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Supercritical and Superhot Geothermal Resources - Some Fundamental Insights

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ABSTRACT

Both wells drilled so far by the Iceland Deep Drilling Project (IDDP) encountered supercritical fluid conditions. There is evidence that if such resources could be exploited routinely, power output per well may be several times higher than from conventional wells drilled into high-enthalpy fields. Until recently, however, supercritical resources have remained poorly understood: little was known about the possible abundance, structure, and how they link to overlying high-enthalpy systems. Also, there exists confusion about the terminology with the terms "supercritical", "superheated", and "superhot" being used. From a thermodynamic perspective, the suggested differences between "supercritical" and "superheated" are semantic rather than physical as fluid properties vary continuously with pressure and temperature, no phase boundaries exist, and any definitions are essentially arbitrary.

The main part of this contributions reviews findings of the Swiss-funded COTHERM project and related insights that were obtained in the period 2013-2018. As a fundamental finding, advanced numerical modelling suggested that supercritical resources may be an integral part of many natural high-enthalpy geothermal fields with host rock lithology and/or strain rate determining if the supercritical resource is permeable. Basaltic rocks and elevated strain rates favor a higher brittle to ductile transition temperature, allowing geothermal fluids to access hotter rock. In saline systems, intrusion depth is a major control on whether an economically attractive resource can be encountered. This is due to the phase diagram of saltwater: deeper intrusions favor development of a superhot, dry steam zone below about 4.5 km while shallower intrusions favor the development of a highly saline, low-mobility brine layer. In terms of fluid chemistry it is important to realize that due to its low density and dielectric constant, supercritical water is a weak solvent and that possibly corrosive agents (e.g., HCl) will likely have little corrosion or scaling potential at depth. This changes drastically if the supercritical fluid gets mixed with subcritical water in either wells or the periphery of natural high-enthalpy plumes. Hence, the occurrence of wells with drastically different corrosion characteristics in the same geothermal field can be explained without any need for complex subsurface processes.

Key future research directions will be on the controls of temperature, strain rates and stress on permeability of hot rocks; on experimental studies of chemical fluid-rock interaction under supercritical conditions; and on eventually deriving a thermodynamic formalism that is able to accurately describe the properties of solutes in supercritical water under reservoir conditions.

1. INTRODUCTION

The magmatic heat sources that drive conventional high-enthalpy geothermal systems have temperatures between ca. 800 °C and 1200 °C while the exploited resource rarely exceeds 300 °C. The potential for hotter ("supercritical") resources below conventional high-enthalpy systems and at temperature in between these values has been demonstrated by the Iceland Deep Drilling Project IDDP, which drilled two wells and encountered supercritical conditions in both cases (up to 450 °C at well IDDP-1 at Krafla, and possibly as high as >550 °C IDDP-2 at Reykjanes).

While this great success has demonstrated the potential but also revealed the technical challenges for future exploitation of such resources, a series of fundamental questions such as the controls on the occurrence, extent and physical state of such resources as well as about the nature their connection to overlying, high-enthalpy systems have gained relevance. Answering these question would be advantageous for developing smart exploration, reservoir engineering and utilization strategies. In the Swiss SNF-funded COTHERM (2012-2017) project with partners from ETH Zürich, Paul Scherrer Institute, and the University of Iceland, and in collaboration with the Icelandic Deep Roots of Geothermal Systems (DRG), the IDDP, and the European FP7 project IMAGE, a number of these questions were investigated. The studies were done mostly by numerical modelling but also involved geological, geophysical, and geochemical studies of exposed fossil geothermal systems, geochemical studies of fluids from active systems, petrophysical characterization of reservoir rocks, and the cross-disciplinary integration of these approaches.

1.1 Terminology: "Supercritical" vs. "Superheated" vs. "Superhot"

Considerable confusion exists about the correct naming of the fluid's state in these resources. As IDDP-1 fluid pressures were lower than the critical pressure of water and temperature higher than the critical temperature, some preferred the term "superheated", indicating that at these conditions water can be considered a low-density dry steam at temperatures higher than the boiling temperature[1]. While this is permissible, such distinctions based on temperature and pressure become impracticable and essentially semantic when looking at the possible range of conditions: Figure 1 illustrates, at the example of density, the fundamental feature that water properties in the "supercritical" region vary continuously. Crossing the critical pressure (ca. 22 MPa for water) at supercritical temperatures does not change the nature of the fluid and a distinction between "superheated steam" below the critical isobar and "supercritical fluid" above is of little - if any - thermodynamic sense. Equally, the isochoric (equal density) path of a

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[1] In this contribution, the terms "dry steam" and "vapor" are used synonymously as they typically denote the same fluids but reflect the preferences of different scientific and technical communities.

"superheated steam" would cross the critical isobar upon temperature increase and would then have to be re-labelled "supercritical fluid" although essentially no important changes in properties happen.

A common way around this naming dilemma is to call fluids "supercritical" if their temperature is higher than the critical temperature (i.e., ca. 374 °C for water) and then, depending on whether their density is higher or lower than the critical density (322 kg m^{-3} for water) to add either "liquid-like" or "vapor-like" (Heinrich and Williams-Jones, 2005). Although this pragmatic approach isn't perfect (e.g., do we really see water at 400 kg m^{-3} as a "liquid-like" fluid?) is offers an unambiguous distinction based on a relevant physical property of (nearly) pure fluids.

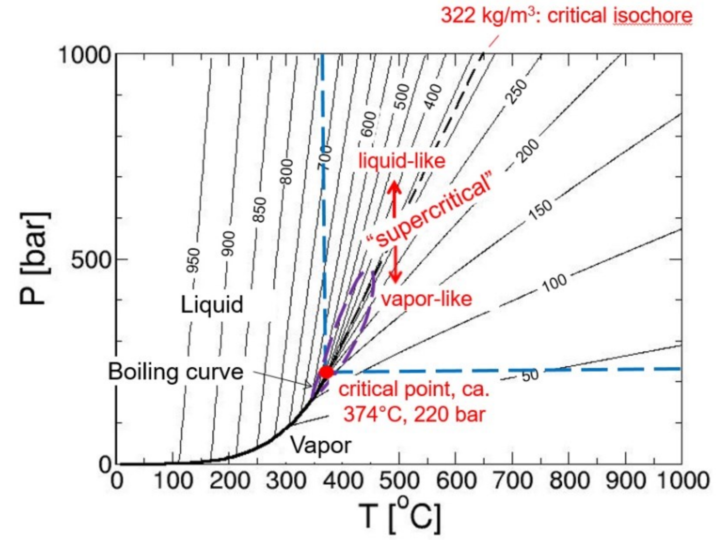

Figure 1. Temperature-pressure diagram showing the variation of water density (black lines, numbers denote density in kg m^{-3}) across the phase diagram. Dashed blue lines represent the critical temperature and pressure; isochores cross-cut these smoothly, implying that a definition of "supercritical" based on these two values is an arbitrary choice. The purple dashed line represents a definition of a "near- and supercritical" region based on the "anomalous" compressibility of water under these conditions.

However, things get more complicated if the fluid is not (nearly) pure water. For example, adding salt to water will greatly enhance the range of liquid+vapor coexistence (e.g., Driesner & Heinrich, 2007): heating single-phase saltwater with 5 mass% NaCl from subcritical temperature and at a pressure 1 MPa higher than the critical pressure for water, will induce boiling upon at ca. 381°C and at ca. 436°C halite (solid NaCl) will start to precipitate and the last liquid will boil off before the fluid enters a field of halite-saturated dry steam plus halite; i.e., instead of entering a region of a homogeneous physical state with gradually changing properties, just the opposite happens. Calling this temperature-pressure-composition region "supercritical" violates the original meaning of "supercritical" as it was developed for single-component fluids. And things get increasingly more complicated the more components the fluid contains. There is no easy route out of this dilemma.

These complications also propagate into economic assessments, exploration strategies, and reservoir engineering. The attractiveness of these resources stems from the fluid's high enthalpy combined with low viscosity and the single-phase status. In an enthalpy-pressure-composition diagram of the model system H_2O-NaCl, it becomes clear that such conditions are restricted to certain parts of the diagram, namely relatively low salinities. The addition of other salts will make the situation much more complicated (likely expanding the regions of multiphase conditions) so that exploration should favorably focus on systems with dominantly meteoric water. However, in lucky circumstances (such as possibly IDDP-2), the dry steam +salt(s) region of the phase diagram may be encountered, which can be a potentially attractive resource. Scott et al. (2017) demonstrated that the combination of multiphase flow physics and the effects of fluid phase relations can lead to very specific scenarios in which such resources can be expected (see Section 2.3).

In summary, these resources should best be called either "supercritical" or "superhot" with the implicit assumption that this is a pragmatic working term that cannot uniquely be defined based on physical criteria.

1.2 Enthalpy in supercritical systems

The two IDDP wells were drilled into systems with very different geothermal fluids. While IDDP-1 at Krafla encountered dilute aqueous fluid of meteoric origin and can essentially be understood in terms of the properties of pure water, the fluid in the Reykjanes system with IDDP-2 is dominantly seawater and assessment of the fluid state and properties as well as its energetic potential requires understanding the phase relations of salty water. A complete model for the relevant conditions is currently only available for the model system H_2O-NaCl and further complications can be expected when additional salts would be added. Figure 2A shows how the location of the various phase regions of the H_2O-NaCl system in enthalpy-concentration-pressure space.

The most prominent feature in Figure 2A is the large volume of liquid+vapor coexistence, as enveloped by the black mesh surface. Any fluid inside this volume will be in this two-phase state with a low-salinity, low-density vapor on the surface left of the critical curve, coexisting with a higher salinity liquid on the surface part to the right, at the respective temperature and pressure. As a rule of thumb, vapor-like fluids are higher enthalpy than the coexisting liquid, less saline, and more mobile.

Figure 2B shows how the temperature-pressure-enthalpy relations for pure water plot onto the diagram. The red lines are the well-known isotherms in an enthalpy-pressure diagram as frequently used in geothermal studies. Also displayed are three representative isothermal surfaces in the single-phase region, at 300 °C, 400 °C, and 600 °C. It is obvious from the geometry of these surfaces that producing any single-phase fluid with considerable salinity (from above the liquid+vapor surface) would likely lead to salt precipitation in the well and/or surface installations in response to pressure lowering. The effect will be reduced for vapor-like fluids with low salinities, for which it may potentially be mitigated by adequate reservoir engineering practices.

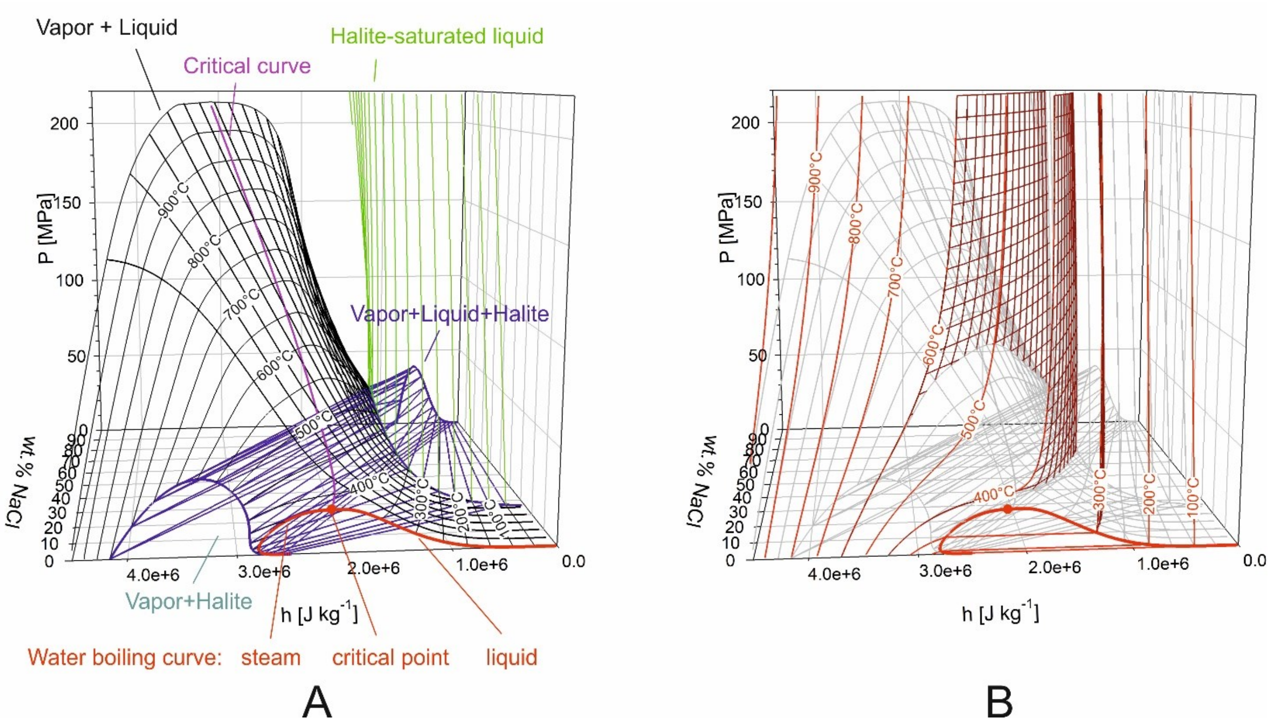

Figure 2. Enthalpy-Temperature-Pressure-Salinity relations in the system H_2O-NaCl a computed from the correlations of Driesner & Heinrich (2007) and Driesner (2007). A. Relations for the different phase states; notice that pure water denotes the front side of the diagram and temperature values only refer to the vapor+liquid coexistence surface. B. Isotherms for water (single red lines) on the same diagram and composition dependence in the single-phase region for three selected temperatures (300 °C, 400 °C, and 600 °C, dark red meshes).

2. LESSONS LEARNED FROM ADVANCED NUMERICAL MODELLING OF SUPERCRITICAL RESOURCES

2.1 Geologic controls on supercritical resource formation

The prime geologic control on the formation of supercritical resources is the temperature dependence of permeability (Scott et al., 2015). As already highlighted by Fournier (1991) and Hayba & Ingebritsen (1997), permeability will greatly be reduced when rocks become ductile. For quartz-rich rocks this may commece at temperatures as low as 360 °C. In simple words, if a rock is tight at temperatures that are supercritical in terms of the phase relations of water, there will be no exploitable supercritical resource and the ductile nature of the rock will likely by a strong challenge to EGS-type techniques.

Sufficient permeability at supercritical temperatures can be achieved in two types of settings: in quartz-poor rocks such as basalt (the major host rock in Iceland), for which ductile behavior may start only above 500 °C and even higher, or in settings with active tectonic extension where strain rates and stress orientation may favor the continuous re-creation of permeability even in rocks that would be nominally ductile and impermeable in other settings (Watanabe et al., 2017). As many regions with high-enthalpy resources are located in such settings, the occurrence of supercritical resources beneath these conventional fields may be quite common.

The results of Scott et al. (2015) imply that the volume of supercritical resources may be largest in systems with an intermediate permeability (around 10^{-15} m^2) and quite restricted at a permeability of 10^{-15} m^2. The reason is the stronger cooling effect of cooler groundwater more rapidly being entrained into the convection in the higher permeability case. However, under those conditions, higher inflow rates can be expected upon production. The effects of heterogeneous permeability distribution, and, namely, the role of major fracture zones has so far remained unexplored.

Intrusion depth may play a significant role in determining the potential economics of a supercritical resource. As it is apparent from Figure 2B, at supercritical temperatures below ca. 450 °C there is a significant pressure dependence of the enthalpy at a given temperature, i.e., deeper intrusions - unlike in the case of saline systems, see section 2.3, may be less favorable. This, however, would need a careful and site-specific evaluation as different flow patterns may counteract this seemingly obvious conclusion (Scott et al., 2015).

In general, future exploration strategies for locating supercritical resources will have to take such findings into account, and further developing numerical simulation methods that can adequately model the physics of the system and are informed by geologic observations and conceptual thinking will be a key method for reduced risk in targeting.

2.2 The link to conventional high-enthalpy resources

The current state of knowledge is that supercritical resources form just above the magmatic heat source that drives conventional high-enthalpy systems and are actually the deeper part of the high-enthalpy resource. The great difference in natural enthalpy (~3 MJ/kg in the supercritical part vs. 1.x MJ/kg in the high-enthalpy resource), however, is not immediately understood as it is commonly assumed that the natural convective upflow in geothermal systems is nearly isenthalpic. Initial ideas, e.g., at the IDDP workshop in 2012 (Elders et al, 2012) therefore speculated whether the two resource types represent two discrete convection systems, possibly separated by an impermeable zone at depth.

The simulations of Scott et al. (2015, 2016), however, demonstrated that the convective upflow is likely not isenthalpic at all. The supercritical zone is the hottest part of an overall convective system, typically re-charged by meteoric water. By labelling water that passed the supercritical zone with a virtual tracer, Scott et al. (2015) demonstrated that significant mixing with cooler circulating groundwater (that did not reach the deepest part of the convection), the enthalpy content of the geothermal water gets diluted and reduced (Figure 3) and the degree of dilution is a function of the system's bulk permeability - the higher the permeability the stronger the dilution and the cooler the system.

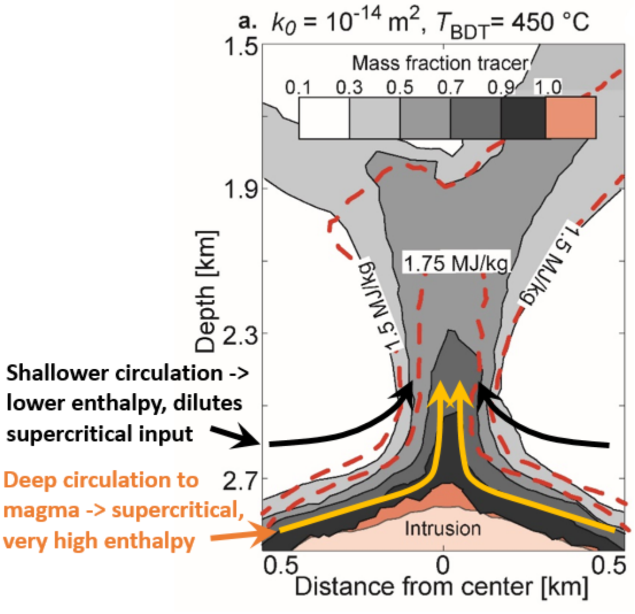

Figure 3. Conceptual representation of the deep link between supercritical and conventional resources, modified from Scott et al. (2015). Just above the magmatic intrusion, a small supercritical resource is formed in a system with high permeability (10^{-14} m^2) and a permeability reduction due to rock ductile behavior above 450 °C. The buoyantly rising, very high enthalpy fluid from the supercritical resource is diluted and cooled by cooler meteoric water that also is part of the convective system but didn't reach the magma body.

This finding has major implications for understanding conventional high-enthalpy resources and for designing the possible future utilization of the underlying supercritical resource:

- Supercritical water buoyantly rising from the supercritical resource appears to be the major heat transferring agent towards the conventional geothermal system, i.e., both resources are hydraulically well connected.
- This implies that direct production from the supercritical resource would likely reduce the natural heat recharge of the conventional system. As most systems produce at much higher rates than the natural recharge the effect may be not of immediate impact on the sustainability of the high-enthalpy resource but it is recommended that the possibility of such an effect should be studied.
- If, on the other hand, wells into the supercritical resource would be used as injectors, it is likely that an enhanced recharge of the high-enthalpy zone may happen. The consequences of such an enhanced recharge on possibly increasing production or lifetime have not yet been studied.

These implications should further be tested by enhanced numerical modeling and testing against observations at the IDDP wells. the upcoming IDDP-3 well in the Hengill-Nesjavellir area has been chosen to pursue this route already during the exploration phase.

2.3 How the complexity of saline fluid phase relations affects the development of economically attractive resources

The IDDP-2 well was drilled into the saline Reykjanes system. The possible implications of the salinity on the systems thermo-hydraulic nature and the possibly complex phase relations encountered along the different flow-paths in the system were studied by Scott et al. (2017), already prior to the drilling of IDDP-2. Indeed, the combination of flow physics and fluid phase relations and properties turned out to be a major control on these systems.

The key finding is that depending on the depth of the magmatic heat source, downward circulating seawater will hit the liquid+vapor surface on different sides with drastically different implications for geothermal hydrology:

- For a shallow intrusion and accordingly low pressures, the downward circulating seawater will intersect the liquid side of that surface (to the right of the pink critical curve in Figure 2) and start boiling. The consequence is an increase in salinity and decrease in mobility of the liquid while the relatively small amount of mobile vapor is buoyantly removed; eventually a layer of dense, high-salinity brine will develop above the magma intrusion, limiting convective heat transfer and rendering the resource economically unattractive.
- For deep intrusions (> ca. 4 km) downward circulating seawater will be heated at higher pressures, allowing it to hit the liquid+vapor surface to the left of the critical curve, on the vapor side. It will condense out small amounts of saline brine but can rise as a very high enthalpy vapor-like fluid and feed the overlying, high-enthalpy parts. No significant brine layer evolves and these systems seem to be energetically attractive. Apparently, IDDP-2 encountered such a situation with a deep heat source.

2.4 Chemical variability in high enthalpy fluids within a single field reflects flow paths in the supercritical part

Similar principles of how different paths through the phase diagram affect fluid physics and chemistry also explains previously enigmatic findings that different wells in the same field may have drastically different corrosive nature of the fluids. E.g., at Krafla, fluids from "acid wells" have ambient temperature pH of 2-3 and are highly corrosive while other wells do not have such extreme fluids at all.

Heřmanská et al. (2019) have shown how this difference results from different flow paths within the system. Downward circulating groundwater that reaches the immediate vicinity of the magma can lose most of its non-volatile dissolved mineral components when it reaches a vapor-like density. However, most of the volatile (and potentially corrosive) components remain. Under supercritical conditions these components are associated, neutral species with little corrosion potential. However, if this fluid rises and encounters tow-phase conditions, it can condense out liquid that is enriched in these acid components and different processes may accumulate such condensate, depending on the exact position in the flow field.

Further integration of such chemical modeling with the numerical simulation of fluid flow (Sections 2.1 to 2.3) would potentially allow predicting, at least qualitatively, the systematics of such corrosion potential in a given field. However, a lack of a formalism to model supercritical thermodynamics and to link it to existing subcritical modeling currently severely hampers such efforts.

3. CURRENT CHALLENGES AND LACKS OF UNDERSTANDING

While well and flow tests of IDDP-1 have provided a plethora of relevant data (see Elders et al.,2014), in situ data at depth and drill core have remained scarce. Any deep observational data as well as well tests that have been planned to probe the reservoir with the specific properties of supercritical fluids taken into account will provide most useful constraints. The problems encountered with IDDP-2 highlight the value of analyzing deep core when no probes can be sent downhole. The learning from IDDP-1 and IDDP-2 will likely influence the characterization and monitoring in IDDP-3.

Besides these challenges with the actual wells, a number of very fundamental scientific challenges and knowledge gaps hamper further progress in understanding these systems. If these gaps could be closed, we could likely make major steps forward, clearly much bigger ones than without closing them in my personal opinion, three truly fundamental knowledge gaps exist:

3.1 Understanding permeability of hot rocks

Given the key role of the temperature- (and stress-/strain-) dependence of permeability in controlling the size and nature of supercritical resources, a systematic quantification of these dependencies is the very fundament of understanding supercritical resources. Unfortunately, relevant data have remained very scarce and the nature of porous vs. fracture permeability in nominally ductile rocks under different loads and fluid pressures is difficult to study experimentally.

3.2 Fluid properties in hot rocks

Similarly, very little data (in situ or experimentally) exist on what the chemistry and phase state of fluids at reservoir conditions is. While the phase diagrams in Figure 2 may seem already quite complicated, they are overly simplified when it comes to complex fluids such as seawater interacting with basalt at ca. 600 °C and a few hundred bars as expected at depth in IDDP-2. The chloride in the fluid may liberate cations (e.g., of Fe and Ca) from the rock and the presence of these additional components will "smear out" the sharp boundary between the liquid+vapor and vapor+salt predicted from simulations invoking the H_2O-NaCl model system. Understanding such effects requires a comprehensive experimental campaign, which would be very high value to any further studies.

3.3 The lack of a formalism to accurately describe supercritical fluid thermodynamics

Even worse: even if such experimental data on supercritical fluids were available, we currently lack a formalism that allows an accurate and reliable description of salts, gases, etc. in supercritical fluids and that would smoothly link to the existing formalisms for subcritical fluids.

This is due to a fundamental conceptual drawback in existing equations of state such as the widely used HKF model: its theoretical basis is "by design" unsuitable to deal with the chemistry in aqueous, high temperature fluids with densities below 0.35 g/cm3 (and, more realistically, even below 0.5), i.e., exactly those found in supercritical geothermal resources (Figure 4). This is because HKF's fundament (the Born theory of electrolytes) assumes water to be an incompressible, homogeneous, dielectric medium, an assumption that breaks down in under supercritical geothermal resources conditions where water is highly compressible and where the solvent water structure around solute molecules and ions is dramatically different from bulk solvent water (e.g., Driesner, 2013).

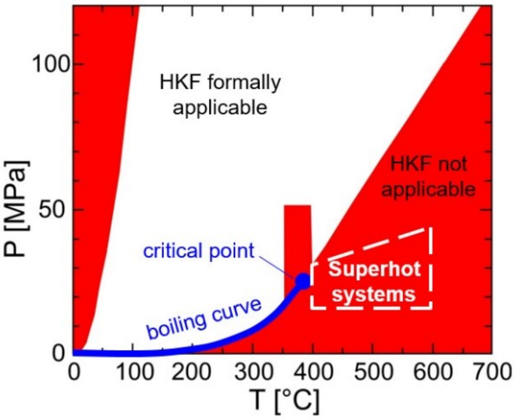

Figure 4. Range of applicability (white area) of the widely used HKF model for geofluid thermodynamics.

Without such a formalism we will not be able to correctly model and predict the chemical evolution of geothermal fluids as they circulate through the deep parts of geothermal systems. It should be strongly emphasized that this is not a question of finding the right modeling software, it is a fundamental lack of having equations that can be implemented in the modeling softwares.

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