

# Superhot Hydrothermal Fluid Reservoirs Identified using Boron and Chlorine Geothermometry

Andri Stefánsson

Institute of Earth Sciences, University of Iceland, Sturlugata 7, 102 Reykjavík, Iceland, on one line <Address style>

as@hi.is

**Keywords:** Superhot fluids, Geochemistry, Geothermometry

## ABSTRACT

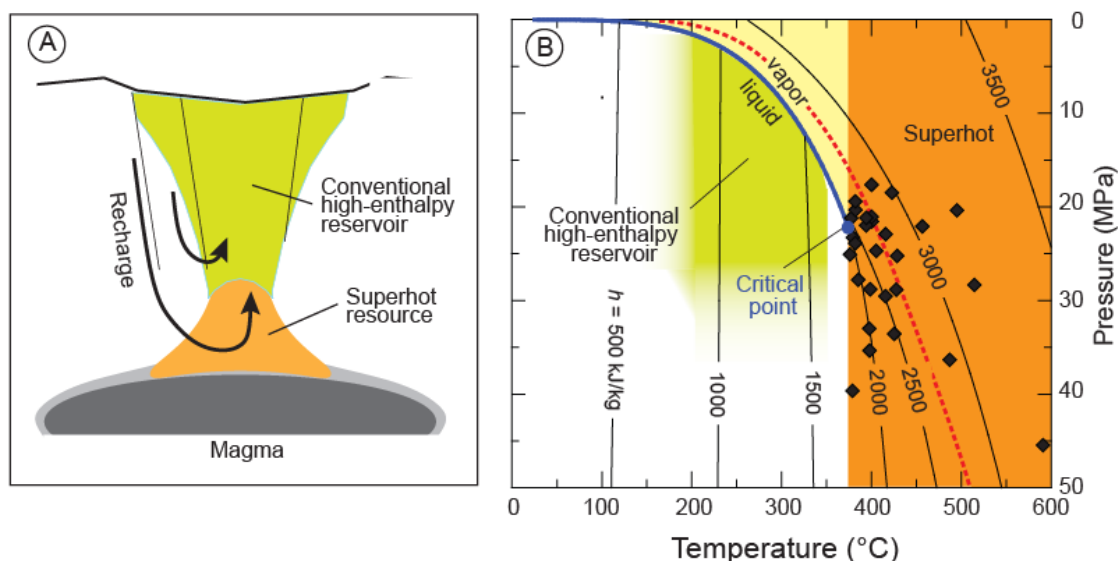
High-enthalpy geothermal systems, driven by volcanic and tectonic activity, offer potential for sustainable energy production. Superhot hydrothermal fluids, occurring near magmatic heat sources, exhibit temperatures exceeding critical temperature of water (374°C), enhancing geothermal efficiency. However, accessing these superhot fluid reservoirs presents challenges due to extreme conditions and limited understanding of their properties. This study introduces a novel geothermometry method based on the temperature-dependent volatility of boron (B) and chlorine (Cl) to assess vapor formation temperatures and mechanisms in three Icelandic geothermal systems, Hellisheiði, Nesjavellir and Krafla. Results highlight the potential of B and Cl as tracers to distinguish superhot fluids from vapor formed upon decompression boiling, advancing exploration and utilization of geothermal resources. Reservoir fluids at Hellisheiði, Nesjavellir and Krafla span a range from pure liquid to superheated vapor and superhot fluids in the case of Krafla. Boron and Cl geothermometry reveal that decompression boiling predominantly drives vapor formation, particularly at Hellisheiði and Nesjavellir, where localized zones also show input from superheated vapor and superhot fluids. At Krafla, widespread evidence of superhot fluids highlights the role of conductive heat transfer in vapor generation. Reservoir liquid temperatures range from 200°C to 325°C across systems, with vapor formation temperatures extending up to 440°C. These findings underscore the critical role of pressure, temperature, and heat transfer mechanisms in shaping reservoir dynamics and the potential common occurrence of superheated vapor and superhot fluids below conventional high-enthalpy geothermal reservoirs.

## 1. INTRODUCTION

High-enthalpy geothermal systems are found in regions with active volcanic and tectonic activity, where magma heats groundwater. The temperature of the magma typically ranges from 800°C to 1200°C, while conventional high-enthalpy geothermal systems generally have fluid temperatures between 200°C and 300°C (Chambefort and Stefánsson, 2021; Hurwitz et al., 2025). The temperature window between conventional geothermal systems and their magmatic heat source presents a new frontier for utilizing fluids from “superhot” resources. Such resources, which naturally occur within the Earth's crust or could be engineered by drilling into magma (Reinsch et al., 2017; Petty et al., 2020), have the potential to increase the efficiency and output of geothermal power plants, thereby boosting the delivery of sustainable, green energy for future generations.

Conventional boreholes in high-enthalpy geothermal systems typically reach depths of ~2-4 km, producing ~3-10 MWe, with some reaching up to ~30 MWe (Sanyal and Morrow, 2012). However, numerical modeling suggests superhot fluids may exist closer to magmatic intrusions (Hayba and Ingebritsen, 1997; Scott et al., 2015). Indeed, superheated vapor and superhot fluids have been encountered during drilling for conventional geothermal resources. The fluids encountered were primarily superheated vapor with temperatures between 360 and 400°C and pressure below 220 bar but temperatures above >500°C have also been measured or inferred (Ruggieri and Gianelli, 1995; Ikeuchi et al., 1998; Bali et al., 2020). Also, exploratory wells targeting superhot fluids, such as the IDDP-1 well in Krafla, Iceland, have successfully produced such fluids (Elders et al., 2014) (Fig. 1). However, targeting and accessing superhot fluid reservoirs remains challenging as they typically exist below conventional geothermal resources where conditions like high temperature gradients, thermal stresses, and mineral deposition occur highlighting the need for advances in drilling technology and a better understanding of superhot reservoirs (Kruszewski and Wittig, 2018).

In this context, a new geothermometry approach is introduced, based on the temperature-dependent volatility of boron (B) and chlorine (Cl), to assess vapor formation temperatures and mechanisms in borehole fluids within geothermal wellfields. Boron and Cl exhibit a sharp shift in their vapor partitioning behavior at high-temperature geothermal conditions (i.e., >300°C) but do not participate in secondary processes like fluid-rock interactions. This makes these elements ideal tracers for distinguishing vapor formed at superheated and superhot temperatures, as opposed to vapor formed at lower temperatures within conventional geothermal systems due to decompression boiling during fluid ascent to the surface. The method is demonstrated on three geothermal systems in Iceland Hellisheiði, Nesjavellir, and Krafla.



**Figure 1: (A) Conceptual model of a magma-driven geothermal system showing the relation between conventional high-enthalpy geothermal reservoir, the deeper superhot reservoir, and the magmatic heat source. (B) Water phase diagram and possible definitions of the “superhot” region in temperature-pressure coordinates. Orange denotes the conditions of temperature being higher than the critical temperature of water (373.95 °C), and yellow those of single-phase superheated vapor below the critical pressure of water. The red specific enthalpy exceeding the maximum specific enthalpy along the liquid-vapor phase boundary ( $h^v = 2803.3$  kJ/kg). The black diamonds represent measured temperatures of superhot fluids or inferred from fluid inclusions at depth within active geothermal systems worldwide.**

## 2. HYDROTHERMAL FLUID COMPOSITION

The Hellisheiði and Nesjavellir geothermal fields both lie in the Hengill volcanic region, in southwestern Iceland. The Hengill volcano is characterized by subglacial hyaloclastites, interglacial lava flows and postglacial eruptions along NE-SW trending fissure swarms, fault zones, and high heat flow, which provide the necessary conditions for geothermal energy. Today, Nesjavellir host a geothermal power plant producing 120 MWe and 300 MW<sub>t</sub> and Hellisheiði a power plant producing 303 MWe and 200 MW<sub>t</sub>. Krafla geothermal field is situated in the northern part of Iceland and is part of the Krafla volcanic system. It is characterized by an active central volcano including a caldera and a N-S trending fissure swarm with its lithology is mainly comprised of basaltic rocks with minor rhyolites. Krafla hosts a geothermal power station producing 60 MWe.

The Hellisheiði, Nesjavellir and Krafla geothermal field all provides access to deep geothermal fluids via borehole discharges. As a part of this study these borehole fluids were sampled at surface and analyzed for major solutes and gases. Fluid samples (liquid and vapor phases) were collected and analyzed for major elements according to previously proposed procedures (Arnórsson et al., 2006). Liquid samples were filtered using a 0.2µm cellulose acetate filter, acidified with 1% HNO<sub>3</sub> (Suprapur®, Merck), and analyzed for major cations (Si, B, Na, K, Ca, Al, Fe) using ICP-OES. Anions (F, Cl, SO<sub>4</sub>) were analyzed in filtered samples by IC (Dionex ICS-2000), without further treatment. CO<sub>2</sub> and H<sub>2</sub>S were analyzed on-site (or within 1-2 days) using alkalinity titration and Hg-precipitation titration, respectively. Vapor samples were collected in pre-evacuated gas bottles containing 10 ml of 50% KOH in 100 ml bottles, with CO<sub>2</sub> and H<sub>2</sub>S analyzed in the vapor condensate by titration. H<sub>2</sub>, N<sub>2</sub>, Ar, and CH<sub>4</sub> were analyzed in the gas phase by GC (Shimadzu GC-2010 Plus). Separate vapor samples for B and Cl measurements were obtained by cooling and condensing the vapor phase, then treated and analyzed as described for liquid samples. Analytical precision for all major elements, based on duplicate determinations, was within 3%.

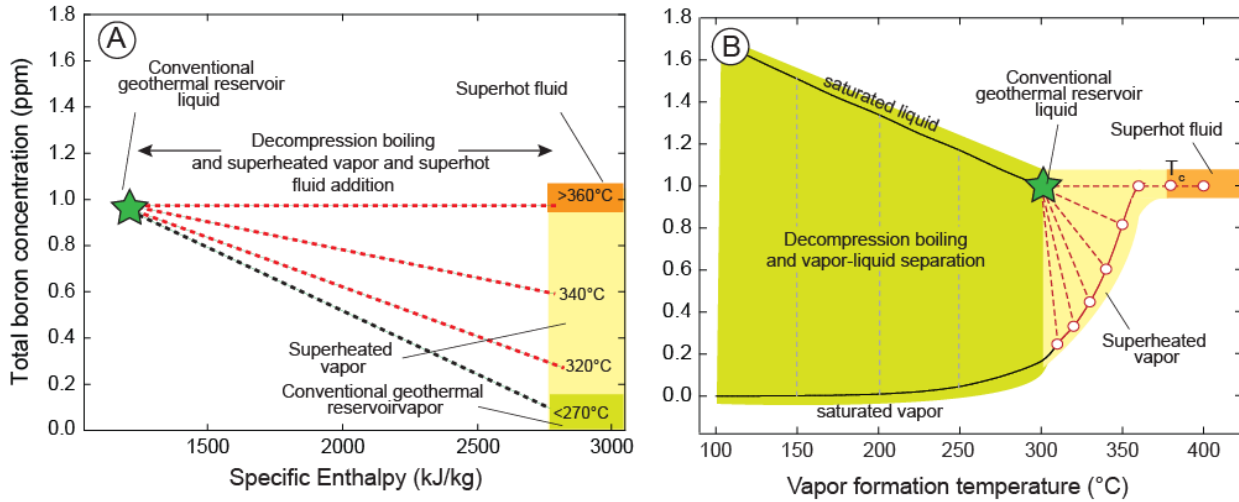
## 3. WELL FLUID ENTHALPY, TEMPERATURE AND COMPOSITION

### 3.1. Background

Vapor formation processes in geothermal systems are typically visualized based on measurements of well discharged properties, including liquid-to-vapor ratios, subsurface temperature, and pressure. Wells are often classified by their enthalpy, with "excess enthalpy" discharges defined as those where the vapor-to-liquid ratio exceeds that corresponding to the liquid enthalpy of the hydrothermal fluids at reservoir temperatures. However, interpreting the mechanism behind this excess enthalpy or vapor is challenging, as it is unclear whether it results from decompression boiling and phase separation induced by permeability restrictions, or from enhanced boiling of reservoir liquids due to heat from a nearby magma source, the latter processes capable of resulting in the formation of superheated vapor and superhot fluids. Fluid geothermometry can help distinguish between these two vapor formation processes and here a new type of geothermometry is applied based on temperature dependent volatility of B and Cl.

### 3.2. Well discharge enthalpy, vapor fraction and total fluid composition

The vapor fraction at sampling were obtained from mass flow rate measurements using a Thermochem's MicroMod TFT® equipment, ThermoTrace™ liquid-phase tracer and SF<sub>6</sub> gas tracer. The tracers were injected into the two-phase flow at the wellhead and samples



**Figure 2: The relationship between total B concentration in hydrothermal fluids and (A) specific enthalpy, and (B) vapor formation temperature. These relationships provide the basis for the B (here as an example) geothermometry to calculate vapor formation temperature (vapor, superheated vapor and superhot fluid) in excess well discharges. For hydrothermal liquid initially containing 1 ppm B, decompression boiling leads to vapor with ~0 ppm B, accompanied by a decrease in total B concentration as the vapor fraction increases indicated by the rise in specific enthalpy. As vapor formation temperature increases, the B content of the vapor phase also rises, eventually becoming fully volatile above ~360°C. These trends can be used to assess vapor formation temperatures in excess enthalpy well discharges, as shown by the mixing lines (red). Similar trends have been observed in geothermal systems in Iceland (filled circles).**

collected ~20 – 40 m downstream after separation of the vapor and liquid phases using a Webre separator. The concentration of the SF<sub>6</sub> gas tracer ThermoTrace™ liquid were analyzed using a GC system (Thermo Scientific TRACE-1310) and spectrophotometrically (ThermoTrace Analyzer).

From the concentration of the tracers the mass flow rate of vapor and liquid, vapor ( $x_{T^s}^v$ ) and liquid ( $x_{T^s}^{lq}$ ) fraction at the sampling temperature ( $T^s$ ) and the total discharge enthalpy ( $h^{total}$ ) is calculated based on the equation of state (EoS) of water (IAPWS R6-95, 2016) via,

$$h^{total} = x_{T^s}^v h_{T^s}^v + x_{T^s}^{lq} h_{T^s}^{lq} = x_{T^s}^v h_{T^s}^v + (1 - x_{T^s}^v) h_{T^s}^{lq} \quad (1)$$

and solving steam fraction at sampling temperature at wellhead

$$x_{T^s}^v = \frac{h^{total} - h_{T^s}^{lq}}{h_{T^s}^v - h_{T^s}^{lq}} \quad (2)$$

Following, the total concentrations of an element ( $m_i^{total}$ ) in the hydrothermal fluid were calculated from the analyzed of liquid ( $m_{i,T^s}^{lq}$ ) and vapor ( $m_{i,T^s}^v$ ) sample concentrations and  $x_{T^s}^v$  (Eqn. 2) from the expression

$$m_i^{total} = x_{T^s}^v m_{i,T^s}^v + (1 - x_{T^s}^v) m_{i,T^s}^{lq} \quad (3)$$

Based on the total well discharge enthalpy, the liquid ( $x_{T^{res}}^{lq}$ ) and vapor ( $x_{T^{res}}^v$ ) fractions within the geothermal reservoir corresponding to the inflow conditions of the boreholes at the reservoir temperatures ( $T^{res}$ ) were obtained from downhole and measured borehole temperatures or average quartz and Na-K geothermometry (see following section) when not available via,

$$x_{T^{res}}^v = \frac{h^{total} - h_{T^{res}}^{lq}}{h_{T^{res}}^v - h_{T^{res}}^{lq}} \quad (4)$$

where  $h_{T^{res}}^{lq}$  and  $h_{T^{res}}^v$  are the liquid and vapor enthalpies at  $T^{res}$ .

Elemental concentrations between the liquid and vapor phases in the reservoir were calculated assuming equilibrium vapor-liquid distribution for a given volatile elements and mass balance and mass action equations for the same element. The details are given by

Arnórsson et al. (2007) and not explained in further here as they are not critical for the present study. The calculations were conducted using the WATCH program (Bjarnason, 2010).

### 3.3. Liquid geothermometry

The temperatures of the reservoir's hydrothermal liquid were calculated using silica and NaK geothermometry. These solute-based geothermometers rely on the equilibrium between aqueous silica in the liquid phase and quartz, as well as the equilibrium between aqueous  $\text{Na}^+$  and  $\text{K}^+$  concentrations in the liquid phase and albite and K-feldspar, respectively. The calculations for both solute geothermometry were performed using the WATCH program (Bjarnason, 2010).

### 3.4. Vapor geothermometry

Excess enthalpy wells are defined here as those with excess vapor fraction exceeding 30%, i.e.  $x_{T^{res}}^v > \sim 0.3$ . Using new type of geothermometry based on temperature dependent volatility of B and Cl the vapor formation temperature was calculated. It is based on solving mass action and mass balance for B and Cl within liquid and vapor and calculating the vapor formation temperature needed to explain total B and Cl concentrations in excess well discharge fluids (Fig. 2)

Total B and Cl concentrations is defined by Eqn. (3) and given as for B and Cl, respectively:

$$m_B^{total} = x_{T^{res}}^v m_{B,T}^v + x_{T^{res}}^{lq} m_{B,T^{res}}^{lq} \quad (5)$$

$$m_{Cl}^{total} = x_{T^{res}}^v m_{Cl,T}^v + x_{T^{res}}^{lq} m_{Cl,T^{res}}^{lq} \quad (6)$$

where reservoir vapor ( $x_{T^{res}}^v$ ) and liquid ( $x_{T^{res}}^{lq} = 1 - x_{T^{res}}^v$ ) fractions are obtained from enthalpy measurements of well discharges at surface (Eqn. 1) and reservoir liquid concentrations ( $m_{B,T^{res}}^{lq}$  and  $m_{Cl,T^{res}}^{lq}$ ) are based on liquid only reservoir fluids, i.e. when  $h^{total} = h_{T^{res}}^{lq}$  or  $x_{T^{res}}^v = \sim 0$  for a particular geothermal field.

The vapor concentration of B and Cl depends on temperature as the liquid-vapor equilibrium distribution factor is temperature dependent. For B this is described by the reaction and equilibrium distribution constant ( $K_{D,B(OH)_3}$ )



$$K_{D,B(OH)_3} = m_{\text{B(OH)}_{3(aq)}} / m_{\text{B(OH)}_{3(g)}} \quad (8)$$

And for chlorine this is described by the reaction



$$K_{D,HCl} = m_{\text{HCl}_{(aq)}} / m_{\text{HCl}_{(g)}} \quad (10)$$

Assuming  $\text{B(OH)}_{3(g)}$  and  $\text{HCl}_{(g)}$  to be the only B and Cl species in the vapor phase, it follows that

$$m_B^v = m_{\text{B(OH)}_{3(g)}} = \frac{m_{\text{B(OH)}_{3(aq)}}}{K_{D,B(OH)_3}} \quad (11)$$

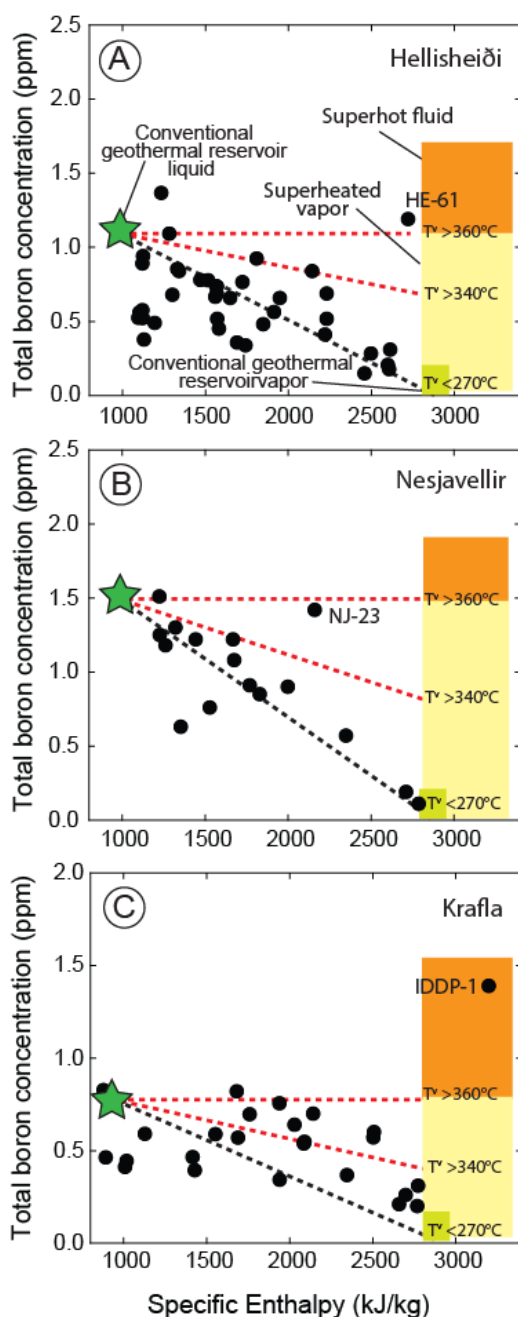
$$m_{Cl}^v = m_{\text{HCl}_{(g)}} = \frac{m_{\text{HCl}_{(aq)}}}{K_{D,HCl}} \quad (12)$$

The concentration of  $\text{B(OH)}_{3(aq)}$  and  $\text{HCl}_{(aq)}$  can be obtained via aqueous speciation calculations of B and Cl with the aid of the WATCH program for example (Bjarnason, 2010). For the calculations the following B species were included:  $\text{B(OH)}_{3(aq)}$  and  $\text{H}_2\text{BO}_3^-$  and Cl species were included:  $\text{HCl}_{(aq)}$ ,  $\text{Cl}^-$ ,  $\text{NaCl}_{(aq)}$ ,  $\text{KCl}_{(aq)}$ ,  $\text{FeCl}^+$ ,  $\text{FeCl}_{2(aq)}$ ,  $\text{FeCl}_2^{2+}$ ,  $\text{FeCl}_2^+$ ,  $\text{FeCl}_{3(aq)}$  and  $\text{FeCl}_4^-$ . The values for  $K_{D,B(OH)_3}$  were taken from Plyasunov (2011) and for  $K_{D,HCl}$  were taken from Palmer et al. (2004). The vapor formation temperature of excess well discharges were subsequently solved using iterative approach.

## 3. SUPERHOT HYDROTHERMAL TEMPERATURES IN ACTIVE GEOTHERMAL SYSTEMS

### 3.1. Boron and Chlorine relationship

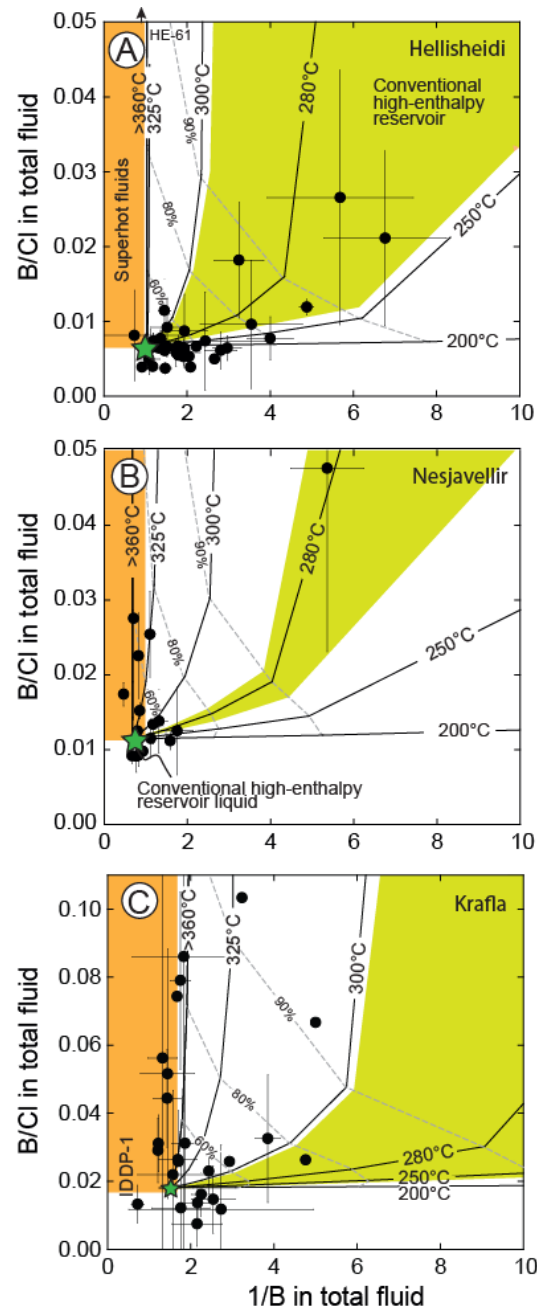
The measured enthalpy of well discharges at Hellisheiði (1096–2721 kJ/kg), Nesjavellir (1224–2787 kJ/kg), and Krafla (879–2774 kJ/kg) corresponds to geothermal reservoir fluids ranging from pure liquid to pure vapor across all systems. In many cases, the B concentrations in the high-enthalpy well discharges indicate mixing between reservoir liquid and vapor formed at lower temperatures due to decompression boiling ( $T^v < T^{res}$ ). This is particularly evident in the Hellisheiði and Nesjavellir geothermal fields. However, in some wells, elevated total B concentrations at high enthalpy suggest an input of superheated vapor and/or superhot fluids from deeper zones into the conventional high-enthalpy geothermal reservoir. Examples are well HE-61 at Hellisheiði and NJ-23 at Nesjavellir. At Krafla, most well discharges with intermediate to high enthalpy are enriched in total B, indicating the widespread occurrence of superheated vapor and superhot fluids in the deeper parts of the geothermal system. Clear evidence of superhot fluids is observed in the IDDP-1 well fluids that



**Figure 3: The relationship between measured total B concentration in well discharge as a function of measured enthalpy for boreholes at (A) Hellisheiði, (B) Nesjavellir and (C) Krafla geothermal fields. Also shown are the concentration of reservoir liquid in the systems (green star) and concentration of B in vapor formed upon boiling of such liquid at variable temperatures. Samples lying on the black line correspond to vapor formed upon decompression boiling and phase separation whereas red lines are vapor formed upon conductive heat boiling at higher temperatures than corresponding to the geothermal liquid (i.e.  $T^v > T^{\text{res}}$ ).**

had measured well fluid temperatures at surface of  $\sim 440^\circ\text{C}$ . Based on the relationship between boron concentration and enthalpy in the Hellisheiði, Nesjavellir, and Krafla geothermal systems, it is evident that superheated vapor and/or superhot fluids are present in all three systems. These fluids appear localized in the Hellisheiði and Nesjavellir systems but are more widespread at depth in Krafla (Fig. 3).

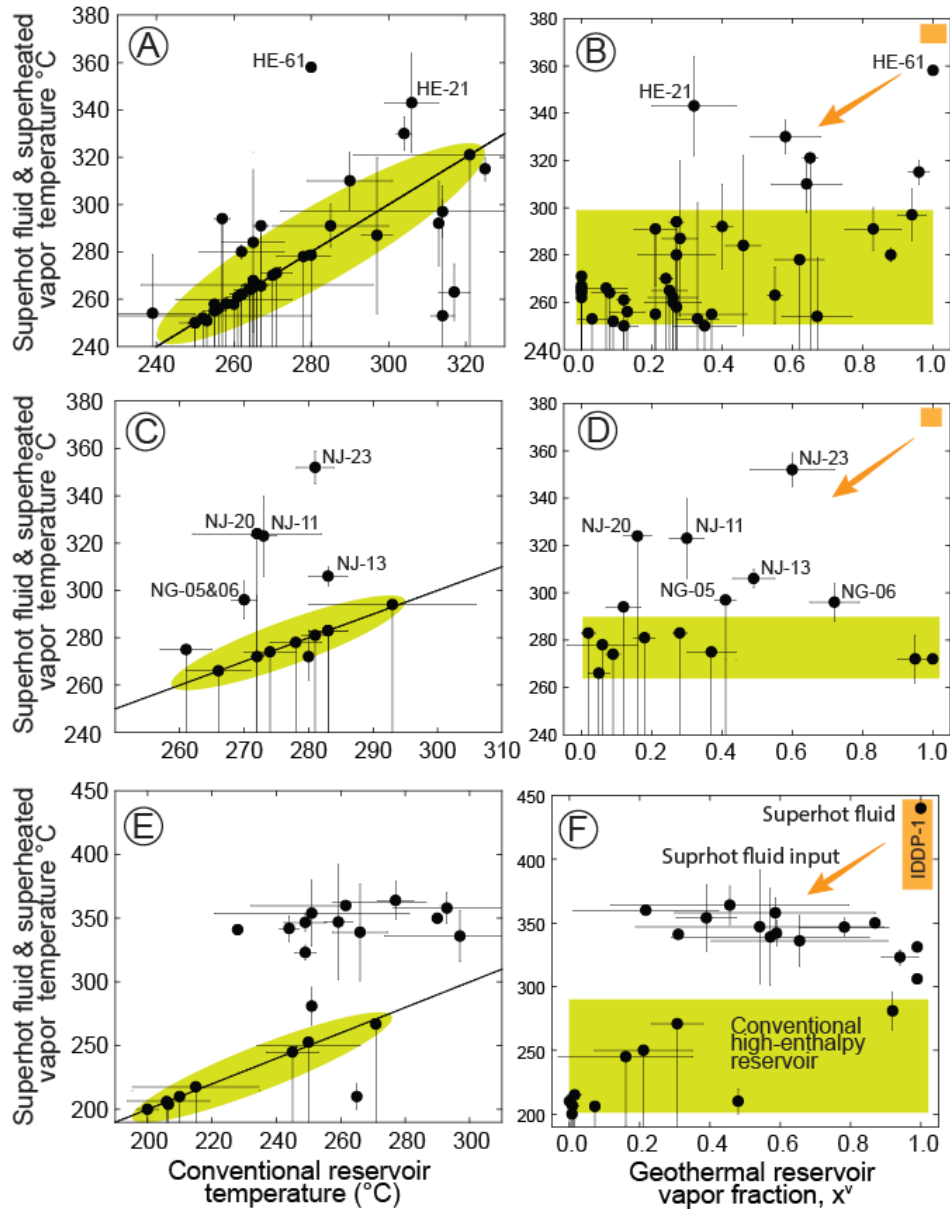
Chlorine partitioning into the vapor phase primarily occurs above  $\sim 400^\circ\text{C}$  and is therefore not a sensitive geothermometer for predicting vapor formation temperatures within the  $\sim 300\text{--}400^\circ\text{C}$  range, which is the main temperature interval of vapor formation as indicated by B geothermometry. This relationship is further demonstrated when B and Cl vapor formation temperatures and their corresponding mixing lines with conventional high-enthalpy reservoir fluids are considered (Fig. 4). Reservoirs characterized by liquid and vapor formed at lower temperatures due to decompression boiling typically exhibit low B/Cl ratios and low overall B concentrations. In contrast,



**Figure 4: The relationship between measured B/Cl ratio and 1/B concentration in well discharge at (A) Hellisheiði, (B) Nesjavellir and (C) Krafla geothermal fields (closed black circles). Also shown are the respective conditions related to vapor formation temperature in excess enthalpy well discharges, the conditions in the conventional high-enthalpy reservoir (green), conditions corresponding to superheated vapor and superhot fluids (orange).**

geothermal reservoir fluids influenced by the input of superheated vapor or superhot fluids into the reservoir liquid display progressively higher B/Cl ratios and B concentrations as vapor formation temperatures increase.

An analysis of the B and Cl data for Hellisheiði indicates that most of the geothermal reservoir fluids are liquids, with minor vapor formed due to decompression boiling, except for one borehole, HE-61. At Nesjavellir, a more diverse trend is observed. While most reservoir fluids are characterized by liquid water with minor vapor formed upon decompression boiling, as seen in Hellisheiði, several boreholes, such as NJ-11, NJ-20, and NJ-23, clearly show evidence of minor to moderate input of superheated vapor or superhot fluids. These boreholes are all located within the same subfield, where deep temperatures as high as ~380°C have been directly measured during drilling. At Krafla, the reservoir fluids are similarly dominated by reservoir liquid influenced by decompression boiling. However, the widespread input of superheated vapor or superhot fluids is evident across large portions of the field.



**Figure 5: The comparison of superhot and superheated vapor formation vs (A,C and E) conventional liquid reservoir temperature and (B,D and F) reservoir vapor fraction for the Hellisheiði (A and B), Nesjavellir (C and D) and Krafla (E and F) geothermal fields**

### 3.2. Reservoir vapor fraction and liquid and vapor temperatures

Using B volatility geothermometry, the vapor formation temperature was calculated for excess-enthalpy well discharges. The reservoir liquid temperature was also determined using silica and Na-K solute geothermometry. The results are presented in Figure 5, as well as in relation to the reservoir vapor fraction.

For the Hellisheiði geothermal system, the reservoir liquid temperature  $T^{\text{res}}$  ranges from 239°C to 325°C, with a reservoir vapor fraction  $x_{T^{\text{res}}}^{\text{v}}$  of 0.0–1.0 and a vapor formation temperature  $T^{\text{v}}$  from  $\leq 253^{\circ}\text{C}$  to  $\geq 358^{\circ}\text{C}$ . At Nesjavellir, the reservoir liquid temperature is  $T^{\text{res}} = 261\text{--}293^{\circ}\text{C}$ , the vapor fraction is  $x_{T^{\text{res}}}^{\text{v}} = 0.0\text{--}1.0$ , and the vapor formation temperature is  $T^{\text{v}}$  from  $\leq 272^{\circ}\text{C}$  to  $\geq 352^{\circ}\text{C}$ . For Krafla,  $T^{\text{res}}$  spans 200–297°C,  $x_{T^{\text{res}}}^{\text{v}}$  is 0.0–1.0, and  $T^{\text{v}}$  ranges from  $\leq 281^{\circ}\text{C}$  to 440°C.

In the Hellisheiði and Nesjavellir geothermal systems, again most vapor in the reservoirs appears to form through decompression boiling and phase separation, consistent with previous findings (Scott et al., 2014). Exceptions include occurrences of superheated vapor in specific locations, such as the Hverhlið subfield at Hellisheiði (well HE-61) and the central part of the Nesjavellir field (wells NJ-11, NJ-20, and NJ-23). At Krafla, the elevated vapor content in the geothermal reservoir is attributed to both decompression boiling with phase separation and conductive heating, which generates superheated vapor and, in some cases, superhot fluids. These findings highlight the

complex interplay of processes influencing vapor formation across geothermal systems and emphasize the importance of site-specific mechanisms in shaping the reservoir conditions.

### 3.3. Formation mechanism of superheated steam cap

In high-enthalpy geothermal systems, vapor is primarily formed through decompression boiling sometimes followed by phase separation, processes that are influenced by the interplay of pressure, temperature, and permeability. At depth, these systems typically contain liquid-dominated reservoir fluids. However, pressure drops - induced naturally by geological conditions or exacerbated by production - can trigger boiling as fluids ascend, particularly in the upper parts of the geothermal system (typically within 1 km of the surface). This decompression boiling leads to cooling and in some cases, the accumulation of vapor near the top of the system results in the formation of so called "steam caps." Moreover, previous studies have shown that adhesion of the boiled liquid phase onto mineral surfaces in the porous, fractured aquifer rock upon rapid decompression boiling, may result in phase separation of liquid and vapor and result in excess well enthalpy discharge (Arnórsson et al., 1990; Scott et al., 2014).

The transfer of heat from underlying hot rocks or magma to the hydrothermal fluid can also drive vapor formation. This process may increase the vapor fraction or enthalpy of the fluid without altering the overall chemical composition of the system. For example, data from Hellisheiði, Nesjavellir, and Krafla demonstrate a continuum of reservoir conditions, ranging from liquid-dominated to vapor-dominated fluids, with decompression boiling being a key mechanism of phase transition in these systems but also the latter process of vapor generated by conductive heat addition, especially at Krafla, such in some cases resulting in the formation of superheated vapor and superhot fluids.

The variable vapor generation mechanisms can also alter the fluid chemistry, leading to phenomena such as mineral precipitation and compositional changes in aquifer fluids - this indeed being the basis behind the B and Cl geothermometry presented in this study to calculate vapor formation temperatures in geothermal systems.

## 4. CONCLUSIONS

High-enthalpy geothermal systems represent a significant energy resource, particularly in volcanic regions, with the potential to evolve into superhot geothermal systems near magmatic heat sources. Understanding and accessing these systems can significantly enhance geothermal energy production.

- Superhot geothermal fluids, with temperatures exceeding 374°C, offer a new frontier for geothermal energy but require innovative drilling technologies and a deeper understanding of high-temperature reservoirs near magmatic intrusions.
- The temperature-dependent volatility of boron (B) and chlorine (Cl) provides a novel method for distinguishing vapor formation processes in geothermal wells in order to target deep superhot fluid temperatures.
- Analyses of hydrothermal well fluids from Hellisheiði, Nesjavellir, and Krafla fields (Iceland) and application of the B and Cl geothermometry revealed superheated vapor and superhot fluid occurrence in all the systems, localized in the first two systems and widespread presence in Krafla.

## REFERENCES

- Arnórsson, S., Björnsson, S., Muna, Z.W., and Bwire-Ojiambo, S.: The use of gas chemistry to evaluate boiling processes and initial steam fractions in geothermal reservoirs with an example from the Olkaria field, Kenya. *Geothermics*, 19, (1990), 497-514.
- Arnórsson, S., Stefánsson, A., and Bjarnason, J.Ö.: Fluid-Fluid Interactions in Geothermal Systems. *Reviews in Mineralogy and Geochemistry*, 65, (2007), 259–312.
- Bali, E., Aradi, L.E., Zierenberg, R., Diamond, L.W., Pettke, T., Szabó, Á., Guðfinnsson, G.H., Friðleifsson, G.Ó., and Szabó, C.: Geothermal energy and ore-forming potential of 600 C mid-ocean-ridge hydrothermal fluids. *Geology*, 48, (2020), 1221-1225.
- Bjarnason, J. Ö. Manual for the chemical speciation program WATCH v. 2.4., (2010), [http://www.geothermal.is/sites/geothermal.is/files/download/watch\\_readme.pdf](http://www.geothermal.is/sites/geothermal.is/files/download/watch_readme.pdf)
- Chambefort, I., and Stefánsson, A.: Fluids in Geothermal Systems. *Elements*, 16, (2021), 407-411.
- Elders, W.A., Friðleifsson, G.Ó., and Pálsson, B.: Iceland Deep Drilling Project: The first well, IDDP-1, drilled into magma. *Geothermics*, 49, (2014), 1.
- Hayba, D.O., and Ingebritsen, S.E.: Multiphase groundwater flow near cooling plutons. *Journal of Geophysical Research*, 102, (1997), 12,235–12,252.
- Hurwitz, S., Stefánsson, A., Shock, E.L., and Kleine-Marshall, B.I.: The geochemistry of continental hydrothermal systems. *Treatise on Geochemistry*, 3, (2025), 301-345.
- Ikeuchi, K., Doi, N., Sakagawa, Y., Kamenosono, H., and Uchida, T.: High-temperature measurements in well WD-1a and the thermal structure of the Kakkonda geothermal system, Japan. *Geothermics*, 27, (1998), 591–607.



- International Association for the Properties of Water and Steam, IAPWS R6-95: Revised Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use (2016), available from: <http://www.iapws.org>
- Kruszewski, M., and Wittig, V.: Review of failure modes in supercritical geothermal drilling projects. *Geothermal Energy*, 6, (2018), 28.
- Palmer, D.A., Simonson, J.M., and Jensen, J.P.: Partitioning of electrolytes to steam and their solubilities. In: Palmer, D.A., Fernández-Prini, R., Harvey, A.H. (Eds.), *Steam. Aqueous Systems at Elevated Temperatures and Pressures: Physical Chemistry in Water, Steam and Hydrothermal Solutions*, (2004), 410–438.
- Petty, S., Cladouhos, T., Watz, J., and Garrison, G.: Technology needs for superhot EGS development. *Proceedings 45th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA, (2020) 1-8.
- Plyasunov, A.V.: Thermodynamics of B(OH)<sub>3</sub> in the vapor phase of water: vapor–liquid and Henry’s constants, fugacity and second cross virial coefficients. *Fluid Phase Equilibria* 305, (2011), 212–218.
- Reinsch, T., Dobson, P., Asanuma, H., Huenges, E., Poletto, F., and Sanjuan, B.: Utilizing supercritical geothermal systems: A review of past ventures and ongoing research activities. *Geothermal Energy*, 5, (2017), 1–25.
- Ruggieri, G., and Gianelli, G.: Fluid inclusion data from the Carboli 11 well, Larderello geothermal field, Italy. In *Proceedings of the World Geothermal Congress*, Florence, 2, (1995), 1087–1091.
- Sanyal, S.K., and Morrow, J.W.: Success and the learning curve effect in geothermal well drilling—A worldwide survey. *Proceedings 37th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA, (2012), 1-8.
- Scott, S., Driesner, T., and Weis, P.: Geologic controls on supercritical geothermal resources above magmatic intrusions. *Nature Communications*, (2015) 6.