

Sub- and Supercritical Geothermal Fluids – A Global Database

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ABSTRACT

Despite significant technical challenges (Kibikas et al., 2026), drilling into supercritical fluids offers access to exceptionally high-energy resources, with the potential to deliver up to ten times more power than conventional geothermal wells. In addition to engineering hurdles, the origin and chemical composition of these fluids remain active areas of research. Sub- and supercritical fluids may originate from magmatic degassing or be trapped during the late stages of crystallization of magmatic intrusions. Recent high-temperature flow-through experiments have provided new insights, revealing the chemical and mineralogical transformations associated with supercritical fluid formation during conductive heating and boiling of subcritical geothermal groundwater by magmatic intrusions. These studies suggest that resulting supercritical fluids are typically depleted in major rock-forming elements such as Si, Na, K, Ca, Mg, and Al, but enriched in volatile elements including C, S, and B.

As part of the Supercritical Drilling Material Analysis (Kibikas et al., 2026), we have compiled detailed fluid chemistry data from both subcritical and supercritical geothermal wells. With the release of this publicly accessible dataset on the Geothermal Data Repository (GDR, <https://gdr.openei.org>), we aim to advance our understanding of the characteristics and behavior of fluids across the sub- to supercritical transition.

In this study, we examine differences in fluid chemistry across subcritical to supercritical geothermal fields to establish a foundation for further investigations of drilling and completion materials. This integrated approach helps refine conceptual models of supercritical geothermal systems and supports the development of more efficient, targeted drilling strategies, as well as informed selection of well construction materials for future exploration.

1. INTRODUCTION

Sub- and supercritical geothermal resources offer significantly higher energy densities compared to conventional hydrothermal systems. Due to their low viscosity and high enthalpy, supercritical fluids can transport substantially more thermal energy, potentially increasing the energy output per well by up to an order of magnitude. Fluids with sub- or supercritical temperatures in the range of 375-500 °C have been reported in several active geothermal fields worldwide including those at The Geysers, Salton Sea, and Hawaii, USA (e.g., Garcia et al., 2016; Kaspereit et al., 2016; Teplow et al., 2009); Kakkonda, Japan (Kato et al., 1998); Larderello, Italy (e.g., Bertini et al., 1980; Ruggieri and Gianelli, 1995); Krafla, Nesjavellir, and Reykjanes, Iceland (e.g., Steingrímsson et al., 1990; Friðleifsson et al., 2010; Friðleifsson and Elders, 2017); Los Humeros, Mexico (e.g., Espinosa-Paredes and Garcia-Gutierrez, 2003); and Menengai, Kenya (Sekento, 2012).

Despite successful drilling into reservoirs exceeding 350°C, a persistent challenge across all projects is the combination of extreme temperatures and corrosive fluids, which leads to rapid degradation of drilling and well-construction materials and can result in failures such as casing collapse and drill-bit damage. To enable future supercritical drilling, the Supercritical Drilling Material Analysis (Kibikas et al., 2026) focuses on evaluating site-specific conditions worldwide, including characterization of fluid chemistry at supercritical sites and assessment of potential correlations. The fluid-chemistry data analyzed in this study are organized and publicly available through the Geothermal Data Repository (GDR; Kibikas et al., 2025). Additionally, as part of the effort Meng et al. (2026) details current materials capabilities and testing for drilling and well construction materials needed for reaching and producing supercritical conditions economically.

Also, the occurrence and chemical composition of supercritical fluids remain poorly constrained (Heřmanská et al., 2020). Near and above the critical point of water, the dielectric constant decreases sharply, causing a strong reduction in water ionization and limiting the stability of free aqueous ions (Marshall & Franck, 1981; Bandura & Lvov, 2006). Under these conditions, electrolytes are dominated by ion pairs, neutral complexes, and molecular clusters rather than fully dissociated ions (Oelkers & Helgeson, 1990; Franck, 1998). Although

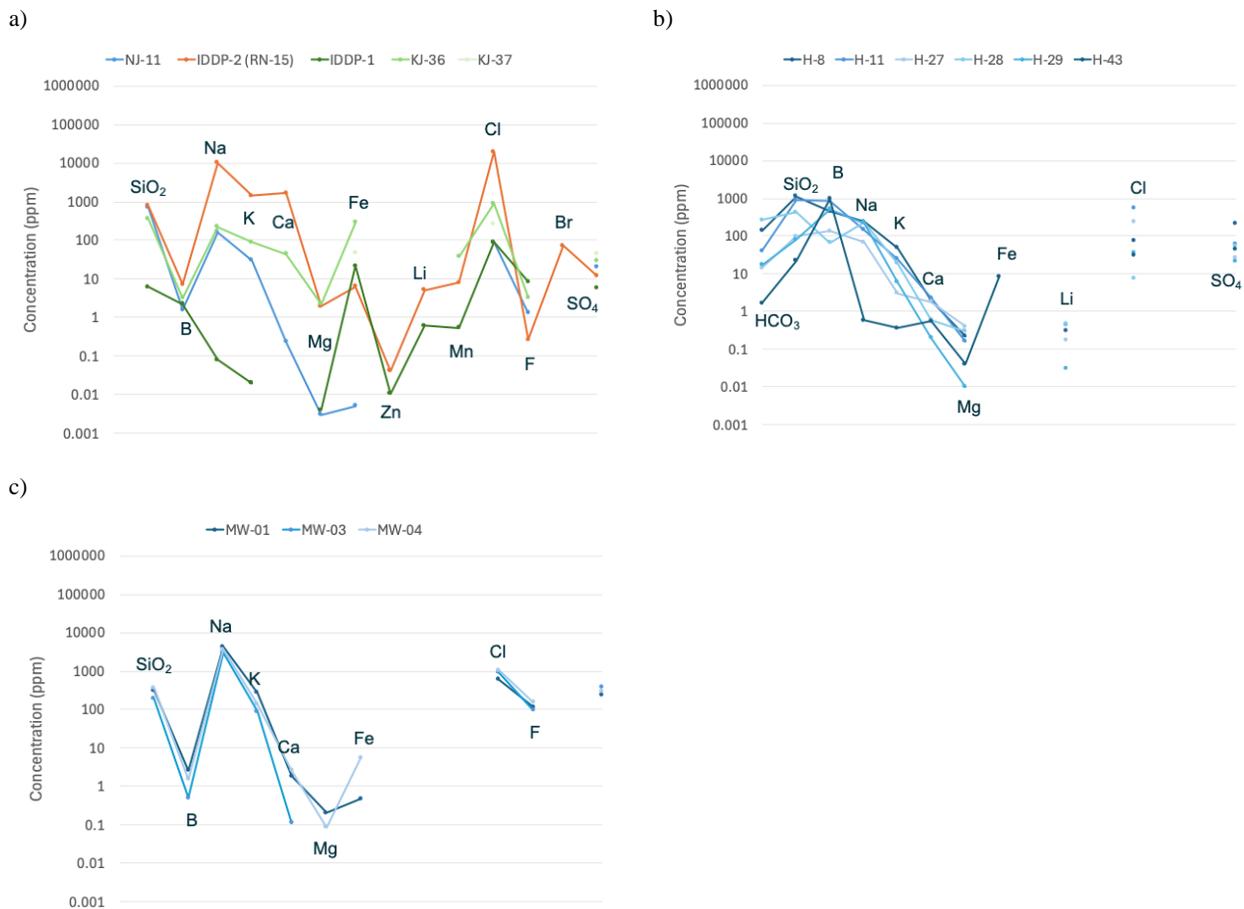
electroneutrality is maintained at the microscopic scale, the concentrations of analytically measurable charged species no longer represent the true charge distribution of the fluid (Seward & Driesner, 2004). As a consequence, classical aqueous charge-balance (ion balance) calculations yield large apparent errors that are inherent to supercritical and near-critical fluids and do not indicate analytical inconsistency (Driesner & Heinrich, 2007). Therefore, elemental mass balance and thermodynamic speciation models that explicitly account for ion pairing and non-ideal behavior are more appropriate than charge balance as quality criteria in supercritical systems (Reed & Palandri, 2013; Seward & Driesner, 2004).

Sub- and supercritical fluids may originate from magmatic degassing, characterized by elevated concentrations of CO₂, SO₂, HCl, and HF (Fischer and Chiodini, 2015), or form through fluid entrapment during magma crystallization (e.g., Kasai et al., 1998a, 1998b). Geochemical experiments and modeling further suggest that supercritical fluids can develop via conductive heating and boiling of subcritical geothermal groundwater in the presence of magmatic intrusions in subduction-zone settings (Heřmanská et al., 2020). Consequently, these fluids are typically depleted in mineral-forming elements such as Si, Na, K, Ca, Mg, and Al, with concentrations controlled by the solubility of salts, oxides, and aluminosilicates in high-temperature (>400 °C) and low-density (<300 kg m⁻³) fluids. In contrast, supercritical fluids are often enriched in volatile elements (e.g., C, S, B) derived from crustal and/or mantle sources, with concentrations that can be comparable to those observed in subcritical geothermal fluids.

With the aim of identifying characteristic fluid-chemical signatures associated with subcritical to supercritical temperatures that may influence cement and material degradation in such wells, this study compares fluid-chemistry data from approximately 20 wells worldwide, gathered through a combination of literature review and targeted outreach. Although supercritical fluids are expected to deviate from classical fluid-chemistry patterns, we initiate the analysis using conventional ternary diagrams and geothermometers (i.e., Powell and Cumming, 2010) as a point of reference.

2. STATISTICS AND COMPLETENESS OF THE FLUID CHEMISTRY DATABASE

The database comprises fluid-chemistry data from wells in geothermal fields where temperatures exceeding the supercritical point of water have been reached. In these fields, data were collected from wells with temperatures above 350 °C.



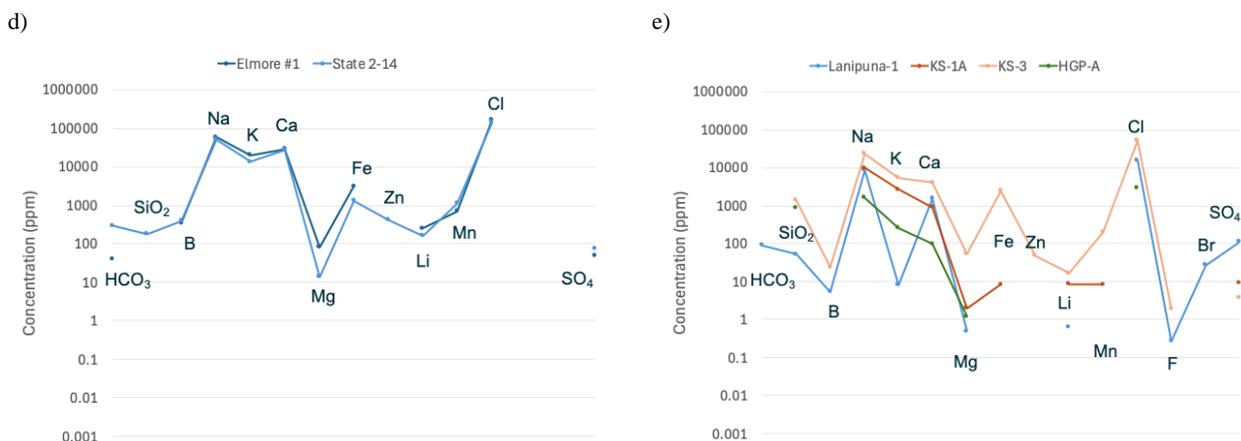


Figure 1: Data availability for major and selected other elements from the sub- to supercritical wells of a) Iceland, b) Mexico, c) Kenya, d) California (Salton Sea) and e) Hawai'i (Puna).

In total, fluid-chemistry data are available for 25 wells from Iceland, Mexico, Kenya, Italy, Greece, and from Hawai'i and California in the United States. For three wells, information is available for fewer than 50% of the generally analyzed elements. Excluding these wells, still fewer than 50% of the remaining wells, namely IDDP-2, KJ-36, Lanipuna-1, KS-3, HGP-A, Elmore #1, State 2-14, H-8, Mofette-005, and Nisyros-1, exhibit a charge-balance error below 15%. High charge imbalance can be attributed to missing information on major elements such as Cl or HCO₃. In particular, the data from the Los Humeros field (Mexico) and the Menengai field (Kenya) show large charge imbalances. At Los Humeros, different wells exhibit either anion or cation dominance, whereas fluids from Menengai are consistently cation-dominated. Figure 1 illustrates the data availability for major and selected metals of interest from Iceland, Mexico, Kenya and the United States.

The pH values across the different geothermal fields (Figure 2) span a wide range, from approximately 2.4 in the IDDP-1 well at Krafla (Iceland) to 8.3–9.3 in Menengai (Kenya). More acidic conditions, which are associated with elevated corrosion risk and sulfate scaling potential, are observed primarily in Krafla and the Salton Sea. In contrast, more alkaline conditions, which are indicative of chemically mature, deep reservoir fluids and water–rock equilibrium with silicate minerals, characterize the Menengai and Nesjavellir wells.

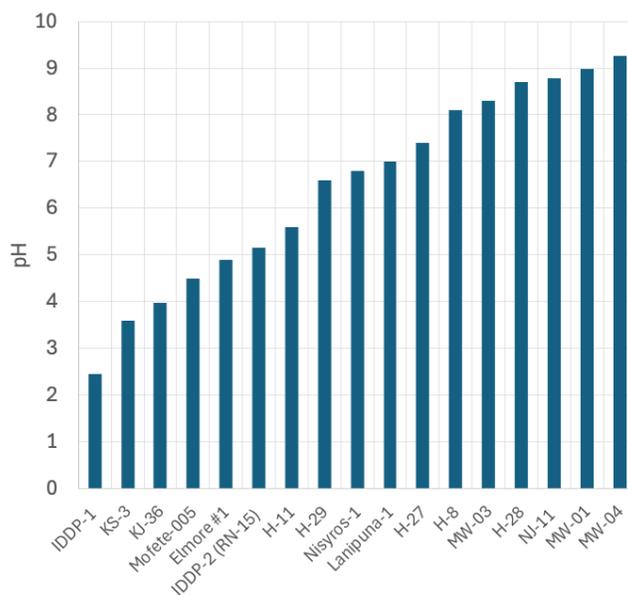


Figure 2: Range of pH-values from wells in Iceland (IDDP-1, KJ-36, IDDP-2, NJ-11), Italy (Mofete-005), Los Humeros (H-11, H-29, H-27, H-8, H-28), Greece (Nysiros-1), Kenya (MW-01, MW03, MW-04), Salton Sea (California, Elmore #1), and Puna (Hawai'i, KS-3, Lanipuna-1)

Oxygen isotope data are available for the wells IDDP-1 (Krafla, Iceland) and H-8 (Los Humeros, Mexico). Owing to the limited dataset, isotopic results are not discussed further here. A comprehensive analysis of oxygen isotope data from the Los Humeros field is presented in Schill et al. (this issue).

3. FLUID COMPOSITION

In the following, we present and discuss fluid-chemistry data using various conventional ternary plots. Depending on the specific diagram, wells are included when a complete set of required data is available.

The anion ternary plot (Figure 3) includes data from Puna (Hawai'i), Salton Sea (California), and Los Humeros (Mexico). The US wells KS-3, State 2-14 and Elmore #1 are chloride-dominated. In conventional systems, high chloride concentrations are an indicator for deep reservoir fluids with magmatic or connate influence. In sub- or supercritical systems, chloride partitions strongly into the liquid phase.

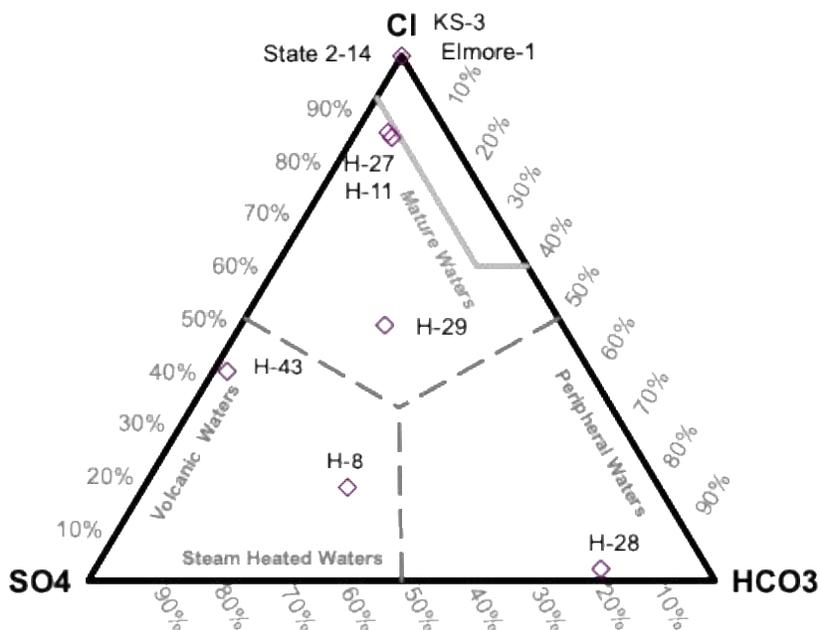


Figure 3: Cl-SO₄-HCO₃ ternary plot indicating the proportions of the major anions present in wells from Puna (Hawai'i), Salton Sea (California), and Los Humeros (Mexico) based on Giggenbach (1991).

Despite sampling sub- to supercritical reservoir temperatures, the Los Humeros fluids plot outside the “mature waters” field and instead fall within the peripheral waters, volcanic waters, or steam-heated waters domains. This indicates that the sampled fluids have undergone substantial chemical overprinting during ascent, which may include phase separation, steam loss, gas–water interaction, and mixing with shallow or condensate waters, rather than preserving deep reservoir signatures. Also, The wells are usually completed throughout the geothermal reservoir, so that there are likely feed zones from cooler portions of the reservoir that mix with those from the sub- to supercritical zones near the bottom of the wells. Thus, the produced fluids likely represent a mixture of fluids sourced over a range of reservoir temperatures at Los Humeros. Notably, fluid chemistry across the Los Humeros wells exhibits considerable variability. Consequently, the fluid chemistry does not reflect equilibrium at reservoir conditions, underscoring that in our case the ternary water-type diagrams classify fluid evolution pathways but do not diagnose true reservoir maturity in >350 °C geothermal systems.

Given the limited information on SO₄ and HCO₃ concentrations in many wells, the Na-K-Mg Giggenbach plot (Figure 4, Giggenbach, 1991) combining the Na-K with the K-Mg geothermometer allows including a larger number of wells.

The cation composition of the fluids confirms the heterogeneity of the fluids in the Los Humeros field. Fluids from Menengai (Kenya), the Salton Sea (California), southern Iceland (Reykjanes and Nesjavellir) are dominated by Na + K, indicating evolved fluids characteristic of high-temperature systems. Fluids from Menengai (Kenya) shows very low Mg and relatively high Na concentrations.

Although all wells sample reservoirs with temperatures exceeding 350 °C, the Giggenbach (Na–K–Mg) diagram shows that more than 50% of the fluids plot within the immature to partially equilibrated fields, with only few approaching full Na–K equilibrium. This apparent contradiction indicates that the Na–K–Mg system does not reliably record deep reservoir equilibrium in these high-temperature

environments. Instead, the diagram serves primarily as a comparative tool, reflecting substantial chemical modification possibly during ascent; consequently, it neither constrains deep equilibrium conditions nor implies the absence of high-temperature fluids.

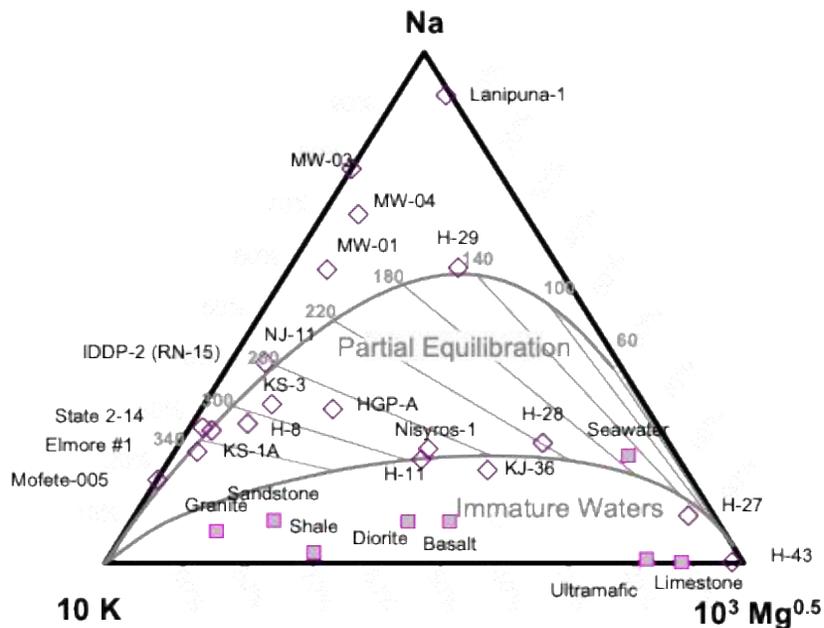


Figure 4: Na-K-Mg ternary plot of indicating the proportions of the major cations present in wells from Puna (Hawai'i), Salton Sea (California), Los Humeros (Mexico), Iceland, Italy and Greece based on Giggenbach (1991).

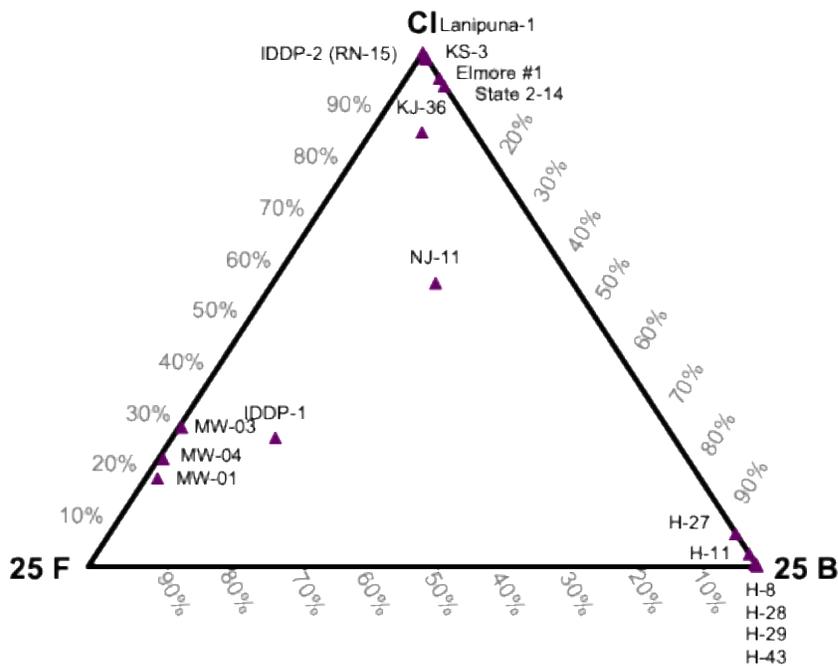


Figure 5: Cl-F-B ternary plot for wells from Puna (Hawai'i), Salton Sea (California), Los Humeros (Mexico), and Iceland based on Giggenbach (1991).

The Cl-F-B ternary plot (Figure 5) reveals distinct concentrations for Los Humeros with a high B content (see Schill et al., this issue). The Menengai fluid samples and the IDDP-1 well share a high F concentration. The spread toward the F- and B-rich fields indicates chemical modification possibly during ascent, indicating that even fluids sourced from >350 °C reservoirs can display diverse halogen and metalloid signatures that primarily record upflow and degassing processes rather than reservoir temperature itself. The clustering toward the Cl apex reflects fluids dominated by deep, high-salinity reservoir components, consistent with magmatic or connate fluid influence typical of very high-temperature geothermal systems.

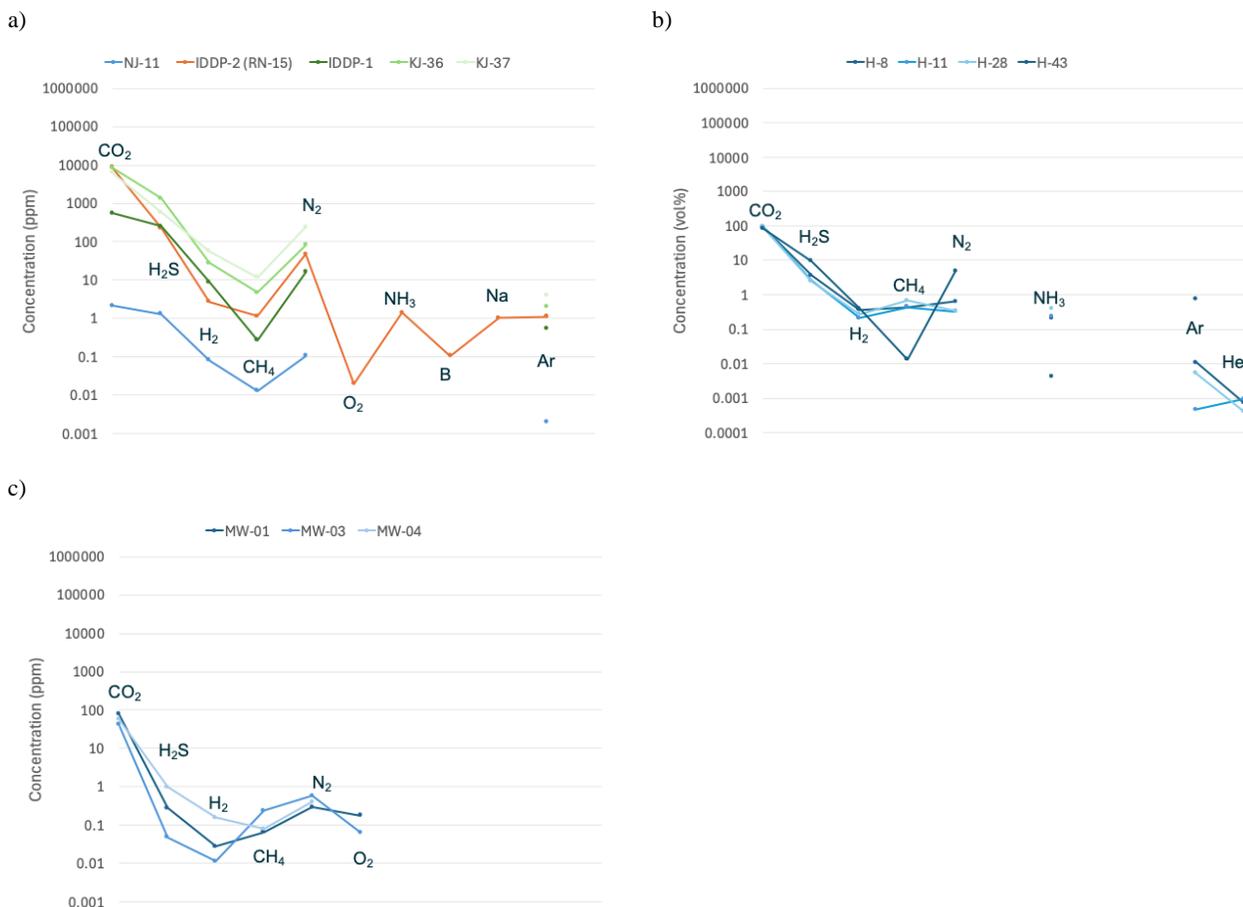
4. GEOTHERMOMETRY

The evaluation of the different ternary diagrams indicates mature fluids for the wells Lanipuna-1 and KS-3 (Hawai'i), Elmore #1 and State 2-14 (Salton Sea, CA), IDDP-2 and KJ-36 (Iceland), and Mofette-005 (Italy). For mature waters, several cation geothermometers yield temperature estimates that are close to the minimum reservoir temperatures. Note that quartz geothermometers generally underestimate the minimum reservoir temperature by about 100-300 °C. Except for Elmore #1, also the two Mg-bearing geothermometers systematically underestimate these minimum temperatures. The closest and most consistent agreement is obtained using the Na/K geothermometer of Tonani (1980). Together, these results support the inference from the ternary diagrams that fluids derived from reservoirs hotter than ~350 °C commonly record the effects of upflow and degassing, rather than faithfully preserving the original reservoir temperature.

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4. GAS COMPOSITIONS

Supercritical geothermal fluids commonly contain elevated concentrations of dissolved and free gases (Giggenbach, 1997; Arnórsson et al., 2007) reaching a few vol% in the wells that we investigated (Figure 6). CO₂ is typically the dominant gas phase and exceeds 95 vol% in Los Humeros (Mexico), Menengai (Kenya), and Salton Sea (California) vapor phases. H₂S is the second most abundant gas with concentrations in a similar range in Iceland (except IDDP-2), Puna (Hawai'i) and even exceeding the concentration of CO₂ in the well KS-3 in Puna. H₂, CH₄, and N₂ are also observed.



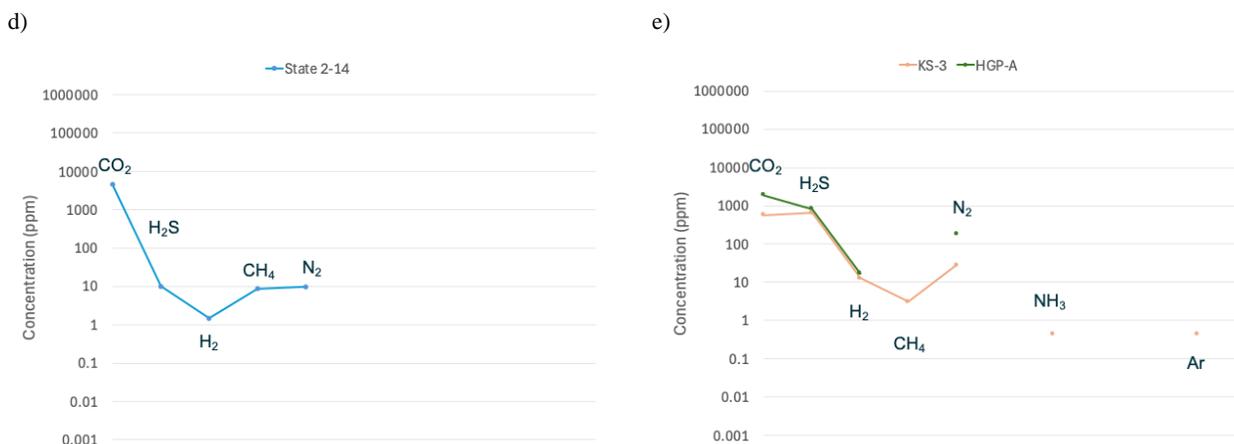


Figure 6: Gas concentration of the vapor phase from the sub- to supercritical wells of a) Iceland, b) Mexico, c) Kenya, d) California (Salton Sea) and e) Hawai'i (Puna).

5. DISCUSSION AND COMPARISON TO THE NEWBERRY EGS SITE

Mature water conditions are indicated in several wells by alkaline pH, high chloride concentrations, and/or low Mg combined with elevated Na + K concentrations. These fluids commonly originate in high-temperature reservoirs, including near- or supercritical systems, even if measured surface pH appears neutral to alkaline. There is no indication for shallow overprinting. These characteristics are observed in wells IDDP-2 (Reykjanes), KJ-36 (Krafla), NJ-11 (Nesjavellir), MW-01, MW-03, and MW-04 (Menengai), Mofete-005 (Italy), Lanipuna-1 and KS-3 (Puna), as well as State 2-14 and Elmore #1 (Salton Sea). Notably, in Elmore #1, despite comparatively high Cl concentrations, the combination of low pH (< 5) and elevated SO₄ concentrations indicates a more acidic fluid signature.

More acidic conditions, typically associated with steam-heated waters and the oxidation of H₂S to SO₄, indicate fluids that are generally decoupled from the deep reservoir and strongly influenced by near-surface processes. Low pH values therefore reflect gas–water interaction and vapor condensation rather than primary reservoir chemistry. Such acidic conditions are linked to elevated corrosion risk and increased sulfate scaling potential. Within our database, fluids from Krafla and the Salton Sea provide representative examples of these processes. Although pH is a critical parameter for materials selection, it must be interpreted in conjunction with gas chemistry and mineral saturation indices.

The Supercritical Drilling Material Analysis (Kibikas et al., 2026) aims at supporting the development of such fluid condition in the United States. Recently, the technical feasibility of EGS at subcritical temperatures, which is important for creating supercritical systematic EGS, was demonstrated in 2025 at a pilot site at Newberry Volcano, Oregon, USA (Grubac et al., 2025). This pilot involves two deviated wells to a depth of 3,100m. After propped hydraulic stimulation of both wells, initial circulation and diagnostic testing confirmed strong hydraulic communication and stable fluid flow within the engineered reservoir, which reached temperatures of approximately 331 °C (Schill et al., 2026). Chemically, the site has been characterized in the 932m deep Newberry-2 well with a bottom hole temperature of 265 °C during a 20-hour flow test between September 29 and 30, 1981 (Ingebritsen et al., 1986). The fluid entering the bottom of the wellbore was largely or entirely steam and CO₂ and is therefore very diluted and not representative of a geothermal brine from this.

The major element concentrations reported for Newberry 2 are generally lower than those observed in most wells included in the comparative database, indicating a relatively dilute fluid composition. Carothers et al. (1987) note that the very low silica concentrations and water isotope values of water produced during the flow test indicate that the aqueous fluid produced from the borehole was almost all water vapor. The non-condensable gas phase is strongly dominated by CO₂, which reaches nearly 95 vol%, while H₂S is the second most abundant gas, with concentrations of approximately 1.8 vol%. Minor gas species occur at much lower abundances. This gas composition points to significant volatile partitioning and degassing, consistent with upflow and phase separation processes rather than direct sampling of reservoir fluids.

To identify optimal geothermal analogues for the Newberry EGS project and to better constrain material requirements, additional detailed fluid chemistry analyses, including both gas and aqueous components, are required.

6. CONCLUSION

The compiled database includes fluid-chemistry data from 25 wells in geothermal fields where temperatures exceed 350 °C, spanning sites in Iceland, Mexico, Kenya, Italy, Greece, and the United States. Although data completeness and charge balance vary among fields, the dataset captures a broad range of chemical conditions characteristic of near- and supercritical geothermal systems. Mature reservoir fluids are identified by alkaline pH, high chloride concentrations, and low Mg with elevated Na + K, reflecting extensive water–rock interaction at high temperatures and minimal shallow overprinting. These conditions are observed across multiple fields, indicating common deep-reservoir processes despite differing geological settings. In contrast, acidic fluids with elevated sulfate record steam heating, gas–water interaction, and vapor condensation, and are decoupled from primary reservoir chemistry. Such fluids pose increased corrosion

and scaling risks and therefore have critical implications for well construction materials. The gap in information on the fluid chemistry of the Newberry wells underscores the need for integrated gas and aqueous geochemical analyses to identify appropriate analogues and to guide materials selection for future supercritical EGS development.

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