Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Mixing Models of Ulubelu Geothermal Field

Jodhi Pramuji Giriarso, Anjani Puspadianti AM, Fraga Luzmi Fahmi, Mulyanto

jodhi.pramuji @pertamina.com

Keywords: mixing models, chloride-boron

ABSTRACT

Ulubelu is one of Indonesia's most developed geothermal areas. Its production capacity has increased to 220 MW by a decade of operation. To determine the primary fluid and the procedures it goes through to surface, we look at the mixing model's properties in this study. The fluid flow pattern flows from north to southwest according to the chloride-boron ratio of its thermal manifestations fluids. The parent fluid is known as the reservoir fluid, and the surface-appearing reservoir fluid is known as the WPTM manifestation fluid due to its presence on the chloride apex. The correlation of water isotopes and chloride-boron ratio provide evidence that the parent fluid and the WPTM manifestation fluid come from the same source, as well as according to the enthalpy-silica mixing model. From the chloride-enthalpy mixing model we determine the processes that the parent fluid undergoes as it rises to the surface. There are two possible scenarios for this to happen. The first scenario is that there is conductive cooling, then equilibrium on the surface and mixing with the surface fluid seems more plausible. However, we are challenged to prove the second scenario if we can obtain reservoir fluid data in the GTTM area in future occasion.

1. ULUBELU GEOTHERMAL FIELD (UGF)

Ulubelu Geothermal Field is in the southernmost Sumatra Island, administratively in Lampung Province. It lies on a volcano-tectonic depression zone which is part of Semangko segment in The Great Sumatran Fault (TGSF). The main geological structure are the NW-SE trending structures, parallel with TGSF according to Nurseto (2015). The tectonic depression as low as 700–800 masl and the highest elevation almost 1700 masl in Gunung Rendingan in the north. Thermal manifestation features appeared as fumarole complex, hot mudpools, acid lake, neutral hotsprings, and ground alteration.

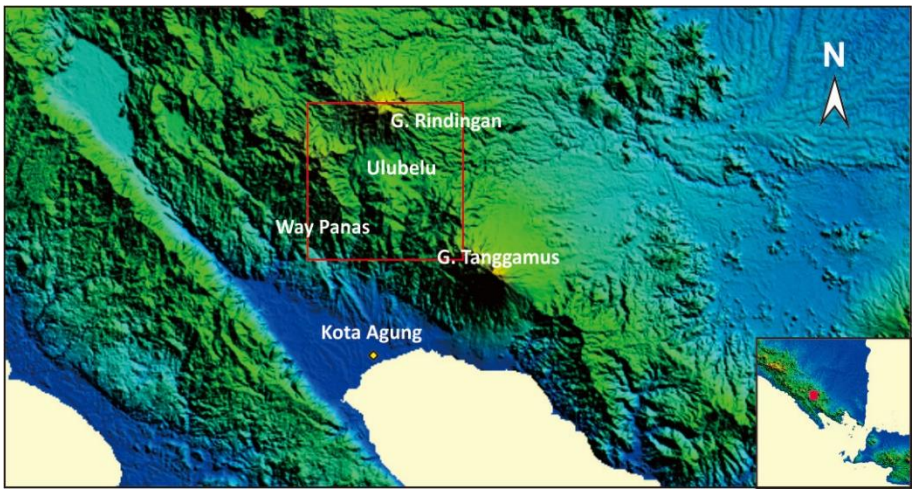

Figure 1: Administrative location of Ulubelu Geothermal Field

Preceding its 4 x 55 MW electricity production, The UGF has a long geoscience survey activity. Pertamina conducted reconnaissance survey in 1989, and they continued detailed geoscience surveys from 1991 to 1993. In 1995, they began to drill exploration well (UBL-1), a slim 1160 m deep hole in the southern part of the targeted area. A production test was conducted and found out that the well produced liquid saturated fluid with temperature around 200-210 deg-C in Hochstein (2008). Then, they drilled more slim hole wells in the northern part from the first one. Evaluation of the exploration wells has concluded; this area has promising resources. The development drilling began in the mid-2000s. The first unit (1 x 55 MW) commissioned in 2012, followed the second unit (1 x 55 MW) in 2015, and then doubled its power generation capacity to 220 MW in 2017.

Ulubelu's fluid is a two-phase, water-dominated geothermal system. Given the nature of these fluids, we keep track on the concentration of chemical constituents in well fluid, including chloride, silica, boron, and water isotopes, as well as the measured enthalpy. We describe the distinctiveness of the Ulubelu geothermal fluid using the fluid mixing model. The hydrogeochemistry of this field must first be presented to grasp the geothermal system.

2. HYDROGEOCHEMISTRY

There are three main areas of thermal manifestation. The northern part, we called Ulubelu thermal manifestation (UTM) group. The middle part: Gunung Tiga (GTTM), and the southernmost: Way Panas (WPTM). The UTM and GTTM groups are characterized as fumaroles, hot mud pools, hot and warm springs, and altered ground. In some thermal manifestation, fumaroles emitted steam with enough pressure to be sampled. In others, the steam condensed in surface water and heated the water to 40-60 deg-C. The fluids from these two areas appeared in ternary diagram as steam-heated and bicarbonate water.



(a) (b)

Figure 2: Thermal manifestation in UTM group: (a) Danau Hijau acid lake, (b) Pagar Alam fumarole and altered ground



(a) (b)

Figure 3: Thermal manifestation in GTTM group: (a) Datarajan hot pool, (b) Gunung Tiga fumarole and altered ground

The Way Panas group is exclusively characterized as neutral hot springs and hot pools. The temperatures are around 70-90 deg-C, tending to get higher in the dry season. The WPTM is characterized as chloride water and partial equilibration. Subsurface temperature estimation varies from 180-270 deg-C. Some of it had been disappearing due to tide of river stream, like WP DAM.



(b) (b) (c)

Figure 4: Thermal manifestation in WPTM group: (a) Kukup Way Panas fountain-like hot spring, (b) Way Panas, intermittent geyser-like hot spring (c) Way Panas hot pool

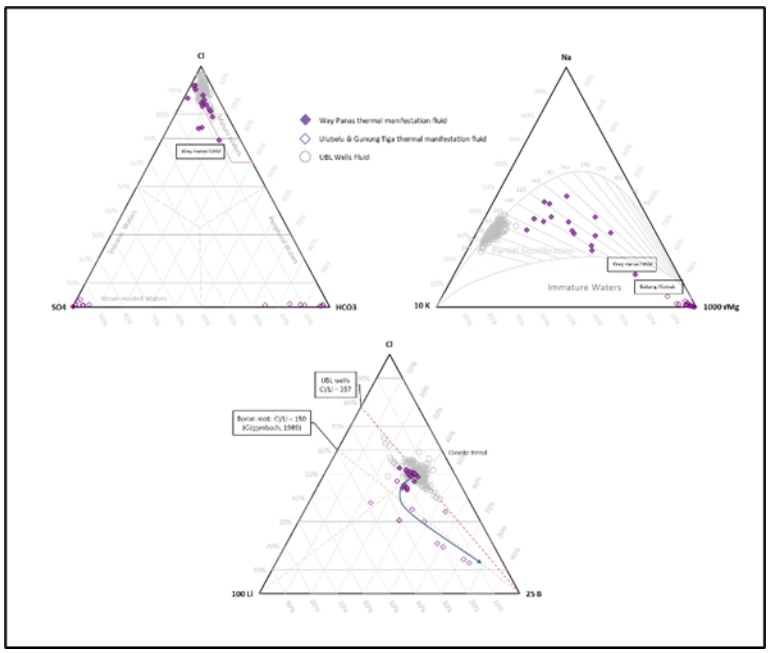

Figure 5: Water ternary diagrams (a) Cl-HCO_3-SO_4, (b) Na-K-Mg (c) Cl-Li-B

Generally, the UTM and GTTM fluids are steam-heated and bicarbonate water, and WPTM are chloride water with partial equilibration. Using UBL well fluids as a reference, we understand that WPTM fluids are the closest to reservoir fluids in terms of their water type representation. The fluid equilibration also tells us about its water rock interaction. With higher magnesium, the UTM and GTTM tended to be influenced by surface water. Giggenbach (1989) used Cl/Li ratio to describe boron mobilization as the fluids interacted with more steam. The UTM and GTTM fluids follow this Giggenbach ratio suggests to us about their interaction with evolving steam from subsurface boiling. This pattern is good indicator that the UTM and GTTM fluids as an upflow. Meanwhile the WPTM fluids followed different Cl/Li ratio as we understand really close with the reservoir fluids.

Arnórsson (2000) in his book stated that chloride and boron are considered as conservative elements, meaning that they are not or relatively less reactive than other elements in geothermal brine. In their investigation, Arnórsson and Andrésdóttir (1995) noted that Cl/B reduces at higher temperatures. We assessed the Cl/B ratio in thermal manifestation brine, and the results showed a similar trend: the ratio tends to increase as fluid moves toward the south and southwest. It denotes that the fluid pattern streams to the south-southwest as an outflow in WPTM after flowing from the north as an upflow in UTM.

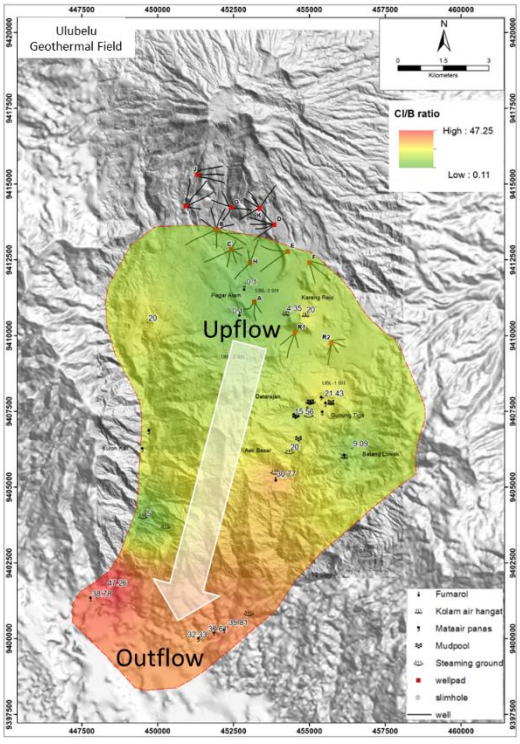

Figure 6: Hydrogeochemistry of Ulubelu Geothermal Field

3. MIXING MODELS

When evaluating geochemical fluids, two different types of mixing models should be used. The silica-enthalpy mixing model approach was first developed by Fournier and Truesdell (1974), and subsequently it was made easier to use by Truesdell and Fournier (1977). The silica content and its enthalpy of their spring source must be identified, as indicated by the name. Using a steam table, the saturated enthalpy may be computed from the measured temperature of the springs. We utilized the fluid properties of the well to make it more pertinent. The saturated enthalpy and silica content, which are similar quantities from wells, allowed us to examine the pattern more closely.

The enthalpy-chloride mixing model, developed by Truesdell and Fournier (1975), is the other mixing model. The initial temperature of hot water that is over 200°C can be determined using this approach. The following assumptions must be met, according to Fournier (1977): no heat loss or gain happens before or after mixing; no quartz re-equilibration occurs after mixing; no silica precipitation occurs during ascent of mixed water to the surface sample sites.

To investigate the mixing properties of the WPTM fluid, we compared it to deep reservoir water in this study.

3.1 Enthalpy-Silica Mixing Model

The silica mixing model is useful for understanding the chemical evolution of geothermal fluids because it allows us to predict the chemical composition of geothermal fluids based on the proportions of the two end-member fluids and the temperature and pressure conditions in the geothermal system. This can be helpful for identifying and characterizing geothermal resources, as well as for understanding the geochemical processes that are occurring in the Earth's crust and mantle.

This model is available in two varieties. The first one is predicated on the absence of steam or heat heated before fluids are mixed, but the second one involves steam or heat release prior to fluids being mixed, as identified by Nicholson (1993). The first type linearly regressed to the junction of no steam loss quartz solubility correlates the silica content of its springs with nearby meteoric water. The latter type draws a line horizontally to the maximum steam loss quartz solubility curve, where it intersects with the initial silica concentration and enthalpy. This extrapolates the linear regression between local spring water and local meteoric water to the temperature at which boiling is supposed to have happened (100°C, 419 kJ/kg).

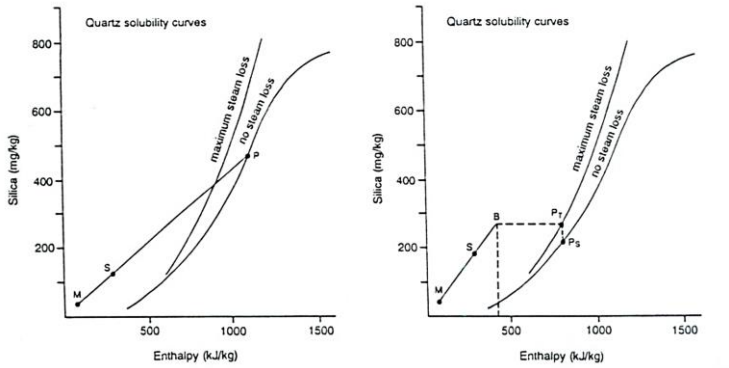

Figure 7: Enthalpy-Silica Mixing Model from Nicholson (1993)

We used the first kind to practically correlate quartz solubility in local meteoric water with no steam loss and spring water from Way Panas. As we refer to them as source fluid, we have three possible values. The first one was based on intersection of the mixing trend line and the quartz solubility curve the non-steam loss. Using the second method, we calculated the average saturation enthalpy and silica concentration of brine, which fit within the Fournier and Potter (1982) silica solubility curve. The third one was performed using saturated enthalpy at the mixing trend line-crossing average reservoir temperature of 266°C. The following values are:

Parent fluid determination approach	Enthalpy (kJ/kg)	Silica content (ppm)
Intersect mix. line & qtz no steam loss	1060	460
Average from well fluid	1097.2	476.7
Intersect sat. enthalpy at ave. temp. res. & mix. line	1164.8	505.6

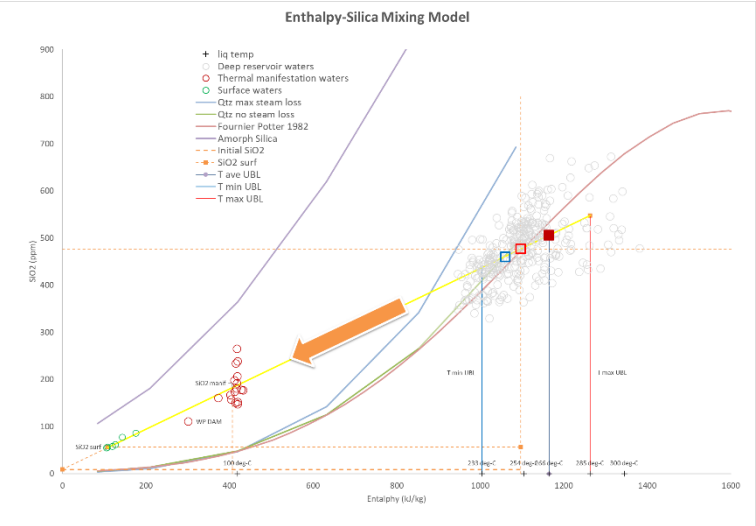

Figure 8: Enthalpy-Silica Mixing Model of Ulubelu Geothermal Field

Modeling based on graphs between the water isotopes deuterium and oxygen-18 confirms that the source of WPTM fluid comes from reservoir UBL production zones. The shift in oxygen-18 between the reservoir fluid and the analogous WPTM fluid is depicted in this diagram. The WPTM fluid is different since it has been enhanced with deuterium. Due to the extensive evaporation, this is a possibility. The manifestation fluid will be subjected to air pressure once it has surfaced. At this stage, the lighter deuterium separates from the fluid while the heavier deuterium remains in the liquid phase. Kim (2011) demonstrated that the enrichment of water isotopes brought about by evaporation had a significant effect. For example, oxygen-18 experienced an enrichment of 7.8–8.9, and deuterium experienced an enrichment of 12.6–16.5. Deuterium enrichment is increased more by evaporation than by oxygen-18 enrichment.

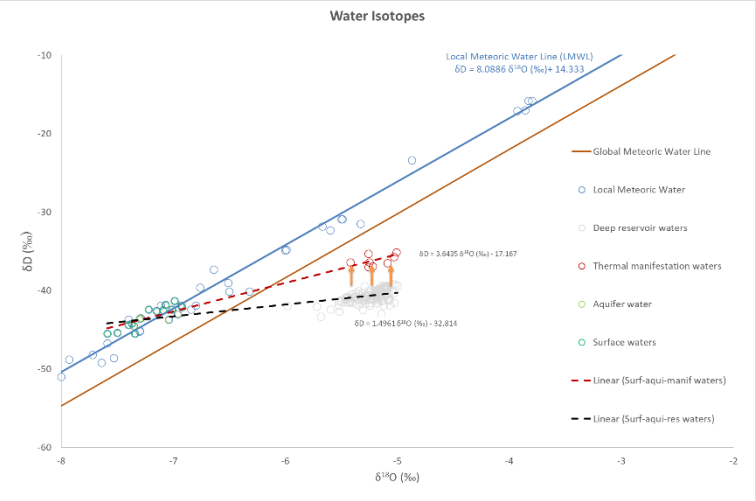

Figure 9: Water isotopes of Ulubelu Geothermal Field

The link between chloride and boron supports this as well. While boron can be found in water in both the liquid and vapor phases as in Glover (1988). Chloride was not known to be incorporated in altered minerals and did not reach chemical equilibrium in the geothermal system, thus its concentration in the water will be dictated by its availability. as in Arnórsson (1983). Saturation with respect to halite—which controls the behaviour of chloride—is only obtained in extremely unusual natural conditions. As a result, it is safe to utilize chloride as the mobile species of reference for examining how other dissolved constituents behave as in Marini (2004). Surface fluids (river and shallow aquifer water), WPTM water, and UBL's wells water all correlate favourably. Even a tiny fraction of the WPTM and UBL's wells correspond, demonstrating that the two fluids come from the same reservoir. The relationship between the chloride and boron contents increases with chloride content, creating a straight trend line. Even though one sample of the WP DAM manifestations had rather intense mixing, it was still in the appropriate mixing line.

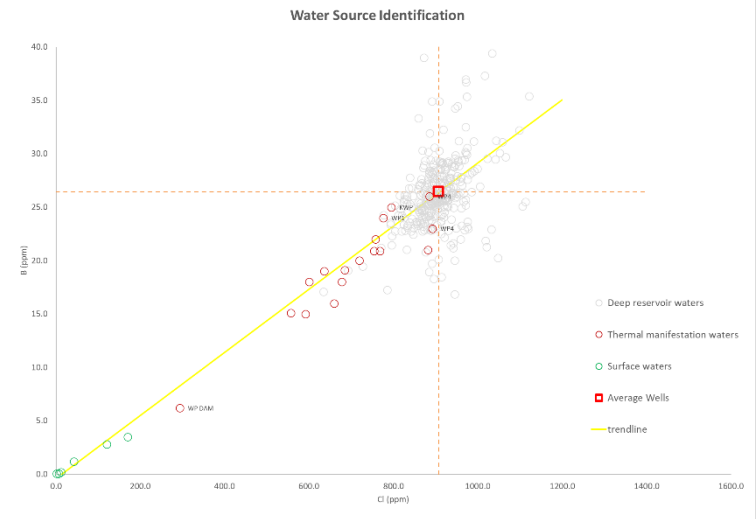

Figure 10: Water Source Identification of Ulubelu Geothermal Field

3.2 Chloride-Enthalpy Mixing Models

This model contrasts the fluid saturation enthalpy and the chloride content. The process of reservoir fluid rising to the surface –mixing or boiling process– can be determined using this model as in Arnórsson (1985). The parent fluid that appears as a source of water in the WPTM is regarded to be reservoir fluid. The average chloride content (907.25 ppm) and saturation enthalpy (1097.2 kJ/kg) of the UBL's wells fluid are used to identify the parent fluid. Following the determination of the parent fluid, we connect it to the fluid's chloride concentration in the WPTM and its enthalpy saturation at the determined temperature in each manifestation. We then connect with surface fluids (rivers and shallow aquifers).

This relationship gives us two potential outcomes. In the first scenario, the primary fluid (R) undergoes conductive cooling as shown by a downward vertical shift toward the WPTM fluid, specifically WP4 (C), before equilibrating with other WPTM fluids and going through dilution (D) with surface water. The main fluid (R) in the second scenario mixes with non-reservoir fluid (M), then boils (C), becoming visible at the surface as WPTM fluid and also as WP4, then achieves equilibrium with other WPTM fluids, and ultimately undergoes dilution (D). The presence of WP DAM, which is undergoing intense mixing, serves as proof that the two scenarios share parallels in their experiences of dilution to surface water. However, there is still a disconnect in this second scenario, and we still require proof of mixing operations with non-reservoir water and subsequent boiling (M to C). To explain how reservoir fluid rises to the surface, the first scenario is thus still the simpler one.

On the other hand, if we receive data on the reservoir fluid characteristics in the GTTM region, we will have the chance to demonstrate whether the second scenario is accurate. The characteristics of surface manifestations at GTTM, such as fumaroles and mud pools, suggest that significant heating occurs once more when the fluid flows from the north to the southwest.

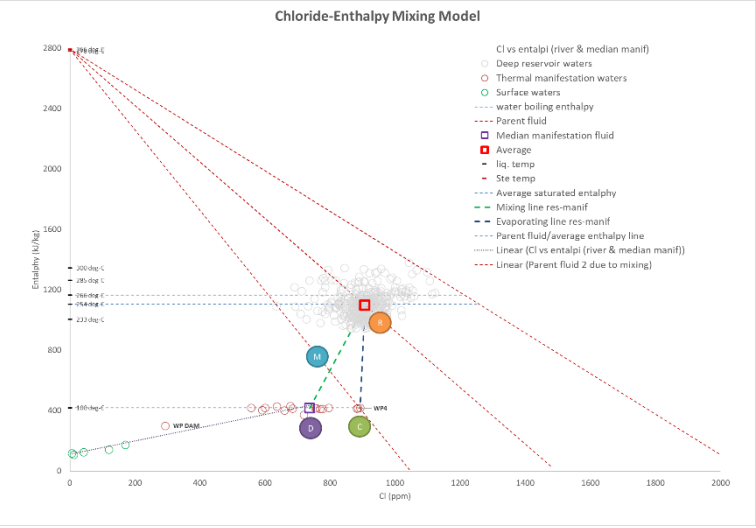

Figure 11: Chloride-Enthalpy Mixing Model of Ulubelu Geothermal Field

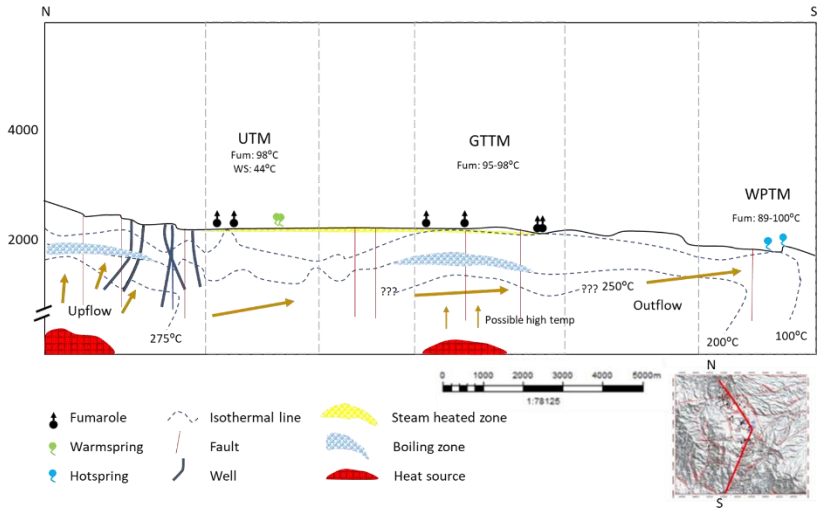

Figure 12: Ulubelu's conceptual model based on geochemistry of fluids.

4. CONCLUSION

Hydrologically, the fluid flow pattern in Ulubelu flows from the production zone in the north to the south. The silica-enthalpy mixing model confirms that reservoir fluids move south and mix with non-reservoir fluids until they appear on the surface (WPTM). Process-wise, there are two scenarios that are most likely to increase the reservoir fluid to WPTM, namely: first, the fluid undergoes conductive cooling followed by dilution by surface fluid; secondly, mixing with non-reservoir fluids followed by reheating and then dilution by surface water. The second scenario requires further proof to be used as a reference. However, surface manifestations in the GTTM which are dominated by steam features offer a strong indication of reheating.

5. REFERENCES

Arnórsson, S., Andresdottir, A.,: Processes controlling the distribution of boron and chlorine in natural waters in Iceland. Geochim. Cosmichim. Acta 59, (1995), 4125–4146.

Arnórsson, Stefán (editor),: Isotopic and Chemical Techniques in Geothermal Exploration, Development and Use: Sampling Methods, Data Handling, Interpretation INTERNATIONAL ATOMIC ENERGY AGENCY, - Edited by Stefán Arnórsson, Non-serial Publications, IAEA, Vienna (2000)

Arnórsson, Stefán,: Chemical equilibria in icelandic geothermal systems—Implications for chemical geothermometry investigations, Geothermics, Volume 12, Issues 2–3, (1983), Pages 119-128,

Arnórsson, Stefán,: The use of mixing models and chemical geothermometers for estimating underground temperatures in geothermal systems, Journal of Volcanology and Geothermal Research, Volume 23, Issues 3–4, (1985), Pages 299-335.

Fournier, R O, White, D E, and Truesdell, A H.: Geochemical indicators of subsurface temperature. Part I. Basic assumptions. United States: N. p., (1974). Web.

Fournier, R O.: Chemical Geothermometers and Mixing Models for Geothermal Systems, Geothermics, Vol. 5, (1977), pp. 41-50.

Fournier, R. O., White, D. E. and Truesdell, A. H,: Convective heat flow in Yellowstone National Park (Proc. U. N. Syrup. on the Development and Use of Geothermal Resources), San Francisco, Vol. 1, (1975), pp. 731-739.

Fournier, R. O.,: Chemical Geothermometers and Mixing Models for Geothermal Systems, Geothermics, Vol. 5, (1977), pp. 41-50.

Fournier, R.O., and Potter, R.W.: A revised an expanded silica (quartz) geothermometer, Geoth. Res. Council Bull., 11(10), (1982), 3-12.

Giggenbach, W. F.: The chemical and isotopic position of the Ohaaki Field within the Taupo Volcanic Zone, Proc. NZ Geothermal Workshop 11, (1989), 81-88.

Glover,: Boron distribution between liquid and vapour in geothermal fluids: Proceedings, 10th New Zealand Geothermal Workshop, New Zealand (1988)

Hochstein, M.P. and Sudarman, S.: History of geothermal exploration in Indonesia from 1970 to 2000. Geothermics 37. (2008), pp. 229-266.

Kyounghee Kim, Xuhui Lee,: Isotopic enrichment of liquid water during evaporation from water surfaces, Journal of Hydrology, Volume 399, Issues 3–4, (2011), Pages 364-375.

Marini, Luigi, Geochemical techniques for the exploration and exploitation of geothermal energy, Viareggio, Italy (2004)

Nicholson, K. N.: Geothermal Fluids. Chemistry and Exploration Techniques. (1993), xv + 263 pp.

Nurseto, Sapto & Sardiyanto, & Koestono, Hary & Thamrin, M & Kamah, M,: Evaluation of the productive geological structure in Ulubelu Geothermal System. Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015