Modelling of Permeability Changes in Argillaceous Sandstones due to Fluid Injection

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ABSTRACT

Injection of formation water can cause formation damage due to the migration of fines, clay swelling, gas bubble formation, as well as the precipitation and dissolution of minerals. Because the injected water has approximately the same chemical characteristics as the production water, fines migration and gas bubbles will be the main sources of formation damage. The near vicinity of the well will be most affected.

A regional reservoir study was conducted to evaluate the potential for geothermal energy production. Percolation experiments are being carried out in France and The Netherlands on core plugs from relevant geothermal reservoir formations to study the effects of fines migration. The results of field tests in Germany and The Netherlands together with the results of the percolation experiments, are being used to model and simulate the formation damage process on plug-, well- and field scale.

1. INTRODUCTION

During the injection of water in hydrocarbon or geothermal reservoirs the permeability of a well may decrease as a result of formation damage. The following major processes cause formation damage during injection (Khilar and Fogler, 1983; Vetter *et al.*, 1987; Boisdet *et al.*, 1989):

1) precipitation of dissolved solids due to the mixing of injected water and formation water, or due to temperature effects;
2) clay swelling resulting from interaction of clays with the injected water;
3) plugging of pore throats by fines introduced into the formation by the injected water, or by fines which are eroded by the injected water in the vicinity of the well;
4) blocking of pore throats by gas bubbles formed due to degassing of the injected water.

Because, in low-enthalpy geothermal operations, the injected water and the water present in the reservoir have basically the same chemical composition, and because, after an initial stabilisation phase, the situation around the well can be considered as isothermal, precipitation will not be of major importance for injectivity reduction in geothermal reservoirs. Plugging of pore throats by fines and gas bubbles, on the other hand, can cause significant formation damage. To a lesser extent, clay swelling can also result in formation damage in geothermal reservoirs, despite the fact that the composition of the injected water and the formation water **is** very similar. Clays, in particular, are very sensitive to small variations in water composition (Baudracco, 1989).

The following study on the injectivity of argillaceous sandstones has been divided into the following areas of investigation :

- Reservoir studies
- Laboratory investigations
- Modelling and simulation

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2. REGIONAL GEOLOGY

In the western Netherlands a location near the village of De Lier has been identified as a possible site for a future geothermal test-bed project (Figure 1). This area is particularly suitable for a new geothermal venture, because, apart from large-scale greenhouse complexes, the area possesses oil and gas wells that provide a rich data set on the subsurface. This will make a geothermal venture less uncertain. The Rijswijk Sandstone, Berkel Sand–Shale and Berkel Sandstone Members of the Early Cretaceous Rijnland Group have been selected as a potential reservoir for the exploitation of geothermal energy.

The regional transpression regime has resulted in the formation of flower structures. The 'De Lier' and the 'Gaag' flower structures are found in the area of interest. Both structures are separated by the 'De Lier Fault', a **SE-NW** trending normal fault of which the south-westem block has been down thrown by a maximum of 300 m. The reservoir depths are between approximately 1 750 and 2 100 m in the north-eastem block and between 2 190 and **2 350** m in the south-western block. The Berkel Sandstone is 40 to 60 m thick, the Rijswijk Sandstone approximately **45** to 65 m. The reservoir temperature is about 76 °C in the north-eastern block and 87 °C in the lower south-western block.

Wells Gaag-1 and Lier-45 are the best documented and are thought to be representative for the immediate surroundings to the north and to the south of the Lier fault, respectively. The results of the petrophysical evaluation of these wells and a speculative interpretation of the Lier-39 are shown in Table 1.

Table 1. Petrophysical evaluation of wells Gaag-I, De Lier-45, and De Lier-39. The values for the latter are inferred.

	Gaag-1	De Lier-45	De Lier-39
thickness (m)	163	200	217
porosity (%)	15.0	11.0	12.7
permeability (mD)	232	37	109
transmissivity (Dm)	28	8.0	21.8

Simulation studies have indicated that the realisation of a doublet on the south side of the De Lier fault would be the most profitable. **In**

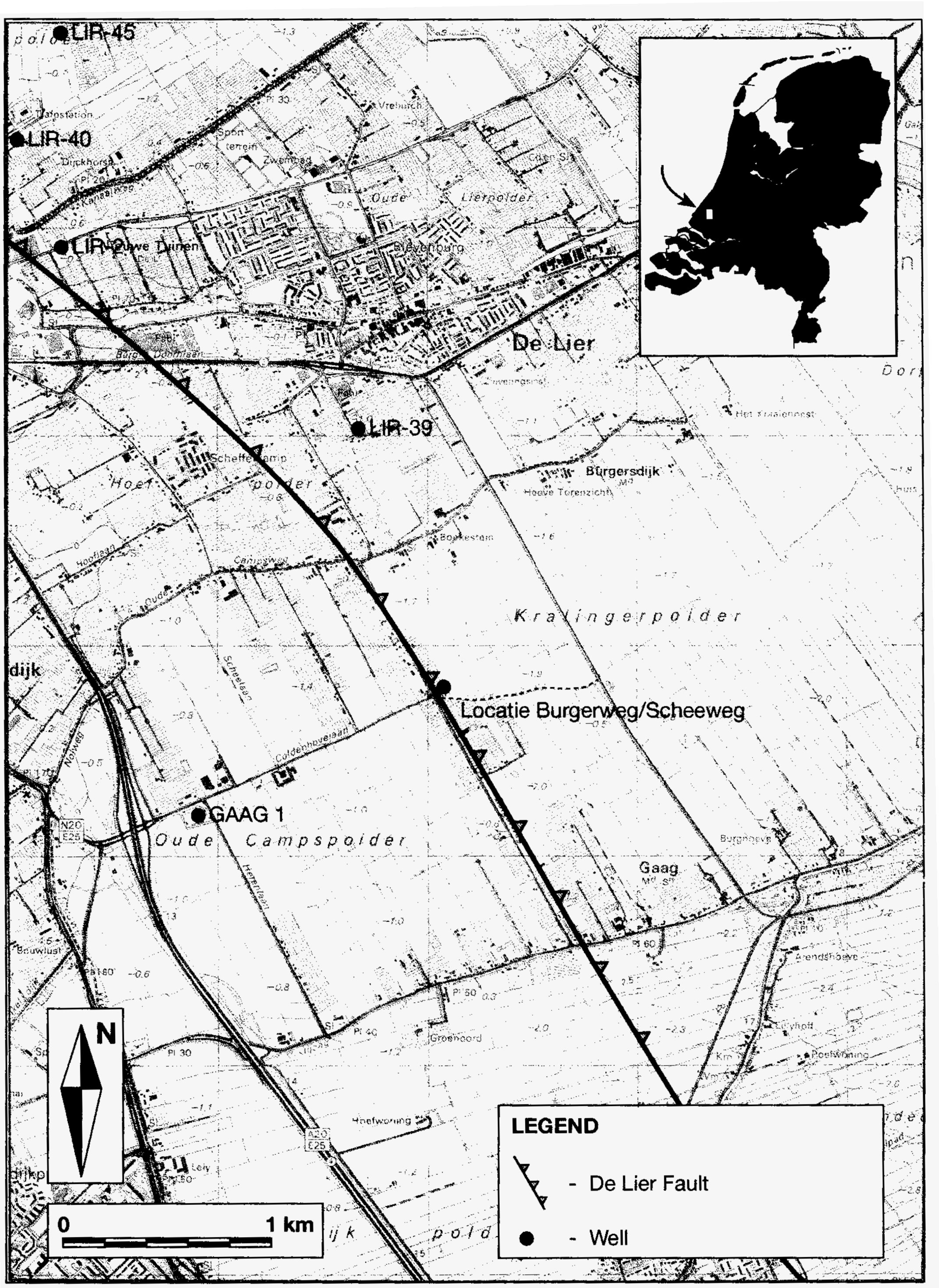


Figure 1. Map of the study area with the location of the existing oil and gas wells, the proposed location of the geothermal doublet ('locatie Burgerweg-Scheeweg'), and the normal 'De Lier' fault. The latter is marked by the bold notched line that runs from the upper left to the lower right comer; the teeth point to the footwall.

this configuration the produced water will show only a negligible decrease in temperature during the proposed production time of 25 years. The well distance will be 1600 metres, with a production rate of 300 m^3/h and an injection temperature of **46** °C.

Analysis of the Cretaceous formation waters show that for this doublet design (pressurised, closed system) formation damage due to pore blocking **by** gas bubbles, clay swelling and carbonate and iron sulfide precipitation is not likely to occur (Dufour and Vierhout, 1983). However it **is** possible that permeability will be reduced due **to** the migration of fines.

Literature shows that fractures may occur due to the lowering of the hydraulic fracture pressure caused by cooling of the reservoir by cold water injection (Perkins and Gonzalez, 1985; Clifford *et al.* 1991; Simpson and Paige, 1991). Fractured wells have an enlarged injection face and a higher permeability. Preliminary calculations for this project indicate that the first fractures may occur after approximately 3 years when the reservoir cools by 17 °C near the injection well.

3. LABORATORY INVESTIGATIONS

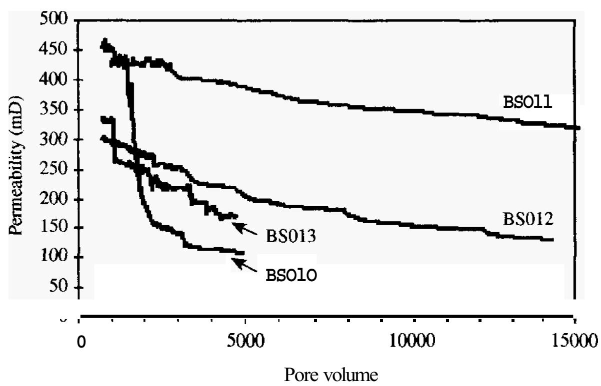
A core-flow test unit was specifically designed by BRGM to simulate the injection of a brine under bottom hole conditions. Experiments were carried out on Berea Sandstone samples with NaCl "solid-free'' brines (i.e. brines filtered through a 0.2 µm cartridge filter) at different salinities by increasing the flow rate (between 1 and 14 cm^3/s). The purpose of experiment BSOlO was to reproduce the "water sensitivity" of sandstones (Khilar and Fogler, 1983). Table *2* gives the experimental conditions.

Table 2. Experimental parameters for flow experiments

Exp #	material	fluid	flow rate (cm^3/s)	duration	permeability (mD)
BS013	Berea L = 4.5 cm	0.01 M NaCl	1 → 7	8 hours 4800 PV	330 → 160
BS012	Berea L = 4.5 cm	0.1 M NaCl	2 → 14	8 hours 14000 PV	340 → 190
BS011	Berea L = 4.5 cm	0.5 M NaCl	3.6 → 14.5	9 hours 20500 PV	480 → 280
BS010	Berea L = 4.5 cm	0.5 M NaCl / H_2O	1.2 → 5.4	9 hours 5000 PV	430 → 100

L : Plug length. PV : Pore volume

Permeability and flow rate as a function of time, expressed in pore volume, are plotted in Figure 2. The first three experiments (BS011, BS012 and BS013) generally show a gradual permeability decrease.



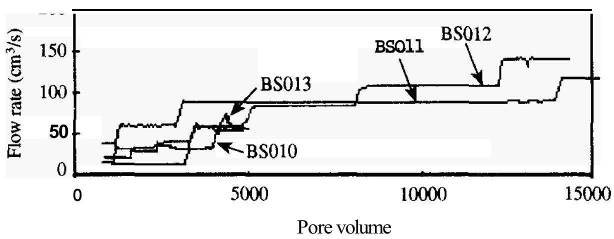


Fig. 2. Permeability reduction of Berea Sandstone plugs

Permeability will be reduced with increasing flow rate. When the injection fluid is switched from NaCl brine to pure water, permeability shows an inmediate and drastic decrease at low flow rates (experiment BSOlO). In all cases, the permeability decrease can be interpreted by detachment of the particles contained in the porous matrix and migration and entrapment of these particles at pore constriction.

The critical flow rates for all the experiments are of the same order of magnitude (1.5 to 6 cm^3/s) but seem to increase with salinity (Table 3). If we compare the permeability decrease for the same pore volume (4800 PV) and in the same flow rate range (< *6* cm^3/s) we see that the permeability decrease is less important at high salinity.

exp #	salinity (g/l)	critical flow rate (cm^3/s)	permeability decrease (after 4800 PV)
BSOlO	0		75 %
BS013	0.6	1.5 < Qc < 3	50 %
BS012	6	2 < Qc < 2.8	40 %
BSOll	30	3.6 < Qc < 6	**20 %**

The experiments were interpreted by using the DLVO theory to explain the mechanisms of particle release. The details of this study are given in Ochi and Vernoux (1994), here we present the main conclu-*sions:*

1) In all experiments (except water shock) the permeability decreases from a critical flow rate. The decrease is rapid when this critical is flow rate is reached, then it becomes gradual.
2) The permeability decline is less important when salinity increases.
3) The influence of fluid velocity when injecting a "particle-free" fluid is rather different than when injecting a fluid with particles: Prevailing capture processes (size exclusion, bridging, interception, diffusion) could be different in the two cases.
4) The permeability curves are very different when the decrease is due to a critical salt concentration and when it is due to a critical velocity. With chemical effects, the permeability decrease is very fast because all the particles are detached at the same time. With mechanical effects, the permeability decrease is more progressive because the velocity field in the porous medium changes with time.

From a physical point of view, the particles contained in the porous matrix can be released under hydrodynamic forces induced by the fluid mechanics. When the tangential hydrodynamic force is sufficiently increased, it can overcome the forces of interaction between a grain and a particle. The quantification of this phenomenon by double layer or DLVO theory is in qualitative agreement with the experimental results (Ochi and Vernoux, 1994). These first results are of great interest for modelling the permeability decrease in clayey sandstones and give guidelines for the prevention of injectivity decrease.

4. MODELLING OF THE LIFETIME OF A DOUBLET

A detailed study was first carried out about the models of Eylander (1988) and Van Velzen *et al.* (1993). Next, an improved model has been formulated, based on these earlier models.

Eylander (1988) assumed, as did Barkman and Davidson (1972), that at a certain distance (D) particles start to deposit due to surface and/or gravitational forces. Consequently, a filter cake forms due to pore bridging, which grows in the direction of the injection well. **A** disadvantage of this model is that the model parameter (D) is difficult to assess. Moreover, as Eylander (1988) remarks, experiments have shown that deposition starts already at the injection surface.

In the model of Van Velzen *et al.* (1993) the problem of the inaccessible parameter (D) is avoided by assuming that deposition can occur everywhere following a kinetic equation based on filtration theory.

In the case of an axial (filter) medium, Iwasaki **(1937)** proposed the following equation[1]) :

$$-\frac{\partial c}{\partial x} = \lambda c \qquad (1)$$

where x is the depth of the medium and h the so-called filtration coefficient. Equation (1) shows that the decrease of the concentration c of the suspension due to attachment to the medium is proportional to the concentration. The equation is seemingly a simple first order differential equation, however the difficulty of the equation arises from the coefficient λ, because it depends on the capture mechanisms. These mechanisms *are* not yet well understood, implying that there is no complete expression for λ. Nevertheless, in the literature many expressions for λ have been proposed, containing constants which are determined experimentally. It is generally accepted that h is inversely proportional to the interstitial velocity (Ives and Homer, **1973).**

Since in this study the reservoir geometry is assumed to be radially symmetric, equation (1) is transformed into the radial symmetric form:

$$-\frac{\partial c}{\partial r} = \lambda \frac{r}{r_w} c. \qquad (2)$$

Van Velzen ***et al.* (1993)** assume that deposition of fines in principle occurs everywhere in the medium. The volume of the deposited material depends on the distance r dictated by equation **(2)** where λ is taken to be

$$\lambda = \frac{2\pi r_w h\ \lambda_v}{q_0}$$

with λ_v being a constant which can be determined experimentally.

The following expression shows the relationship between the injection time (ta) and the injectivity index ***a*** (the total pressure drop Ap is constant during the injection):

$$t_\alpha = \frac{1}{2q_0C}\left(\frac{1}{\alpha^2} - 1\right)$$

where C is a constant depending on h, porosity and permeability of the impaired and unaffected zone, and the concentration of fines in the injection fluid. Van Velzen ***et al.* (1993)** take a constant value for the filtration coefficient h. However, the properties like permeability and porosity change during injection. This of course, affects the process of deposition and hence h changes during injection. **As** mentioned before, λ is inversely proportional to the interstitial velocity v_i (h ~ $1/v_i$) according to the literature on filtration theory. Hence, a decrease of the interstitial velocity will be accompanied by an increase of the deposit. In a radial symmetric geometry the decay of the interstitial velocity (v_i) is inversely proportional to the distance from the injection well (r). Moreover, the volumetric flow rate **(q)** will decrease with time (at least if the pressure drop remains constant). Furthermore, the porosity decreases with time which in turn, influences the interstitial velocity. So, v_i and therefore λ is a function of time and distance. **It** can be argued that there will be a maximal interstitial velocity vi* where λ = 0, suggesting that $\lambda - 1/v_i - 1/v_i^*$ (Ives and Homer, **1973).** This corresponds with the existence of a critical velocity at which there is an equal amount of deposition and release. This leads to the expression:

$$\lambda = c_1 \frac{2\pi r h}{q}(\sigma^* - \sigma) \qquad (3)$$

where c_1 is a constant. The following system of coupled differential equations utilises the above considerations:

[1]) **Symbols are given at end of paper**

For 0 I t and $r_w \le r \le r_e$,

(a) $$\frac{\partial c}{\partial r} = -\frac{2\pi r h}{q}(1 - \varphi_c)\frac{\partial \sigma}{\partial t},$$ mass balance

(b) $$-\frac{\partial c}{\partial r} = \lambda \frac{r}{r_w} c,$$ kinetic equation

(c) $$\frac{\partial p}{\partial r} = -\frac{\mu}{k(\varphi)}\frac{q}{2\pi r h},$$ Darcy's law

where h is defined by (3) and the permeability **k** of the damaged zone depending on the changing porosity φ.

5. CONCLUSIONS

The laboratory investigations show that a sandstone reservoir can be damaged when injecting a brine at high flow rate, even if the injected brine is filtered. When the flow rate is greater than a critical value, particles contained in the porous matrix can be released, transported and entrapped in the pore constrictions, involving permeability decrease. Percolation tests make it possible to evaluate the risks of injectivity decrease and to fix the maximum flow rate for injection without treatment. Finally, percolation tests associated with quantitative study of particles enable to determine the input parameters (critical velocity and filtration coefficient) necessary for the simulation of injectivity decrease.

Existing models for predicting lifetime of a doublet make assumptions which are not supported by experimental data. Based on the model of Van Velzen et al. **(1993)** an adjusted model is propesed. The most important improvement is that the filtration coefficient is taken to be inversely proportional to the interstital velocity. Further study will be conducted towards this model.

6. NOTATION

c:	concentration of suspension, vol./vol.
σ:	amount of deposit, vol./vol.
σ*:	maximum of amount of deposit, vol./vol.
λ:	filter coefficient, 1/m.
φ_c:	porosity of the filter cake
k:	permeability
μ:	viscosity
r:	distance from the centre of injection well.
r_w:	radius of the injection well.
h:	height of injected zone.
q:	volumetric flow rate as a function of time.
q_0:	initial volumetric flow rate.
***a*:**	injectivity index, $a = [q/\Delta p]_{(t=t)}/[q/\Delta p]_{(t=0)}$.

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