Deep geothermal fluid resources: Energetic use and beyond

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Abstract

Unlike countries with or close to volcanic areas, Germany is not blessed with high temperature geothermal resources at shallow depths. However, also there deep geothermal energy can yield a significant contribution to the future renewable energy mix once a number of scientific and technical challenges have been overcome. Apart from improved exploration strategies required to drill into productive reservoirs these challenges predominantly relate to characterizing and appropriately handling the energetic resource itself, the geothermal fluid. This fluid, rarely, is simply pure water but rather a compositionally complex aqueous solution containing various dissolved solid and gaseous species at high concentrations that can range up to 300 g/L and several Nm^3, respectively. Consequently, a number of fluid-rock-materials interactions may occur when hot fluids are produced from the reservoir, their heat is extracted at the surface, and the cooled fluids are injected back into the formation during a geothermal energy cycle. In this contribution these interactions, the related physico-chemical processes, and ways to control these will be reviewed. Also, it will be discussed to what extent the fluid is valuable beyond heat energy as it relates to the dissolved elements and compounds it contains.

Introduction

The earth's heat content, with a share of approximately 20:80, originates (1) from times when the earth was formed by compaction of dust during planetary accretion and (2) by decay of radioactive isotopes. Heat from the interior is transported towards the earth's surface by conduction and convection processes. This heat can be energetically used by technical means.

The use of geothermal energy for electricity generation has gained increasing interest due to the political goals of reducing greenhouse gas emissions, reducing the consumption of finite energy resources, and increasing sustainability of energy supply. Geothermal power plants generate power from an alternative source of energy that is independent of season and time of day and offers a significant potential at a worldwide scale (e.g. Goldstein et al., 2011). Only a small part of this huge potential is currently being used. The globally installed electrical power in 2011 summed up to about 11 GW (Goldstein et al., 2011). The largest share of this capacity is generated from high-enthalpy or high-temperature geothermal reservoirs that are, geologically, located at exceptionally favorable sites (e.g. Italy and Iceland) with high geothermal gradients (Fig. 1). Less than 1 % of the capacity, but the predominant part of the still unexploited geothermal potential, is located outside these areas and is found in reservoirs of low temperature (typically between 100 and 200°C), at greater depths and with often low natural permeabilities. In Germany (Fig. 2), a typical region with low enthalpy geothermal resources, four geothermal power plants are currently operated and several more are being planned or presently constructed (e.g. Schellschmidt et al., 2010).

For the sustainable and effective exploitation of these reservoirs at least two deep wells, a production and an injection well, are drilled. In order to obtain a sufficient fluid flow from the geothermal reservoir, generally, further technical measures to obtain higher permeabilities need to be undertaken (Enhanced Geothermal System, EGS; Huenges, 2010).
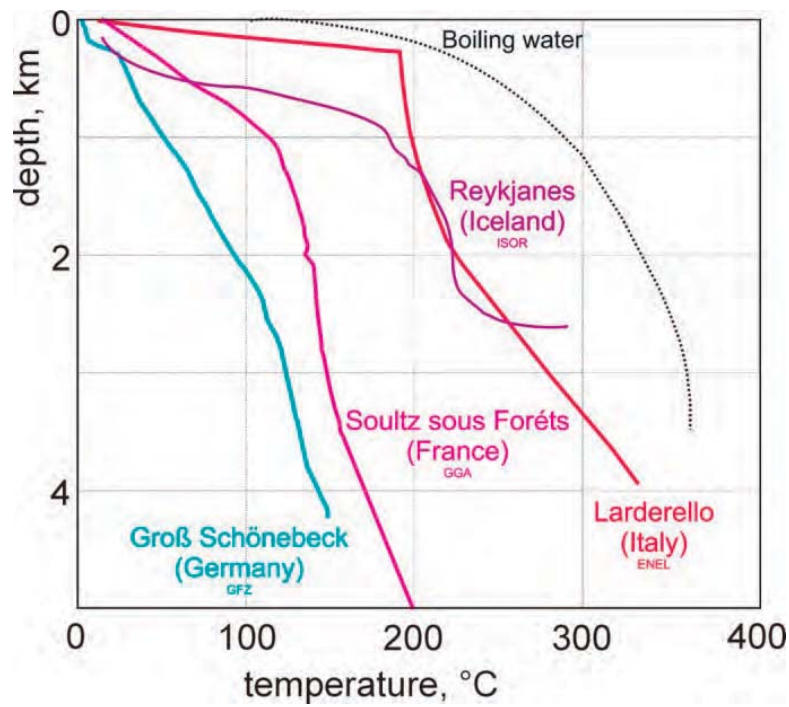
Fig. 1: Comparison of geothermal gradients at four different geothermal sites as examples for low (Germany), medium (France) and high enthalpy (Italy and Iceland) geothermal systems.

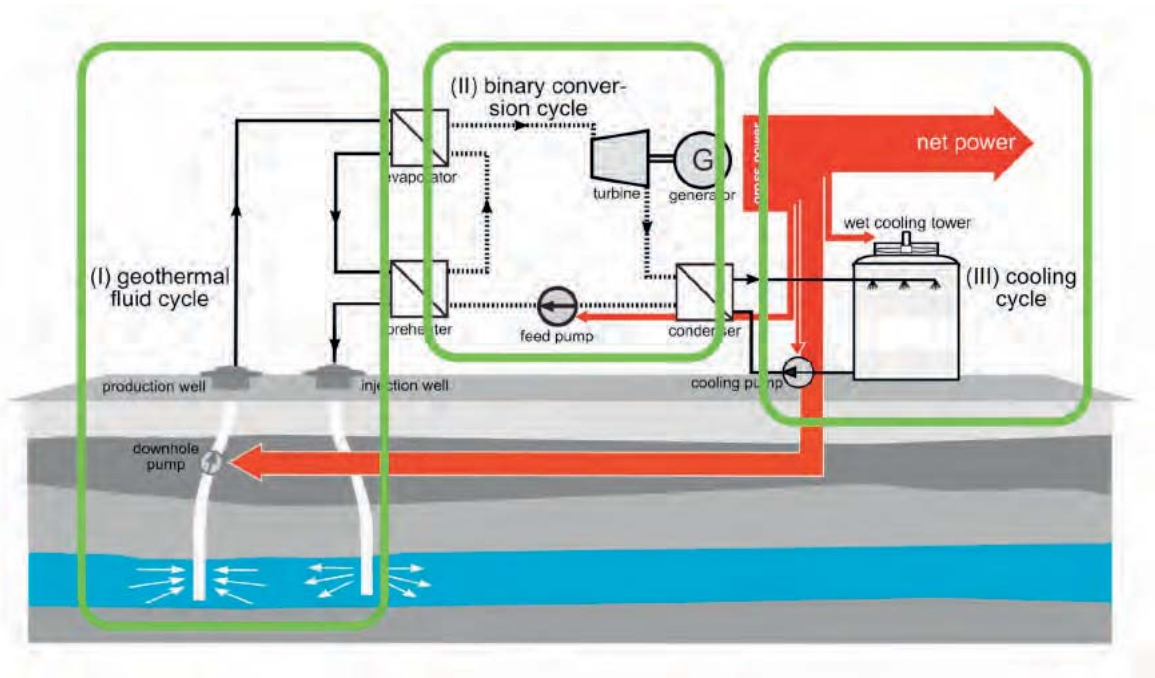*Fig. 2: German regions (orange) with the highest potential for geothermal energy supply.*

Fig. 3: Schematic of a low enthalpy geothermal system with (1) a geothermal fluid cycle, (2) a binary conversion cycle and (3) a cooling cycle.
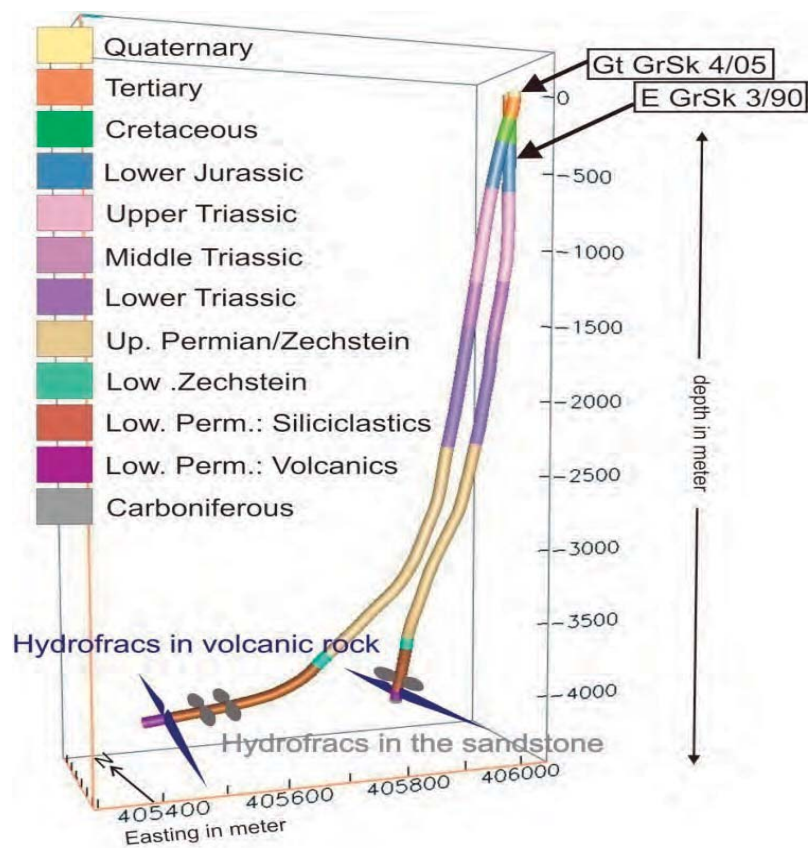

Fig. 4: Stratigraphy at the geothermal research platform Groß Schönebeck showing the well doublet with hydraulic fractures.

During operation, the geothermal fluid is pumped from the geothermal reservoir to the surface. For power generation, part of the heat contained in the geothermal fluid is transferred in a heat exchanger to a so-called binary conversion cycle (Fig. 3). In the binary unit a working fluid with low boiling point is circulated mostly because the direct use of the geothermal fluid in the conversion cycle is not as efficient from a thermodynamic point of view (e.g. DiPippo, 2008). Geothermal fluids can also be used for the supply of heat and chill.

An example of such an EGS-system is the geothermal research platform Groß Schönebeck at approximately 60 km northeast of Berlin, Germany. At this site within the North German Basin (NGB) a geothermal doublet has been installed accessing a Lower Permian sandstone reservoir at approximately 4300 m depth (Fig. 4; Moeck et al., 2009). Within the reservoir section in both wellbores hydraulic stimulation treatments have been performed to enhance productivity (Zimmermann et al., 2010). Reservoir and wellbores were complemented with technical components at the surface (e.g. a gas separator, coarse and fine filters, and an injection pump) as well as an Organic-Rankine-Cycle (ORC) binary power plant (Fig. 5; Frick et al., 2011).

Fig. 5: Surface installations at the geothermal research platform Groß Schönebeck with production well (red), injection well (blue), function hall (rear left) and ORC-plant with cooling towers (rear right).

At reservoir depth the temperature and pressure of the geothermal fluid are approximately 150°C and 45 MPa, respectively. The fluid itself is a highly saline basinal fluid of Na-Ca-Cl type containing 265 g/L of total dissolved solids (Fig. 6a; Regenspurg et al., 2010). Additionally, the fluid contains around 1 Nm^3 of dissolved gases, mainly N_2, CH_4, and CO_2 (Fig. 6b).
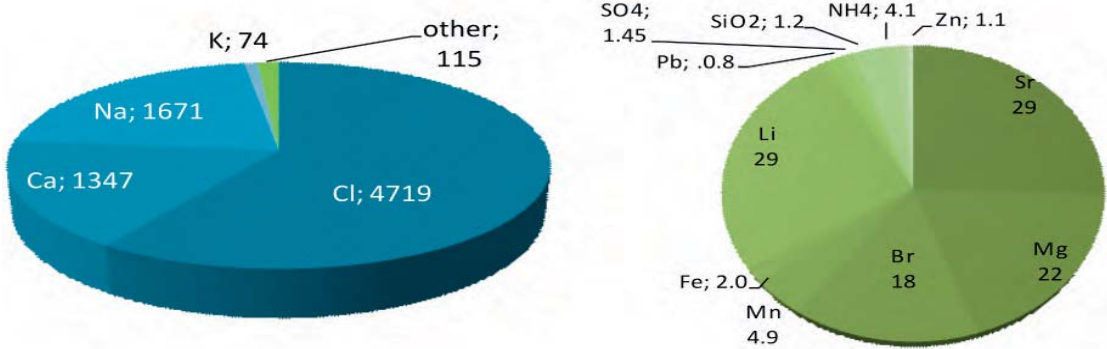

Fig. 6a: Composition of the geothermal fluid (liquid part) at the geothermal research platform Groß Schönebeck.
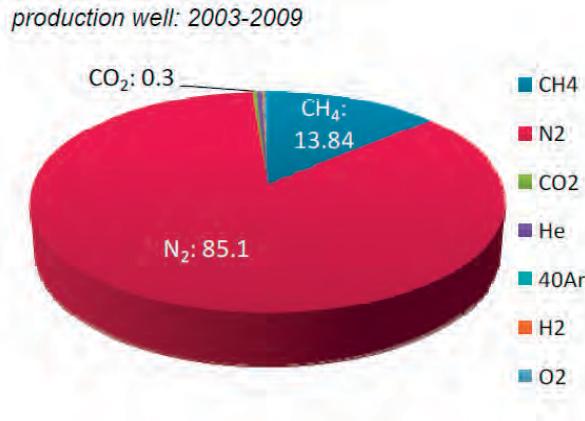
Fig. 6b: Composition of the geothermal fluid (gas phase) at the geothermal research platform Groß Schönebeck.
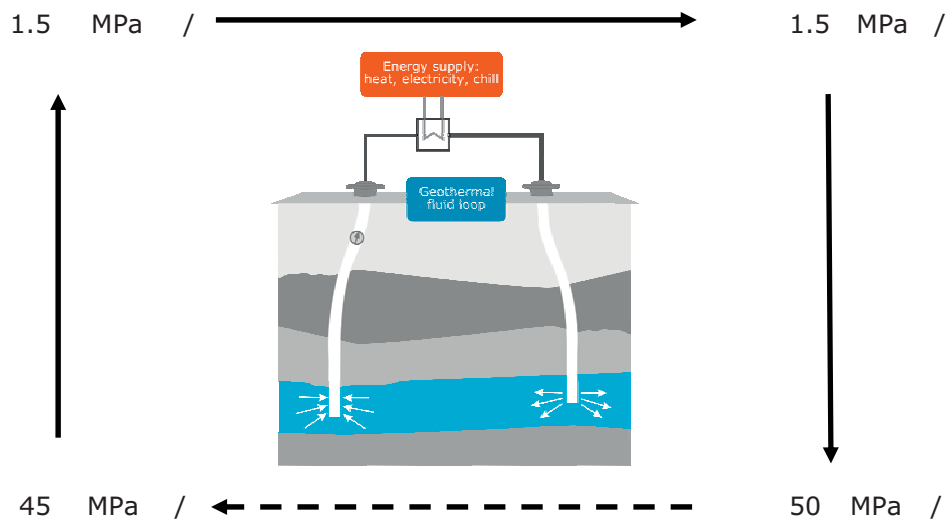

Fig. 7: Pressure and temperature changes during operation of a geothermal water loop.

Operational Risks

During production, heat extraction and reinjection the geothermal fluid undergoes severe changes in its thermodynamic pressure and temperature state (Fig. 7). Depending on the site-dependent fluid composition a number of operational risk processes then might be induced that will be illustrated in the following in relation to geothermal systems in the North German Basin having the highest overall energetic potential at a national level.

Two-phase flow:

Two-phase flow in the reservoir will occur (1) when free gas is present in the formation or (2) when degassing would occur during production as a result of fluid pressure decrease. In both cases the presence of a non-wetting gas phase will decrease the number and size of flow paths available (Fig. 8) and thereby decrease the effective permeability of the rock for flow of the liquid phase. The drastic decrease in relative permeability for the liquid phase, i.e. the ratio between effective permeability and liquid-only permeability, as a function of liquid saturation

is shown in Fig. 9. One notices that relative permeability decreases by approximately 20 % with only 5 vol% of free gas present and even 80 % when the gas content by volume is 20 %. This implies that even small amounts of free gas within the pores of the reservoir rock can significantly affect the productivity of a geothermal system. Gas content of a geothermal fluid at in situ reservoir conditions therefore is a key parameter to be investigated during site assessment.
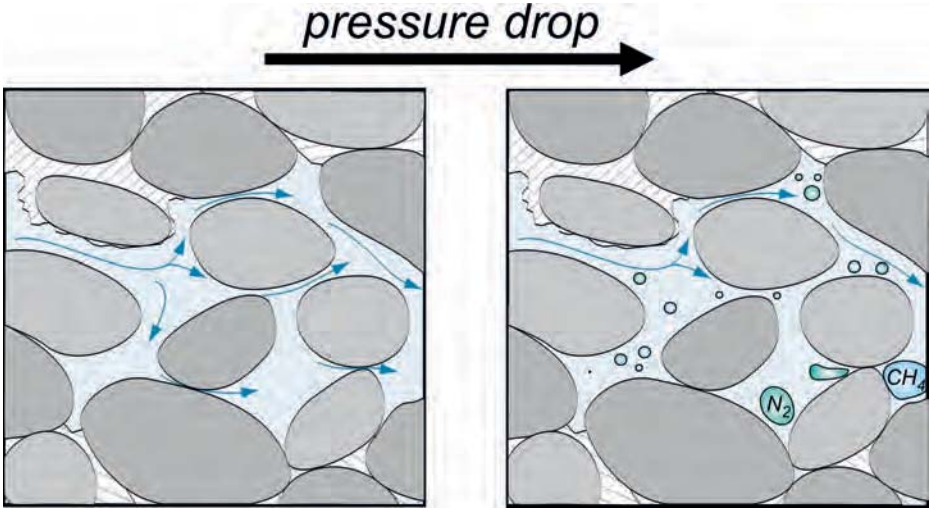

Fig. 8: Schematic of gas exsolution (e.g. N_2 and CH_4) and trapping of gas bubbles in pore throats reducing effective permeability for flow of the liquid phase.
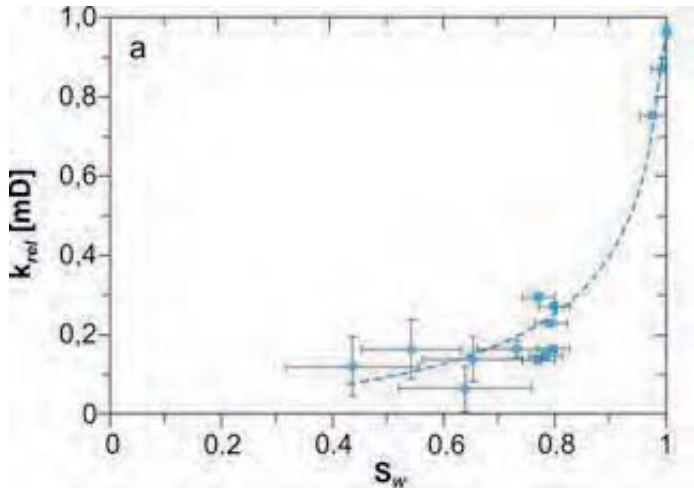

Fig. 9: Relative permeability as a function of liquid phase saturation measured during an experiment with a reservoir sandstone with N_2 as the non-wetting phase.

Redox reactions - well side:

When copper dissolved in a geothermal fluid, either ionic or as chloro-complex, comes into contact with a less noble material, e.g. the iron in a steel casing reinforcing the well, a reduction to native copper and concurrent oxidation of iron may occur as indicated in the chemical reaction equations (1-4) below. Iron ions would then further react with water to form iron hydroxide and/or iron oxide (magnetite). Native copper, having a high density, would not be transported to the surface during operation of the plant but would sediment within the well yielding progressive clogging and decreased reservoir productivity (Fig. 10; Regenspurg et al., 2015).

(1) $Cu^{2+} + 2\,e^- \rightarrow Cu_0$ (Reduction)

(2) $Fe_0 \rightarrow Fe^{2+} + 2\,e^-$ (Oxidation)

(3) $Fe^{2+} + 2\,H_2O \rightarrow Fe(OH)_2 + H_2$

(4) $3\,Fe(OH)_2 \rightarrow Fe_3O_4 + H_2O + 2\,H_2$

Fig. 10: Sediment recovered from the production well at the geothermal research platform Groß Schönebeck containing substantial amounts of native copper.
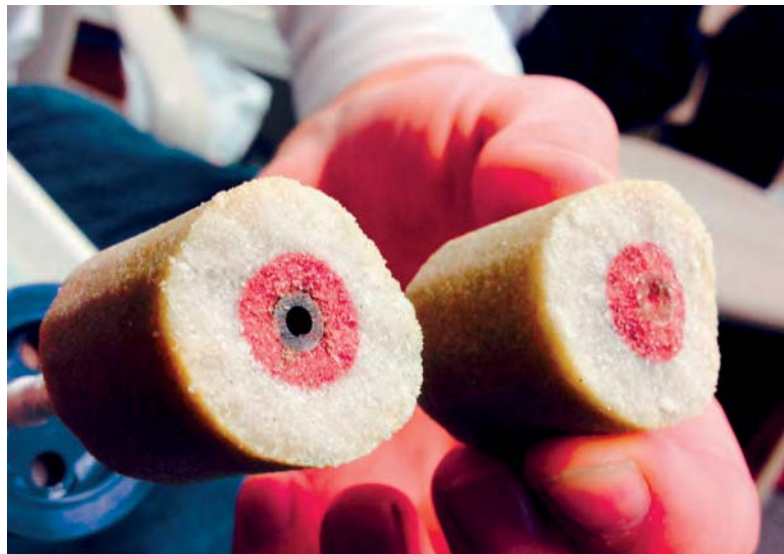

Fig. 11: Copper precipitation (orange rim) in an experimentally simulated rock-casing contact yielding clogging of pores and reservoir damage.

Redox reactions - formation side:

As long as an electrically intact contact between the casing and the fluid exists it can be assumed that the same reactions outlined above would also occur within the formation. The viability of this process has been proven experimentally as shown in Fig. 11. The orange rim within the rock sample consists of copper completely filling the pore space near the wellbore simulated here with a steel capillary. This reduction in pore space available for flow towards the well would significantly reduce the productivity of the reservoir and needs to be addressed by appropriate materials selection as outlined further below.

Temperature-induced precipitation processes:

The solubility of individual minerals within a fluid depends on the overall fluid composition and the pressure and temperature conditions this fluid is subjected to. When pressure and or temperature conditions are changed, e.g. during production or within the heat exchanger of the power plant, minerals dissolved within the fluid may become oversaturated yielding solid substance precipitation (scaling) within plant components interfering with the overall system's functionality. An example of such precipitates (barite, $BaSO_4$ scales) is shown in Fig. 12.

The tendency of a fluid to precipitate a certain mineral for a given ionic concentration of its constituents can be simulated numerically with geochemical programs (e.g. PhreeqC) as illustrated in Fig. 13. The key parameter being calculated is the saturation index (SI), where barite precipitation will occur when SI > 0 as temperature is decreased to below 50°C for a fluid containing Ba^{2+} and SO_4^{2-} ions at concentrations indicated in the figure.
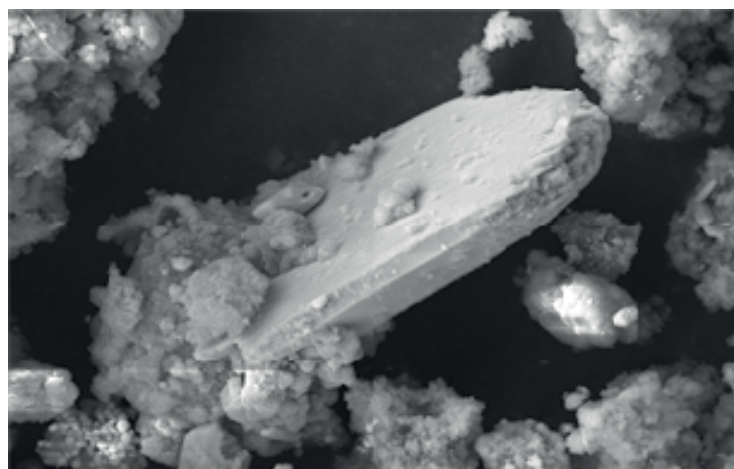

Fig. 12: Barite ($BaSO_4$) crystal found as temperature induced precipitate in a filter bag within the surface installations at the geothermal research platform Groß Schönebeck.
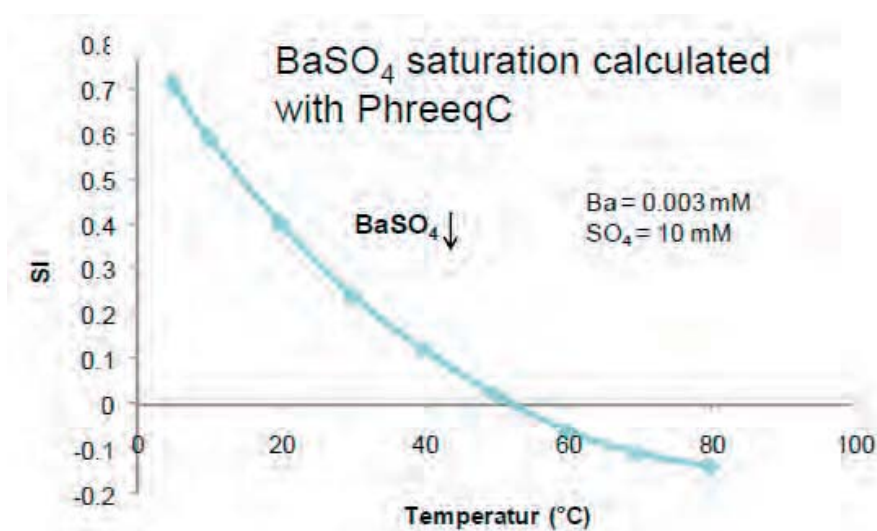

Fig. 13: Saturation index (SI) as a function of temperature simulated for Barite ($BaSO_4$) precipitation with the geochemical program PhreeqC.

Corrosion processes:

Depending on the fluid composition at a particular site and in combination with individual structural designs of plant components the materials used may be subject to a variety of corrosion processes as illustrated in Fig. 14. These may include uniform, pitting and crevice corrosion as well as stress and sulfide stress corrosion cracking rendering a material non-functional. High chloride contents favor corrosion processes and the selection of plant materials has to be made based on economic considerations in dependence on fluid chemistry. It also has to be considered whether a plant component constitutes an integral safety part or if it can be easily replaced.

Pitting corrosion is of particular danger as component failure is difficult to predict. Here, the passivation layer on alloy surfaces normally providing corrosion protection cannot rebuild after local damage and corrosion at these points will be amplified.

Sulfide stress corrosion cracking, as another example, occurs when metals come into contact with H_2S bearing gas which induces metal sulphide formation and liberates H_2 as indicated with the chemical reaction equations (5-7) below. H_2 then diffuses into the metal matrix and reacts with the carbon of a steel alloy producing methane (CH_4). CH_4 molecules finally create pressure within the material which would crack, embrittle and ultimately fail.

$$(5)\ H_2S + Me \rightarrow MeS + 2\ H^+$$

$$(6)\ 2\ H^+ \rightarrow H_2$$

$$(7)\ 2\ H_2 + C \rightarrow CH_4$$
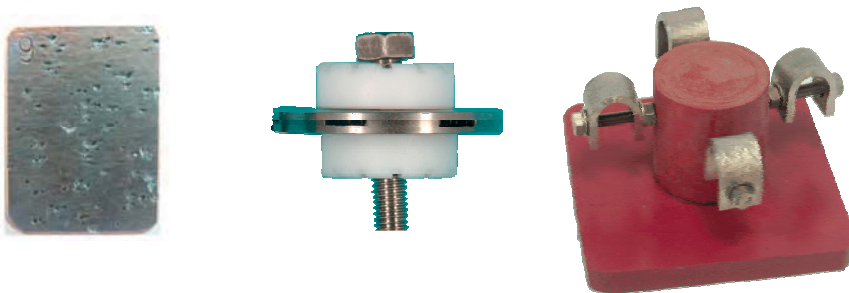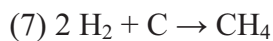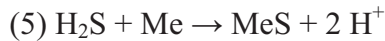
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Fig. 14: Materials samples for corrosion tests symbolizing different types of corrosion processes occurring in technical geothermal plant components: (left) pitting, (center) crevice and (right) stress corrosion.

Dissolution-precipitation reactions:

This type of fluid-rock interaction implies the dissolution of solid mineral material within the reservoir into the geothermal fluid and the precipitation of minerals from the fluid at some other place within the formation. This may yield either a decrease in pore throat diameters and/or an alteration of the mineral surfaces both resulting in a decrease in rock permeability and thus hydraulic reservoir performance. This process would predominantly occur at the injection side of a geothermal doublet system when cooled fluids depleted with respect to specific ionic content are injected into the hot reservoir causing a disturbance of its thermodynamic equilibrium. In laboratory experiments the occurrence and hydraulic consequences of such reactions have been investigated at simulated in situ reservoir conditions (Fig. 15; Schepers et al., 2013a, b). This figure compares mineral surfaces

representing the main constituents of reservoir sandstones (quartz, plagioclase, K-feldspar) before and after alteration. The changes in surface morphology are significant for the plagioclase and K-feldspar minerals. The roughening of the mineral surfaces is directly correlated with a decrease in rock permeability as concurrently evidenced and quantified during these experiments.
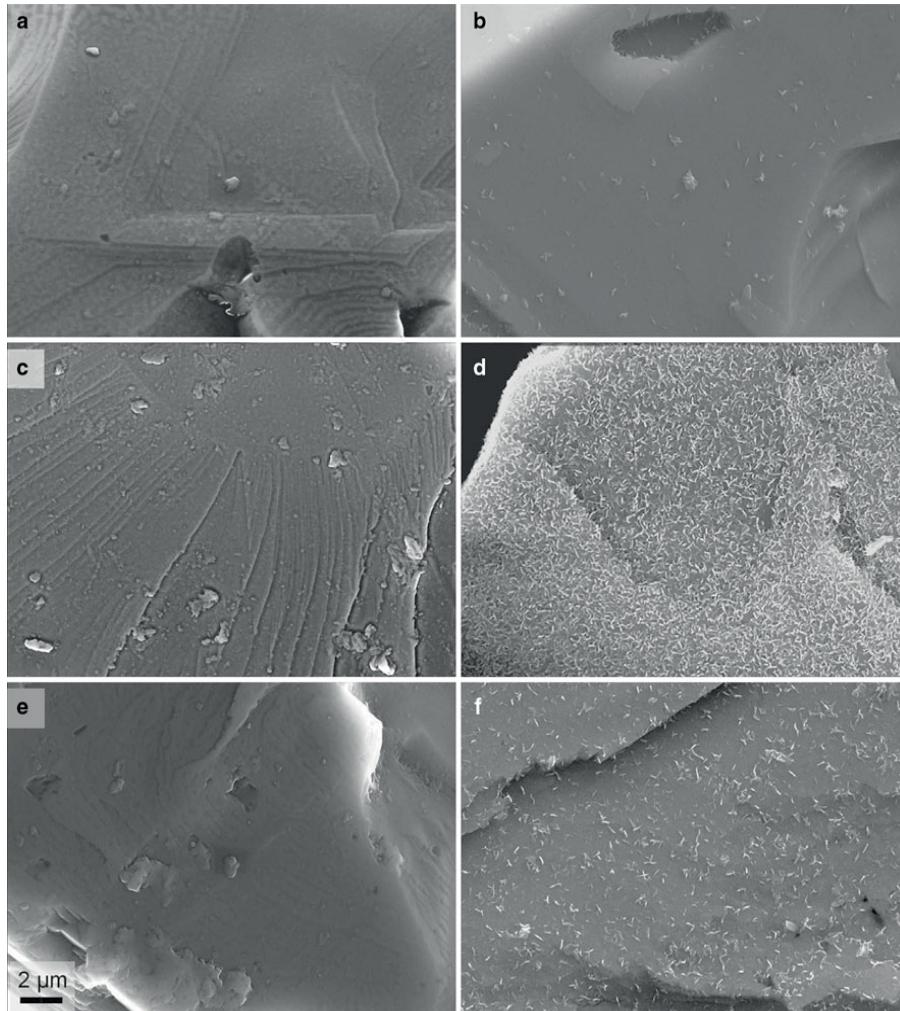

Fig. 15: Comparison of mineral surfaces representing the main constituents of reservoir sandstones (top to bottom: quartz, plagioclase, K-feldspar) before (a, c, e) and after (b, d, f) alteration as a result of dissolution-precipitation reactions.

Fines migration:

Fines migration implies the transport of small solid particles within the pore space of a rock. Such particles are ubiquitous and, e.g., emanate from clay minerals as shown in Fig. 16. When fluids are produced from or injected into a reservoir these particles may detach by hydrodynamic forces and might become accumulated in narrow pore throats yielding a decrease in rock permeability. This process is amplified when an incompatible fluid, e.g. low salinity water, is injected into the formation saturated with high salinity brine. Here, clay swelling would liberate even more fine material. Consequently, the presence of swellable clay minerals within the reservoir has to be assessed before injection of any technical fluid into the reservoir, e.g. in connection with hydraulic stimulation treatments. This is of particular importance as reservoir damage induced by fines is hardly reversible.
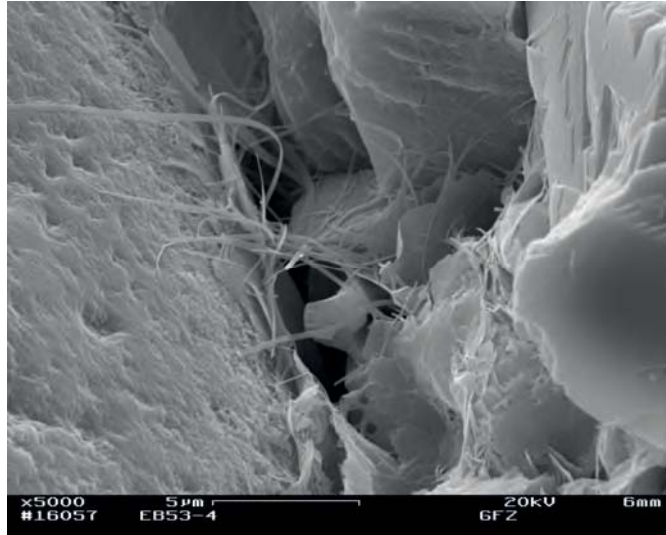
Fig. 16: SEM-micrograph of a broken sandstone sample highlighting the pore space partly filled with clay fibers (illite) yielding a risk of fines migration and pore clogging.

Process Control

With the aim to avoid or at least handle the risks interfering with the overall system's functionality a number of measures can be undertaken that will be briefly outlined in the following. As the occurrence of individual processes is strongly dependent on the fluid, rock and materials properties at a particular site these have to be known and an understanding of interaction processes has to be gained before designing the plant and starting operation.

For *two-phase flow* the true gas content of the fluid within the reservoir needs to be known to optimally run the production pump. For a critical gas content degassing can only be handled by keeping the draw-down within the production well as low as possible which in turn would imply that the production rate is lower than desired or technically possible.

For avoiding *redox reactions* and *corrosion* processes the selection of appropriate materials is imperative but generally achievable. In cases where specific materials cannot be substituted active or passive protection can be applied. Examples are: (1) cathodic protection with sacrificial anodes (Mg, Zn), (2) corrosion inhibitors that remove dissolved oxygen from the fluid and (3) coatings, either metallic (Zn, Ni, Cr) or organic (resins, thermoplastics, rubber, polymers) or mixed organic-metallic (zinc coating with an organic layer).

Temperature-induced *scaling by oversaturation* of particular species can only be avoided by keeping the temperature within the plant's heat exchanger as high as possible which in turn feeds negatively back on efficiency. The use of appropriate scaling inhibitors would then be an option. These are chemical substances added to the geothermal fluid which always need to be designed for specific types of scales (e.g. sulfates, carbonates). Examples of such substances are phosphonates, polymers (e.g. polycarboxylate) and acids (e.g. HCl for calcite).

To avoid the occurrence of *dissolution-precipitation reactions* optimum injection temperatures need to be chosen to minimize the disturbance of thermodynamic equilibrium within the reservoir. Finally, *particle transport* within the reservoir can be handled by keeping the injection rate below a critical threshold if only hydrodynamics is an issue and/or by avoiding the injection of incompatible fluids (e.g. during stimulation treatments) if sensitive minerals (e.g. clays) are rock constituents.

In summary, for some processes countermeasures are directly available, for others the operating conditions need to be optimized for each individual site and fluid-rock-materials combination.

Beyond Energy

Depending on the individual location and thus geological situation, geothermal fluids can contain a plethora of dissolved elements and compounds. These may constitute an economic value if (1) their concentration is sufficiently high and (2) appropriate techniques exist to separate them either from the fluid or a precipitate. Substances of interest are, e.g.: silica (SiO_2), lithium (Li), copper (Cu) and rare earth elements (REE) in the liquid phase and helium (He) in the gas phase. For the example of the geothermal research platform Groß Schönebeck the fluid at this site contains 72 mg/L of SiO_2, 200 mg/L of Li, 10 mg/L of Cu and > 20 NL/m^3 of He. The rate at which the fluid would be produced on average is 50 m^3/h.

Silica is mainly of interest for high enthalpy geothermal systems, e.g. in Indonesia (Fig. 17), where large quantities are encountered and also imply an operational risk. For silica use there exist various industrial applications as fillers (e.g. paper, paint, plastics, rubber), abrasives (e.g. sandpaper), polishers (e.g. silicon wafers), desiccants (e.g. food) and feedstock (e.g. semiconductors, catalysts). Technologically, for separating silica from geothermal fluids there exists an example from the Wairakei geothermal field, New Zealand (Brown and Bacon, 2000) where enriched silica sol is produced from colloidal silica.

Fig. 17: Plant components at an Indonesian geothermal power plant showing massive silica precipitation (scaling) and a significantly reduced cross-sectional area available for flow.

Lithium, to date, is predominantly produced from ores and Li-bearing minerals like spodumen ($LiAl[Si_2O_6]$) or from salt lakes (e.g. LiCl). There also exist various industrial applications for lithium use where the most prominent is manufacture of batteries with an estimated lithium consumption of 8000 t in 2015 which is approximately 25 % of the total lithium production worldwide. For separating lithium from a geothermal fluid some laboratory-scale processing technologies have been investigated providing the basis for later prototype plant-scale installations: (1) solvent extraction (Hano et al., 1992), (2) co-precipitation with AlOH (Takuechi, 1980), (3) HMnO ion-sieve adsorbent (Ooi et al., 1986; Miyai et al., 1988) and (4) Li ion-sieve adsorbent (Zhu et al., 2014).

Summary and Outlook

Energy from geothermal fluids is an overall environmentally friendly, decentralized, base load and inexhaustible type of renewables that can deliver electricity, heat and chill and may significantly contribute to present and future demands. Most of the vast global geothermal resources are yet unexploited.

This, to a significant part, relates to challenges in reliably handling geothermal fluids as the heat carrier during production, usage and injection. A site-specific fluid assessment is imperative for plant design and later operative conditions. However, individual interaction processes still need understanding from substantial fundamental research to derive guidelines for optimum plant setup and operation.

Geothermal fluids produced for energy supply can, site-dependently, contain a plethora of dissolved elements and compounds that may represent an economic value at an amount that can exceed the value of the fluid's energy content. To separate species of economic value, e.g. lithium, silica and rare earth elements (REE), from a geothermal fluid both at the surface and during operation novel chemical process technologies will need to be developed.

Once this is achieved geothermal fluids would constitute a powerful resource for the concurrent provision of both energy and raw materials at individual sites securing local demands, decreasing import needs and yielding transfer of technologies.

Acknowledgements

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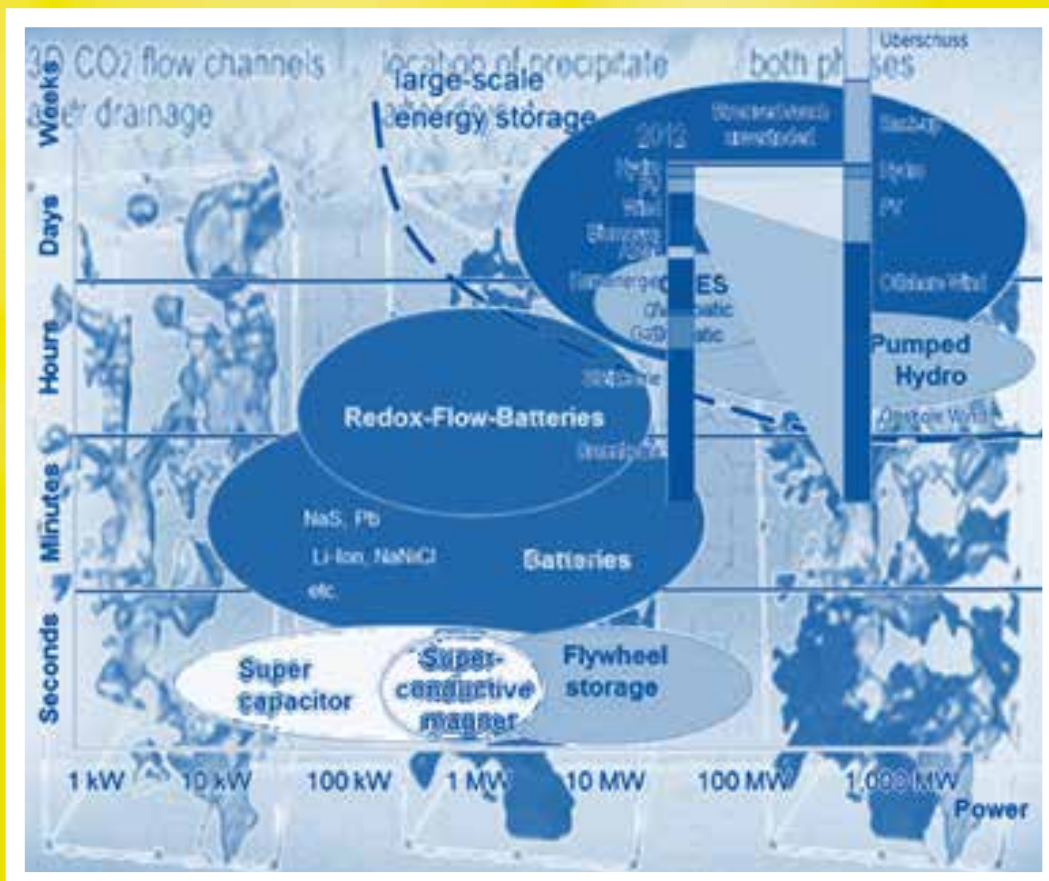
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