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Seasonal Deep Aquifer Thermal Energy Storage in the Gassum Sandstone Formation

H.D.H. Holmslykke* (GEUS), C. Kjølner (GEUS), I.L. Fabricius (DTU)

Summary

Seasonal storage of excess heat in hot deep aquifers is considered to optimise the usage of commonly available energy sources. The potential chemical reactions caused by heating the Gassum Sandstone Formation to up to 150°C is investigated by core flooding experiments combined with petrographic analysis and geochemical modelling. Synthetic formation water is injected into two sets of Gassum Formation samples at 25°C, 50°C (reservoir temperature), 100°C and 150°C with a velocity of 0.05 PV/hr and 0.1 PV/hr, respectively. A significant increase in the aqueous concentration of silicon and iron with increasing temperature is observed due to dissolution of silica and siderite. Increasing the reservoir temperature from 50°C to 100°C enhanced the naturally occurring weathering of Na-rich feldspar to kaolinite. Dissolution of quartz increased sharply above 100°C and was the dominating process at 150°C. At temperatures $\leq 100^\circ\text{C}$, the silicon concentration was controlled by a dynamic equilibrium between feldspar dissolution and kaolinite precipitation while the concentration was kinetically controlled by quartz dissolution at 150°C. The results imply that storage of excess heat in the Gassum Formation in the Stenlille area may be possible provided operational precautions are taken.

Introduction

Typically, a temporal incongruity exists between the supply and the demand for heat. Excess heat is for example produced from waste incineration during the summer, while the demand for energy peaks during the winter. This mismatch between the supply and the demand for heat may be managed by seasonal storage of surplus heat in the subsurface. During summer, formation water is extracted from the aquifer and heated using the available surplus energy prior to reinjection into the reservoir. During winter, the stored hot water is extracted and used for district heating.

In Denmark, seasonal storage of excess heat in deep sandstone aquifers with temperatures up to 75°C is considered, as these aquifers are already being used for geothermal energy for district heating. The relative high *in situ* temperature and low flow rate in these aquifers may minimise the heat loss during the storage. Also the utilisation of geothermal energy may benefit from the heat storage, as the injection of heated formation water may increase the heat potential in the aquifers and possibly prolong the life time of the geothermal aquifer (Kabus *et al.*, 2005; Réveillère *et al.*, 2013).

The increase in the reservoir temperature caused by the heat storage will disturb the initial thermodynamic equilibria in the reservoir and potentially trigger geochemical reactions that may affect the reservoir properties. Temperature is known to exert an important control on both the extent and rate of chemical reactions. Generally, elevated temperatures increase reaction rates, while mineral solubility can either increase or decrease, depending on the thermodynamic properties of the mineral (e.g. Appelo and Postma, 2005). A major concern regarding heat storage in the hot deep aquifers is that the heat may permanently damage the aquifer making extraction of further geothermal energy unfeasible. For example, dissolution of the cementing material in the aquifer may reduce the mechanical strength of the aquifer and the heat or the associated dissolution/precipitation processes in the aquifer may affect the permeability of the aquifer by changing the pore space geometry (Moore *et al.*, 1983; Schembre and Kovsky, 2005; Tenthorey *et al.*, 1998).

In this study the potential geochemical reactions due to heat storage of up to 150°C in the deep subsurface of Denmark is investigated. Core flooding experiments combined with petrographic analysis and geochemical modelling is conducted to identify the primary chemical reactions that potentially occur when heated formation water is injected into the aquifer. As a case study the Upper Triassic – Lower Jurassic Gassum Formation is used because this is the most widespread geothermal aquifer in Denmark (Nielsen *et al.*, 2012).

Materials and methods

Two cylindrical specimens ($S_{0.05}$ and $S_{0.1}$) were prepared from a cored interval of the Upper Triassic – Lower Jurassic Gassum Formation in the Stenlille-2 well. The tested samples were selected from the same depth in the core (1539.50 m) to ensure close similarity. Two core flooding experiments were performed such that one experiment was performed with each of the two specimens. Synthetic Gassum brine was used as the flooding fluid, and flow velocities of 0.05 PV/hr and 0.1 PV/hr were applied for specimen $S_{0.05}$ and $S_{0.1}$, respectively. Upon testing, the brine saturated specimens were placed in a Viton sleeve in a hydrostatic core holder and connected to a high precision Quizix® pump assuring a constant flow with synthetic formation water. A confining pressure of 275 bar and a pore pressure of 170 bar was applied corresponding to the *in situ* pressures. For both flow rates, tests were performed at 23°C, 50°C (reservoir temperature), 100°C and 150°C allowing flow for minimum one week at each temperature. Effluent brine for chemical analysis was collected from either of two sampling loops placed downstream the core holder.

Water chemistry, mineralogical changes and geochemical modelling

Upon temperature increases, a clear and immediate increase in the aqueous silicium and iron concentration is observed (Figure 1). At each temperature, a constant level of silicium in the effluent is observed, the only exception being at 150°C where the silicium concentration does not seem to

reach steady state, especially at a flow rate of 0.05 PV/hr. The plateau reached at each temperature is identical for the two experiments, irrespective of the flow velocity, except at 150°C where a lower silicium concentration is measured for the slower flow rate. No observable changes were identified for the concentration of chloride, sulphate, potassium, calcium, magnesium and sodium. Aluminium remains below detection limit (0.03 mg/L) throughout the experiments. The measured pH is relatively constant between 5 and 6 at all temperatures. An accurate pH measurement was difficult to obtain, since the pH drifted considerably during measurement. As a consequence both the pH measured immediately after sampling and the pH at the beginning of the alkalinity measurement are shown in Figure 1.

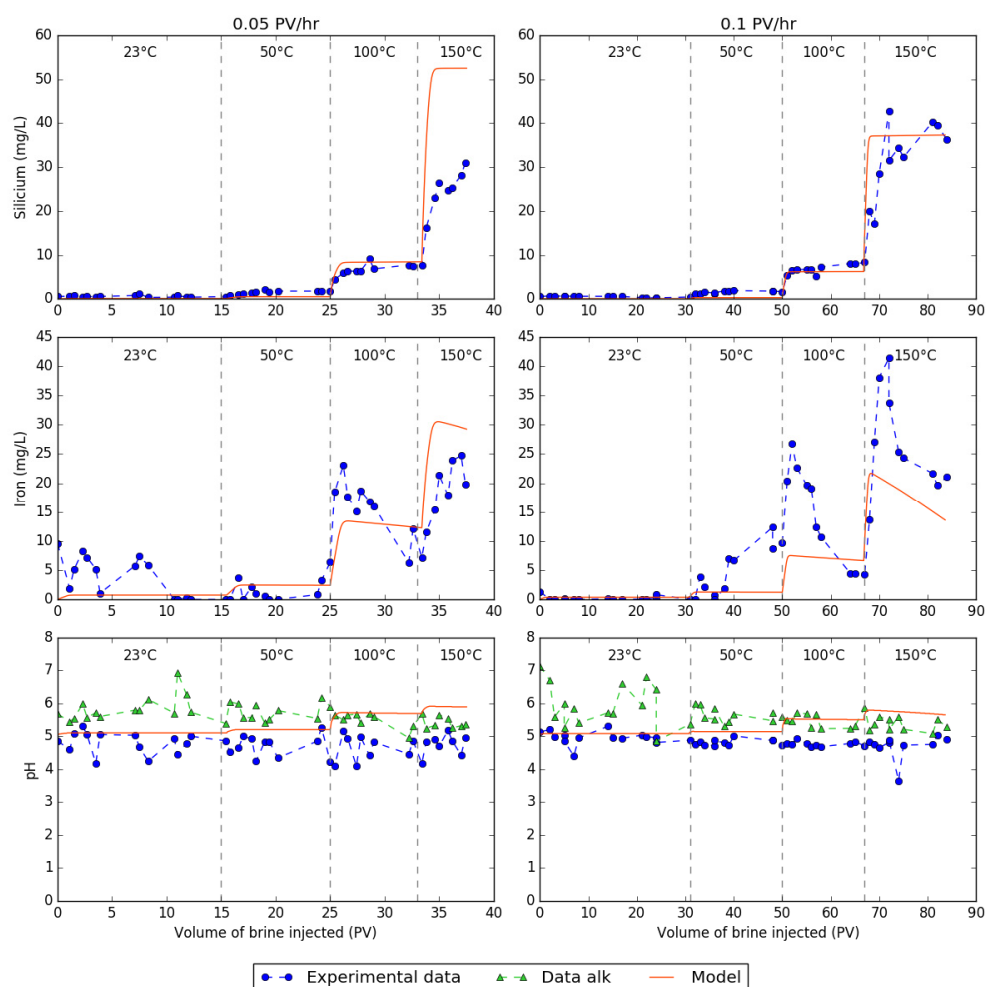


Figure 1 Measured and modelled silicium and iron concentration and pH in the effluent of a Gassum Formation column flushed with synthetic Gassum brine at 23°C, 50°C (reservoir temperature), 100°C and 150°C and with a flow velocity of 0.05 PV/hr and 0.1 PV/hr. Measured data for the pH includes both the pH measurement (Experimental data) and the pH measured as the starting point in the alkalinity measurement (Data alk). The model includes kinetically controlled dissolution/precipitation of albite, kaolinite, quartz and siderite.

Mineralogical changes of the specimens were identified by thin section analyses using optical microscope and backscatter electron microscopy prior to and after the flooding experiment. For the dominating quartz mineral, no changes were observed as a result of flooding. As previously observed in natural samples (Weibel *et al.*, 2010), the Na-rich part of exsolved alkali feldspar is partly degraded and to some extent replaced by kaolinite. This process may well have been promoted by the flooding experiments. The flooding has caused siderite to go into dissolution as evidenced by the presence of moulds after siderite crystals among mica flakes.

The injection of heated formation water into the Gassum Formation was modelled using the 1D reactive transport code PHREEQC version 3.0 (Parkhurst and Appelo, 2013) and the thermodynamic data from the Thermoddem database (Blanc *et al.*, 2007). The model includes the thermo-kinetic processes of mineral dissolution/precipitation reaction of the minerals albite (as a proxy for Na-rich alkalifeldspar), kaolinite, quartz and siderite. The geochemical model was fitted to the experimental data from the 0.1 PV/hr experiment and subsequently tested against the results of the 0.05 PV/hr experiment. For both experiments, the model reproduces the observed changes in the aqueous chemistry reasonably well (Figure 1). However, particularly for the 0.1 PV/hr experiment, the model underestimates the iron concentration and dissolution of siderite may thus not account for all of the iron released to solution during the core flooding experiments.

Confirming the petrographic analysis, the model results show that at reservoir conditions (50°C) dissolution of Na-rich alkali feldspar and precipitation of kaolinite occurs. Upon a temperature increase to 100°C, the conversion of feldspar to kaolinite increases. The negative saturation indices simulated for temperatures $\leq 100^\circ\text{C}$ indicate that the aqueous silicium concentration is not controlled by equilibrium with either of the silicium containing mineral phases. Instead, the silicium concentration appears to be controlled by a dynamic equilibrium between feldspar dissolution and kaolinite precipitation as suggested by the close to constant aqueous silicium concentration measured irrespective of the flow velocity (Figure 1). The flow rate affects the magnitude of the dissolution/precipitation processes in this dynamic equilibrium. Thus depending on the flow rate, the dynamic equilibrium was reached at different levels of saturation indices.

With increasing temperature, dissolution of quartz becomes increasingly important, and at 150°C quartz dissolution becomes the predominant process, completely suppressing the dissolution of feldspar and thereby the precipitation of kaolinite. At 150°C, the silicium concentration is solely controlled by the dissolution kinetics of quartz.

Implications for heat storage in the Gassum Sandstone Formation

Extrapolation of the model results indicates that less than 0.05% and 0.6% of the quartz in the reservoir will dissolve during storage at 100°C or 150°C, respectively, for six months and thus quartz dissolution is not expected to significantly deteriorate the reservoir properties. Up to 3.2% of the Na-rich feldspar present in the reservoir will dissolve during a six month storage at 100°C. Due to the small content of feldspar present in the reservoir this is not expected to reduce the mechanical strength of the reservoir. The formation of kaolinite will, however, increase the formation damaging potential of the reservoir as the presence of even small amounts of kaolinite is known to potentially decrease the reservoir permeability under certain conditions (Schembre and Kovscek, 2005).

To prevent clogging of the injection well due to re-precipitation of silicium and iron upon cooling of the brine appropriate removal of these elements e.g. by filtration in the surface facility is critical to ensure sustainable energy production from the heat storage. As the aqueous concentration of both silicium and iron increases sharply above 100°C, keeping the storage temperature below 100°C, as observed at other heat storage facilities (Kabus and Wolfgramm, 2009), may help reduce the chemical effects of the heat storage on the reservoir and thereby any injection problems.

Conclusions

Core flooding experiments, petrographic analysis and geochemical modelling have been performed to investigate the chemical reactions likely to occur when heated formation water is stored in the Gassum Sandstone Formation. The results show that the chemically induced effects of heat storage in the Gassum Formation in the Stenlille area may be of minor importance and that heat storage in this area may be possible provided operational precautions are taken.

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