A New Experimental Procedure for Formation Damage Assessment in Geothermal Wells

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ABSTRACT
Difficulties in the reliable assessment of formation damage in numerous geothermal reservoirs, including the Salamander-1 well (Pretty Hill Sandstone Formation, Otway Basin), arise from the unavailability of cores. However, rock fragments are readily available. Thus this work presents a new method to assess the properties of permeability damage in a reservoir and other contributing reasons through laboratory tests on rock fragments. Analysis of field data from other wells of the same formation suggests that fines migration is a possible cause for permeability damage in Salamander-1.

A novel approach for the assessment of formation damage using rock fragments includes the following experimental steps: development of a composite porous medium which consists of borosilicate glass beads and rock fragments; mobilisation of fines from fractions by alternating of velocity and salinity of water flowing through the composite porous medium; identification of minerals in collected fines by Scanning Electron Microscopy coupled with Energy Dispersed Analysis of X-rays; as well as calculation of the Derjaguin-Landau-Vervey-Overbeek (DLVO) total potential of interaction between fines and rock matrix, to determine experimental conditions favourable for particle immobilisation. Validation of this method was carried out via comparison of fines migration results for rock cores and fragments from Ladbroke Grove-1 of the same formation. The method was successfully applied to fines migration results on fragments from Salamander-1.

This method determines the fines capacity removal from rock fragments and its effect on formation damage. An analytical model taking into account the amount of particles retained in the porous media and causing formation damage was successfully applied to the experimental fines migration data, and resulted in the prediction of well clogging and a poor performance of Salamander-1.

1. INTRODUCTION
The productivity of geothermal sandstone-based wells can be significantly affected by the mobilisation of clay particles due to high water velocities and/or low water salinity acting separately or in combination. These particles can pass through a porous medium without being captured, or be retained inside a porous matrix. If a particle is mobilised by a flowing fluid, then the hydrodynamic force exceeds the resulting DLVO attraction force, and particle capture due to the attraction to a porous matrix is not considered as a particle retaining mechanism anymore. In this case, the following conditions should remain unchanged along the fluid path: fluid salinity and pH, suspension velocity, porous matrix surface chemistry, and fluid temperature. Among these conditions, it is very difficult to estimate the effect of sandstone surface chemistry non-homogeneity on particle capture due to attachment. Elevated fluid temperatures have a detrimental effect on formation permeability due to particle mobilisation (Schembre and Kovscek 2005, Rosenbrand, Fabricius et al. 2013b, Rosenbrand, Hauwitz et al. 2014). Rock permeability reduction is caused by retention of the mobilised particles by straining (Bradford, Simunek et al. 2006), bridging at pore entrance (Rosseau, Hadi. L. et al. 2008), size exclusion of larger particles in smaller pores-throats (Bradford, Simunek et al. 2006), and internal cake formation (Nabzar, Chauveteau et al. 1996).

Estimation of the effect of the above particle capture mechanisms on formation damage is a routine laboratory procedure provided rock plugs are readily available from the field. However, due to various reasons rock plugs are often not available. For such a case, when only rock fragments are available, we developed a laboratory method, which aims to assess formation damage due to fines migration. This method was tested on core plugs and rock fragments of the same piece of core. These core plugs were sampled from Ladbroke Grove-1 (LG) within the same formation (Pretty Hill Sandstone Formation, Otway Basin) and depth as well as a similar geological structure as rock fragments from Salamander-1 (S), for which core plugs are not available.

The laboratory procedure included the following experimental steps: study permeability variation of rock cores with increasing water velocities and decreasing water salinity; study the effect of the above alternating process parameters on particle mobilisation in rock cores and in composite porous media made of spherical borosilicate glass beads and rock fragments from both wells; measurements of particle concentrations in outlet streams; calculation of retained particle concentration as a function of water velocity; collection of particles mobilised in porous media and their SEM-EDAX analyses for identification of minerals; and calculation of DLVO total potential of interaction between porous matrix and particles at various experimental conditions. This method determines conditions favourable for particle mobilisation, determines fines removal capacity of core plugs and rock fragments, and their effect on formation damage.

2. MATERIALS
Sandstone samples were obtained from The Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE) Drill Core Storage Facility (CSF) of the Government of South Australia (Australia). Two core plugs LG-1/c (2553.25 m depth) and LG-2/c (2557.12 m depth) from LG well were drilled in horizontal direction of a 2/3 core slab. These core plugs have the following
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dimensions: diameters 3.92 cm and lengths of 4.86 and 6.33 cm, respectively. Leftover pieces of rock were crushed to prepare rock fragments LG-1/f and LG-2/f. Fragments from Salamander-1 were also obtained from CSF and were labelled as S/f. According to the well log data, fragments from Salamander-1 consist of about 60 % sandstone, 30 % siltstone and 10 % claystone, with kaolinite and chlorite being the predominant clays. Initially, all samples were dried in the atmospheric oven at 60 °C for 24 hours. Then, they were placed in a desiccator and exposed to a residual vacuum of 1.5 Pa for 24 hours. After that, 0.6 M NaCl solution prepared from degassed MilliQ water was introduced into the desiccator. The samples remained to absorb this solution for 24 hours. Application of this imbibition method resulted in the following porosities of rock samples: 18.2 % and 17.2 % for LG-1 and LG-2 core plugs and fragments, respectively, and 10.6 % for S/f sample. It is important to preserve particles in a porous matrix from mobilisation during sample saturation. Therefore, 0.6 M NaCl solution was used; at this fluid salinity, an attractive electrostatic force favours the attachment of clay particles to the sandstone matrix, preventing them from mobilisation (Badalyan, Carageorgos et al. 2013).

3. EXPERIMENTAL

3.1 Experimental setup

Experimental studies on fines mobilisation in rock cores and fragments were carried out using the real-time permeability apparatus (Badalyan, Carageorgos et al. 2012) as shown in Figure 1.

![Figure 1: Setup for liquid permeability measurements and fines migration studies.](image)

The core plug is placed inside a Viton sleeve. This arrangement is located within a TEMCO (CoreLab, Tulsa, USA) coreholder. The manual valve is used for fixing an overburden pressure which is measured by a PA-33X pressure transmitter (PT). Overburden pressure was generated by an HPLC pump (Scientific Systems, Inc., Lab Alliance, PA, USA) by pumping MilliQ deionised water. The same pump is used to deliver the brine solutions via a manual valve. For better HPLC pump operation and maintaining pressure inside the coreholder a backpressure regulator is placed at the outlet of the coreholder. Outlet pressure was measured by a PA-33X pressure transmitter. Differential pressures across the rock core were measured by differential pressure transmitters (DPT) (Validyne Engineering, CA, USA) with three measuring ranges: 0-1.25, 0-12.5, 0-125 and 0-1250 psi. Manual valves were used for connection of the respective DPT to a flow-through system. Electrical signals from PTs and DPTs were fed into a real-time data acquisition system incorporating an ADAM-4019+ inlet data acquisition module (ADVANTECH™, Taipei, TAIWAN) and an RS-232/RS485/RS-422 signal conditioner ADAM-5060. (ADVANTECH™). Recording of all experimental parameters (pressure, differential pressure and time) in real-time mode was carried by a custom built data acquisition software (Advantech ADAMView Ver. 4.25 application builder) by a stand-alone computer. Effluent suspensions were collected in plastic beakers, and their concentrations and particle size distribution were measured by a PAMAS S4031 GO portable particle counter (PAMAS GmbH, Salzufeln, GERMANY).

Experiments with rock fragments were carried out using a different arrangement. A composite porous medium (CPM) consisted of rock fragments and was placed inside (surrounded by) borosilicate glass beads of 30-50 μm in diameter. This CPM was placed inside a thick-walled stainless steel cylinder at wet conditions (0.6 M NaCl solution), excluding ingress of air. Stainless steel mesh of 20 μm aperture was glued to inlet and outlet parts of the stainless steel cylinder, thus, keeping the composite porous medium inside the cylinder. During filling, this porous medium was compacted. The choice of certain-sized glass beads is explained by the fact that the pore throat size of a glass bead-formed porous medium should not be smaller than that of the rock fragments; all particles mobilised in the rock fragments should not be trapped by glass bead-formed pore throats. Monte-Carlo simulation resulted in LogNorm pore throat size of 3.145±0.48 μm for glass beads; it is determined as a radius of an inscribed circle between three touching glass beads. Maximum permeability of all rock samples used in the present study is equal to 28.316 mD with a porosity of 0.18. This results in mean pore-throat size of 2.66 μm, which is slightly smaller than that of the glass bead-formed porous medium.
3.2 Effect of fluid velocity on rock permeability and fines migration

Higher fluid velocities may lead to the mobilisation of fines in sandstone samples due to an increase of the hydrodynamic force. In this study, the flowing fluid has a salinity of 0.6 M NaCl in MilliQ water. The study was carried out on rock cores using a range of fluid velocities from $1.38 \times 10^{-5}$ to $1.38 \times 10^{-4}$ m/s. The validity of application of the Darcy equation for permeability calculations for the entire range of studied fluid velocities was experimentally proven according to the procedure described elsewhere (Aji, Badalyan et al. 2013). The experimental program was carried out as follows: Initially, overburden pressure of 1000±2 psi was created by the HPLC pump; then at the lowest fluid flowrate effluents were collected until the permeability of the rock core was stabilised within the experimental uncertainty for permeability (3.1 %). At this stage it is assumed that no more particles are mobilised by the hydrodynamic force; after that, the next higher fluid velocity was established with the effluent suspensions being collected. This procedure was repeated until the highest fluid velocity was achieved. A similar experimental procedure was repeated for rock fragments.

3.3 Effect of fluid salinity on rock permeability and fines migration

The effect of fluid salinity on rock permeability and fines migration was studies after the fluid velocity alternation experiments were completed. For this purpose, we chose a fluid flowrate of $1.38 \times 10^{-4}$ m/s. At this flowrate, there is a linear relationship between pressure drop across the rock core and superficial velocity; therefore, Darcy’s equation can be used for calculating the liquid permeability of a rock core. Fluid salinity was reduced step-wise from 0.6 to 1.28×10^{-4} M NaCl. For each fluid salinity, effluent samples were collected until the stabilisation of permeability was reached, assuming no particles were released due to the reduction of electrostatic force attracting particles to a sandstone matrix.

3.4 Concentration measurements and SEM-EDAX analyses for mobilised and collected fines

A portable particle counter PAMAS S4031 GO (PAMAS GmbH, Salzulven, Germany; late in the text as PAMAS) was used to measure concentration and size distribution of released fines. This instrument was calibrated against ISO Standard 21501-2:2007 (International Organisation for Standardisation 2007), and delivered the number of particles in effluent streams in the 0.641-to-9.584 µm particle size range with 16 equally spaced size intervals. In order to obtain reliable and reproducible particle number measurements, according to the manufacturer, all samples were diluted to get less than 12,000 particles/mL. For each particle size interval the total number of particles were multiplied by the volume of one particle, and the sum of the respective volumes of particles was converted to particle concentration expressed in parts-per-million (ppm). This dilution was performed by using MilliQ water with a salinity equal to that at which the quoted effluent sample was collected. This was done to keep the conditions for our particle number/size measurements equivalent to that inside a porous medium. It is known, that attractive force exists not on particle and a porous matrix, but between particles themselves (Elimelech, Gregory et al. 1995). Therefore, if zero-salinity (MilliQ) water is used for dilution, clay particles can separate from each other, and PAMAS will deliver a higher number for low-sized particles, whereas in reality, larger particle agglomerates flow through the porous medium. In this case, erroneous conclusions about the effect of mobilised particles on rock permeability (formation damage) will be made.

All effluents left after PAMAS measurements were filtered through a 0.45 µm nylon filter, and dried in the atmospheric oven at 60 °C for 12 hours. The obtained powder was fixed on a sample holder by a double-stick, electrically-conductive carbon tape, vacuumized and coated with carbon. Philips XL30 and XL40 Scanning Electron Microscopes coupled with the thin film Energy Dispersed Analysis of X-rays detector (EDAX) were used, respectively, for imaging of sample surfaces and X-ray analyses for the identification of minerals presented in fines released due to fluid salinity alterations.

3.5 Estimation of formation damage and retained particle concentration

Particles, released due to velocity and/or salinity alternation, flow through a porous medium. It is assumed, that formation damage due to particle attachment is significantly smaller than that for particles strained in pore-throats (Lemon, Zeinijahromi et al. 2011). These retained particles are responsible for permeability decline of a porous medium. Inversed normalised permeability is a linear function of the retained particle concentration (Pang and Sharma 1997). Truncating after the first two terms in Taylor’s expansion for normalized reciprocal permeability one obtains an equation for permeability decline with particle retention:

$$\frac{k_o}{k(\sigma)} = 1 + \beta \sigma$$

(1)

where $k_o$ is initial permeability of a porous medium, m²; $k(\sigma)$ is $\sigma$-dependent permeability of a porous medium, m²; $\beta$ is formation damage coefficient; $\sigma$ – is normalised (to the volume of a porous medium) concentration of strained particles.

Critical retention concentration of attached particles, $\sigma_{cr}$, is a quadratic function of fluid velocity, according to (Bedrikovetsky, Siqueira et al. 2011):

$$\sigma_{cr}(U) = \sigma_0 \left[1 - \left(\frac{U}{U_{min}}\right)^2\right] = \left[1 - \left(\frac{\mu r^2 U}{\phi H F_c x}\right)^2\right](1 - \phi_c)\phi$$

(2)

where $\sigma_0$ is the maximum retention concentration of colloidal particles at zero velocity; $U$ is fluid velocity, m/s; $U_{min}$ is the minimum velocity for which no particles can be held on the grain surface by electrostatic and gravity forces, m/s; $r$ is an internal cake thickness, which is a function of velocity, m; $H$ is thickness of a rectangular pore channel, m; $F_c$ is the total electrostatic force calculated as the sum of attractive London-van der Waals (LW); short-range electrostatic double layer repulsive (EDL) and Born repulsive (B) forces according to DLVO theory (Derjaguin and Landau 1939, Verwey and Overbeek 1999), $N_c$ is the ratio between the drag and electrostatic forces (Bedrikovetsky, Siqueira et al. 2011); and $\phi_c$ is porosity of the cake formed on the internal surface of a porous medium due to particle deposition; $\phi$ fractional porosity of a porous medium.
3.6 DLVO interaction between particles and pore matrix

Interaction between particle and porous matrix was studied and quantified using the DLVO theory of particle-particle and particle-porous matrix interaction. Within this theory, the following energy potentials determine particle-porous matrix (surface) interaction and contribute to the total particle-surface potential energy:

\[ V_{\text{tot}} = V_{\text{LW}} + V_{\text{EDL}} + V_B \]  \hspace{1cm} (3)

where \( V_{\text{LW}}, V_{\text{EDL}}, \) and \( V_B \) are London-van der Waals, electrostatic double layer and Born potential energies, respectively, \( k_B T \).

Particle-porous matrix retarded attraction \( V_{\text{LW}} \) potential is calculated according to the following formula (Gregory 1981):

\[ V_{\text{LW}} = -\frac{A_{123} \sigma_{\text{p,wmm}}}{6h} \left[ 1 - \frac{5.32h}{\lambda} \ln \left( 1 + \frac{\lambda}{5.32h} \right) \right] \]  \hspace{1cm} (4)

where, \( A_{123} = 5.539 \times 10^{-21} \text{J} \) is Hamaker constant for a system clay-water-sand (Israelachvili 2011); \( r_{\text{p,wmm}} \) weighted mean particles size, \( m; \lambda = 100, \text{nm} \) is the characteristic wavelength of interaction (Gregory 1981); and \( h \) is particle-surface separation distance, \( h \ll r_{\text{p,wmm}}, m \).

Electrical double layer interaction between particle and a porous matrix surface was calculated according to (Gregory 1975):

\[ V_{\text{EDL}} = \frac{128 \pi r_{\text{c,wmm}} n_0 k_B T}{K^2} y_\gamma Z e^{-\kappa h} \]  \hspace{1cm} (5)

where, \( \kappa = \sqrt{\frac{e^2 \Sigma n_i z_i^2 \varepsilon_0 \varepsilon_r}{n_0 k_B T}} \) is the Debye-Hückel parameter, the so-called “inverse Debye length”, \( m \); \( e = 1.602 \times 10^{-19} \text{C} \) is the elementary electric charge; \( n_0 \) – number concentration of ions “i” in bulk solution, number/m\(^3\); \( z \) is valence of a symmetrical electrolyte solution, \( z = 1 \) for NaCl; \( \varepsilon_0 = 8.854 \times 10^{-12} \) is dielectric permittivity of vacuum; \( \varepsilon_r \) is relative permittivity of an electrolyte solution; \( k_B = 1.381 \times 10^{-23} \text{J/K} \) is Boltzmann constant; \( T \) is absolute temperature of the system, K; \( n_\text{p} = 6.022 \times 10^{25} \text{number/m}^3 \) is bulk number density of ions; \( y_\gamma = \text{tanh} \left( \frac{\zeta_p}{k_B T} \right) \); \( \gamma_1 = \text{tanh} \left( \frac{\zeta_{\text{pwm}}}{k_B T} \right) \); \( \zeta_p \) and \( \zeta_{\text{pwm}} \) are reduced zeta potentials for particles and porous matrix (Elimelech, Gregory et al. 1995), respectively, \( V \).

Experimental zeta potential data for fines collected in effluent streams were measured by Zetasizer Nano Z (Model ZEN3600, Malvern Instruments Ltd., Worcestershire, UNITED KINGDOM). The Smoluchowski model according to (Hunter 1981) was used for conversion of electrophoretic mobilities into zeta-potentials. Zeta potentials of mobilized fines were measured at various studied suspension salinities and pH ≈ 7.2. Zeta potentials for sand were adopted from elsewhere (Cerda 1987).

Short-range Born repulsion potential between particles and a porous matrix was calculated according to the following formula (Ruckenstein and Prieve 1976):

\[ V_B = A_{123} \sigma_e \frac{8r_{\text{c,wmm}} + h}{(2r_{\text{c,wmm}} + h)h^2} + \frac{6r_{\text{c,wmm}} - h}{h^2} \]  \hspace{1cm} (6)

where \( \sigma_e = 0.5 \text{nm} \) is collision diameter according to (Elimelech, Gregory et al. 1995).

4. RESULTS AND DISCUSSION

4.1 Effect of fluid velocity on rock permeability and fines migration

Results for the fluid velocity effect on rock core permeability are shown in Figure 1. Significant initial reduction in permeability for LG-1/c samples is explained by the presence of the so-called “loose” particles which are not attached to the surface of a porous matrix by DLVO electrostatic forces. Even very low fluid velocity was sufficient for these particles to be mobilised and cause significant formation damage (almost 70 % reduction of initial permeability). Starting from about 2.77x10^{-4} \text{m/s}, permeability of rock core samples was insignificantly affected by increasing velocity: 3.44 and 2.91 % standard deviation in permeability for LG-1/c and LG-2/c samples, respectively.

different behaviour was observed for the so-called composite porous media formed by glass beads and rock fragments. As an example, we consider the case for fragments prepared from LG-1 rock sample. The following parameters were measured for a glass beads-only-formed porous medium: \( \ell_p = 5.089 \times 10^{-2} \text{m}, r_p = 1.213 \times 10^{-2} \text{m}, \) and \( k_B = 1.148 \text{mD} \). Permeability of a non-damaged LG-1/c sample is 28.316 mD; we adopt this value as permeability for a non-damaged LG-1/c sample. In all calculations for a composite porous medium, we use equivalent values of lengths for glass beads and fragments: we measure volumes of glass beads and rock fragments used, then assuming they fill the entire cross-section of a thick-walled stainless steel cylinder (see Section 3.1) the equivalent lengths for glass beads and fragments are calculated, respectively: \( \ell_p^{eq} = 4.067 \times 10^{-7} \text{m} \) and \( \ell_f^{eq} = 1.022 \times 10^{-7} \text{m} \). The following equation was used for the evaluation of permeability of fragments from that for a composite porous medium:

\[ k_f = \frac{k_{comp}}{k_{comp}} \frac{k_f^{eq}}{k_p^{eq}} \]  \hspace{1cm} (7)

where \( \ell_{\text{comp}} = 5.089 \times 10^{-2} \text{m} \) is the length of a composite porous medium; \( k_{\text{comp}} \) is permeability of a composite porous medium at various fluid velocities, mD; \( \alpha \) is an empirical fitting coefficient which is also a function of rock porosity. Fitting experimental data \( k_f \) – data (with the above assumption that \( k_f = 28.32 \text{mD} \)) the following value was obtained: \( \alpha = 4.27 \times 10^{-2} \). When applying this
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value to a composite porous medium based on S/f sample, the following value for permeability of a non-damaged sample was obtained: \( k_f = 10.12 \text{ mD} \). According to the well completion report, this value varies between 2.9 and 6.9 mD. However, as follows well petrophysics report, this value according to lin-log method is 10.5 mD which with increasing fluid velocity declines to 5.58 mD. We regard the agreement between the present result and that from the two reports as satisfactory. The obtained results together with equation (7) we use for the evaluation of permeability of fragments.

It was observed that at fluid velocities higher than \( 3.60 \times 10^{-4} \text{ m/s} \), fluid predominantly flows through glass beads-formed porous medium. Therefore, we limited processing of experimental data by this fluid velocity. Applying equation (7) to the experimental \( k_{comp} \)-data, we obtained the following relationships for all studied fragments, \( k_f = f(u) \) (see Figure 2). As follows from Figure 2, there is a good agreement between experimental permeability data for LG core samples. Re-calculated permeability for S/f sample using conversion coefficients for LG-1/f sample also agrees well with data from the well completion report.

Figure 2: Effect of fluid velocity on rock permeability: red circles - LG-1/c; blue circles - LG-1/f calculated according to equation (7); red triangles – LG-2/c; blue triangles – LG-2/f according to equation (7); blue squares – S/f according to equation (7).

At each fluid velocity effluent sample were collected and their concentration and particle size distributions were measured with results presented elsewhere (Badalyan, Carageorgos et al. 2013). These concentrations were later used for calculation of \( \sigma_{cr} \).

4.2 Effect of fluid salinity on rock permeability and fines migration

Experiments on velocity-induced fines mobilisation were followed by studies on the effect of fluid salinity on fines migration. Gradual decline of permeability with fluid salinity decrease for LG-1/c and LG-2/c were reported elsewhere (Badalyan, Carageorgos et al. 2013). In this paper, we present these results in a slightly different form (see Figure 3).

Figure 3: Effect of fluid salinity on rock permeability. red circles - LG-1/c; blue circles - LG-1/f calculated according to equation (7); red triangles – LG-2/c; blue triangles – LG-2/f according to equation (7); blue squares – S/f according to equation (7).
As follows from Figure 3, the permeability for all studied samples decreases with lowering fluid salinity. The greatest permeability decrease was observed for LG-1/c sample: from \approx 8 down to \approx 1.3 \text{ mD}. Permeability for fragments was calculated according to the procedure outlined in Section 4.1. For S/f sample, permeability dropped from 5.59 to 0.33 \text{ mD} with salinity decreasing from 0.6 \text{ M NaCl} to 1.25 \times 10^{-4} \text{ M NaCl (MilliQ water). Reservoir water salinity for Salamander-1 varies from 0.2 to 0.025 NaCl; this according to Figure 3 corresponds to permeabilities from 1.238 to 0.459 mD, which very well agrees with the formation permeability of 1.2 mD after our acidising and discharge test. At each fluid salinity, effluent samples were collected and their concentration and particle size distributions were measured with results presented elsewhere (Badalyan, Carageorgos et al. 2013). For all three fragments, the highest particle concentrations in effluents were observed at low salinities of 0.005, 0.001 and 1.25 \times 10^{-4} \text{ M NaCl}. Low salinity of discharge (reservoir water) is the mostly probable reason responsible for fines mobilisation and consecutive formation damage of Salamander-1 geothermal well.

4.3 Estimation of formation damage and retained particle concentration

Results of our SEM analyses for fines released from L-1/f and S/f are presented in Figures 4 and 5. As follows from these figures kaolinite and chlorite are present in the studied samples. There are similarities between two the samples with regards to the presence of kaolinite and chlorite distributed in the entire area of SEM photograph. Analysis of all gathered SEM photographs showed that clays are the principal minerals in collected fines with EDAX elemental analysis supporting SEM observations. Mineral percentage in mobilized fines was not identified.

![Figure 4. SEM image and EDAX spectrum for L-1/f sample (EDAX spectrum is shown for kaolinite only).](image1)

![Figure 5. SEM image and SEM spectrum for S/f sample (EDAX spectrum is shown for chlorite only).](image2)

4.4 Estimation of formation damage and retained particle concentration

For calculation of critical retention function from experimental permeability and particle concentration data for L-1/c sample we used equations (1) and (2). Formation damage coefficient was adopted as $\beta = 250$ with an assumption that only strained particles are responsible for formation damage. This resulted in an experimental critical retention function shown in red filled circles in Figure 6. As follows from this figure, there are 4 distinct parts of the $\alpha_{cr} = f(u)$-relationship. The first one (almost horizontal at lower fluid velocities), corresponds to the removal of the so-called “loose” particles not electrostatically attached to the porous matrix surface. The three remaining parts are the result of interplay between hydrodynamic and electrostatic forces and, probably, particle size. To match model (2) to the experimental data the following parameters were used for four fluid velocity ranges: mean particle radius varied from 1.3 to 1.82 \text{ \mu m}; lifting force coefficient was fixed at $\gamma = 650$; drag force coefficient, $\omega$, varied from 3750 to 60; rock porosity $\phi = 0.18$; cake porosity $\phi_c = 0.94$. Agreement between experimental data and modelling results is good (see Figure 6).

![Figure 6.](image3)
We applied a similar approach to S/f experimental data at fluid velocities from 0 to 3.606×10⁻⁴ m/s with the same formation damage coefficient and the following model parameters: mean particle radius 1.104 μm; lifting force coefficient was fixed at γ = 650; drag force coefficient ω = 1200; rock porosity φ = 0.106; cake porosity φc = 0.96. Agreement between experimental data and modelling results is good (see Figure 6). Lower initial value of retaining concentration for S/f sample (σ₀_greater_than = 4.27×10⁻³) than that for L-1/c sample (σ₀_greater_than = 1.01×10⁻³) is an indication of the less capacity of the sample to release clay particles, and, therefore, less formation damage, which is supported by experimental data in Figure 2.

4.4 DLVO interaction between particles and pore matrix

Zeta potentials for fines and sand matrix necessary for calculation of DLVO total potential of interaction were reported elsewhere (Badalyan, Carageorgos et al. 2013). As follows from Figure 7, at 0.6 M NaCl fluid salinity the total potential of interaction for L-1/c sample is negative with the primary minimum at -1929 k_BT indicating to a significant attraction between clay particles and sand matrix. Salinity decrease from 0.1 through 0.05 to 0.001 M NaCl results in primary minimum becoming positive (-89.04, 1744 and 9592 k_BT, respectively). Additionally, significant positive repulsive barriers of 400, 1987 and 10362 k_BT, respectively, are sure signs of a strong repulsive “clay-sand matrix” potential. This electrostatic repulsion is responsible for clay particles mobilisation leading to significant permeability reduction (see Figure 3).

Lower magnitude of a repulsive “clay-sand matrix” potential of -554 k_BT is observed for S/f rock sample for 0.6 M NaCl. It means that clay particles are more readily to be mobilised in this sample. The following parameters in equation (5) make V_ELDO temperature-dependent: T, κ, γ₁ and γ₂. Thickness of electric double layer is characterised by the Debye-Hückel parameter, κ⁻¹ (Ohshima 2006): although, κ⁻¹ should increase with absolute temperature according to notes to equation (5) at constant electrolyte concentration, in reality, this relationship is more complex due to the fact that ε_r^NaCl-H₂O decreases with temperature (Rosenbrand, Haugwitz et al. 2014). When temperature increases from 25 to 130 °C, κ⁻¹ decreases by 15.8 %. This results in a thinner EDL and a reduced EDL “clay-sand matrix” repulsion translating to a more mutually attractive nature of their interaction. Reduced surface potentials for clay and quartz are functions of both absolute temperature and respective zeta potentials. Zeta potentials for kaolinite and quartz decrease with temperature (Ramachandran and Somasundaran 1986, Schember and Kovscek 2005, Rodriguez and Araujo 2006): we used their zeta-potential gradients for kaolinite and quartz to extrapolate our zeta-potentials (Badalyan, Carageorgos et al. 2013) to temperature of up to 130 °C. Four DLVO curves presented in Figure 7 show that the total potentials of interaction corresponded to primary minima increase with temperature rise from 25 to 130 °C: -554, -70, -61 and -57 k_BT, respectively. Similar negative energy of interaction was reported for the kaolinite-quartz system at 80 °C and 0.34 M NaCl (Rosenbrand, Fabricius et al. 2013a). As follows from Figure 7, the fact that DLVO curves move towards less negative values means that temperature effect on zeta potentials is more pronounced than on the Debye-Hückel parameter. Taking into the account that lower salinity of reservoir water in Salamander-1 well will further increase EDL thickness at 130 °C, the green DLVO curve in Figure 7 will move towards positive potential values, resulting in more clay particle mobilisation and reduction in permeability.
5. CONCLUSIONS

Evaluation of well formation damage was performed on rock core samples and rock fragments with a good agreement between them. The proposed approach correlates core plug and rock fragment permeability data very well.

Initial permeability reduction in rock samples is caused by mobilisation of the so-called “loose” particles not attached to the surface of a porous matrix due to DLVO electrostatic forces.

Low-salinity water is responsible for greater formation damage than velocity-induced fines migration, due to an increased EDL repulsion force between clay particles and sand grain surfaces. At low salinities, rock samples were irreversibly damaged since the released clay particles were trapped inside pores.

Clay minerals are the main reason for formation damage in Ladbroke Grove-1 and Salamander-1 due to their mobilisation and consecutive plugging pore throats in the studied sandstones.

Elevated temperatures have a greater effect on zeta potentials of clay particles and a porous matrix than on the Debye-Hückel parameter resulting in an expansion of the EDL and, therefore, a mutual “clay particle”-“porous matrix” repulsion, leading to an additional (low salinity) clay particle mobilisation and further formation damage.

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