International Journal of Hydrological and Environmental for Sustainability
Volume 2, Issue 1, 01-12.
e_ISSN: 2828-5050
https://www.journal.foundae.com/index.php/ijhes

Characterization of Thermal Waters Origin from the Back Arc Lampung Province, Indonesia: An Evaluation of Stable Isotopes, Major Elements, and Li/Cl Ratios

Mochamad Iqbal*
[1] Graduate School of Engineering,
Kyoto University,
JAPAN
[2] Geological Engineering,
Institut Teknologi Sumatera,
INDONESIA

Brenda Ariesty Kusumasari
Graduate School of Engineering,
Kyoto University,
JAPAN

Tedi Atmapradhana
Graduate School of Engineering,
Kyoto University,
JAPAN

Afi Candra Trinugraha
[1] Laboratory of Molecular Immunobiology, Nara
Institute of Science and Technology (NAIST),
JAPAN
[2] Research Center for Food Technology and
Processing, National Research and Innovation
Agency (BRIN),
INDONESIA

Endah Kinarya Palupi
Graduate School of Science and Technology,
Kwansei Gakuin University,
JAPAN

Ikhsan Maulidi
[1] Graduate School of Natural Science & Technology,
Kanazawa University,
JAPAN
[2] Fakultas Matematika dan Ilmu Pengetahuan
Alam, Universitas Syiah Kuala,
INDONESIA

***Correspondence e-mail:** mochamad.iqbal@gl.itera.ac.id

Article Info

Article history:

Received: January 10, 2023
Revised: February 04, 2023
Accepted: February 10, 2023

Abstract

This study reports chemical and isotope data from thermal water samples collected in the Natar area (back-arc Lampung province), Indonesia. Based on the geologic map, Lampung-Panjang Fault is the source of this thermal water appearance with Quaternary volcanic and metamorphic rock in the basement. It is located close to the Quaternary extinct volcano (Mount Betung) around 20 km to the southwest. Therefore, this study aims to provide information on geochemical characteristics and the origin of thermal waters in Natar's non-volcanic area. Variables such as stable isotopes, major, and Li/Cl ratios were analyzed. Furthermore, the thermal waters collected from a well in a different location have a moderate temperature ranging from 47°C to 54°C with 6.23 pH. Lithium and Chloride concentrations as well as Isotope $\delta^{18}O$ and δD ranges from 0.02 mg/L to 0.04 mg/L, 5.19 mg/L to 46.12 mg/L, -5.26 ‰ to -2.65 ‰, and -5.26 ‰ to -2.65 ‰, respectively. The stable isotope showed that the thermal water samples have a shift value of ó^{18}O similar to hydrothermal water. The result also has a positive correlation with the distribution of the Li/Cl ratio plotted close to the magmatic water. Consequently, the Natar hot springs may have formed due to the magmatic process of Mount Betung Quaternary with a lower temperature than an active volcano.

Keywords: thermal water; major elements; stable isotopes; chlorine-lithium ratio; sumatra

To cite this article: Iqbal, M., Kusumasari, B. A., Atmapradhana, T., Trinugraha, A, C., Palupi, E, K, and Maulidi, I. (2023). Characterization of Thermal Waters Origin from the Back Arc Lampung Province, Indonesia: An Evaluation of Stable Isotopes, Major Elements, and Li/Cl Ratios. *International Journal of Hydrological and Environmental for Sustainability, 2*(1), 01-12. https://doi.org/10.58524/ijhes.v2i1.171

INTRODUCTION

The majority of the hot spring systems in Indonesia are related to volcanic and subduction activity (Deon et al., 2015; Idroes et al., 2019; Lange et al., 2018; Riogilang et al., 2012; Takahashi et al., 2000) with Sumatra having the longest row of volcanoes (Hanuš et al., 1996). The volcanic chains in the highland area of Bukit Barisan Sumatra (BBS) extend from northern Sumatra (Aceh province) to the south (Lampung Province) (Hanuš et al., 1996; Liu et al., 2021; Nukman & Hochstein, 2019). The Bukit Barisan Sumatra Plateau (BBS) was formed due to the subduction of the Indian-Australian Ocean plate in the western region of Sumatra and moves 7.2 mm/year and 5.2 mm/year in the south and northern part, respectively (**Figure 1**) (Hanuš et al., 1996; Lin et al., 2014; Liu et al., 2021; Nishimura et al., 1986).

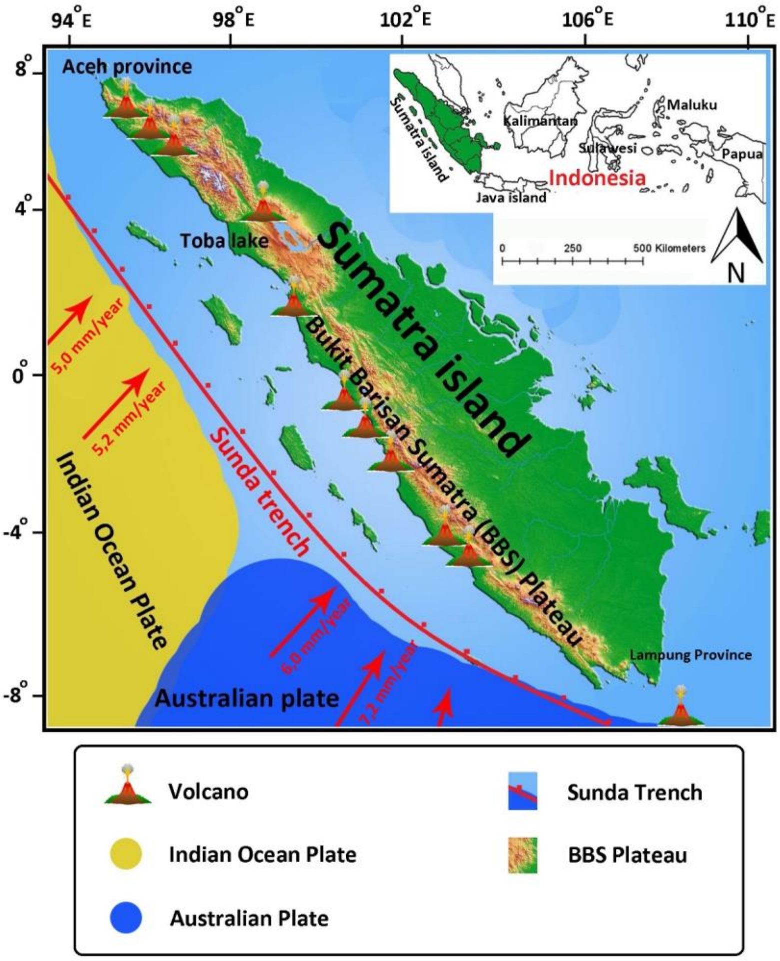

Figure 1. The tectonic setting of Sumatra includes the active volcanoes (Anuar et al., 2021; Bronto et al., 2012; Hariyono & S, 2018; Kusumayudha et al., 2018; Nakada et al., 2019), Sunda Trench and the motion of the Indo-Australian plate relative to a fixed Eurasian plate (Hanuš et al., 1996; Lin et al., 2014; Liu et al., 2021; Malod et al., 1995; Nukman & Hochstein, 2019; Sabara et al., 2021; Utama et al., 2021)

The difference in subduction speed between the northern and southern parts of Sumatra is caused by the Australian plate thrust in the south. (McCaffrey, 2009). Furthermore, subduction activity is faster in southern Sumatra as compared to the north, causing a series of more active volcanoes (Anuar et al., 2021; Hochstein & Sudarman, 1993; Utama et al., 2021). Likewise, other phenomena such as earthquakes (Lin et al., 2014) and the emergence of thermal waters (Riogilang et al., 2012). Generally, thermal waters are commonly found in volcanic area surfaces, but also emerge in non-volcanic areas such as in the Arima area, Southwestern Japan (Fujita Y, 2014; Kazahaya et al., 2014; Kusuda et al., 2014; Masuda et al., 1985; Matsubaya et al., 1973; Morikawa et al., 2008, 2016; Nakamura et al., 2016; Tanaka et al., 1984).

In the Natar back-arc region of Lampung province, several thermal water appeared near the Quaternary Betung Mount at around 15 km with a water discharge of 0.03 - 1 liter/second (Iqbal et al., 2019). However, this mountain is no longer active or there is no volcanic activity (Mulyasari et al., 2019). The hot springs that appear in the back-arc region of Lampung Province, have a distance of about 20 kilometers from a row of volcanoes.

The thermal waters that appeared in the Natar area (**Figure 2**) were sampled in this study to determine their type, characteristics, and origin. Geochemical analysis was also carried out using several methods such as major elements, stable isotopes (oxygen and hydrogen), and the Cl/Li ratio. This study is expected to provide deeper information on the origin of thermal water formation in the Natar back-arc region of Lampung province, Indonesia.

Study Area

Lampung Province is an area that has several active volcanoes, dormant (never erupted), and inactive volcanoes (Quaternary Mount) (Hariyono & S, 2018; Kusumayudha et al., 2018; Nakada et al., 2019). On the other hand, the western part of Lampung province has an elongated plateau, which is part of the Sumatran Bukit Barisan (BBS) (Hanuš et al., 1996; Hochstein & Sudarman, 1993; Lange et al., 2018; Malod et al., 1995; McCaffrey, 2009; Nishimura et al., 1986). There are dormant volcanoes in the Lampung highlands whose activities are still used as geothermal manifestations (Hochstein & Sudarman, 1993; Utama et al., 2021).

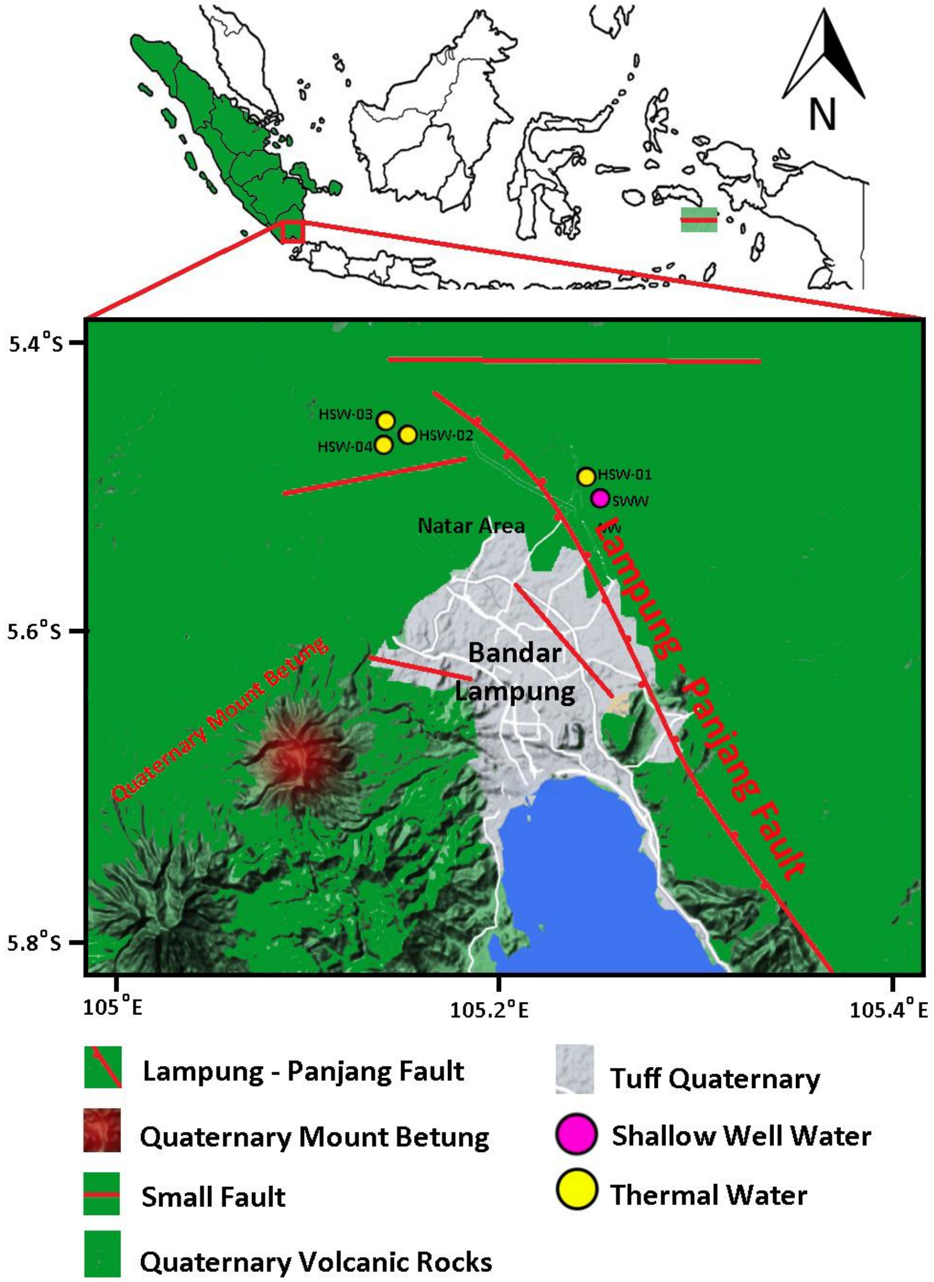

Figure 2. Map showing the study area, major fault systems, and geological background in Natar back-arc Lampung province, Indonesia. The sampling location is indicated on the circle point with the color and name of the locality

Based on the geographical structure, the Lampung region has a large fault (Sumatra fault) along with the BBS, which was formed due to the oblique subduction beneath Sumatra and the convergent motion of the Mentawai Faults in the western region (Malod et al., 1995). There is also a Panjang fault that extends from around Mount Betung to a dormant active volcano (Rajabasa volcano) (Hariyono & S, 2018; Iqbal et al., 2019). Lampung province is a fluvial-terrestrial rock of the Pliocene-Pleistocene age and is composed of pumiceous tuff, rhyolite-dacite tuff, and tuffaceous sandstone (Darmawan et al., 2015). This fluvial-terrestrial rock or formation has a thickness of about 200 meters and covers virtually the entire province of Lampung (Jansen et al., 2021).

METHOD

The sampling points on the map of Natar back-arc Lampung Province, Indonesia were marked (**Figure 2**). The groundwater samples from 4 thermal and 1 shallow well water in June 2018 as shown in **Table 1** and **Table 2** were collected in Natar area. The water temperature, pH, debit, and temperature were measured at the sampling location (in situ). All chemical analyses were performed in the PAIR-BATAN Jakarta, Indonesia for support in analyzing the thermal water samples. The water analysis techniques use 2 machines namely Ion Chromatography (Dionex ICS-3000, Thermo Fisher Scientific) for major cations of Ca, Na, Mg, K, and anions including SO_4, HCO_3, and Cl.

Table 1. Analytical thermal water results and seawater from the reference in trace element, ratio, and stable isotopes

Fluid Type (Source)	Date and Location	Sample name	Trace Element	Ratio		Stable Isotope	
			Li (ppm)	Cl/Li	Li/Cl	$\delta^{18}O$ (‰)	δD (‰)
Thermal water (this study)	2018, Natar Lampung, Indonesia	HSW-01	0.03	1344.33	0.000743863	-4.97	-40.4
		HSW-02	0.02	1766.50	0.000566091	-2.65	-27.2
		HSW-03	0.02	2306	0.000433651	-5.18	-37.4
		HSW-04	0.02	1945	0.000514139	-5.26	-40.1
Shallow well water (this study)		SWW	0.04	129.75	0.007707129	-3.27	-35.4
Modern seawater (Oi, T et al., 1996)	1992, Sezaki, Japan	Seawater	0.17	111764	8.94737E-06	0	0

Table 2. Analytical thermal water results and seawater from the reference to environmental conditions and major elements

Sample name	Condition		Major Elements (mg/L)						
	pH	Temp (°C)	Mg^{2+}	Na^{+}	K^{+}	Ca^{2+}	Cl^{-}	SO_4	HCO_3^{-}
HSW-01	6.23	54.3	12.55	97.72	6.92	3.86	40.33	23.81	253.39
HSW-02	7	50	15.93	120.11	3.81	44.79	35.33	20.81	459.47
HSW-03	7	47	15.03	93.24	8.12	4.38	46.12	20.57	246.97
HSW-04	7	40	15.42	98.43	5.29	15.77	38.90	20.11	307.06
SWW	7	nm	15.55	26.86	2.46	28.11	5.19	35.66	205.22
Seawater	8.03	12.6	1400	10600	431	394	19000	2470	2750.52

RESULTS AND DISCUSSION

The results of 4 thermal water samples have a quite high concentration of Chlorine (Cl) ranging from 38.90 mg/L to 46.12 mg/L. Despite the lower Cl concentration from these thermal waters compared to the modern seawater (± 19000 mg/L) (Kazahaya et al., 2014; Oi et al., 1996), it still exceeds that of the shallow ground and surface water (Ii et al., 2019). Sodium (Na) and Potassium (K) concentration has a quite high value ranging from 93.24 mg/L to 120.11 mg/L and 3.81 mg/L to 8.12 mg/L in Ca and K, respectively. The concentration of Calcium (Ca), magnesium, and sulfate range from 3.86 mg/L to 44.79 mg/L, 12.55 mg/L to 15.93 mg/L, and 20.11 mg/L to 23.81 mg/L respectively. The concentration of fluoride in groundwater varies from 2.12 mg/L to 2.91 mg/L.

Based on the piper diagram (**Figure 3**), almost all thermal water samples belong to the sodium bicarbonate type and are mostly found in the fluvial-terrestrial rocks (Triani et al., 2021) or karst region (limestone) (Hariyono & S, 2018; Nakada et al., 2019) in the groundwater category.

Meanwhile, piper diagrams are excellent for tracking the origins of early groundwater based on species dominance (Kumar et al., 2009; Nazri et al., 2016; Ravikumar & Somashekar, 2017; Singh et al., 2020; Umar Kura et al., 2013). However, further confirmation is needed on the origin of the thermal water samples.

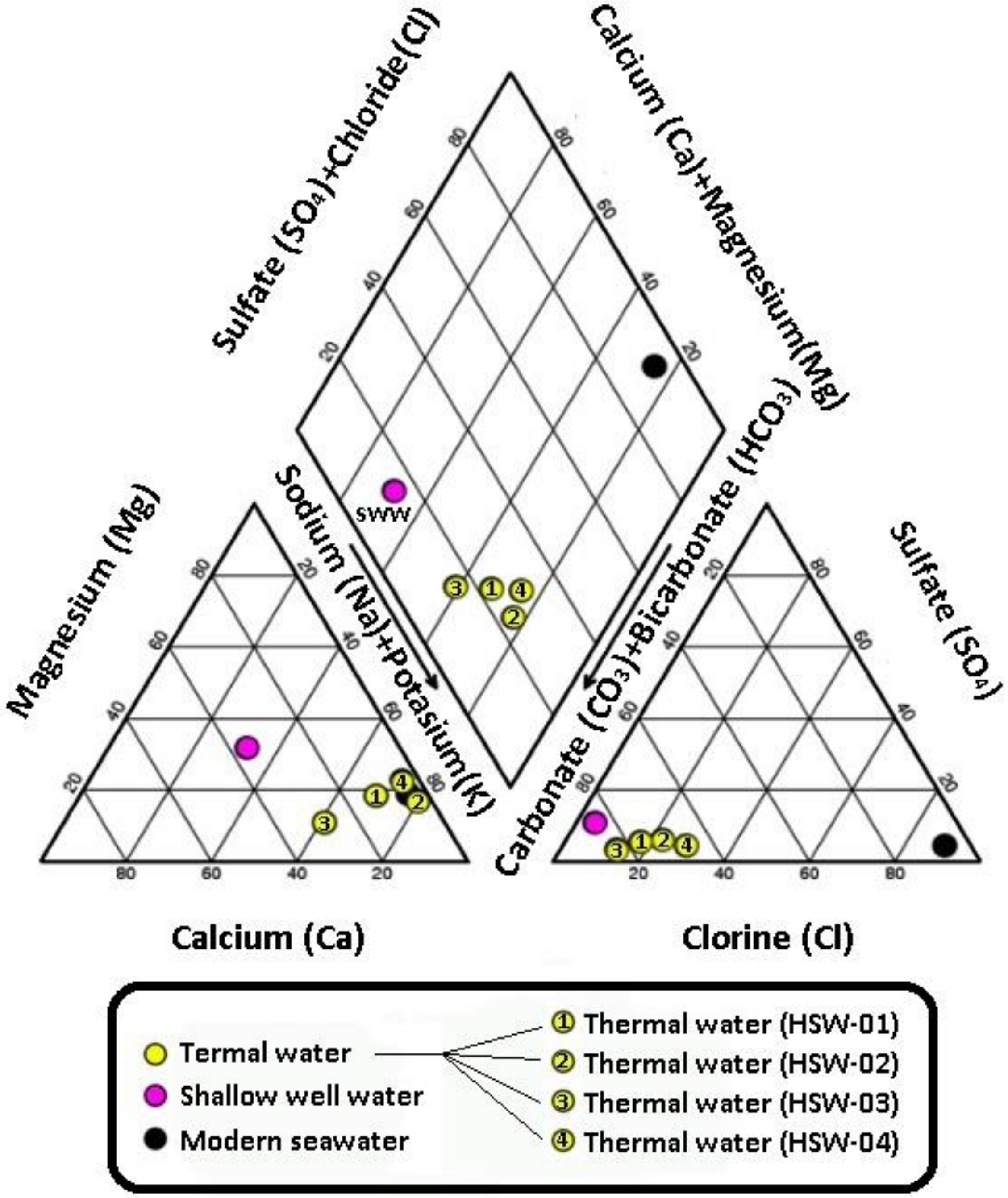

Figure 3. The Piper diagram shows the origin of the fluid according to the predominance of chemical composition (Briel, 1993; Sadashivaiah et al., 2008)

In previous research, Kazahaya et al., (2014) used the Cl/Li ratio of thermal water in Japan and discovered very useful information that a Cl/Li ratio > 1000 is a characteristic feature of hydrothermal waters. Millot et al., (2012) and Tanimizu et al., (2021) confirmed that Lithium (Li) is very sensitive to high temperatures. Furthermore, groundwater with a high Li concentration is commonly found in the inner layer, namely the mantle (Meredith et al., 2013; Nishio et al., 2010; Tang et al., 2007; Tomascak, 2004). Information on the high Li concentration in groundwater supports the results of (You et al., 1996) comparing the behavior of Lithium (Li) and Boron (B) when experiencing changes in temperature (**Figure 4**).

The interpretation results of the isotope stable (**Figure 5**) showed that thermal water samples have a range of δD from -27.2 ‰ to -40.2 ‰ with shift value $\delta^{18}O$ ranging from 0.745 to 1.33 (from Global Meteoric Water Line). The shift value $\delta^{18}O$ for shallow well water is 2.40. According to Matsubaya et al. (1973), a high shift value occurs due to the long water-rock interaction process compared to surface or meteoric water. Furthermore, thermal water samples have a high shift than surface water and are similar to the geothermal from TVZ, New Zealand (Millot et al., 2012). However, the shift value $\delta^{18}O$ on geothermal hydrothermal water is not as high as the hydrothermal (Arima Type) from the non-volcanic area, in Japan (Kusuda et al., 2014; Masuda et al., 1985; Matsubaya et al., 1973; Morikawa et al., 2016; Nakamura et al., 2016).

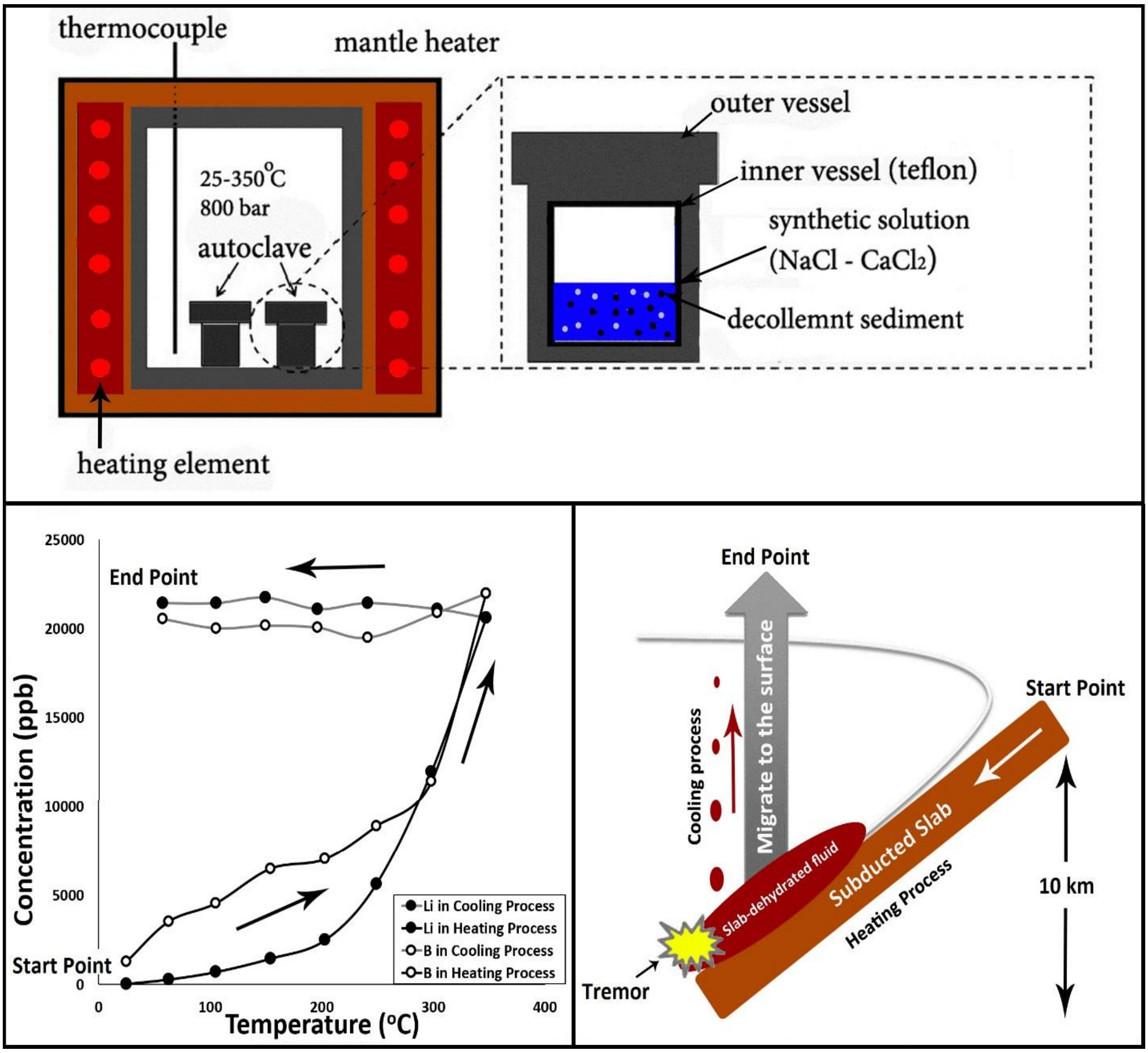

Figure 4. Chemical evaluation of fluids affected under high temperature and pressure variations (You et al., 1996)

The interpretation of Li/Cl and 1/Cl ratios from thermal water samples in **Figure 6** shows a positive correlation with the stable Isotopes in **Figure 3**. Furthermore, all thermal water samples have plot points close to the magmatic type, while the shallow well is plotted far away. The result of Kazahaya et al., (2014) using 49 thermal water spread throughout Japan showed that magmatic water has Li/Cl > 0.001 (in wt. ratio) with 1/Cl < 0.001.

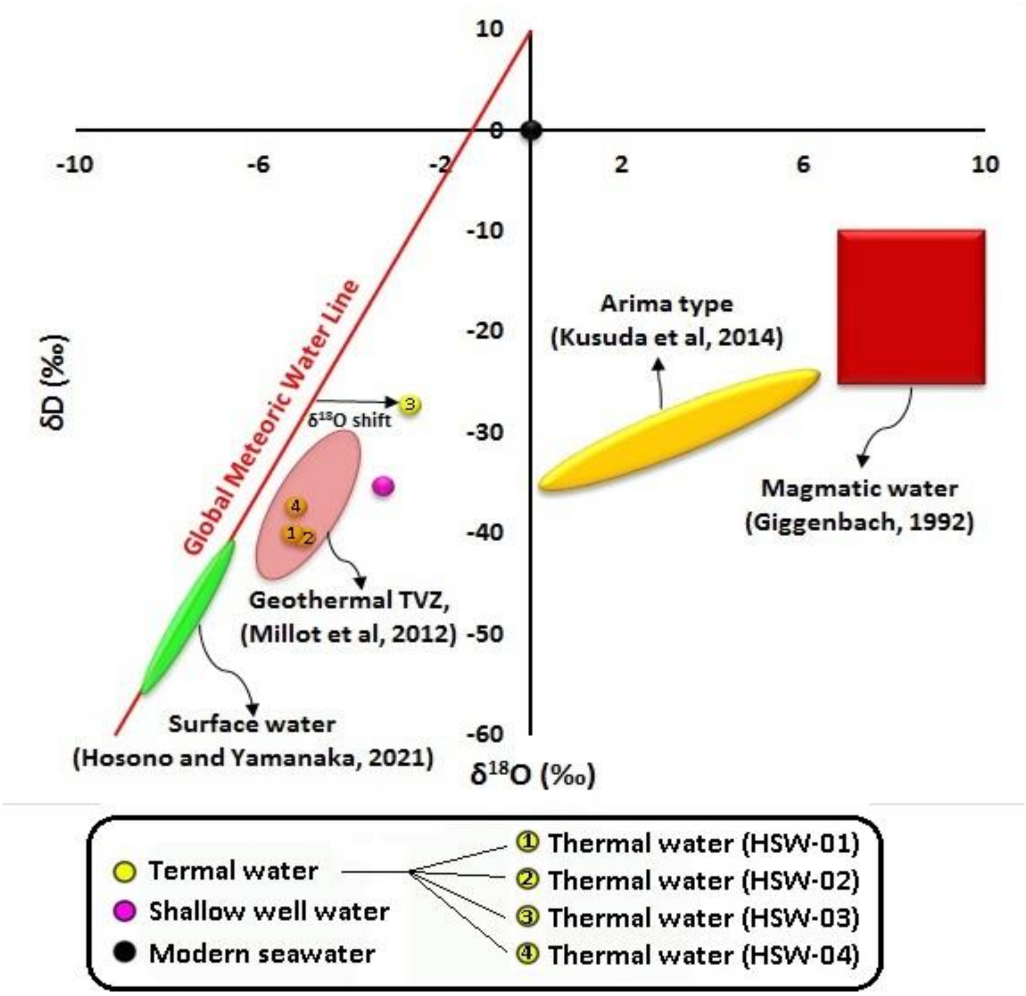

Figure 5. Stable isotope from groundwater samples in the Natar area

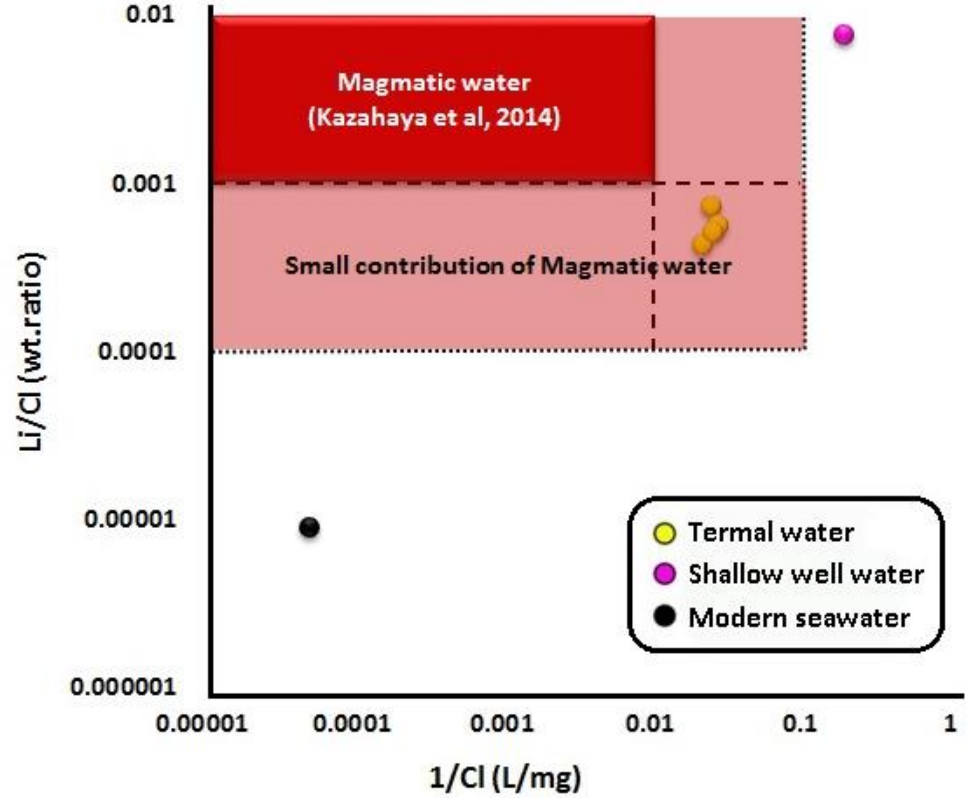

Figure 6. Interpretation ratio Li/Cl dan 1/Cl from thermal water and shallow well water samples

These results are also positively correlated with previous studies by Tanimizu et al., (2021) and Hosono et al., (2020) about the contribution of hydrothermal water (magmatic water) to the aquifer. Combing these results using the mixing equation (Faure, 1986; Tanimizu et al., 2021). The difference in Li content between surface and deep groundwater can be seen using the mixing equation up to a sensitivity of 0.01% since Lithium is abundant in the earth (mantle) (Umam et al., 2022).

CONCLUSION

This study's results and previous investigations showed that the trace elements (Li) can be used as a potential hydrothermal tracer. Furthermore, the piper diagrams interpretation of thermal water samples that emerges in the sampling location has the dominant type of sodium bicarbonate. This indicates a relationship with the surrounding rock formations, namely fluvial-terrestrial rock formations of the Pliocene-Pleistocene age. Therefore, there is a possibility that the origin of Natar's thermal water formation is due to the magmatic process of Mount Betung Quaternary with a lower temperature than an active volcanic mountain. The table isotope interpretation also shows that Natar thermal water is plotted in the distribution area of New Zealand's TVZ geothermal water distribution.

AUTHOR CONTRIBUTIONS

Conceptualization, MI and TA; methodology, BAK and ACT; software, TA; validation, EKP, IM, and MI; formal analysis, ACT and IM; investigation, MI, BAK, and TA; resources, MI; data curation, EKP; writing—original draft preparation, MI and ACT; writing—review and editing, MI, EKP, and IM; visualization, BAK; supervision, MI; project administration, MI; funding acquisition, MI.

ACKNOWLEDGMENT

The authors would like to thank all reviewers who have provided suggestions to improve this article.

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

Anuar, M. N. A., Arifin, M. H., Baioumy, H., & Nawawi, M. (2021). A geochemical comparison between volcanic and non-volcanic hot springs from East Malaysia: Implications for their origin and geothermometry. *Journal of Asian Earth Sciences*, *217*(August 2020), 104843. https://doi.org/10.1016/j.jseaes.2021.104843

Briel, B. L. I. (1993). *Documentation of a Multiple Technique Computer Program for Plotting Major Ion Composition of Natural Waters*.

Bronto, S., Asmoro, P., Hartono, G., & Sulistiyono, S. (2012). Evolution of Rajabasa Volcano in Kalianda Area and Its Vicinity, South Lampung Regency. *Indonesian Journal on Geoscience*, *7*(1), 11–25. https://doi.org/10.17014/ijog.v7i1.132

Darmawan, I. G. B., Setijadji, L. D., & Wintolo, D. (2015). Geology and Geothermal System in Rajabasa Volcano South Lampung Regenc , Indonesia (Approach to Field Observations , Water Geochemistry and Magnetic Method). *Proceedings World Geothermal Congress 2015*, *April*, 12.

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

Faure, G. (1986). Isotope systematics of two component mixtures. In *Principles of Isotope Geology* (2nd ed., p. 141–153). John Wiley & Sons.

H Fujita Y, N. (2014). Rare Earth Elements and Sr-Nd-Pb Isotopic Analyses of the Arima Hot Spring Waters, Southwest Japan: Implications for Origin of the Arima-type Brine. *Journal of Geology & Geosciences*, *03*(04). https://doi.org/10.4172/2329-6755.1000161

Hanuš, V., Špičák, A., & Vaněk, J. (1996). Sumatran segment of the Indonesian subduction zone: Morphology of the Wadati-Benioff zone and seismotectonic pattern of the continental wedge. *Journal of Southeast Asian Earth Sciences*, *13*(1), 39–60. https://doi.org/10.1016/0743-9547(96)00004-9

Hariyono, E., & S, L. (2018). The Characteristics of Volcanic Eruption in Indonesia. *Volcanoes - Geological and Geophysical Setting, Theoretical Aspects and Numerical Modeling, Applications to Industry and Their Impact on the Human Health*, *July*. https://doi.org/10.5772/intechopen.71449

Hochstein, M. P., & Sudarman, S. (1993). Geothermal resources of Sumatra. *Geothermics*, *22*(3), 181–200. https://doi.org/10.1016/0375-6505(93)90042-L

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

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 application in the North Zone of Seulawah Agam, Aceh Besar District, Indonesia. *Energies*, *12*(23). 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

Jansen, D., Sihombing, P., Harbowo, D. G., Priadi, B., & Ardhianto, L. (2021). *Chemostratigraphy of Paleozoic Carbonate in Natar , South Lampung , Indonesia*. 1–4.

Kazahaya, K., Takahashi, M., Yasuhara, M., Nishio, Y., Inamura, A., Morikawa, N., Sato, T., Takahashi, H. A., Kitaoka, K., Ohsawa, S., Oyama, Y., Ohwada, M., Tsukamoto, H., Horiguchi, K., Tosaki, Y., & Kirita, T. (2014). 西南日本におけるスラブ起源深部流体の分布と特徴. 日本水文科学会誌, *44*(1), 3–16. https://doi.org/10.4145/jahs.44.3

Kumar, S. K., Rammohan, V., Sahayam, J. D., & Jeevanandam, M. (2009). Assessment of groundwater quality and hydrogeochemistry of Manimuktha River basin, Tamil Nadu, India. *Environmental Monitoring and Assessment*, *159*(1–4), 341–351. https://doi.org/10.1007/s10661-008-0633-7

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

Kusumayudha, S. B., Lestari, P., & Paripurno, E. T. (2018). Eruption characteristic of the sleeping volcano, Sinabung, North Sumatera, Indonesia, and SMS gateway for disaster early warning system. *Indonesian Journal of Geography*, *50*(1), 70–77. https://doi.org/10.22146/ijg.17574

Lange, D., Tilmann, F., Henstock, T., Rietbrock, A., Natawidjaja, D., & Kopp, H. (2018). Structure of the central Sumatran subduction zone revealed by local earthquake travel-time tomography using an amphibious network. *Solid Earth*, *9*(4), 1035–1049. https://doi.org/10.5194/se-9-1035-2018

Lin, J. Y., Sibuet, J. C., Hsu, S. K., & Wu, W. N. (2014). Could a Sumatra-like megathrust earthquake occur in the south Ryukyu subduction zone? *Earth, Planets and Space*, *66*(1), 1–8. https://doi.org/10.1186/1880-5981-66-49

Liu, S., Suardi, I., Xu, X., Yang, S., & Tong, P. (2021). The Geometry of the Subducted Slab Beneath Sumatra Revealed by Regional and Teleseismic Traveltime Tomography. *Journal of Geophysical Research: Solid Earth*, *126*(1), 1–29. https://doi.org/10.1029/2020JB020169

Malod, J. A., Karta, K., Beslier, M. O., & Zen, M. T. (1995). From normal to oblique subduction: Tectonic relationships between Java and Sumatra. *Journal of Southeast Asian Earth Sciences*, *12*(1–2), 85–93. https://doi.org/10.1016/0743-9547(95)00023-2

Masuda, H., Sakai, H., & Chiba, H. (1985). Geochemical in Arima and characteristics its vicinity of Na-Ca-CI-HCO3 in the western Kinki type district waters Japan. *Geochemical Journal*, *19*(1), 149–162. https://doi.org/10.1111/j.1523-1739.2009.01332.x

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

McCaffrey, R. (2009). The tectonic framework of the sumatran subduction zone. *Annual Review of Earth and Planetary Sciences*, *37*, 345–366. https://doi.org/10.1146/annurev.earth.031208.100212

Meredith, K., Moriguti, T., Tomascak, P., Hollins, S., & Nakamura, E. (2013). The lithium, boron and strontium isotopic systematics of groundwaters from an arid aquifer system: Implications for recharge and weathering processes. *Geochimica et Cosmochimica Acta*, *112*, 20–31. https://doi.org/10.1016/j.gca.2013.02.022

Millot, R., Hegan, A., & Negrel, P. (2012). Geothermal waters from the Taupo Volcanic Zone, New Zealand: Li, B, and Sr isotopes characterization. *Applied Geochemistry*, *27*, 677–688. https://doi.org/doi:10.1016/j.apgeochem.2011.12.015

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

Morikawa, N., Kazahaya, K., Takahashi, M., Inamura, A., Takahashi, H. A., Yasuhara, M., Ohwada, M., Sato, T., Nakama, A., Handa, H., Sumino, H., & Nagao, K. (2016). Widespread distribution of ascending fluids transporting mantle helium in the fore-arc region and their upwelling processes: Noble gas and major element composition of deep groundwater in the Kii Peninsula, southwest Japan. *Geochimica et Cosmochimica Acta*, *182*, 173–196. https://doi.org/10.1016/j.gca.2016.03.017

Mulyasari, R., Utama, H. W., & Haerudin, N. (2019). Geomorphology study on the Bandar Lampung Capital City for recommendation of development area. *IOP Conference Series: Earth and Environmental Science*, *279*(1). https://doi.org/10.1088/1755-1315/279/1/012026

Nakada, S., Maeno, F., Yoshimoto, M., Hokanishi, N., Shimano, T., Zaennudin, A., & Iguchi, M. (2019). Eruption scenarios of active volcanoes in Indonesia. *Journal of Disaster Research*, *14*(1), 40–50. https://doi.org/10.20965/JDR.2019.P0040

Nakamura, H., Chiba, K., Chang, Q., Morikawa, N., Kazahaya, K., & Iwamori, H. (2016). Origin of the Arima-type and Associated Spring Waters in the Kinki District, Southwest Japan. *Journal of Geology & Geophysics*, *05*(02), 240. https://doi.org/10.4172/2381-8719.1000240

Nazri, M. A. A., Tan, L. W., Kasmin, H., Syafalni, S., & Abustan, I. (2016). Geophysical and Hydrochemical Characteristics of Groundwater at Kerian Irrigation Scheme. *IOP Conference Series: Materials Science and Engineering*, *136*(1). https://doi.org/10.1088/1757-899X/136/1/012070

Nishimura, S., Nishida, J., Yokoyama, T., & Hehuwat, F. (1986). Neo-tectonics of the Strait of Sunda, Indonesia. *Journal of Southeast Asian Earth Sciences*, *1*(2), 81–91. https://doi.org/10.1016/0743-9547(86)90023-1

Nishio, Y., Okamura, K., Tanimizu, M., Ishikawa, T., & Sano, Y. (2010). Lithium and strontium isotopic systematics of waters around Ontake volcano, Japan: Implications for deep-seated fluids and earthquake swarms. *Earth and Planetary Science Letters*, *297*(3–4), 567–576. https://doi.org/10.1016/j.epsl.2010.07.008

Nukman, M., & Hochstein, M. P. (2019). The Sipoholon Geothermal Field and adjacent geothermal systems along the North-Central Sumatra Fault Belt, Indonesia: Reviews on geochemistry, tectonics, and natural heat loss. *Journal of Asian Earth Sciences*, *170*(November 2018), 316–328. https://doi.org/10.1016/j.jseaes.2018.11.007

Oi, T., Ikeda, K., Nakano, M., Ossaka, T., & Ossaka, J. (1996). Boron isotope geochemistry of hot spring waters in Ibusuki and adjacent areas, Kagoshima, Japan. *Geochemical Journal*, *30*(5), 273–287. https://doi.org/10.2343/geochemj.30.273

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

Riogilang, H., Itoi, R., & Taguchi, S. (2012). Origin of Hot Spring Water in the Kotamobagu Geothermal Field, Northern Sulawesi, Indonesia. 日本地熱学会誌, *34*(3), 151–159.

Sabara, Z., Umam, R., Prianto, K., Junaidi, R., & Rahmat, A. (2021). Anak krakatau mountain (AKM) causes a rare tsunami phenomenon: Impact around the Sunda strait, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *739*(1). https://doi.org/10.1088/1755-1315/739/1/012036

Sadashivaiah, C., Ramakrishnaiah, C. R., & Ranganna, G. (2008). Hydrochemical analysis and evaluation of groundwater quality in Tumkur Taluk, Karnataka State, India. *International Journal of Environmental Research and Public Health*, *5*(3), 158–164. https://doi.org/10.3390/ijerph5030158

Singh, K. K., Tewari, G., & Kumar, S. (2020). Evaluation of Groundwater Quality for Suitability of Irrigation Purposes: A Case Study in the Udham Singh Nagar, Uttarakhand. *Journal of Chemistry*, *2020*. https://doi.org/10.1155/2020/6924026

Takahashi, M., Urai, M., Yasukawa, K., Muraoka, H., Matsuda, K., & Akasako, H. (2000). Geochemistry of Hot Spring Waters At Bajawa Area , Central Flores , Nusa Tenggara Timur , Indonesia. *Western Pacific Earth Sciences*, 1807–1812.

Tanaka, K., Koizumi, M., Seki, R., & Ikeda, N. (1984). Geochemical study o Arima hot-spring waters, Hyogo, Japan, by means of tritium and deuterium. *Geochemical Journal*, *18*, 173–180.

Tang, Y. J., Zhang, H. F., & Ying, J. F. (2007). Review of the lithium isotope system as a geochemical tracer. *International Geology Review*, *49*(4), 374–388. https://doi.org/10.2747/0020-6814.49.4.374

Tanimizu, M., Sugimoto, N., Hosono, T., Kuribayashi, C., Morimoto, T., Ito, A., & Umam, R. (2021). *Application of B and Li isotope systematics for detecting chemical disturbance in groundwater associated with large shallow inland earthquakes in Kumamoto , Japan*. *55*, 241–250. https://doi.org/10.2343/geochemj.2.0633

Tomascak, P. B. (2004a). Developments in the understanding and application of lithium isotopes in the earth and planetary sciences. *Reviews in Mineralogy and Geochemistry*, *55*(1), 153–195. https://doi.org/doi.org/10.2138/gsrmg.55.1.153

Tomascak, P. B. (2004b). Developments in the Understanding and Application of Lithium Isotopes in the Earth and Planetary Sciences. *Reviews in Mineralogy and Geochemistry*, *55*(1), 153–195. https://doi.org/10.2138/gsrmg.55.1.153

Triani, Umam, R., & Sismanto. (2021). 3D Modeling of Subsurface Lawanopo Fault in Southeast

Sulawesi, Indonesia Using Grablox and its Consequence to Geohazard. *Indonesian Journal of Geography*, *53*(1), 67–77. https://doi.org/10.22146/IJG.50878

Umam, R., Tanimizu, M., Nakamura, H., Nishio, Y., Nakai, R., Sugimoto, N., Mori, Y., Kobayashi, Y., Ito, A., Wakaki, S., Nagaishi, K., & Ishikawa, T. (2022). Lithium isotope systematics of Arima hot spring waters and groundwaters in Kii Peninsula. *Geochemical Journal*, *56*(5), 8–17. https://doi.org/10.2343/geochemj.GJ22015

Umar Kura, N., Firuz Ramli, M., Azmin Sulaiman, W. N., Ibrahim, S., Zaharin Aris, A., & Mustapha, A. (2013). Evaluation of factors influencing the groundwater chemistry in a small tropical Island of Malaysia. *International Journal of Environmental Research and Public Health*, *10*(5), 1861–1881. https://doi.org/10.3390/ijerph10051861

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

You, C. F., Castillo, P. R., Gieskes, J. M., Chan, L. H., & Spivack, A. J. (1996). Trace element behavior in hydrothermal experiments: Implications for fluid processes at shallow depths in subduction zones. *Earth and Planetary Science Letters*, *140*(1–4), 41–52. https://doi.org/10.1016/0012-821X(96)00049-0