International Journal of Hydrological and Environmental for Sustainability
Volume 3, Issue 3, 163-173.
e_ISSN: 2828-5050
https://www.journal.foundae.com/index.php/ijhes

Geothermal Waters from the Alpine Mountain Region, Europe: A Comprehensive Geochemical and Isotopic Analysis

Cornelia Victoria Anghel
Faculty of Resita Engineering Science, Technical University of Cluj-Napoca,
ROMANIA

Glenaldo Achmad Zhafran Evito
School of Integrative and Global Majors,
University of Tsukuba,
JAPAN

Mikael Syväjärvi
Alminica AB, Ulrika, Östergötlands Län,
SWEDEN

***Correspondence: E-mail:** s2019505@u.tsukuba.ac.jp

Article Info

Article history:

Received: August 21, 2024
Revised: September 20, 2024
Accepted: October 10, 2024

Abstract

The Alpine region of Europe, which covers several countries including France, Switzerland, Italy, Austria and Germany, is characterised by its complex geology and significant geothermal potential. This research investigates the geochemical characteristics of geothermal water in the Alpine region, focusing on understanding the origin, evolution, and potential applications of these geothermal resources. Through comprehensive hydrochemical and isotopic analyses, we have identified key geochemical signatures that distinguish the various geothermal systems in the region. The results show that these geothermal waters are mainly influenced by deep magmatic processes, extensive water-rock interactions, and mixing of meteoric and magmatic fluids. Elevated concentrations of elements such as sodium (Na), lithium (Li), and chloride (Cl), as well as different stable isotopes, provide insights into the thermal and geochemical environments of geothermal reservoirs. Based on isotopic analysis oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$), the most of the geothermal water in the Alpine mountain region of Europe is of meteoric origin (derived from meteoric waters). The isotopic composition can reveal the mixing between meteoric and magmatic water. Intermediate values between GMWL and magmatic water compositions indicate such mixing, helping to understand the fluid dynamics within geothermal systems. This research underlines the importance of integrating geochemical studies in the exploration and management of geothermal resources in tectonically active regions such as the Alps.

Keywords: alpine mountain region; geochemical analysis; geothermal waters; isotopic analysis; water-rock interactions

To cite this article: Anghel, C, V., Evito, G, A, Z. and Syväjärvi, M. (2024). Geothermal Waters from the Alpine Mountain Region, Europe: A Comprehensive Geochemical and Isotopic Analysis. *International Journal of Hydrological and Environmental for Sustainability, 3*(3), 163-173. https://doi.org/10.58524/ijhes.v3i3.5331

INTRODUCTION

The Alpine mountain region in Europe is a unique and dynamic area characterized by its complex geological history and diverse geothermal resources. The topography of the Alpine region, with its high mountains and deep valleys, affects groundwater flow and the distribution of geothermal resources. Groundwater systems are often influenced by topography, with recharge areas located in high mountains and discharge areas in valleys. The region spans across eight countries, including France, Switzerland, Italy, Austria, Germany, Slovenia, Liechtenstein, and Monaco, and is known for its stunning landscapes, rich biodiversity, and significant geothermal potential (Harlaux et al., 2017; Michalski, 2010).

The geology of the Alpine region of Europe is complex and diverse, which plays an important role in the formation and behaviour of geothermal waters. The Alps were formed by the collision of the African and Eurasian tectonic plates, which led to intense tectonic activity and the creation of many faults and fractures. These structural features provide pathways for geothermal fluids to rise to the surface. The Alpine region consists of a mixture of Precambrian and Phanerozoic rocks. Older Precambrian rocks are found in the northeast, while younger Phanerozoic rocks are more dominant in the southwest (Huang & Korai, 2025; Rafiq et al., 2024). The region exhibits high heat flow due to its tectonic activity. This high heat flow contributes to the geothermal gradient, which is the rate of temperature increase with depth. The presence of faults and fractures allows for the circulation of hydrothermal fluids. These fluids can be heated by the geothermal gradient and rise to the surface, forming hot springs, geysers and hydrothermal reservoirs (Schäffer et al., 2018).

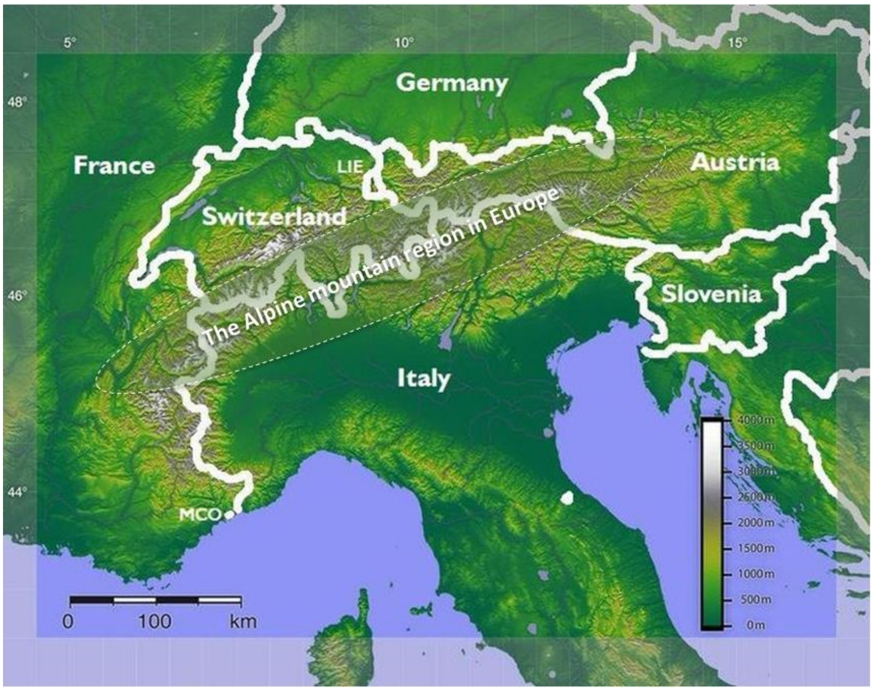

Figure 1. Topography map of Alpine mountain region in Europe

Geothermal waters in the Alpine region are primarily derived from deep within the Earth's crust, where they are heated by the natural geothermal gradient. These waters can be found in various forms, including hot springs, geysers, and hydrothermal reservoirs. The geothermal activity in the Alps is closely linked to the tectonic processes that have shaped the region over millions of years, including the collision of the African and Eurasian tectonic plates (Hristov et al., 2019; Rybach et al., 2003; Schäffer et al., 2018; Vuataz, 1983). The utilization of geothermal energy in the Alpine region offers a sustainable and renewable solution to meet the increasing energy demands while reducing carbon emissions. Projects like GRETA (Geothermal Resources Exploitation in the Alpine Territories) aim to promote the use of near-surface geothermal energy (NSGE) to meet heating energy demands and support the transition to low-carbon energy sources (Deon et al., 2015). The project has developed guidelines and tools to help municipalities and administrations incorporate NSGE into their energy plans and strategies.

Geothermal waters in the Alpine region also have significant potential for balneological (therapeutic) use, with many hot springs and thermal baths attracting visitors seeking health and wellness benefits (**Figure 1**). The region's geothermal resources are a valuable asset that can contribute to sustainable development, energy security, and environmental conservation (Mibei, 2014). Geochemical characterisation of geothermal water in the Alpine region of Europe has an important goal of Resource Identification. Geochemical analysis helps identify and characterise geothermal resources, including their temperature, flow rate and chemical composition. This information is critical for assessing the potential of geothermal systems for energy production. In addition, by analysing the chemical and isotopic composition of geothermal water, this research is expected to trace the origin of these fluids, distinguishing between magmatic, meteoric and mixed water. This helps in understanding the geological processes taking place (Hristov et al., 2019; Meju & Le, 2002; Parrone et al., 2020; Rybach et al., 2003).

METHOD

Sample Collection

Geothermal water samples were collected from previous research by Vuataz, (1983). The various hot springs and geothermal wells located within the Alpine mountain region of Europe. Sampling sites were chosen based on their accessibility and representativeness of different geothermal systems in the region. All samples were collected in clean, pre-rinsed polyethylene bottles to prevent contamination. During sampling, in-situ measurements of temperature, pH, and electrical conductivity were recorded using portable field instruments calibrated prior to each sampling campaign. The concentrations of major cations (Na, K, Ca, Mg) and anions (Cl, SO_4, HCO_3) were determined. Trace elements, including lithium (Li), Strontium (Sr), and others, were analyzed. Stable isotopes of oxygen ($\delta^{18}O$) and hydrogen (δ^2H) were measured. Water samples were equilibrated with CO_2 (for $\delta^{18}O$) and H_2 (for δ^2H) gases, and the isotopic ratios were determined relative to the Vienna Standard Mean Ocean Water (V-SMOW). Geochemical modeling was conducted using Excell software to simulate water-rock interactions and to understand the thermodynamic behavior of the geothermal fluids. The isotopic data were plotted on $\delta^{18}O$ vs. δ^2H diagrams to distinguish between different fluid sources and mixing processes.

Table 1. Physiochemical properties of the water samples collected from the Alpine mountain region of Europe

Location	Name	$\delta^{18}O$ (‰)	δ^2H (‰)	Cl/Li	$1000\sqrt{Mg}$	10K	Na/(Na+Ca)	Na/Cl	SO_4/Cl
Yverdon	Bath Spring	-11	-76.9	2125	4582.57	19.7	0.58	0.70	0.14
Lostorf	Well 3	-10.2	-71.3	93.75	7300.68	19.6	0.04	0.71	42.67
Lostorf	Well 4	-10.4	-70.9	427.77	11575.83	41.2	0.06	0.71	36.36
Schinznach	Bath Spring	-9.96	-71.9	927.27	8899.43	175	0.50	0.71	1.86
Baden	Walderhut Spring	-9.03	-70.5	240.24	10295.63	703	0.57	0.60	1.07
Zurzach	Well 2	-10.3	-74.9	111.86	509.90	76.8	0.95	2.18	1.67
St-Gervais	Gontard 1 Spring	-13.5	-95.7	88.80	5224.94	392	0.82	1.46	2.17
Lavey	Well 200 m	-13	-96.9	65.04	1584.29	115	0.87	1.64	2.51
Leukerbad	San Lorenz Spring	-14.5	-104	63.33	8185.35	19.7	0.04	2.26	136.84
Weissenburg	Mineral Spring	-12	-83.2	160	8706.31	41.4	0.05	2.11	131.25
Bad-Ragaz	Pfafers Spring	-13.3	-95.1	135.18	3949.68	24.8	0.33	0.81	0.66
Pr~-St-Didier	Bath Spring	-14.3	-105	475	4785.39	37.5	0.34	1.58	4.32
Saxon	Bath Spring	-13.5	-97.8	115.38	6457.55	23.1	0.15	1.45	15.33
Saxon	Well 3	-13.8	-103	106.83	9165.15	136	0.28	1.87	14.40
Combioula	Spring 1	-15.2	-112	750.70	10198.03	360	0.45	0.92	3.85
Brigerbad	Left Spring	-15.1	-111	70.66	1574.80	258	0.66	2.30	5.66
Craveggia	Bath Spring	-11.4	-75.7	125	223.60	16.2	0.80	24.76	56.00
Acquarossa	Albergo Spring	-10.8	-72.6	70	9370.16	164	0.03	2.54	178.57
Vals	Upper Well	-12.9	-91.8	81.25	7641.98	16.3	0.02	3.38	292.31
Masino	Bath Spring	-12.6	-85.3	800	200	38.7	0.76	4.21	10.00
Bormio	San Martino Spring	-13.8	-98.2	135.71	7803.84	29.2	0.07	1.97	71.05

Sources : Data taken from Vuataz, (1983)

RESULTS AND DISCUSSION

Geochemical Analysis

Piper plot analysis are a valuable tool for visualising the chemical composition of geothermal water and identifying its sources and interactions. Based on the analysis results in **Figure 2**, the plot shows distinct clusters representing different water types, including Na-Cl type water, Ca-HCO_3 type water, and mixed water. The piper plot analysis of geothermal data from the Alpine mountain region of Europe highlights the mixing of meteoric water with deeper magmatic fluids. This is evident from the centre position at some data points between the meteoric water field and the magmatic water field. The mixing ratio varies across different sampling locations, reflecting the heterogeneity of the geothermal system (Akoteyon, 2013; Idroes et al., 2019; Ravikumar & Somashekar, 2017).

Over time in the water rock interaction, Piper plots show changes in water chemistry, possibly due to ongoing water-rock interaction and variations in recharge conditions. The results show that almost all geothermals from the Alpine mountain region of Europe are magnesium bicarbonate dominant. This result characterises that the salinity at the study sites is not as high as that of fluids released from subducting slabs. However, if observed in some areas, geothermal samples from the Alpine mountain region of Europe show increased leaching of minerals from the surrounding rocks. Fluids originating from higher temperatures tend to have higher concentrations of certain ions, such as Na and Cl, indicating deeper circulation and higher thermal gradients. If Na and Cl ions are low, there is likely to be mixing and dilution before eventually escaping to the surface.

The results from the Piper plot analysis provide valuable insights into the geochemical characteristics and behaviour of geothermal water in the Alpine region. The identification of different water types and mixing processes helps in understanding the complex interactions between meteoric and magmatic fluids. This knowledge is crucial for the sustainable management and exploitation of geothermal resources. In addition, the observed changes in water chemistry over time highlight the dynamic nature of geothermal systems and the need for continuous monitoring. The thermal influence on water chemistry underscores the importance of temperature as a key factor in geothermal exploration and utilisation. Overall, the Piper plot analysis contributes to a comprehensive understanding of the geochemical processes at play in Alpine geothermal waters, aiding the development of effective strategies to utilise this renewable energy resource (Hristov et al., 2019; Rybach et al., 2003; Schäffer et al., 2018; Vuataz, 1983).

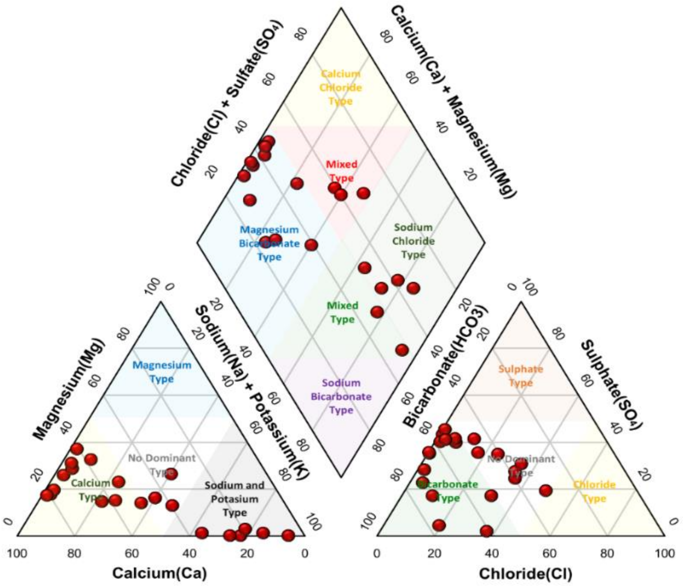

Figure 2. B-Li-Cl diagram for the hot spring water

The Cl-SO_4-HCO_3 ternary plot is a useful tool to visualise the chemical composition of geothermal water and understand its geochemical processes. The chemical data (Cl, SO_4, and HCO_3 concentrations) of geothermal water samples from the Alpine mountain region of Europe were normalised first to ensure that they sum to 100% for each sample. Each corner of the triangle represents 100% of one of the ions (Cl, SO_4, HCO_3), and the position of each sample within the triangle indicates its relative proportion.

Based on the ternary plot **(Figure 3)**, samples from the Alpine mountain region of Europe belong to the Sulfate type, some samples of the Alpine mountain region of Europe show the bicarbonate type. Judging from the chemical results, the samples from the Alpine mountain region of Europe are interpreted as Sulfate reservoir waters (Volcanic waters). On the other hand, some samples from the Alpine mountain region of Europe have a bicarbonate type caused by condensation of vapour and gas into groundwater below the surface (Deon et al., 2015; Hristov et al., 2019). This type of water generally appears on the sides or periphery of both types of geothermal systems, both on volcanic plateaus and flatlands (Doğan et al., 2006; Hristov et al., 2019; Négrel et al., 2010).

The Na-K-Mg ternary diagram provides additional insight into the processes occurring within the geothermal fluid, as shown by Giggenbach, (1992). When plotted on this diagram **(Figure 3)**, most samples from the Alpine mountain region of Europe show evidence of partial and full equilibrium, indicating that they are well integrated into the geothermal system. Some samples are exceptions; as previously mentioned, the thermal water in the Alpine mountain region of Europe does not fully represent the characteristics of typical reservoir water in this region. This interpretation is reinforced by their placement on the ternary diagram **(Figure 2)**, where some samples fall under the category of immature water (no dominant type).

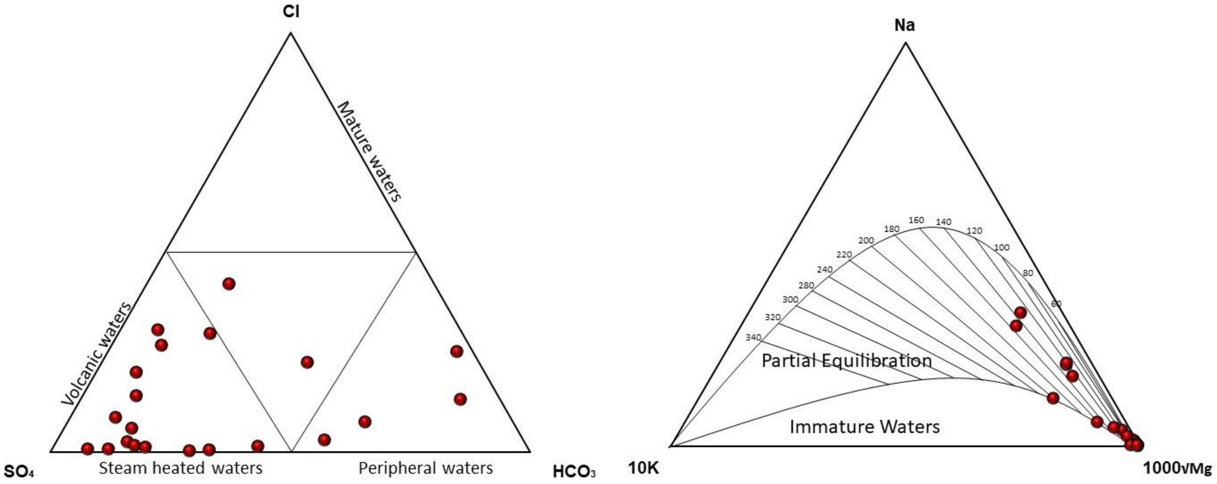

Figure 3. Ternary plot Cl-HCO_3-SO_4 and Ternary plot of Na-K-Mg of the water samples in Alpine mountain region of Europe

The **Figure 4** was proposed by Purnomo et al., (2016) to use major ions to distinguish between volcanic geothermal systems and fault-induced geothermal systems. In Figure 5, geothermal samples from the Alpine mountain region of Europe correlate strongly with systems induced by volcanic geothermal systems. The distribution of geothermal plots from the Alpine mountain region of Europe shows that each thermal water has a different mixing and dilution process before finally coming out to the surface (Cortecci et al., 2005; Deon et al., 2015; Vuataz, 1983).

The Cl/Li (chloride/lithium) ratio in geothermal water is an important geoindicator that can provide insight into geochemical processes and fluid sources within geothermal systems. In the Alpine region of Europe, the Cl/Li ratio can help distinguish different types of geothermal fluids and their interactions with the surrounding rocks. Cl/Li ratios < 1000 usually indicate a strong influence of deep-seated magmatic fluids, as lithium is often derived from magmatic (mantle) sources, while chlorine is more often associated with water-rock interactions at shallower depths. A low Cl/Li ratio also indicates a greater contribution from meteoric water (surface water) and extensive water-rock interactions. However, this needs to be correlated with the respective indicator concentrations of Lithium (Li) and Chlorine (Cl). Intermediate Cl/Li ratios (around 1000) with low Li and Cl concentrations may indicate a mixture of magmatic and meteoric water, reflecting complex interactions in geothermal systems (Millot et al., 2007; Purnomo et al., 2016; Utama et al., 2021).

In **Figure 5**, it can be seen that the Cl and Li concentrations have different explanations. The Cl concentration vs Cl/Li ratios explain that meteoric water and seawater have very clear differences. Thus, the plot results of Cl concentration vs Cl/Li ratio can explain the origin of mixing or dilution in geothermal waters dominated by meteoric waters. Meanwhile, the plot results of Li concentration vs Cl/Li ratios can corroborate the contribution of magmatic water. Some geothermal waters are strongly suspected to be derived from magmatic water, but some geothermal waters also have a small contribution from magmatic water (Millot & Négrel, 2007). Most of the hot springs from the Alpine mountain region of Europe are plotted near meteoric water, this result suggests that the origin of the Alpine mountain region of Europe hot springs is from secondary magmatic water.

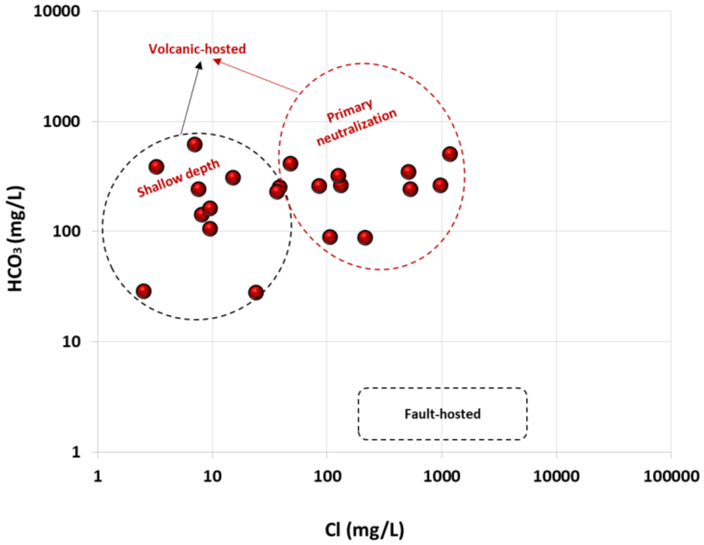

Figure 4. Plot of Cl vs HCO_3 in the geothermal of Alpine mountain region of Europe. Black dashed line is the distribution of hot springs around Java island proposed by Purnomo et al., (2016)

Secondary magmatic water (SMW) refers to geothermal fluids that have undergone significant interaction with magmatic gases and rocks, but are not directly derived from a primary magmatic source. These waters are typically found in geothermal systems where magmatic heat has influenced the hydrothermal fluids, but the fluids themselves have mixed with meteoric water (surface water) and have been altered by water-rock interactions. Secondary magmatic waters often have elevated concentrations of certain elements like chloride (Cl), sulfate (SO_4), and bicarbonate (HCO_3), which are indicative of both magmatic inputs and water-rock interactions (Giggenbach, 1992).

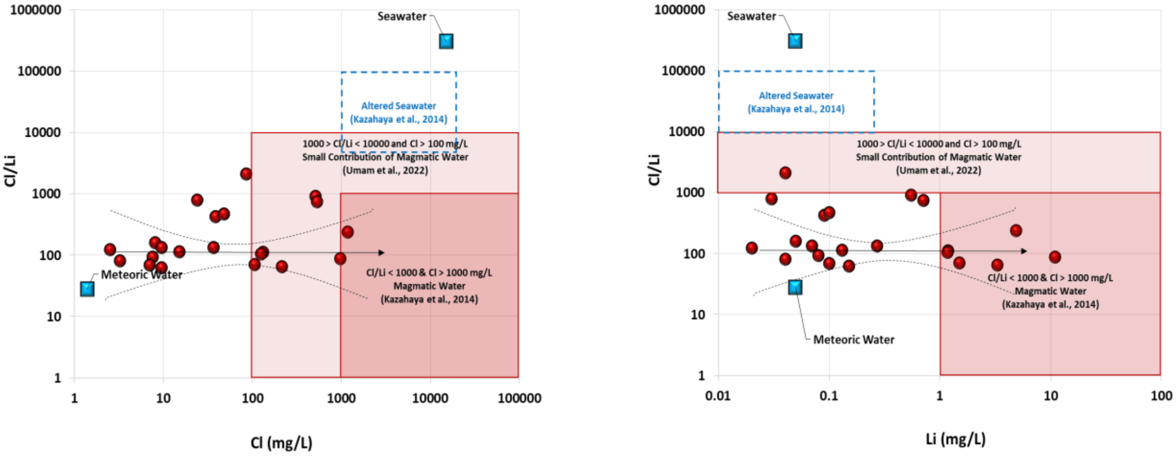

Figure 5. Ternary plot $Cl-HCO_3-SO_4$ and Ternary plot of Na-K-Mg of the water samples in Alpine mountain region of Europe

Isotopic Analysis

Stable isotopes, particularly oxygen ($\delta^{18}O$) and hydrogen (δ^2H), are powerful tools for interpreting the origins and processes affecting geothermal waters in the Alpine mountain region of Europe. The $\delta^{18}O$ and δ^2H values help determine whether geothermal water is of meteoric origin (derived from precipitation) or has a magmatic component (Adachi & Yamanaka, 2024). Meteoric water usually lies along the Global Meteoric Water Line (GMWL), while magmatic water often shows a heavier isotopic composition due to high-temperature interactions with rocks (Matsubaya et al., 1973). Isotope fractionation occurs when water interacts with rocks at high temperatures. This can lead to changes in isotopic composition, which provides insight into the extent and nature of water-rock interactions (Hosono et al., 2020; Javino et al., 2010; Mook, 2006).

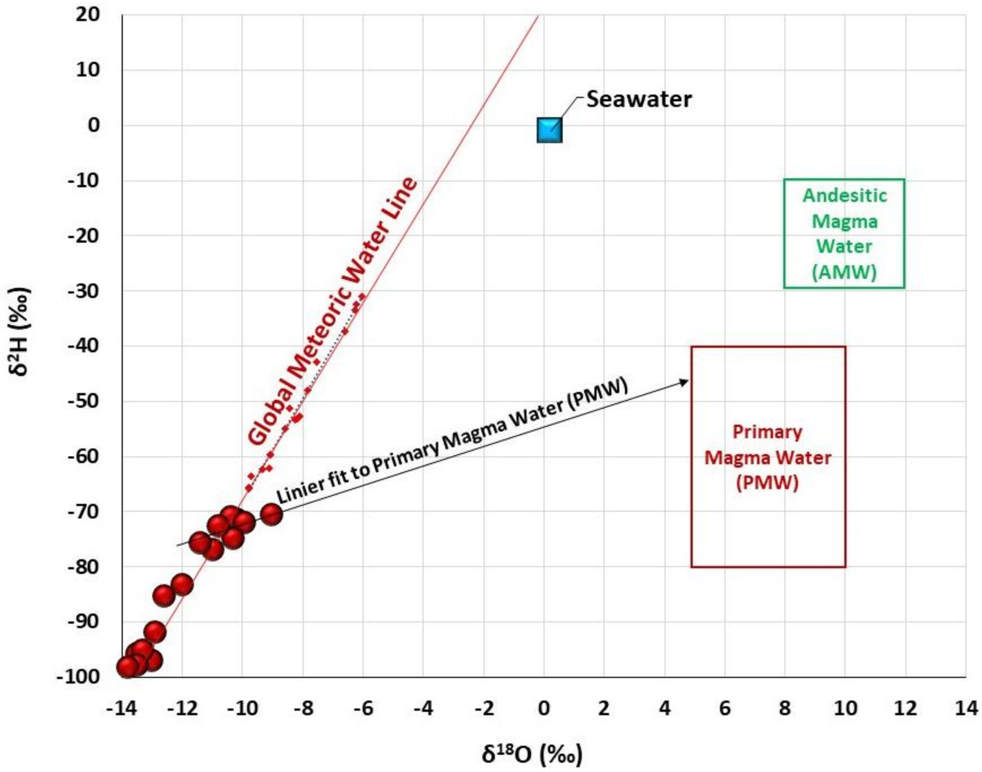

Figure 6. Isotope stable oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) plot on geothermal waters from Alpine mountain region of Europe. The andesitic magmatic water (AMW) was established by Matsubaya et al., (1973) and primary magmatic water (PMW) was established by Giggenbach, (1992)

The interpretation of **Figure 6** explains that most of the geothermal water in the Alpine mountain region of Europe is of meteoric origin (derived from rainfall). The isotopic composition can reveal the mixing between meteoric and magmatic water. Intermediate values between GMWL and magmatic water compositions indicate such mixing, helping to understand the fluid dynamics within geothermal systems. However, some plots appear to have a magmatic component with a linear line to primary magmatic water (PMW). These results have a positive correlation or confirm the previous interpretation in **Figure 5**. Stable isotope analysis is an important component in geothermal exploration and monitoring. It helps in identifying potential geothermal reservoirs, understanding recharge and flow paths of geothermal fluids, and assessing the sustainability of geothermal exploitation (Deon et al., 2015; Hristov et al., 2019; Kruger et al., 1977; Vuataz, 1983).

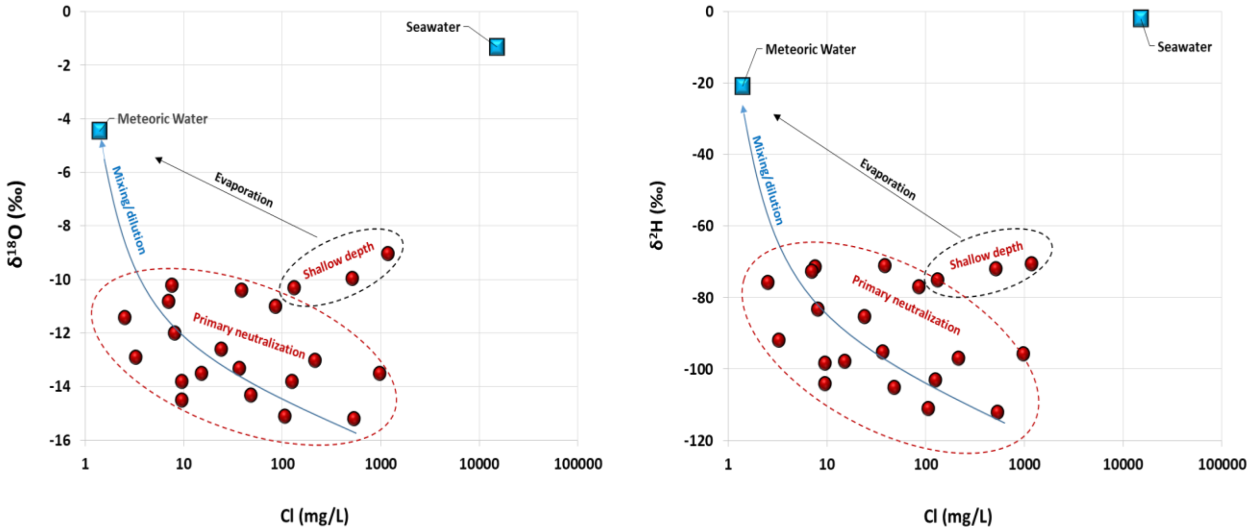

Figure 7. Interpretation of Cl concentration vs Isotope stable oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$)

In the interpretation of **Figure 7**, it can be seen that almost all of the Alpine mountain region of Europe's hot water comes from PMW / primary neutralisation which has undergone mixing and dilution processes before finally coming to the surface (Giggenbach, 1992). However, some of the Alpine mountain region of Europe hot water samples are also suspected to be evaporated before coming to the surface (Arrofi et al., 2024; Iqbal et al., 2019; Iqbal & Kusumasari, 2024; Jamal & Singh, 2018; Kusuda et al., 2014). This result has a positive correlation with the previous interpretation in **Figures 5** and **6.**

The $\delta^{18}O$ values of secondary magmatic waters can indicate the extent of water-rock interaction (Ii et al., 2019; Taira, 2001; Zhao et al., 2009). These waters often show intermediate $\delta^{18}O$ values between meteoric water and magmatic water, reflecting the mixing and exchange processes (Doğan et al., 2006; Guo & Wang, 2012; Morikawa et al., 2008; Rafiq et al., 2024; Rüpke et al., 2006). Similar to oxygen isotopes, δ^2H values help trace the origins and mixing of secondary magmatic waters (Li et al., 2014; Obara, 2002; Wan et al., 2017; Wu et al., 2017). The isotopic composition can reveal the influence of meteoric water and the thermal history of the geothermal system. During water-rock interactions, isotopic exchange can occur, altering the $\delta^{18}O$ and δ^2H values. This exchange is influenced by temperature and the mineralogy of the surrounding rocks (Deon et al., 2015; Hristov et al., 2019; Kruger et al., 1977; Vuataz, 1983).

CONCLUSION

This study provides important insights into the geothermal characteristics of the Alpine region of Europe, highlighting the complex interactions between geological structure, tectonic activity, and fluid geochemistry. The Alps represent a unique geothermal setting where diverse lithologies and active tectonics strongly influence the origin, evolution, and chemistry of geothermal waters. Comprehensive geochemical and isotopic analyses demonstrate that Alpine geothermal waters are primarily controlled by deep magmatic contributions, extensive water–rock interactions, and varying degrees of mixing between meteoric and magmatic fluids. Most geothermal waters in the Alpine mountain region are of meteoric origin, derived from precipitation that infiltrates deeply into the crust. Isotopic compositions effectively reveal mixing processes, where intermediate values between the Global Meteoric Water Line (GMWL) and magmatic water indicate interactions between meteoric and magmatic sources. Several samples show linear trends toward primary magmatic water (PMW), suggesting a clear magmatic influence in certain geothermal systems. The majority of hot waters in the Alpine region originate from PMW and secondary magmatic water (SMW), which undergo dilution, neutralisation, and mixing processes before emerging at the surface. In addition, some geothermal waters show evidence of evaporation prior to discharge. Elevated concentrations of key elements such as sodium (Na), lithium (Li), and chloride (Cl), together with distinctive isotopic signatures, provide valuable indicators of fluid evolution and subsurface processes. These findings emphasize the critical role of integrated geochemical and isotopic approaches in geothermal exploration. Understanding the origin and evolution of geothermal fluids is essential for accurately assessing geothermal potential and supporting the sustainable development of geothermal energy resources in the Alpine region.

AUTHOR CONTRIBUTIONS

Conceptualization, CVA and GAZE; methodology, MS; software, CVA; validation, GAZE, MS, and CVA; formal analysis, GAZE; investigation, MS; resources, CVA; data curation, GAZE; writing—original draft preparation, MS; writing—review and editing, CVA; visualization, GAZE; supervision, MS; project administration, CVA; funding acquisition MS.

ACKNOWLEDGMENT

The author would like to thank the relevant parties who have provided support for this research.

CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

REFERENCES

Adachi, I., & Yamanaka, T. (2024). Isotopic evolutionary track of water due to interaction with rocks and its use for tracing water cycle through the lithosphere. *Journal of Hydrology*, *628*(October 2023). https://doi.org/10.1016/j.jhydrol.2023.130589

Akoteyon, I. S. (2013). Hydrochemical Studies of Ground Water in Parts of Lagos, Southwestern Nigeria. *Bulletin of Geography. Physical Geography Series*, *6*(1), 27–42. https://doi.org/10.2478/bgeo-2013-0002

Arrofi, D., Abu-Mahfouz, I. S., & Prayudi, S. D. (2024). Lithium enrichment in high-enthalpy geothermal system influenced by seawater, Indonesia. *Scientific Reports*, *14*(1), 1–23. https://doi.org/10.1038/s41598-024-74462-w

Cortecci, G., Boschetti, T., Mussi, M., Lameli, C. H., Mucchino, C., & Barbieri, M. (2005). New chemical and original isotopic data on waters from El Tatio geothermal field, northern Chile. *Geochemical Journal*, *39*(6), 547–571. https://doi.org/10.2343/geochemj.39.547

Deon, F., Förster, H. J., Brehme, M., Wiegand, B., Scheytt, T., Moeck, I., Jaya, M. S., & Putriatni, D. J. (2015). Geochemical/hydrochemical evaluation of the geothermal potential of the Lamongan volcanic field (Eastern Java, Indonesia). *Geothermal Energy*, *3*(1), 1–21. https://doi.org/10.1186/s40517-015-0040-6

Doğan, T., Sumino, H., Nagao, K., & Notsu, K. (2006). Release of mantle helium from forearc region of the Southwest Japan arc. *Chemical Geology*, *233*(3–4), 235–248. https://doi.org/10.1016/j.chemgeo.2006.03.008

Giggenbach, W. F. (1992). Chemical Techniques in Geothermal Exploration. In *Chemistry Division* (pp. 119–144).

Guo, Q., & Wang, Y. (2012). Geochemistry of hot springs in the Tengchong hydrothermal areas, Southwestern China. *Journal of Volcanology and Geothermal Research*, *215–216*, 61–73. https://doi.org/10.1016/j.jvolgeores.2011.12.003

Harlaux, M., Mercadier, J., Bonzi, W. M. E., Kremer, V., Marignac, C., & Cuney, M. (2017). Geochemical Signature of Magmatic-Hydrothermal Fluids Exsolved from the Beauvoir Rare-Metal Granite (Massif Central, France): Insights from LA-ICPMS Analysis of Primary Fluid Inclusions. *Geofluids*, *2017*. https://doi.org/10.1155/2017/1925817

Hosono, T., Yamada, C., Manga, M., Wang, C. Y., & Tanimizu, M. (2020). Stable isotopes show that earthquakes enhance permeability and release water from mountains. *Nature Communications*, *11*(1), 1–9. https://doi.org/10.1038/s41467-020-16604-y

Hristov, V., Stoyanov, N., Valtchev, S., Kolev, S., & Benderev, A. (2019). Utilization of low enthalpy geothermal energy in Bulgaria. *IOP Conference Series: Earth and Environmental Science*, *249*(1). https://doi.org/10.1088/1755-1315/249/1/012035

Huang, F., & Korai, S. K. (2025). B-Li-Cl Trend Line Can Distinguish The Dominance of Hydrothermal Water and Surface Water : A Case Study of Geothermal in Tengchong , Southwestern China. *International Journal of Hydrological and Environmental for Sustainability*, *4*(1), 42–54. https://doi.org/10.58524/ijhes.v4i1.636

Idroes, R., Yusuf, M., Saiful, S., Alatas, M., Subhan, S., Lala, A., Muslem, M., Suhendra, R., Idroes, G, M., Marwan, M., & Mahlia, T, M, I. (2019). Geochemistry Exploration and Geothermometry. *Energies MDPI*, *12*(4442), 2–17. https://doi.org/10.3390/en12234442

Ii, H., Kitagawa, H., Kubohara, T., & Machida, I. (2019). Characteristic of water chemistry for arima type deep thermal water in the Kinokawa River catchment, Kii Peninsula, Japan. *International*

Journal of GEOMATE, *17*(62), 158–166. https://doi.org/10.21660/2019.62.7156

Iqbal, M., Juliarka, B. R., Ashuri, W., & Farishi, B. Al. (2019). Hydrogeochemistry of Natar and Cisarua Hot springs in South Lampung, Indonesia. *Journal of Geoscience, Engineering, Environment, and Technology*, *4*(3), 178. https://doi.org/10.25299/jgeet.2019.4.3.4070

Iqbal, M., & Kusumasari, B. A. (2024). Deciphering the Way Ratai geothermal system, Lampung, Indonesia: A comprehensive geochemical and isotopic analysis. *Geothermics*, *119*(March). https://doi.org/10.1016/j.geothermics.2024.102985

Jamal, N., & Singh, N. P. (2018). Identification of fracture zones for groundwater exploration using very low frequency electromagnetic (VLF-EM) and electrical resistivity (ER) methods in hard rock area of Sangod Block, Kota District, Rajasthan, India. *Groundwater for Sustainable Development*, *7*(May), 195–203. https://doi.org/10.1016/j.gsd.2018.05.003

Javino, F., Suratman, S., Pang, Z., Choudhry, M. A., Caranto, J., Ogena, M., & Amnan, I. (2010). Isotope and Geochemical Investigations on Tawau Hot Springs in Sabah, Malaysia. *Proceedings World Geothermal Congress*, *April*, 25–29.

Kruger, P., Stoker, A., & Umaña, A. (1977). Radon in geothermal reservoir engineering. *Geothermics*, *5*(1–4), 13–19. https://doi.org/10.1016/0375-6505(77)90004-9

Kusuda, C., Iwamori, H., Nakamura, H., Kazahaya, K., & Morikawa, N. (2014). Arima hot spring waters as a deep-seated brine from subducting slab. *Earth, Planets and Space*, *66*(1), 119. https://doi.org/10.1186/1880-5981-66-119

Li, H., Zhai, M., Zhang, L., Gao, L., Yang, Z., Zhou, Y., He, J., Liang, J., Zhou, L., & Voudouris, P. C. (2014). Distribution, microfabric, and geochemical characteristics of siliceous rocks in central orogenic belt, China: Implications for a hydrothermal sedimentation model. *Scientific World Journal*, *2014*. https://doi.org/10.1155/2014/780910

Matsubaya, O., Sakai, H., Kusachi, I., & Satake, H. (1973). Hydrogen and oxygen isotopic ratios and major element chemistry of Japanese thermal water systems. *Geochemical Journal*, *7*(3), 123–151. https://doi.org/10.2343/geochemj.7.123

Meju, M. A., & Le, L. (2002). Geoelectromagneticexploration For Natural Resources:Models, Case Studies and Challenges. *Surveys in Geophysics*, *23*, 133–205.

Mibei, G. (2014). *Presented at Short Course IX on Exploration for Geothermal Resources, INTRODUCTION TO TYPES AND CLASSIFICATION OF ROCKS*. 1–12.

Michalski, R. (2010). Environmental applications of ion chromatography in eastern and central europe. *Journal of Chromatographic Science*, *48*(7), 559–565. https://doi.org/10.1093/chromsci/48.7.559

Millot, R., & Négrel, P. (2007). Multi-isotopic tracing (δ7Li, δ11B, 87Sr/86Sr) and chemical geothermometry: evidence from hydro-geothermal systems in France. *Chemical Geology*, *244*(3–4), 664–678. https://doi.org/10.1016/j.chemgeo.2007.07.015

Millot, R., Négrel, P., & Petelet-Giraud, E. (2007). Multi-isotopic (Li, B, Sr, Nd) approach for geothermal reservoir characterization in the Limagne Basin (Massif Central, France). *Applied Geochemistry*, *22*(11), 2307–2325. https://doi.org/10.1016/j.apgeochem.2007.04.022

Mook, W. G. (2006). Introduction to Isotope Hydrolog Stable and Radioactive Isotopes of Hydrology. In *Oxygen and Carbon*. Taylor and Francis Group.

Morikawa, N., Kazahaya, K., Masuda, H., Ohwada, M., Nakama, A., Nagao, K., & Sumino, H. (2008). Relationship between geological structure and helium isotopes in deep groundwater from the Osaka Basin: Application to deep groundwater hydrology. *Geochemical Journal*, *42*(1), 61–74. https://doi.org/10.2343/geochemj.42.61

Négrel, P., Millot, R., Brenot, A., & Bertin, C. (2010). Lithium isotopes as tracers of groundwater circulation in a peat land. *Chemical Geology*, *276*(1–2), 119–127.

https://doi.org/10.1016/j.chemgeo.2010.06.008

Obara, K. (2002). Nonvolcanic deep tremor associated with subduction in southwest Japan. *Science*, *296*(5573), 1679–1681. https://doi.org/10.1126/science.1070378

Parrone, D., Ghergo, S., Frollini, E., Rossi, D., & Preziosi, E. (2020). Arsenic-fluoride co-contamination in groundwater: Background and anomalies in a volcanic-sedimentary aquifer in central Italy. *Journal of Geochemical Exploration*, *217*(March), 106590. https://doi.org/10.1016/j.gexplo.2020.106590

Purnomo, B. J., Pichler, T., & You, C. F. (2016). Boron isotope variations in geothermal systems on Java, Indonesia. *Journal of Volcanology and Geothermal Research*, *311*, 1–8. https://doi.org/10.1016/j.jvolgeores.2015.12.014

Rafiq, J., Abu-Mahfouz, I. S., Soupios, P., Humphrey, J. D., & Tawabini, B. S. (2024). Hydrochemical Characterization, Geothermometry, and Origin of Ain Al-Harrah Hot Spring and Its Relationship to Al-Lith Geothermal System, Saudi Arabia. *ACS Omega*, *9*(23), 24807–24818. https://doi.org/10.1021/acsomega.4c01343

Ravikumar, P., & Somashekar, R. K. (2017). Principal component analysis and hydrochemical facies characterization to evaluate groundwater quality in Varahi river basin, Karnataka state, India. *Applied Water Science*, *7*(2), 745–755. https://doi.org/10.1007/s13201-015-0287-x

Rüpke, L., Phipps Morgan, J., & Dixon, J. E. (2006). Implications of subduction rehydration for earth's deep water cycle. *Geophysical Monograph Series*, *168*, 263. https://doi.org/10.1029/168GM20

Rybach, L., Wilhelm, J., & Gorhan, H. (2003). Geothermal use of tunnel waters – a Swiss speciality. *International Geothermal Conference*, *January 2003*, 17–23. https://www.researchgate.net/publication/237285547_Geothermal_use_of_tunnel_waters_-_a_Swiss_speciality

Schäffer, R., Sass, I., Heldmann, C. D., & Scheuvens, D. (2018). Geothermal drilling in an alpine karst aquifer and its impact on downstream springs – A case study from finkenberg, Tyrol, Austria. *Acta Carsologica*, *47*(2–3), 139–151. https://doi.org/10.3986/ac.v47i2-3.4963

Taira, A. (2001). Tectonic evolution of the Japanese island arc system. *Annual Review of Earth and Planetary Sciences*, *29*, 109–134. https://doi.org/10.1146/annurev.earth.29.1.109

Utama, H. W., Mulyasari, R., & Said, Y. M. (2021). Geothermal Potential on Sumatra Fault System To Sustainable Geotourism in West Sumatra. *JGE (Jurnal Geofisika Eksplorasi)*, *7*(2), 126–137. https://doi.org/10.23960/jge.v7i2.128

Vuataz, F. D. (1983). Hydrology, geochemistry and geothermal aspects of the thermal waters from Switzerland and adjacent alpine regions. *Journal of Volcanology and Geothermal Research*, *19*(1–2), 73–97. https://doi.org/10.1016/0377-0273(83)90125-7

Wan, H., Sun, H., Liu, H., & Xiao, Y. (2017). Lithium Isotopic Geochemistry in Subduction Zones: Retrospects and Prospects. *Acta Geologica Sinica (English Edition)*, *91*(2), 688–710. https://doi.org/10.1111/1755-6724.13126

Wu, D., Purnomo, B. J., & Sun, S. (2017). As and Sb speciation in relation with physico-chemical characteristics of hydrothermal waters in Java and Bali. *Journal of Geochemical Exploration*, *173*, 85–91. https://doi.org/10.1016/j.gexplo.2016.12.003

Zhao, Y. Y., Zheng, Y. F., & Chen, F. (2009). Trace element and strontium isotope constraints on sedimentary environment of Ediacaran carbonates in southern Anhui, South China. *Chemical Geology*, *265*(3–4), 345–362. https://doi.org/10.1016/j.chemgeo.2009.04.015