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Effect of flow rate and salinity on sandstone permeability

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ABSTRACT

The Bentheim sandstone permeability decreases with the increase of the flow rate and decrease of the sodium chloride concentration. The SEM imagery confirms that the permeability decreases due to release of the discretely dispersed clays from the pore walls and their further re-deposition in the narrower pore throats. The injection of the 1M NaCl solution after distilled water causes some recovery of the permeability due to reduction of the bonded water layer thickness around clay particles, which plug the pore channels. While many of the discretely dispersed particles are detached from the sand grains by hydrodynamic forces, the clay pockets, being isolated by surrounding grains, exhibit very high resistance to erosion and remain well preserved even after flooding with a very high flow rate.

KEYWORDS

Geothermal energy, clay particle transport, porous media, permeability.

Introduction

Geothermal energy plays an increasingly important role in carbondioxide emission free energy production in Europe. High fluid production rates are essential for geothermal energy exploitation to be economically viable. Nevertheless the fluid production rate of doublets geothermal systems often decreases with time due to reduction of the geothermal reservoir permeability, particularly in the vicinity of an injection well. This is frequently caused by the plugging with clay and colloidal particles that are released from the rock grain surfaces due to high fluid velocity or alteration of physical-chemical conditions (e.g. salinity drop) in the reservoir during exploitation.

Objectives of the research

The main objective of the research is to improve understanding of influence of re-injected fluids with different physical chemical properties on the permeability development in sandstones. In this paper we particularly focus on: 1) experimentally determining the effect of high fluid velocity and salinity on the sandstone permeability; 2) interpretation of the experiments in terms of the mechanism of the in-situ clay and colloidal particle transport in the rock porous media; 3) detecting and estimating the transformation of the rock microstructure and porous media caused by the permeating fluid.

Background

The porous medium of sandstone can be represented as a network, consisting of pores connected with each other by narrower pore channels (or throats). The widely accepted model of in-situ clay induced formation damage supposes that the permeability reduction occurs due to release of clay particles from pore walls and their subsequent re-deposition downstream in pore throats, which presumably have smaller diameters than the pores (Priisholm et al. 1987).

The stability (or, on the contrary, detachment) of the in-situ clay particles in a reservoir is determined by the balance between the forces effecting a clay particle in a reservoir. The interaction between a clay particle and a pore surface can be described by the following equation:

$F_{total}(h) = F_{LVA}(h) + F_{DLR}(h) + F_{BR}(h) + F_{HR}(h) + F_{IHL}(h)$, where

$F_{total}(h)$ - the resulting force of a clay particle - pore wall interaction (positive, if repulsion dominates, and negative, if attraction dominates); $F_{LVA}(h)$ - London - van der Waals attraction; $F_{DLR}(h)$ - repulsive force due to overlap of double electrical layers of like charged surfaces (i.e. clay and mineral matrix); $F_{BR}(h)$ - Born Repulsion (significant at the distance less than 5 O); $F_{HR}(h)$ - hydrodynamic force (depends on the interstitial velocity of the permeating liquid); $F_{IHL}(h)$ – splitting force of the interfacial hydrate layers; h - distance between a single particle and a pore wall. London - van der Waals attraction force has a negative sign, all other repulsion forces - a positive one.

The similar equation in terms of potentials was introduced by Khilar **K.S.** and Fogler **H.S.** (1987). However they ignored the effect of the interfacial hydrate layers (Deriagin B.V. & Titievskaia A.S. 1953), that also play an important role in interaction between clay particles and pore matrix.

Most of the entities of the equation are mathematically described by the DLVO theory (Deriagin B.V. 1937, Derjaguin B.V. and Landau L.D. 1941, Verway J.J.W. & Overbeek J. Th. G. 1948). Unfortunately it is rather difficult to measure many of the parameters (e.g.

Hamaker constant) which determine these entities. Hence it can be used mostly for semiquantitative evaluation of the clay particle stability in porous media. Nevertheless it allows us to analyse the influence of the physico-chemical factors and flow rate on the sandstone permeability.

The equation shows that the rate of clay particle release (and permeability decline) depends both on the interstitial fluid velocity and the physico-chemical factors controlling the double electrical layer structure around clay particles (and therefore F_{DLR}). For example the internal clay particles start being released if a so called critical flow rate is exceeded (Vernoux J.F. & Ochi J. 1994). The value of the critical flow rate depends on the physico-chemical conditions in the reservoir, the clay and rock matrix mineralogy as well as pore size distribution, which in its turn controls the distribution of the interstitial fluid velocity within the porous medium. The clays can also cause pore plugging if the salt concentration in the permeating fluid falls below a critical salt concentration (CSC), even if the flow rate is relatively small. The value of the CSC depends significantly on the type of salts solved in the permeating fluid (Khilar K. C. & Fogler H.S.1987).

The effect of physical chemical properties of the injected fluid on the particle transport was intensively investigated in petroleum engineering. Strong correlation was found between the permeability and the salinity. However in geothermal wells the injection rates are much higher than in injectors at oilfields. It means that the particle release can occur purely due to high hydrodynamic forces (F_{HR}), even if the physico-chemical conditions do not change (Priisholm S. et al. 1987).

It is a well documented fact (e.g. by Mungan N. 1965) that at low flow rates the abrupt salinity drop causes drastic permeability reduction due to increase of the electrostatic repulsion (F_{DLR}) between clay and sand surfaces. However it still is not clear, what happens if we gradually reduce the salinity of the injected fluid and whether it has any significant effect on the permeability if the flow rate is primarily higher than the initial critical value for the reservoir.

Rock characteristic

In our experiments we used the Bentheim sandstone, collected in the western part of Germany. The sandstone consists of α-quartz (97.2 %), 1.4 % kaolinite and 1.3 % microcline. The sandstone is well sorted with grain's shape varying from subrounded to rounded. The contacts between grains are formed as a result of quartz overgrowth or pressure desolution (both types of the contacts are clearly observed in the SEM images). Clay cement also presents but has a minor importance. The clay fraction is represented mainly by kaolinite, that can be easily identified by the hexagonal shape of the individual particles and "booklet" like aggregates.

Kaolinite is formed as a result of weathering of feldspar grains. If a clay aggregate, replacing a feldspar grain, is not afterwards eroded it remains in place of its formation and consequently the whole clay aggregate inherits the shape of the original feldspar grain (figure la). The aggregates are surrounded by quartz grains and form rather isolated clay "pockets" in the sand structure (figure 5c). The clay pockets have a compact microstructure formed by kaolinite booklets.

Part of the kaolinite microaggregates and particles were eroded and subsequently re-deposited at sand grains (figure lb). This class of clays we call "discretely dispersed" (after Neasham J. W. 1977). The exchange complex of the clays is represented mainly by Na^{+} and Mg^{2+}.

Experimental set-up and procedure

We provide two sets of percolation experiments with Bentheim sandstone cores with a diameter of 1" and length of 3". First, we flood the cores with aqueous NaCl solutions of different concentrations at flow rate of 10 l/h. This laboratory flow rate value corresponds to the injection rate of 150 m^3/h at a well with a diameter of 0.1 m, and the injection interval of 30 m. (Vernoux J.F., Ochi J. 1994). We successively reduce the NaCl concentration in the injected fluid from 1 M to 0 M (1 M, 0.5 M, 0.1 M, 0.05 M, 0.01 M, and distilled water). At the end of one of our experiments we have also switched fiom the distilled water again to 1 M NaCl solution.

In the second set of tests we consequently increase the flow rate from 10 up to 35 l/h. In this experiment we use dimineralized water as an injected fluid.

At every stage of the both experiments we inject about 2000-3000 pore volumes of the fluid, until permeability is stabilized. We run the experiments at the temperature of 25°C. The pH and temperature are monitored and viscosity correction is taken into account during Darcy's permeability calculation.

Results and discussion

Permeability variation with respect to NaCl concentration

EFFECT OF THE SALT CONCENTRATION DECREASE

The percolation experiments show that successive reduction of the NaCl concentration in the permeating fluid causes consecutive reduction of the permeability (figure 3). But the most surveyed permeability drop (20%) occurs after switching from 0.01 N NaCl solution to distilled water. In the experiment where after distilled water we have injected again the 1 M NaCl solution we have detected some recovery of the permeability (figure 3).

The SEM images of the percolated samples show that many of the pore throats are plugged by re-deposited clays that were discretely dispersed in the original sandstone. Nevertheless numerous clay pockets as well as part of the discretely dispersed clay particles are still present in the rock (figure 2).

X-ray microanalysis of the clay plugs and the filtrate show that the migratory fines are mainly kaolinite. Besides the kaolinite a few fine grains of quartz and feldspar are also traced in the filtrate.

The release of the clay particles from the rock mineral skeleton can be explained by the cation exchange reactions occurring during saturation of the rock with highly concentrated NaCl solutions and further percolation with distilled water. The exchange of Mg^{2+} for Na^+ in kaolinite (in highly concentrated solutions), followed by successive reduction of the ionic strength of the permeating fluid, causes increase of the clay ζ-potential (Zlotchevskaia R. et al. 1988). This consequently increases electrostatic repulsion between kaolinite particles, microaggregates and quartz grains (F_{DLR}). Increase of the interfacial water layer thickness as a result of cation exchange for Na^+ in kaolinite also contributes to Na-kaolinite dispersion due to splitting effect of the bonded water layers (F_{IHL}).

While the discretely dispersed clay particles can be easily detached from sand grains by hydrodynamic forces, the clay pockets, being isolated by surrounding grains, remain in many cases preserved (figure 2a).

EFFECT OF THE SALT CONCENTRATION INCREASE

The experiment shows that the injection of the 1M NaCl solution after distilled water causes some recovery of the permeability (Figure 3). We can give the following explanation to this phenomenon. The total permeability of the original sandstone is determined mainly by the inter-granular pore flow because the total clay content is less then 2%. The swelling of kaolinite is very small (Sergeev E.M. et al 1983). Therefore the swelling effect of the discretely dispersed clays on the porosity and permeability of the original sandstone is negligible.

After the discretely dispersed clay particles have been released from pore walls, and consequently part of the pore throats has been plugged, the micro-morphology of the flow changes significantly. In this case within the pores the penneability is still determined by the intergranular flow, but within the plugged pore throats it is controlled by inter-clay microaggregate flow. The permeability within the pore throats depends on the thickness of the interfacial hydrate layers around the clay particles and microaggregates (i.e. swelling of the clay particles). Thus the factors, which influence the swelling of the clay, effect the penneability of the sandstone as well. It is well known that the saturation of clay soils with highly concentrated brines causes reduction of the double electrical layer (Olphen H. van. 1963) and interfacial hydrate layers (Deriagin B.V., et al. 1985). This consequently reduces swelling of the clay soils (Osipov V.I. et al. 1989).

While the Na-kaolinite plugs are saturated with distilled water the clay particles have well developed interfacial hydrate layers. Thus the inter-particle pore space is blocked (partly or completely) by the adsorbed water, which has much higher viscosity than free water. The injection of 1M solution of NaCl (after distilled water) causes reduction of the thickness of the interfacial hydrate layers and closer attachment of the clay particles within the microaggregates. This consequently increases the effective inter-microaggregate pore diameters and permeability of the pore throats. We believe that this as the main reason of the partial permeability recovery of the sandstone after repeated injection of the highly concentrated sodium chloride solution.

EFFECT OF **FLOW** RATE

The percolation experiments show that stepwise increase of the flow rate from 10 L/h up to **30** l/h causes consequent decrease of the sandstone permeability (figure **4).**

The back scattering electron microscope images give evidences of the concentration of the clay material in the corners of pores and within the pore channels (figure5 a,b). From the micro-images one can also see that the clay pockets exhibit high resistance to erosion and remain well preserved even after flooding with very high flow rates (figure 5c). The results allow us to suggest that the increase of the flow rate causes successive permeability decrease due to re-deposition mainly of the discretely dispersed clay particles in the pore throats.

The effect of the flow rate on the clay particle release depends on the distribution of the interstitial velocity, which controlled by the pore sizes, and the strength of the clay-clay and clay-rock matrix bonds. **All** these parameters are stochastic variables. Therefore the degree of the clay detachment can be described by some stochastic distribution as well. This means that the critical flow rate characterizes only the initial flow rate, above which the clay particles start being released in the prevailing physico-chemical conditions. Thus not all particles can be detached under the same flow rate and at the same time. This is a reason why a decreasing of permeability is usually observed in time, even if the flow rate is stable (J. Baudracco, Y. and Tardy. 1988). The stepwise increase of the flow rate causes successive release of new portions of the clay particles and microaggregates from the sand grains and further decrease of the rock permeability. However we are aware that at high flow rates the effect of inertia should also be taken into account for quantification of the clay particle effect on the permeability.

Acknowledgements

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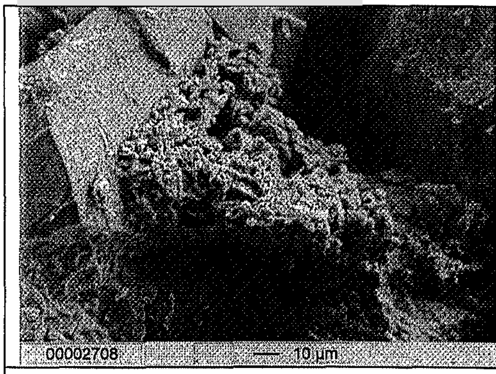
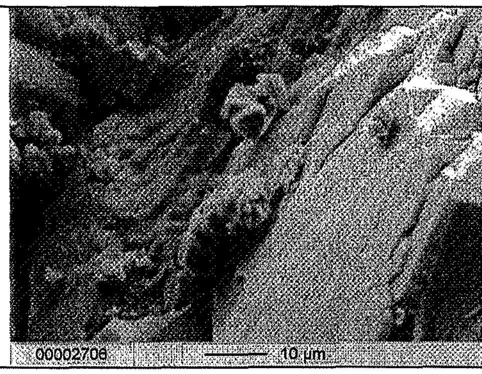
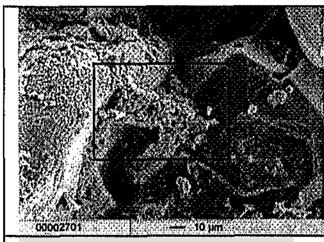


a. Clay Pocket

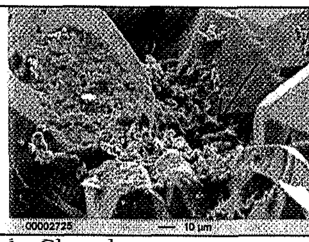


b. Discretely dispersed clays

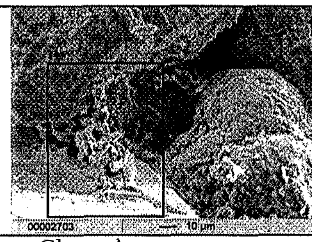
Figure 1. The Bentheim sandstone original micro-structure before percolation



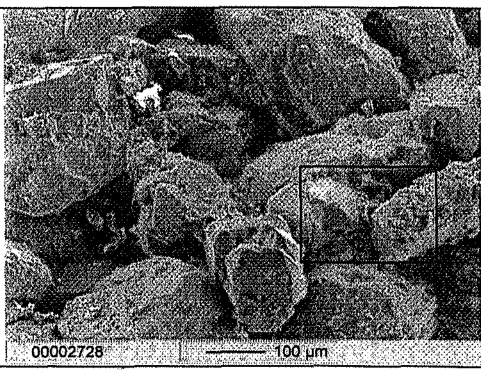
a. Re[illegible] cla[illegible] pocket



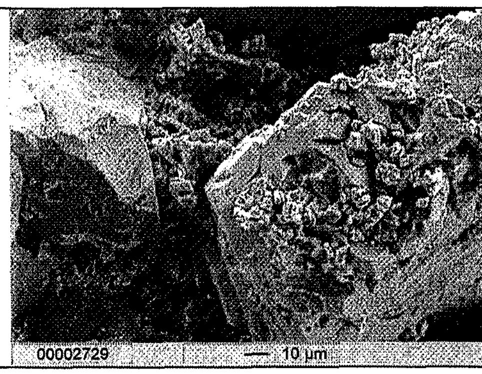
b. Clay plug



c. Clay microaggregate, bridging a pore throat



d. Clay plug at the place of two sand grains contact



e. Zoomed out the image **2d**

Figure 2. The Bentheim sandstone micro-structure after flooding with NaCl solutions of different concentration (1.0 – 0 M)

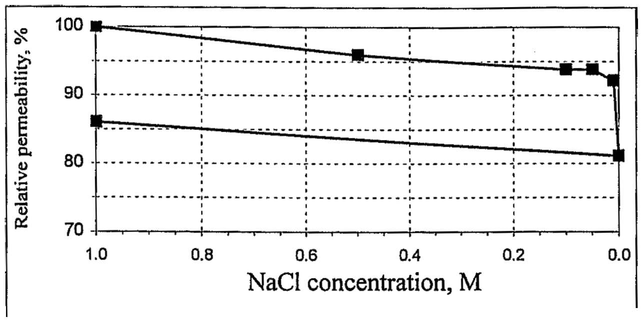


Figure 3. Effect **of** NaCl concentration on the sandstone permeability.

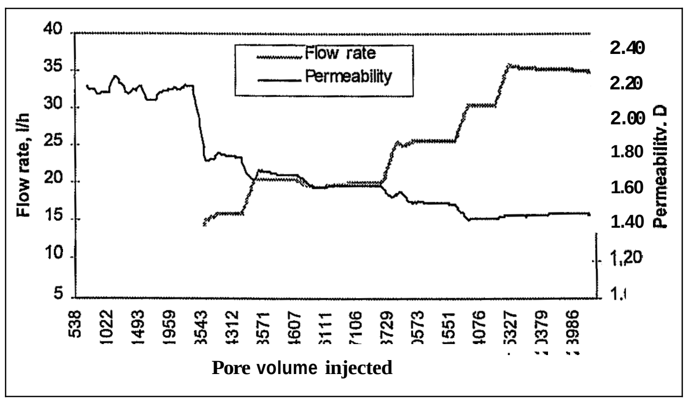


Figure **4.** Relationship between permeability **flow** rate

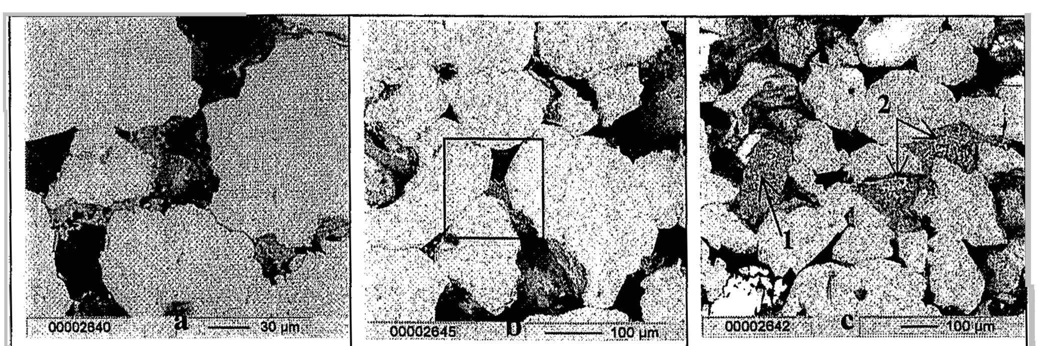


Figure 5. Effect of high flow rates on the sandstone microstructure. (a) Kaolinite particles, re-deposited in the corners of pores and pore throats; (b) Clay plugging entrance to the pore throat; (c) 1 – Feldspar grain, completely replaced by kaolinite; 2 – remaining clay pockets.

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