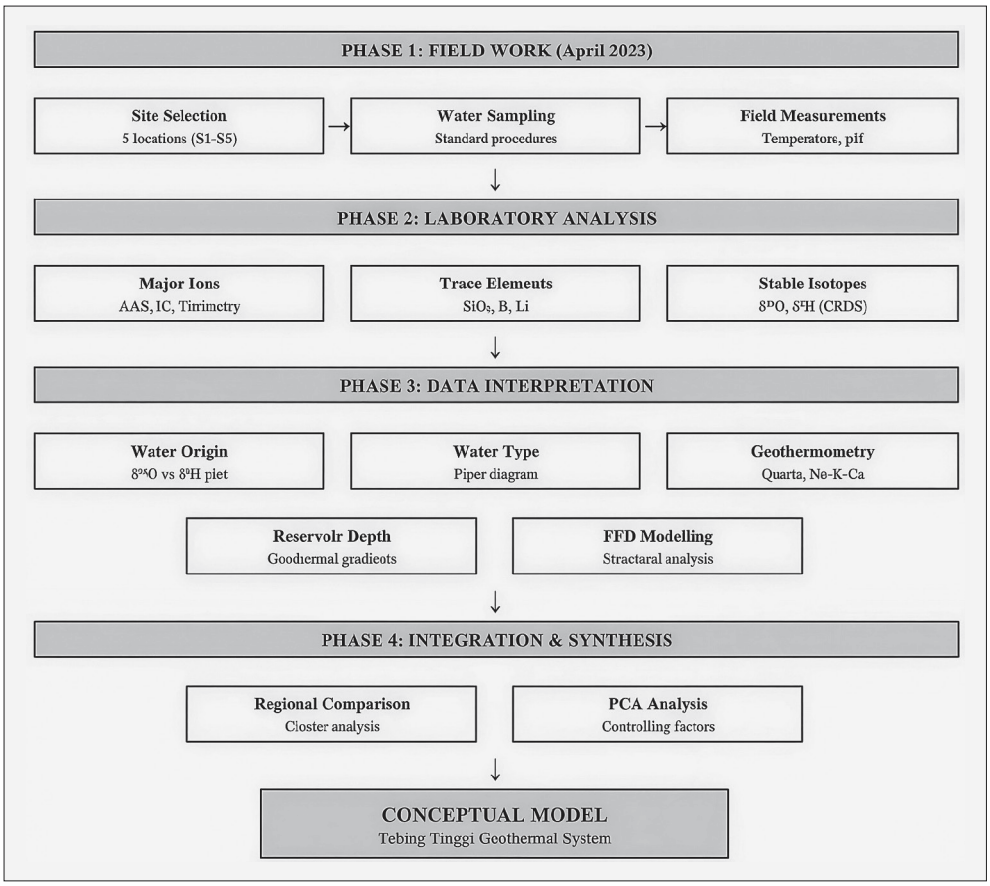


Figure 3: Methodological flowchart illustrating the research workflow from field sampling through laboratory analysis, data interpretation, and integration into a conceptual model

The methodological workflow of this study is illustrated in **Figure 3**.

3. Results

3.1. Field observations and sampling

Four thermal water samples (S1–S4) and one cold artesian well sample (S5) were collected from Tebing Tinggi in April 2023. The thermal water sites are characterised by hilly lowland terrain with elevations ranging from 11 to 27 m above sea level. Field observations identified a river lineament crossing Tebing Tinggi in a NE-SW direction, hypothetically interpreted as a fault lineament (Tebing Tinggi Fault). The results of field measurements are summarised in **Table 1**.

Thermal water temperatures ranged from 43°C to 56°C, with pH values between 8.7 and 9.5, indicating alkaline conditions. All thermal water samples were colourless and tasteless with a slight odour of sulphur. In contrast, the cold artesian well (S5) exhibited a temperature of 23°C and near-neutral pH of 7.4.

3.2. Stable isotope composition

The $\delta^{18}O$ versus $\delta^{2}H$ cross-plot shows that both thermal and cold-water samples plot close to the Global Meteoric Water Line (GMWL), confirming a predominantly meteoric origin for the thermal waters (see **Figure 4**). Thermal water samples exhibit $\delta^{18}O$ values ranging from -9.14‰ to -8.96‰ and $\delta^{2}H$ values from -60.96‰ to -59.22‰. The cold artesian well (S5) shows slightly enriched isotopic composition ($\delta^{18}O$: -8.08‰; $\delta^{2}H$: -52.64‰) but remains within the meteoric water range (see **Table 2**).

3.3. Hydrochemical characteristics

The complete hydrochemical data are presented in **Table 3**. Thermal water samples are characterised by dominant Na^{+} (74.5–89.6 mg/L) and HCO_3^{-} (163.1–229.2 mg/L) concentrations, with low Cl^{-} (1.0–1.5 mg/L) and SO_4^{2-} (1.0–2.1 mg/L) contents. The Piper diagram classifies all thermal water samples as sodium-bicarbonate (Na-HCO_3) water type (see **Figure 5D**). This water type is consistent with peripheral bicarbonate thermal waters associated with steam-heated groundwater from a deeper reservoir.

The Na-K-Mg ternary plot indicates that most thermal water samples fall within the immature water field, with a tendency towards partial equilibration at temperatures around 110°C. The elevated Mg content suggests mixing with shallow meteoric water. The Gibbs diagram (see **Figure 6**) indicates that rock weathering is the dominant process controlling the hydrochemistry of thermal waters in Tebing Tinggi, rather than evaporation or precipitation dominance.

Table 1: Location and Thermal Water Characteristics

ID	Location	Type of Water	Elevation (m)	Easting	Northing	Temp (°C)	pH	Remarks
S1	K. Pane Hospital	Thermal water	21	517268.00 mE	367855.00 mN	50	9.3	Colourless, tasteless water with a slight odour of sulphur.
S2	Al-Hikmah Mosque	Thermal water	23	517910.00 mE	367243.00 mN	56	9.4	Colourless, tasteless water with a slight odour of sulphur.
S3	Bangsal Public Baths	Thermal water	27	518333.00 mE	366813.00 mN	43	9.5	Colourless, tasteless water with a slight odour of sulphur.
S4	Waterpark Gundaling	Thermal water	11	521148.00 mE	369417.00 mN	50	8.7	Colourless, tasteless water with a slight odour of sulphur.
S5	Normal artesian well	Cold water	19	516822.00 mE	366847.00 mN	23	7.4	Water is odourless, colourless and tasteless.

Table 2: Analysis Results of Parameters and Elements in Thermal and Cold-Water Samples from Tebing Tinggi

ID	Parameter										
	$\delta^{18}O$	$\delta^{2}H$	pH	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	Fe^{3+}	Li^{+}	TDS	EC
	‰	‰		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	µS/cm
S1	-9.00	-60.96	9.45	1.94	<LLD	0.05	83.12	<LLD	<LLD	236	331
S2	-9.14	-59.22	9.93	3.47	1.46	0.47	76.76	0.13	0	314	287
S3	-8.96	-59.48	9.72	1.74	0.54	1.05	89.59	0.21	0	168	356
S4	-9.10	-60.00	10	2.6	2.42	0.14	74.5	0.03	0	136	283
S5	-8.08	-52.64	7.26	8.72	4.95	7	20.12	0.31	0	124	131

Table 3: Analysis Results of Parameters and Elements in Thermal and Cold Water in Tebing Tinggi (Cont.).

ID	Parameter									
	SiO_2	B	Al^{3+}	As^{3+}	NH_4^{+}	F^{-}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	CO_3^{2-}
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
S1	25.54	0.24	0.1	0	0.32	0.15	1	1	214.36	6.43
S2	31.79	0.24	0.47	0	1.32	0.13	1.28	1.73	171.39	35.6
S3	32.27	0.24	0.3	0	0.22	0.19	1.49	2.13	229.19	18.29
S4	32.38	0.15	0.51	0	1.14	0.12	1.19	1.73	163.09	30.79
S5	115.26	0.54	0.22	0	0.4	0.14	3	5	97.12	0

Note: LLD Mg^{2+}: 0.0020 mg/L; LLD Fe^{2+}: 0.0018 mg/L; LLD Li^{+}: 0.0027 mg/L

3.4. Geothermometry results

Reservoir temperatures were estimated using quartz and Na-K-Ca geothermometers, which provided the most reliable results for this low-enthalpy system. The quartz geothermometer (**Fournier, 1977**) yielded temperatures of 73–83°C, whilst the Na-K-Ca geothermometer (**Fournier and Truesdell, 1973**) indicated temperatures of 105–123°C (see **Table 4**). Based on these results, the applicable reservoir temperature range is estimated at 73–123°C.

3.5. Reservoir depth estimation

Based on geothermometer results and regional geothermal gradients from nearby wells (52°C/km at Diski Well, 46°C/km at Tanjung Morawa-1 Well, and 58°C/km at NSO-2S Well), the reservoir depth is estimated to range from 1.26 to 2.67 km, with a mean depth of approximately 1.79 km (see **Table 5**).

3.6. Fault and fracture density

FFD modelling identified both major (>1.61 km) and minor (<1.61 km) lineaments in the Tebing Tinggi area. Both lineament types exhibit a predominant NE-SW orientation, aligned with the interpreted Tebing Tinggi Fault (see **Figure 7**). The majority of lineaments are classified as minor. FFD analysis reveals a zone of high fracture density (1.91–2.81 km/km²) concentrated in the centre of Tebing Tinggi town, coinciding with the locations of thermal water wells. This spatial correlation in-

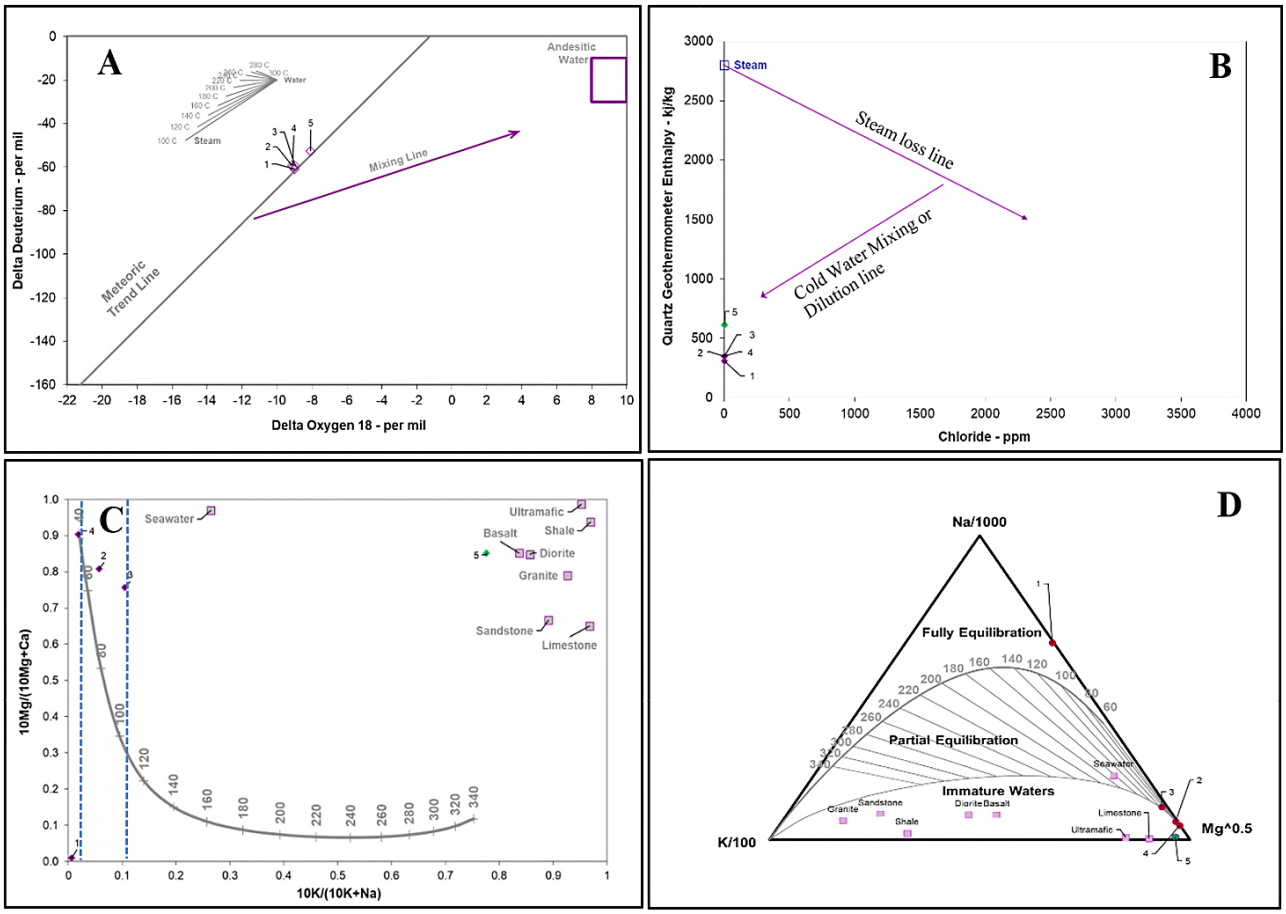


Figure 4: Cross and Ternary Plots of Thermal Water in Tebing Tinggi. A) The δ^2H versus $\delta^{18}O$ cross-plot indicates that the thermal water aligns almost perfectly with the Global Meteoric Water Line. B) The Quartz Enthalpy versus chloride cross-plot shows that the thermal water is associated with a dilution of the mixing line. C) The Na-K versus Mg-Ca cross-plot diagram, presented by Giggenbach and Goguel (1989), suggests that the reservoir temperature of the thermal water ranges from 40 to 110°C. D) The Na-K-Mg ternary plot indicates that the thermal water samples are predominantly associated with immature waters, with Sample 1 from K. Pane Hospital showing an association with fully equilibrated water.

dicates that fracture networks play a critical role in controlling the permeability of the subsurface, facilitating the upward migration of thermal fluids. The dominance of minor lineaments suggests pervasive fracturing within the Toba Tuff, enhancing secondary porosity and enabling effective fluid circulation.

4. Discussion

4.1. Origin of thermal waters

The stable isotope composition of thermal waters in Tebing Tinggi provides clear evidence for a meteoric origin. All samples plot close to the Global Meteoric Water Line (GMWL), with no significant oxygen isotope shift that would indicate prolonged water-rock interaction at elevated temperatures. This isotopic signature is consistent with relatively shallow circulation and/or rapid ascent of meteoric water through fractured zones, with limited residence time in the reservoir.

The slightly enriched isotopic composition of the cold artesian well (S5) compared to the thermal samples may reflect different recharge elevations or seasonal variations in precipitation. The thermal waters likely originate from meteoric recharge at higher elevations in the surrounding hills, which subsequently percolates downward through the Toba Tuff and interacts with deeper heat sources before ascending through fault-controlled pathways.

4.2. Hydrochemical evolution and water type

The sodium-bicarbonate (Na-HCO_3) water type identified in all thermal samples is characteristic of peripheral geothermal waters that have undergone steam heating and condensation processes (**White, 1957; Zhao et al., 2018**). The low chloride content (<1.5 mg/L) and absence of significant sulphate enrichment distinguish these waters from volcanic crater lakes or acid-sulphate systems, indicating that the thermal fluids have not been in direct contact with magmatic gases.

The formation of Na-HCO_3 water in Tebing Tinggi can be explained by the interaction of CO_2-bearing steam with silicate-rich wall rocks. The CO_2 may origi-

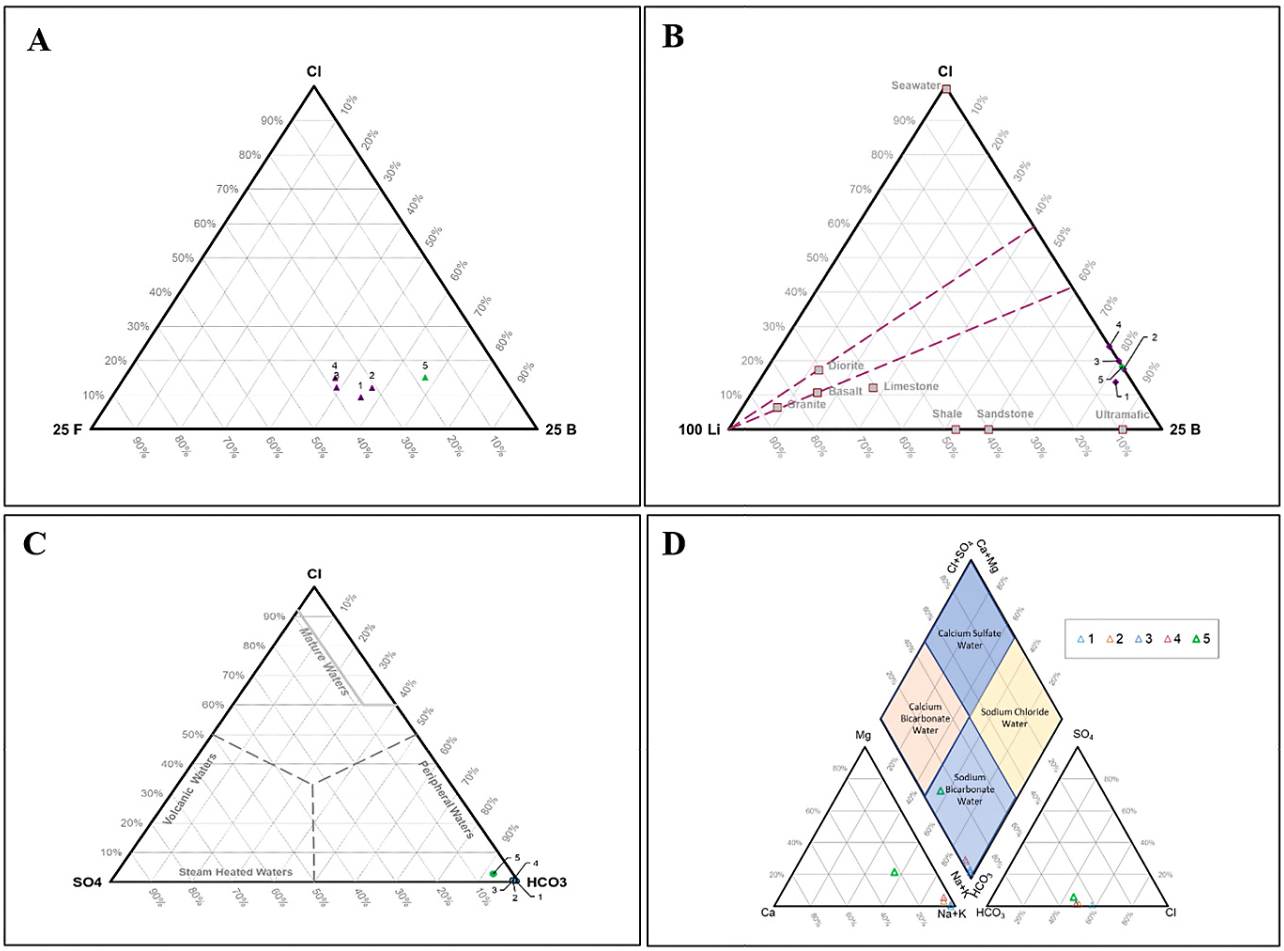


Figure 5: Ternary Plot of Thermal Water in Tebing Tinggi, Indonesia. **A)** The ternary plot of chloride, fluoride, and boron indicates the predominance of boron in the samples. **B)** Ternary plot of chloride, lithium, and boron showing the dominance of ultramafic waters. **C)** The ternary plot of Cl-SO_4-HCO_3 indicates peripheral bicarbonate thermal water with some sulfate and chloride, likely associated with groundwater heated by steam from a deeper reservoir. **D)** The Piper plot indicates that the water samples are related to sodium bicarbonate.

nate from several sources: (a) degassing from a deep magmatic source related to the Toba volcanic system, (b) thermal decomposition of carbonate minerals, or (c) deep circulation of meteoric water interacting with carbonate-bearing sediments (**Zhao et al., 2018**). Given the regional geological setting dominated by Toba Tuff (rhyolitic composition), the interaction between ascending CO_2-rich fluids and silicate minerals likely produces the observed alkaline, bicarbonate-dominated chemistry.

The elevated pH (8.7–9.5) and low TDS (136–314 mg/L) values further support a steam-heated origin rather than direct discharge from a deep chloride reservoir. The classification of thermal waters as 'immature' based on the Na-K-Mg diagram (see **Figure 4D**) indicates that chemical equilibrium with reservoir minerals has not been fully attained, consistent with mixing between ascending thermal fluids and shallow groundwater.

4.3. Reservoir temperature and depth

The discrepancy between quartz geothermometer results (73–83°C) and Na-K-Ca geothermometer results (105–123°C) reflects the immature nature of the thermal waters. Silica geothermometers are generally more reliable for low-enthalpy systems because silica equilibration occurs more rapidly than cation exchange reactions (**Fournier, 1977; Karingithi, 2013**). However, the Na-K-Ca geothermometer may provide insight into deeper reservoir conditions before mixing with shallow groundwater.

The estimated reservoir temperature range of 73–123°C classifies the Tebing Tinggi geothermal system as a low-enthalpy resource according to multiple classification schemes (**Hochstein, 1990; Nicholson, 1993; Axelsson and Gunnlaugsson, 2000**). This temperature range is consistent with the measured surface temperatures (43–56°C), accounting for conductive heat loss during fluid ascent.

The estimated reservoir depth of 1.26–2.67 km (mean ~1.79 km) indicates a deep geothermal resource, as defined by depths greater than 1 km (**Breede et al., 2015; Rybach, 2022**). This depth range is consistent with the regional geothermal gradients observed in the North Su-

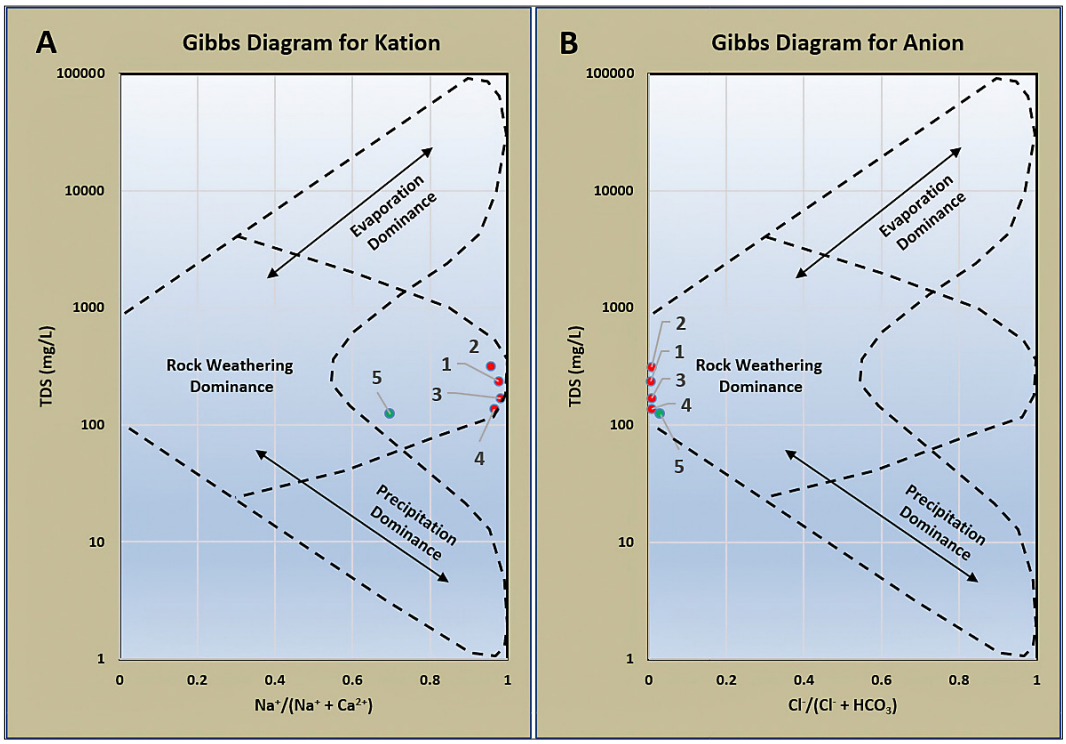


Figure 6: Gibbs Diagram for Cation (A) and Anion (B) of the water samples, indicating rock weathering dominance as the primary control on water chemistry.

Table 4: Geothermometer results for thermal water samples (°C).

Sample	Quartz (Fournier, 1977)	Na-K-Ca (Fournier and Truesdell, 1973)
S1	73	108
S2	82	123
S3	82	105
S4	83	116

matra Basin and suggests that the heat source is located at considerable depth beneath the Toba Tuff sequence.

4.4. Structural controls on thermal fluid circulation

The FFD modelling results demonstrate a clear spatial correlation between high fracture density zones and thermal water occurrences in Tebing Tinggi. The con-

Table 5: Reservoir depth estimation based on geothermal gradients.

Sample	Quartz Geothermometer (in °C)	Geothermal reservoir depth prediction (in km)		
	Quartz Steam loss	Diski	Tanjung Morawa-1	NSO-2S
	Fournier (1977)	52 deg C/km	46 deg C/km	58 deg C/km
S1	77	1.48	1.67	1.33
S2	85	1.63	1.85	1.47
S3	86	1.65	1.87	1.48
S4	86	1.65	1.87	1.48
Sample	**Quartz Geothermometer (in °C)**	**Geothermal reservoir depth prediction (in km)**		
	Quartz No Steam loss	**Diski**	**Tanjung Morawa-1**	**NSO-2S**
	Fournier (1977)	**52 deg C/km**	**46 deg C/km**	**58 deg C/km**
S1	73	1.40	1.59	1.26
S2	82	1.58	1.78	1.41
S3	82	1.58	1.78	1.41
S4	83	1.60	1.80	1.43
Sample	**Na-K-Ca geothermometer (in °C)**	**Geothermal reservoir depth prediction (in km)**		
		Diski	**Tanjung Morawa-1**	**NSO-2S**
	Fournier and Trusdell (1973)	**52 deg C/km**	**46 deg C/km**	**58 deg C/km**
S1	108	2.08	3.35	1.86
S2	123	2.37	2.67	2.12
S3	105	2.02	2.28	1.81
S4	116	2.23	2.52	2.00

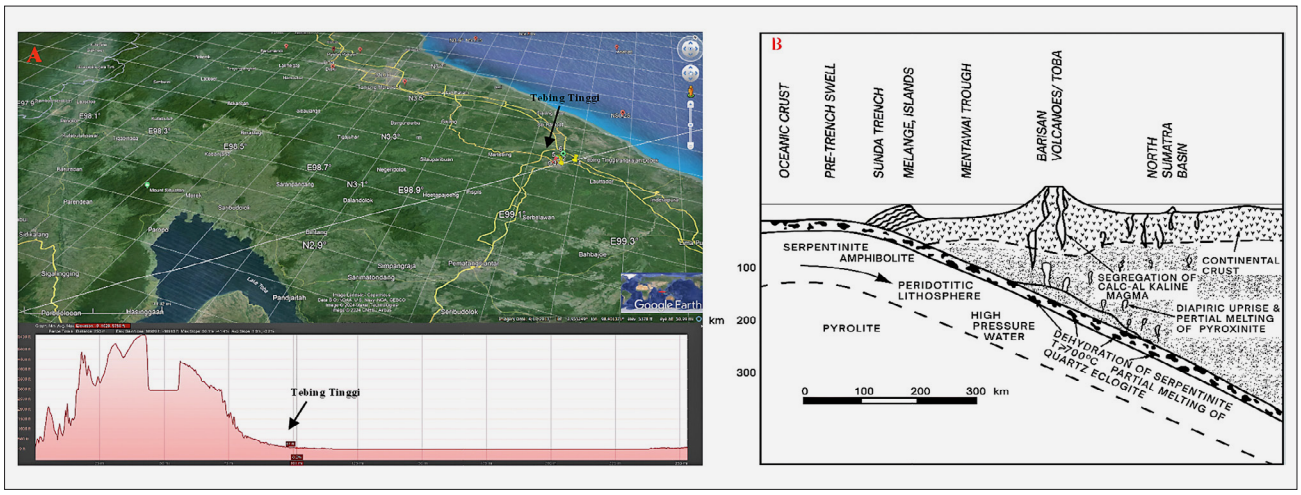


Figure 7: A) Elevation cross-section from the Toba volcanic complex to Tebing Tinggi. B) Subduction cross-section cartoon in the North Sumatra Basin with magmatic diapirs, modified from **Carvalho et al. (1980)**.

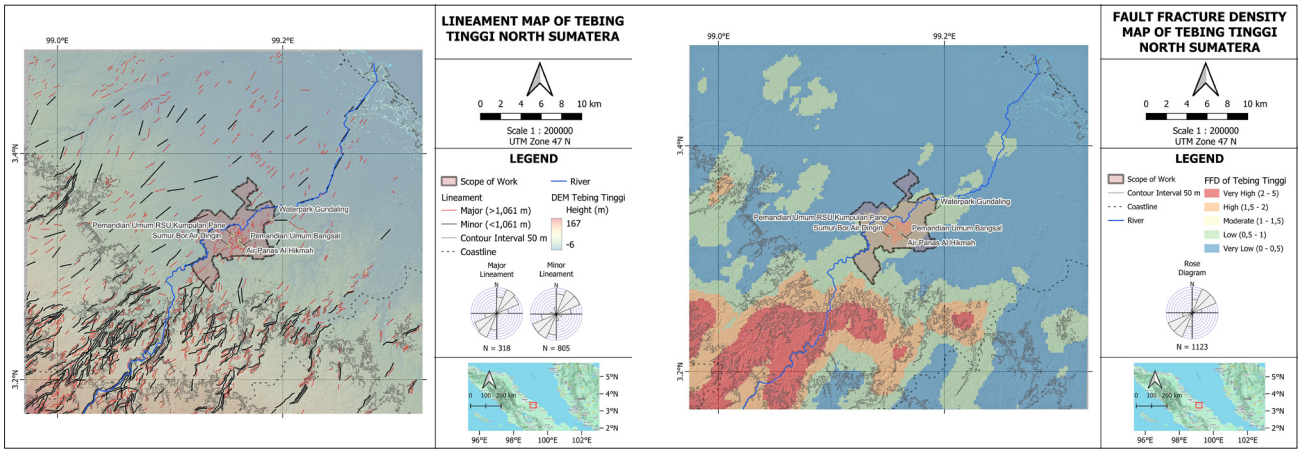


Figure 8: Fault and fracture density (FFD) analysis of the Tebing Tinggi area. A) Map of lineaments based on lineament lengths and orientation in Tebing Tinggi and surroundings. B) FFD modelling results showing zones of high fracture density concentrated in central Tebing Tinggi, coinciding with thermal water well locations.

centration of high FFD values (1.91–2.81 km/km²) in the town centre, aligned with the interpreted NE-SW trending Tebing Tinggi Fault (see **Figure 7**), suggests that this structure serves as the primary conduit for thermal fluid migration from depth to the shallow aquifer.

The predominance of minor lineaments (<1.61 km) indicates pervasive fracturing of the Toba Tuff, which enhances secondary permeability and facilitates fluid circulation. The NE-SW orientation of both major and minor lineaments is consistent with the regional structural grain associated with back-arc extension in the North Sumatra Basin (see **Figure 8**).

The role of faults in controlling thermal manifestations is well documented in geothermal systems worldwide (**Arrofi et al., 2022; Baioumy et al., 2015**). In Tebing Tinggi, the Tebing Tinggi Fault likely creates a permeable pathway connecting the deep heat source with the shallow Toba Tuff aquifer, allowing meteoric water to circulate to depth, become heated, and return to the surface as thermal water.

4.5. Comparison with regional geothermal systems

Principal component analysis (PCA) indicates that the chemical characteristics of Tebing Tinggi thermal waters are controlled primarily by four factors: dissolved silica (SiO_2), bicarbonate (HCO_3^-), total dissolved solids (TDS), and electrical conductivity (EC) (see **Figure 9**). The dominance of SiO_2 reflects water-rock interaction with silica-rich Toba Tuff, whilst HCO_3^- indicates the influence of CO_2-bearing fluids.

Hierarchical cluster analysis comparing Tebing Tinggi samples with thermal waters from the Toba Complex and the west coast of Peninsular Malaysia reveals that Tebing Tinggi waters are geochemically more similar to Toba hot springs than to Malaysian thermal waters (see **Figure 10** and **Table 6**). This similarity suggests a volcanic influence on the Tebing Tinggi geothermal system, despite the absence of surface volcanic manifestations.

The higher silica content in Malaysian hot springs compared to Tebing Tinggi and Toba samples reflects

Table 6: Geothermal Resources Classification Based on Temperature (°C)

	Muffler and Cataldi (1978)	Haenel, Rybach and Stegena (1998)	Hochstein, 1990	Benderitter and Cormy (1990)	Nicholson (1993)	Axelsson and Gunnlaugson (2000)
Low Enthalpy Resources	< 90	≤ 150	< 125	<100	≤ 150	≤ 190
Intermediate Enthalpy Resources	90 - 150	-	125 - 225	100 - 200	-	-
High Enthalpy Resources	> 150	> 150	> 225	> 200	> 150	> 190

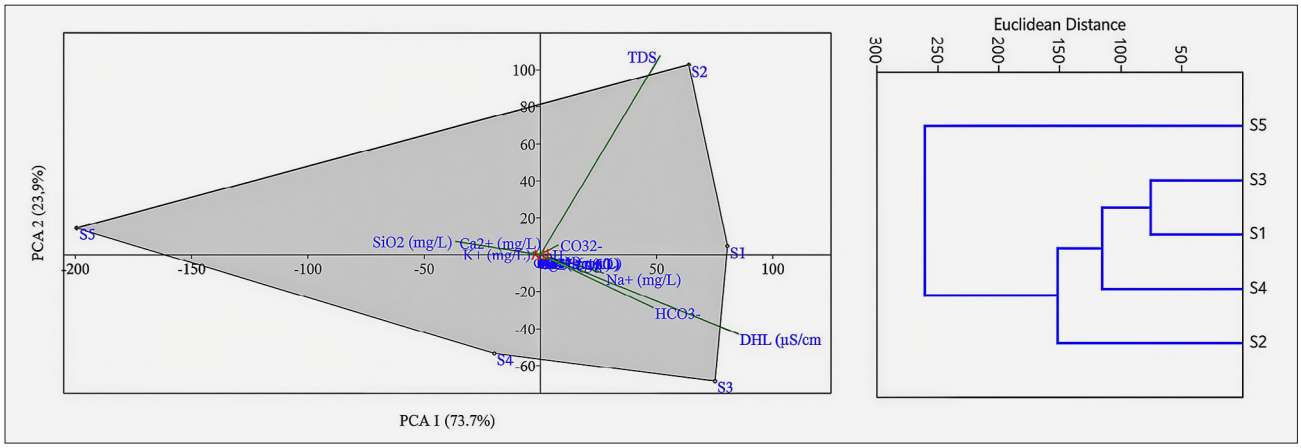


Figure 9: Biplot of PCA for all measured parameters (left) and Hierarchical clustering of the Tebing Tinggi thermal water using the Pair Group (UPGMA) algorithm based on Euclidean Distance (right).

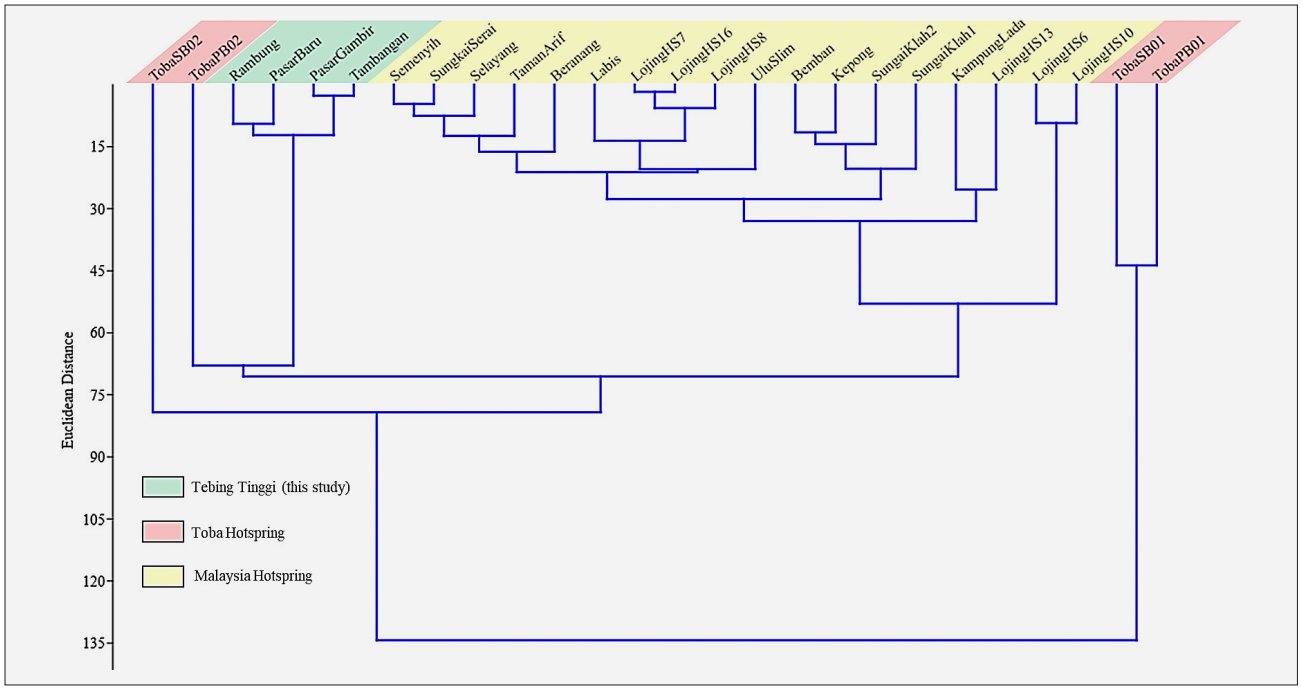


Figure 10: Dendrogram showing the relationships among samples from Tebing Tinggi thermal water and samples from other regions.

the dominant granitoid lithology in Peninsular Malaysia (**Baioumy et al., 2015**). In contrast, the Tebing Tinggi thermal waters exhibit geochemical signatures consistent with interaction with volcanic rocks (Toba Tuff), supporting a genetic link to the Toba volcanic system rather than purely tectonic heat sources (see **Table 7**).

4.6. Conceptual model of the Tebing Tinggi geothermal system

Based on the integrated hydrogeochemical, isotopic, and structural data, we propose the following conceptual model for the Tebing Tinggi geothermal system:

Table 7: Geochemical composition of Tebing Tinggi thermal water (this study) compared to other references (**Prasetio et al. 2017,** and **Baioumy et al. 2015**).

Region	Site	Na	K	Ca	Mg	SiO_2	Cl	SO_4
Tebing Tinggi	Pasar Baru (S1)	83.12	0.05	1.94	0.00	25.54	1.00	1.00
	Pasar Gambir (S2)	76.76	0.47	3.47	1.46	31.79	1.28	1.73
	Rambung (S3)	89.59	1.05	1.74	0.54	32.27	1.49	2.13
	Tambangan (S4)	74.50	0.14	2.60	2.42	32.38	1.19	1.73
West Coast of Malaya Peninsula	Semenyih	44.80	2.80	15.40	0.10	73.00	3.00	1.00
	Beranang	46.80	2.40	26.30	0.20	83.00	1.80	0.90
	KampungLada	45.40	2.70	8.80	0.60	52.00	3.60	2.00
	Labis	41.30	1.90	1.80	0.30	80.00	9.00	4.00
	Selayang	44.10	2.50	16.90	0.20	80.00	1.90	0.90
	TamanArif	32.70	1.90	9.70	1.00	76.00	2.00	0.90
	Bemban	60.80	2.80	4.30	0.30	98.00	6.90	6.00
	SungkaiSerai	40.80	1.90	13.50	0.20	74.00	3.00	0.90
	UluSlim	35.20	1.70	2.00	0.30	93.00	5.30	4.00
	Kepong	57.50	3.10	4.20	0.20	88.00	4.40	10.00
	PangkalanHulu	37.70	2.10	147.00	1.10	65.00	1.30	7.00
	SungaiKlah1	55.00	2.80	0.50	0.10	111.00	1.70	2.00
	SungaiKlah2	48.90	2.60	0.90	0.10	92.00	1.10	2.00
	LojingHS6	51.00	2.30	1.60	0.10	125.00	2.00	20.00
	LojingHS7	47.00	1.90	1.90	0.10	75.00	2.00	14.00
	LojingHS8	44.00	1.50	2.30	0.10	79.00	1.90	12.00
	LojingHS10	53.00	2.50	1.50	0.10	134.00	3.00	20.00
	LojingHS13	54.00	1.50	2.20	0.20	63.00	2.00	22.00
	LojingHS16	48.00	2.10	2.00	0.10	76.00	2.00	15.00
Toba Complex	TobaSB01	7.60	22.90	105.80	63.50	50.60	59.20	50.60
	TobaSB02	9.10	16.10	3.60	6.00	59.50	7.20	59.50
	TobaPB01	17.20	27.80	66.80	55.10	55.30	46.60	55.30
	TobaPB02	85.90	6.90	25.50	32.20	51.80	6.80	51.80

(1) Recharge: Meteoric water infiltrates through the permeable Toba Tuff and younger alluvial deposits in the surrounding highlands.

(2) Deep circulation: Groundwater percolates downward along fault zones, reaching depths of 1.3–2.7 km where it is heated by conductive heat transfer from a deep source. This heat source may be related to residual magmatic heat from the Toba volcanic complex or elevated heat flow associated with back-arc extension in the North Sumatra Basin (Carvalho et al., 1980; Hochstein and Sudarman, 1993).

(3) Fluid-rock interaction: At depth, heated water interacts with silicate minerals in the Toba Tuff, acquiring dissolved silica and cations. CO_2-bearing fluids (possibly of deep magmatic origin) contribute to the formation of bicarbonate-rich chemistry.

(4) Ascent: Thermal fluids ascend along the Tebing Tinggi Fault and associated fracture networks, driven by buoyancy. During ascent, mixing with shallow cold groundwater occurs, resulting in the observed 'immature' water characteristics.

(5) Discharge: Thermal waters are accessed through artesian wells that tap into the shallow aquifer at depths of approximately 100–260 m, where ascending thermal fluids have mixed with local groundwater.

This model explains the key observations: meteoric isotopic signature, Na-HCO_3 water type, immature equilibrium state, moderate reservoir temperatures, and structural control on thermal water distribution.

5. Conclusions

Hydrogeochemical and isotopic investigation of thermal waters from artesian wells in Tebing Tinggi, North Sumatra, reveals the following key findings:

(1) Origin: The thermal waters are of meteoric origin, as evidenced by their stable isotope composition

($\delta^{18}O$ and $\delta^{2}H$) plotting along the Global Meteoric Water Line. The waters are classified as immature due to elevated Mg content, indicating mixing with shallow groundwater during ascent.

(2) Water type: All thermal water samples are classified as sodium-bicarbonate ($Na\text{-}HCO_3$) type, characteristic of peripheral geothermal waters formed through the interaction of CO_2-bearing fluids with silicate-rich Toba Tuff.

(3) Reservoir characteristics: Geothermometry estimates reservoir temperatures of 73–123°C, classifying the system as a low-enthalpy geothermal resource. The reservoir depth is estimated at 1.26–2.67 km (mean ~1.79 km), indicating a deep geothermal system.

(4) Structural control: Fault and fracture density modelling identifies high fracture concentrations in central Tebing Tinggi, aligned with the NE-SW trending Tebing Tinggi Fault. This structure serves as the primary conduit for thermal fluid migration from depth to the surface.

(5) Geothermal affinity: Cluster analysis indicates that Tebing Tinggi thermal waters are geochemically more similar to volcanic-hosted hot springs in the Toba Complex than to tectonically-controlled thermal waters in Peninsular Malaysia, suggesting a genetic link to the Toba volcanic system.

These findings provide baseline hydrogeochemical data for future geothermal resource assessment in the North Sumatra back-arc region and demonstrate the potential for low-enthalpy geothermal utilisation in areas lacking surface thermal manifestations.

Future research should focus on: (1) detailed hydrogeological characterisation including drilling logs and aquifer testing; (2) time-series monitoring of thermal water chemistry and temperature; (3) geophysical surveys to delineate subsurface structures; and (4) assessment of direct-use applications for the low-enthalpy geothermal resources in Tebing Tinggi.

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SAŽETAK

Geokemijsko istraživanje izvora termalne vode u Tebing Tinggiju, Sjeverna Sumatra, Indonezija: geologija i preliminarne spoznaje o njihovim izvorima

U okviru ove studije istražene su hidrogeokemijske i izotopne karakteristike termalnih voda iz arteških zdenaca u Tebing Tinggiju, Sjeverna Sumatra, Indonezija, kako bi se utvrdilo njihovo podrijetlo, temperatura ležišta te identificirala strukturna obilježja koja utječu na cirkulaciju fluida. Prikupljeni su uzorci vode iz četiriju termalnih zdenaca i jednoga hladnoga arteškog zdenca te su izmjerene koncentracije glavnih iona (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-), elementi u tragovima (Li, B, SiO_2) te stabilni izotopi ($\delta^{18}O$ i δ^2H) korištenjem titrimetrije, atomske apsorpcijske spektrofotometrije, ionske kromatografije i laserske spektrometrije. Odnos $\delta^{18}O$–δ^2H potvrđuje meteorsko podrijetlo termalnih voda. Hidrokemijska analiza klasificirala je vodu kao natrijsko-bikarbonatnu, s karakteristikama nezrelih voda zbog povišenoga sadržaja Mg, što upućuje na miješanje s plitkom podzemnom vodom. Primjenom kvarcne i Na-K-Ca geotermometrijske metode procijenjene su temperature vodonosnika između 73 °C i 123 °C, što odgovara geotermalnom sustavu niske entalpije. Dubina vodonosnika procjenjuje se na 1,26 – 2,67 km na temelju regionalnih geotermalnih gradijenata. Modeliranje rasjeda i gustoće pukotina (FFD) otkriva visoke koncentracije pukotina u središnjemu Tebing Tinggiju, što se slaže s interpretiranim rasjedom Tebing Tinggi koji se proteže u smjeru sjeveroistok-jugozapad, a što upućuje na to da geološka struktura kontrolira uzdizanje termalne tekućine. Rezultati istraživanja pokazuju da je cirkulacija termalne vode u Tebing Tinggiju uvjetovana tektonski nastalim pukotinama i zadržanom toplinom vulkanskoga kompleksa Toba te daju osnovu za buduću procjenu geotermalnih resursa u regiji zaleđa Sjeverne Sumatre.

Ključne riječi:
hidrogeokemija termalne vode, geotermometrija, geotermalni sustav niske entalpije, gustoća pukotina, Sjeverna Sumatra

Author's contribution

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All authors have read and agreed to the published version of the manuscript.