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Analysis of Field Case in Salamander-1 Geothermal Well

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ABSTRACT

Analysis of Salamander-1 geothermal well performance for possible formation damage necessitates laboratory tests on its rock materials. Information available from other wells from the same formation indicates that rock deformation and fines migration may contribute to the formation damage. Estimation of these reasons was complicated by unavailability of cores from the well for laboratory analysis.

A novel method for prediction of formation damage from cuttings is proposed. It is especially important when rock cores are not available. According to this method, rock cores from another well, Ladbroke Grove-1 from the same formation, were used in the laboratory study for the evaluation of the effect of effective stress on their liquid permeability, and for velocity- and salinity-induced fines migration which may result in formation damage. Fines migration tests were carried out on a composite porous media including fragments from Ladbroke Grove-1 and Salamander-1 wells. Sandstone core deformation doesn't significantly affect core permeability and doesn't contribute to formation damage. Significant initial reduction of cores permeability was due to fines mobilisation at various velocities of high salinity water. Further formation damage was caused by flow of low salinity water. Similar fines migration results were obtained for composite porous samples with fragments. Scanning Electron Microscopy identified clays (kaolinite and chlorite) as major minerals in collected fines. Application of Derjaguin-Landau-Verwey-Overbeek (DLVO) theory shows that decrease of water salinity to values similar to those for discharge and reservoir water creates a strong repulsion force between clay particles and sand. This results in fines mobilisation, their transport through porous media, capture by smaller pores and formation damage. Good correlation of fines migration data for cores and fragments from Ladbroke Grove-1 well successfully validates the proposed methodology.

1. INTRODUCTION

Salamander-1 geothermal well is located in the Pretty Hill Formation of the Otway Basin in South Australia. Lower than expected performance of this well may be caused by rock deformation or fines migration. Of these, fines migration in the Salamander-1 well may be the most possible cause for the well damage. Difficulties in reliable assessment of formation damage in Salamander-1 well arise from unavailability of cores. However, rock fragments and cuttings are readily available. For the first time, a new method of prediction of formation damage from cuttings (not from cores) is proposed. It is especially important when rock cores are not available. Application of this method for an 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 fragments by alternation of velocity and salinity of water flowing through the composite porous medium; SEM-EDAX analyses of collected fines for identification of minerals; zeta-potential measurements for collected fines and calculation of the total potential of interaction between fines and sand. This method determines fines capacity removal from rock fragments and its effect on formation damage. The proposed methodology was successfully validated by a good agreement between fines migration data for rock cores and fragments from Ladbroke Grove-1 well from the same formation.

2. MATERIALS

In the present study, two rock cores (sandstone) and three fragments (sandstone) were used (see Table 1). Samples porosities were measured by imbibition method saturating them with 0.6 M NaCl solution to prevent lifting of fines in rocks during saturation (lifting of fines cause formation damage, which should be avoided during sample preparation).

Sample Name	Core diameter, cm	Core length, cm	Porosity, %	Fragments volume, cm^3
LBrGr-1 (2553.25 m) - core	3.920	4.860	18.21	N/A
LBrGr-1 (2557.12 m) - core	3.917	6.330	17.18	N/A
LBrGr-1 (2553.25 m) - fragment	N/A	N/A	18.38	4.722
LBrGr-1 (2557.12 m) - fragment	N/A	N/A	16.65	6.149
Salamander 1 (2903-2906 m) - fragments	N/A	N/A	21.00	9.596

Table 1. Characterization of rock samples.

3. EXPERIMENTAL

3.1 Experimental setup

An experimental apparatus (see Figure 1) described in details in Badalyan et al (2012) was used for the following tests: liquid permeability measurements of rock core and composite samples made of 30-50 μm glass beads and rock fragments, and study of velocity- and salinity-induced fines migration leading to formation damage.

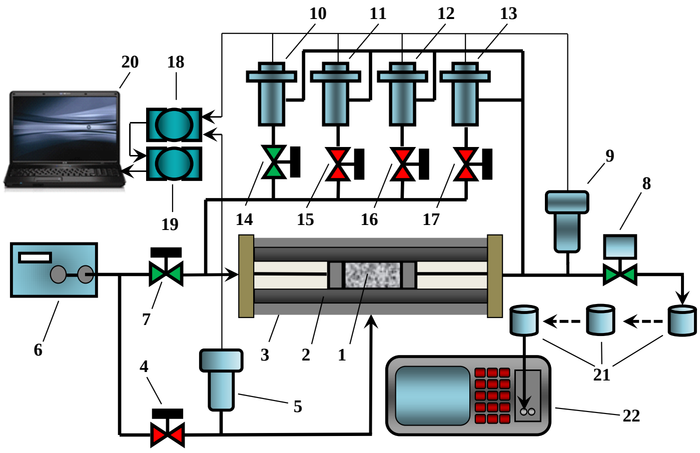

Figure 1: Setup for liquid permeability and fines migration measurements: 1 – rock core; 2 - rubber sleeve; 3 - high-pressure core holder; 4, 7, 14-17 - manual valves; 5, 9 – high-accuracy pressure transducer; 6 - HPLC pump; 8 - back-pressure regulator; 10-13 - differential pressure transducers; 18 - data acquisition module; 19 - signal converter; 20 - personal computer; 21 -beakers; 22 - portable particle counter.

3.2 Effect of rock deformation on permeability

During water production in geothermal wells pressure in formation declines, which is equivalent to an increase in effective stress. These changes can effect rock permeability and, consequently, well performance. The effect of rock deformation on permeability was studied on two Ladbroke Grove-1 rock cores: LBrGr-1 (2553.31 m) and LBrGr-1 (2557.17 m). Due to possible irreversible changes in rock during rock deformation studies the chosen samples are different and located within approximately 5 cm from those listed in Table 1. During these studies, an overburden pressure was maintained at 2000 psi, and liquid permeability of cores was measured at gradually increased pore pressure from 50 to 1990 psi. This was achieved by increasing inlet pressure of 0.6 M NaCl solution by alternation of fluid inlet flowrate and controlling backup/outlet pressure.

3.3 Velocity- and salinity-induced fines migration

Velocity-induced fines migration was performed using the above experimental setup at fluid (0.6 M NaCl in MilliQ water) velocities varied from 1.38×10^{-5} to 1.38×10^{-3} m/s. This was followed by low salinity-induced fines mobilisation at 1.38×10^{-4} m/s. Salinity of flowing solution gradually decreased from 0.6 to 1.28×10^{-5} M NaCl (MilliQ water). Effluent samples were collected for each value of velocity and salinity, and their concentration and zeta-potentials were measured.

3.4 Concentration measurements of released fines

Concentration and size distribution of released fines were measured by a portable particle counter PAMAS S4031 GO (PAMAS GmbH, Salzuflen, Germany). This unit delivered results for particles number in the 0.641-to-9.584 μm particle size range.

3.5 SEM-EDAX analyses of released fines

Effluent suspensions after concentration measurements were filtered through a 0.45 μm filter and dried. 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 velocity and salinity alterations.

3.6 DLVO interaction between particles and pore matrix

In order to calculate interaction between fines and porous matrix, data for their zeta-potentials at various experimental conditions are required. Electrophoretic mobilities of fines released from studied cores and fragments were measured by Zetasizer Nano Z (Model ZEN3600, Malvern Instruments Ltd., Worcestershire, UNITED KINGDOM). 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.

Particle-bead interaction according to Derjaguin-Landau-Verwey-Overbeek (DLVO) theory from Derjaguin and Landau (1993) and Verwey and Overbeek (1999) is determined by attractive long-range London-van der Waals, and short-range repulsive electrical double layer and Born forces contributing to the total particle-surface potential energy, V_{tot}, as follows:

$$V_{tot} = V_{LW} + V_{EDL} + V_B \tag{1}$$

where V_{LW}, V_{EDL} and V_B, are London-van der Waals, electrostatic double layer and Born potential energies, respectively, k_BT. Formulas proposed by Gregory (1981), Gregory (1975) and Ruckenstein and Prieve (1976) were used for calculation of V_{LW}, V_{EDL} and V_B, respectively.

4. RESULTS AND DISCUSSION

4.1 Effect of rock deformation on permeability

As follows from Figure 2, increase of effective stress from 500 to 1980 psi doesn't have an appreciable effect on permeability of studied core samples. At lower values of effective stress which correspond to high pore pressures, core permeability start to negligible increase due to expansion of a porous network. Similar results were reported by Dong et al (2010) for rocks from similar depths. Similar trend in stress-related permeability for Salamander-1 fragments is most likely to occur, since these samples come from the same formation layer.

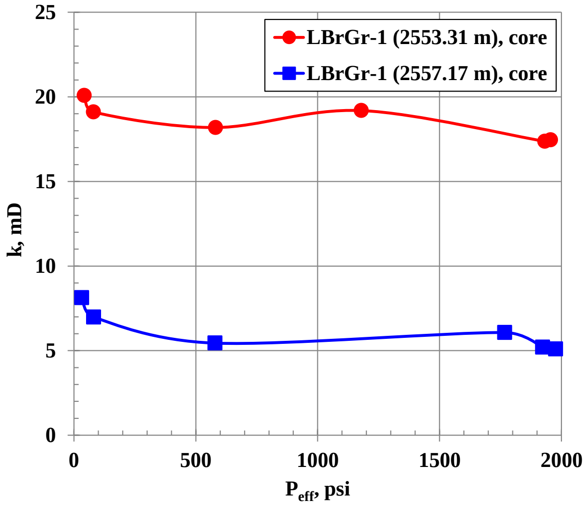

Figure 2: Stress-related permeability for Ladbroke Grove-1 cores.

4.2 Velocity- and salinity-induced fines migration

Results for velocity-induced fines migration for cores and fragments for LBrGr-1 (2553.25 m) and LBrGr-1 (2557.12 m), and for fragments for Salamander-1 (2903-2906 m) are given in Figure 3: here, σ is the ratio of incremental volume of fines collected at each velocity to the volume of a sample (core or fragments). The amount of particles mobilized in cores show increasing trend with solution velocities. Relatively high amount of fines released by fragments at initial very low velocity of solution is caused by the fact that "surface-to-volume ratio" for fragments is higher than that for cores, thus a greater surface area is exposed to flowing solution, causing more particles to be released. These so-called "loose" particles are located in pores but not attached to rock porous matrix by electrostatic forces. Hydrodynamic force of a flowing solution mobilizes such particles located in the close vicinity to fragment surface. The particles are not trapped by deeply located pores of rock and are carried away by a stream of a solution flowing through a porous matrix formed by glass beads (mean pore throat radius r_{pore} = 3.78±0.54 μm) towards the outlet of the sample holder. The fact that these particles are mobilized at high salinity of suspension (0.6 M NaCl) indicates that DLVO forces don't play role in this process, and supports their "loose" nature. Such velocity assisted fines mobilisation was responsible for reduction in permeability of undamaged LBrGr-1 cores from 28.67 to 8.01 mD and from 5.46 to 3.20 mD, respectively.

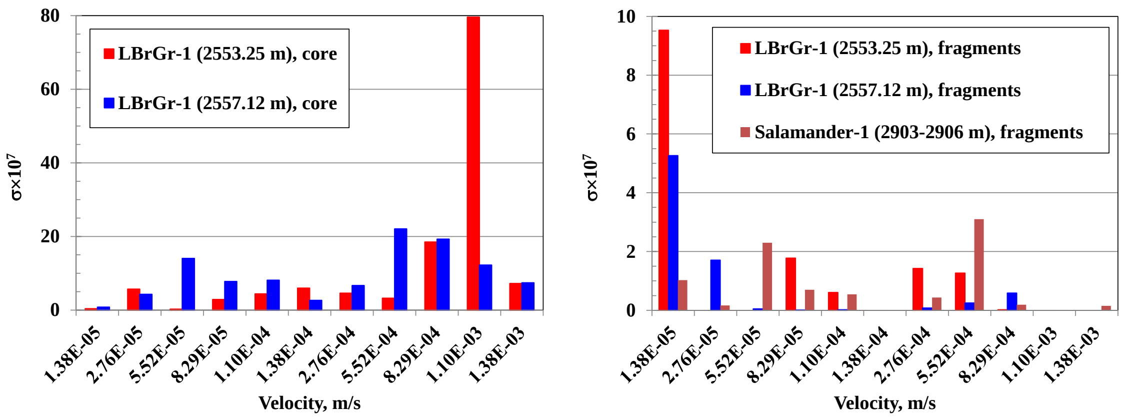

Figure 3: Normalised incremental particle volume in effluents during velocity alterations.

Weighted mean radius for collected particles increased with velocity for both cores from ≈ 1.71 to 2.10 μm and from ≈ 1.23 to 1.57 μm, respectively (see Figure 4). Mean particle radius for particles released from LBrG1-1 (2553.25 m) fragments is slightly higher than that for cores at low velocities due to the fact that larger particles can freely pass through and not be trapped by glass beads-formed porous medium with a mean pore throat radius larger than that for particles.

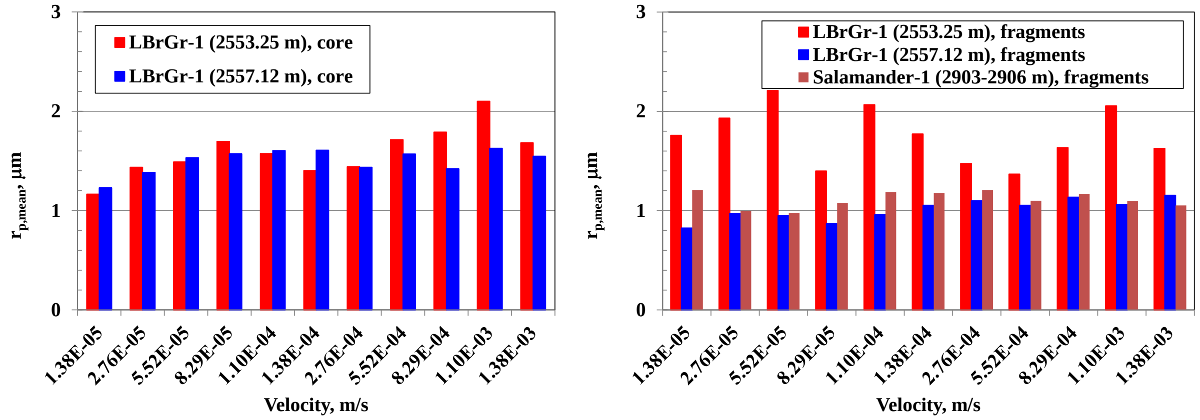

Figure 4: Particle size distribution in effluents during velocity alterations.

Results for low-salinity-assisted formation damage due to fines migration at flowrate of 10 mL/min (velocity ≈ 1.38×10^{-4} m/s) are presented in Figure 4. Two samples LBrGr-1 (2553.25 m) and LBrGr-1 (2557.12 m) show similar step-like trend in permeability reduction with decrease of salinity of flowing solution. For both samples, permeability dropped approximately 8 times when fluid salinity decreased from 0.6 to 1.25×10^{-4} M of NaCl (MilliQ water).

If for Salamander-1 well, either discharge water or reservoir water salinities vary from 0.2 to 0.025 M NaCl, then according to our experimental results presented in Figures 5 and 6, such water salinity values are too low to keep fines attached to the surface of a porous matrix, and, thus, prevent the formation damage. With such low salinity of discharge water, permeability of LBrGr-1 (2553.25 m) decreases from ≈ 8 down to ≈ 1.3 mD and that for LBrGr-1 (2557.12 m) decreases from ≈ 3.2 to ≈ 0.9 mD, which is sufficient for significant well damage. These observations lead to the conclusion, that damage of Salamnder-1 well may be also due to fines migration as the result of a probable low-salinity water flow from this geothermal reservoir (either discharge or reservoir water, or both).

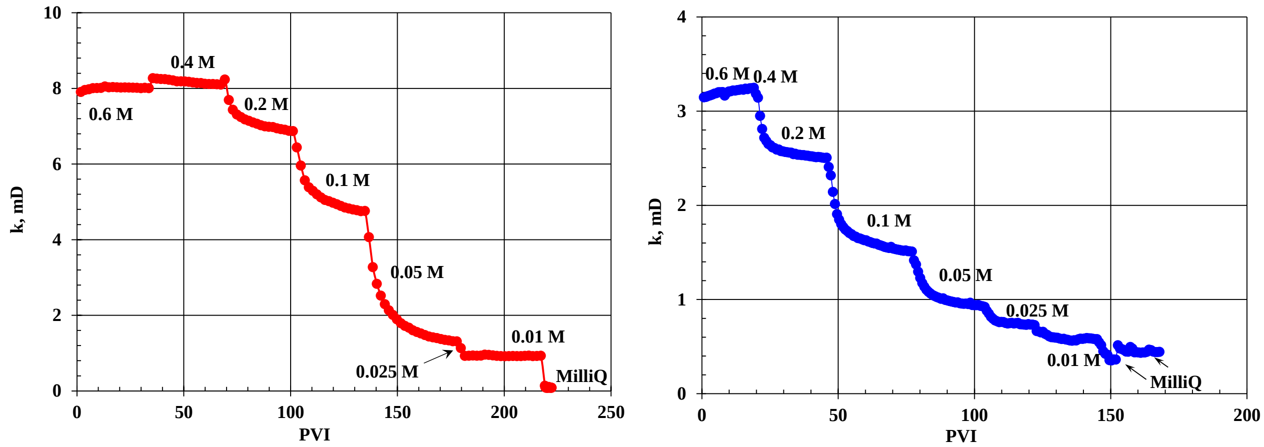

Figure 5: Low salinity-induced formation damage for LBrGr-1 (2553.25 and 2557.12 m) cores.

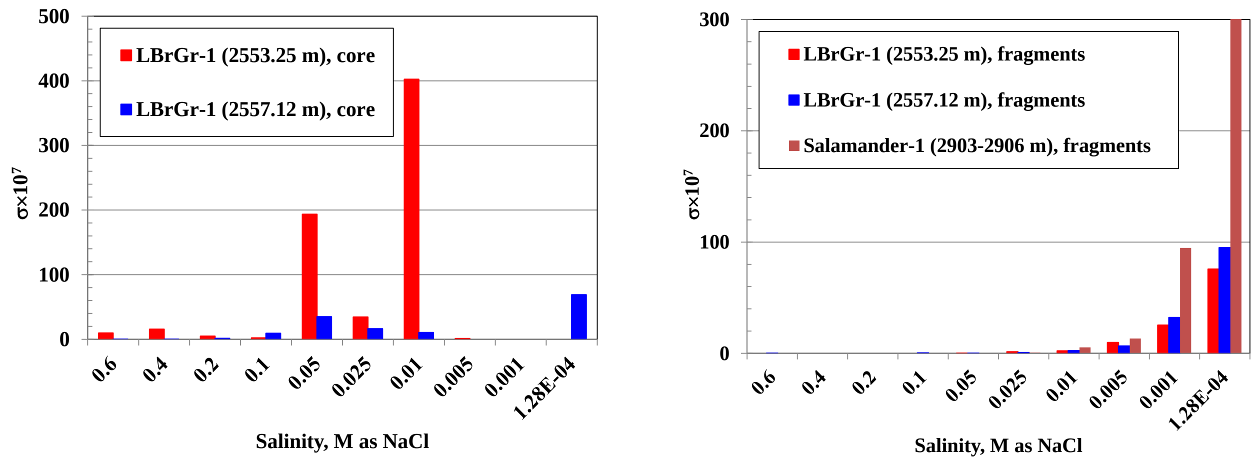

Figure 6: Normalised incremental particle volume in effluents during salinity alterations.

Normalised incremental volumes of effluent particles as a function of solution salinity for cores and fragments are presented in Figure 6. For both cores, appreciable amount of effluent particles were recorded at salinities ranging from 0.05 to 0.01 M NaCl, which is consistent with permeability reduction in this salinity range (see Figure 5). Different behaviour was observed for effluent particles collected from fragments: all three samples showed significant increase of collected particle volume towards very low salinities of 0.001 M NaCl and MilliQ water. This can be explained by the fact, that salinity alteration tests were performed after study of velocity effect on particle mobilisation, and most of the particles from the fragment surface and adjacent volume have been mobilized and removed.

4.3 SEM analyses of released fines

Results SEM analyses for fines released from LBrGr-1 (2553.25 m) and Sal-1 (2903-2906 m) m are presented in Figures 7-9. As follows from these figures kaolinite, chlorite and feldspar are present in the studied samples. There are similarities between two samples in regards to the presence of kaolinite and chlorite distributed in the entire area of SEM photograph. Analysis of all presented SEM photographs showed that clays are the principal minerals in collected fines with EDAX elemental analysis supported observation from SEM. Mineral percentage in mobilized fines was not identified.

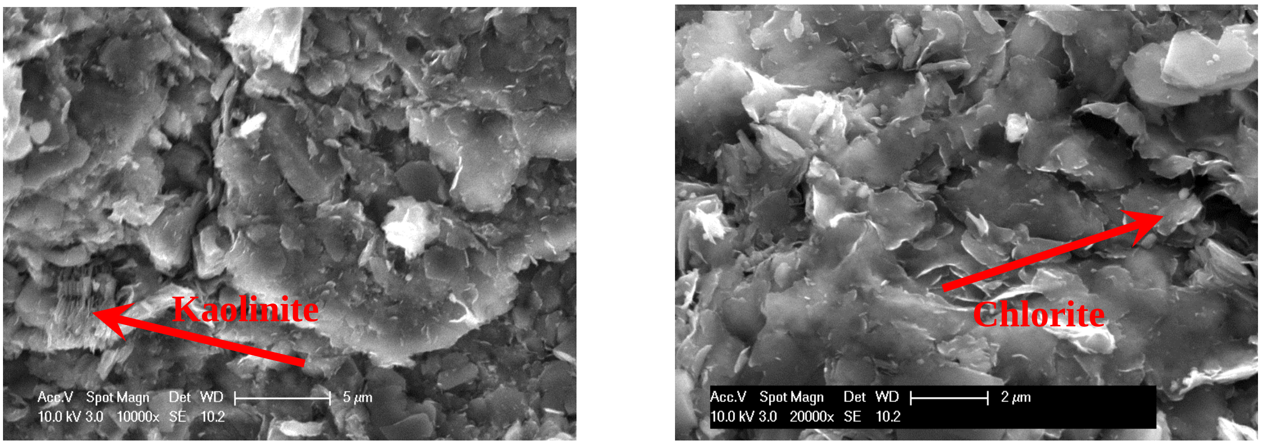

Figure 7. SEM-EDAX for Ladbroke Grove-1 (2553.25 m).

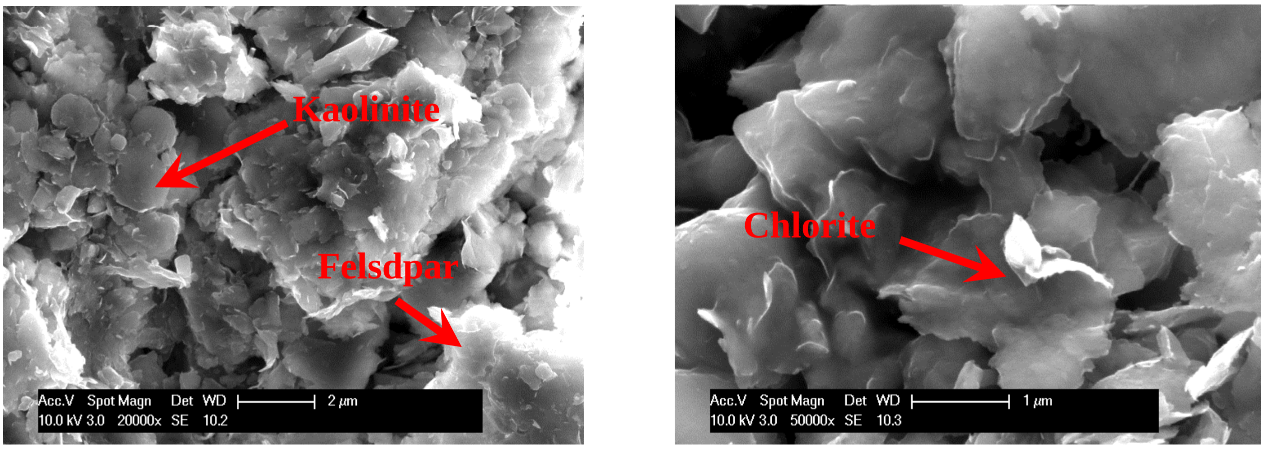

Figure 8. SEM photographs for Salamander-1 (2903-2906 m).

4.4 DLVO interaction between particles and pore matrix

Measured zeta-potentials for fines removed from rock cores and fragments, as well as for sand by Cerda (1987) and by Elimelech et al (2000) are given in Figure 9. These values were used for calculation of total potential of interaction between fines and the porous matrix for LBrGr-1 (2553.25 m) and Salamander-1 (2903-2906 m) shown in Figure 10.

As follows from Figure 5, there exist “clay particle-sand surface” attraction at salinities varying from 0.4 to 0.2 M NaCl – the total potential of interaction is negative. At salinities below 0.1 M NaCl, DLVO potentials become positive, meaning an increase in EDL electrostatic repulsion forces between particle and sand surface. This interaction became possible due to broken bonds in surface groups of kaolinite and sand in the presence of water Rosenbrand et al (2013). Comparing these data with those for core permeability (see Figure 5) indicates that even at 0.2 M NaCl the strength of electrostatic attraction force is not high enough to keep particle on the sand surface at suspension velocity of 1.38×10^{-4} m/s. Similar trend for DLVO curves is observed for Salamander-1 (2903-2906 m) fragments, although the magnitude of repulsion is lower than that for LBrGr-1 (2553 m) sample. Such similarities between particle mobilization from fragments from the two wells indicate that fines detachment, migration and pore blockage are the most probable reasons responsible for formation damage in Salamander-1 well.

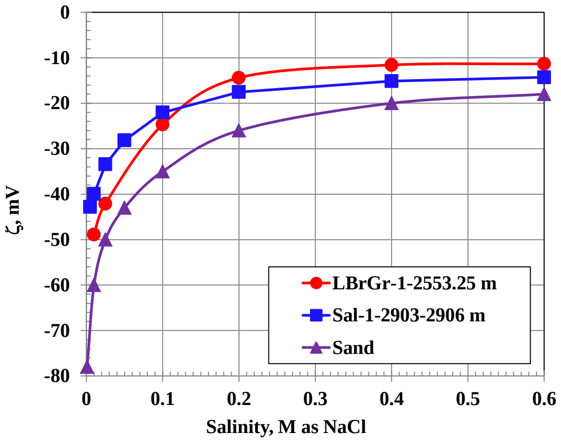

Figure 9: Zeta-potentials-*vs*-salinity for fines removed from cores and fragments, and for sand.

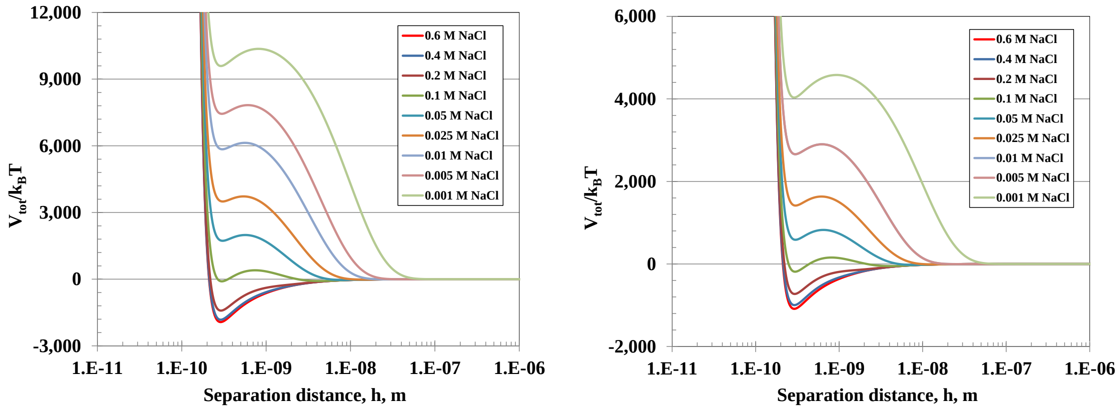

Figure 10: Total potential of interaction for clay-water-sand system forLBrGr-1 (2553.25 m) and Salamander-1 (2903-2906 m).

5. CONCLUSIONS

For the first time, estimation and prediction of well formation damage was carried out by evaluation of fines removal capacity and fines migration in rock fragments, not cores.

Rock deformation during water production doesn't have effect on permeability of studied LBrGr-1 cores and Salamander-1 rock.

Velocity-induced fines migration is responsible for a significant reduction of rock permeability leading to initial formation damage in all studies rocks.

Low-salinity water leads an increase of EDL repulsion force between clay particles and sand surface, further particle mobilisation and formation damage in both Ladbroke Grove-1 and Salamander-1 rock samples, and, therefore in the respective wells.

Kaolinite and chlorite are the major clay minerals presented in fines released from cores and fragments from Ladbroke Grove-1 and Salamander-1 wells, and are responsible for rock permeability reduction.

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