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EXPERIMENTAL STUDY OF MONOPHASIC PERMEABILITY CHANGES UNDER VARIOUS STRESS PATHS

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ABSTRACT

Strains and monophasic permeability changes have been simultaneously measured during experiments performed on a Vosges sandstone. Several loading paths have been investigated together with several pore pressure and confining pressure levels. The results are analyzed in order to evidence the influence of the effective mean stress p' and the influence of the deviatoric stress q. It is shown that a criterion can be defined in the (p'-q) plot for the permeablity evolution. Inside the domain defined by the criterion, the permeability change is nil or small whatever the loading path is. Outside the domain, the permeability steadily decreases and may vary strongly. Finally, the permeability reduction rate can be determined for a given stress path and a given deviatoric stress level.

KEYWORDS

Fluid Flow • Hydraulic Conductivity • In Situ Stresses • Laboratory Tests • Monophasic Permeability • Strain • Stress • Stress Paths • Triaxial Testing

1. INTRODUCTION

When producing a reservoir, the main mechanisms of primary production are the fluid expansion and the pressure drop. The production thus induces a depletion that in turn induces effective stress changes. These stresses finally induce strains. Note that most of the time the rock is assumed to deform uniaxially - the socalled oedometric case. In situ measurements (*Rhett and Teufel*) have shown that the ratio K between the effective horizontal stress variation ($\Delta\sigma'_h$) and vertical stress variation ($\Delta\sigma'_v$) is constant. As a consequence the deviatoric stress change ($\Delta q = \Delta\sigma'_v - \Delta\sigma'_h$) increases while the pressure drop increases :

$$\Delta q = - b\ (1\text{-}K)\ \Delta p_p$$

The changes due to the reservoir depletion induce changes of the mechanical parameters and of the petrophysical characteristics of the rock. The permeability can thus drastically drop, reducing the well productivity and it can even endanger the economics of the well production.

Since *Fatt & Davis* pioneering works (1952), permeability reduction due to the reservoir production has been much studied (*David, Wilhelmi, Gray, Holt, Morita, Rhett, Teufel*). However, few research work dealt with the influence of the stress deviator change in the permeability changes. From a literature review, it appears that the permeability evolution can be split into 3 phases (see Figure 1). The first phase is controlled by the initial closure of the cracks which induces a permeability decrease. The second phase corresponds to a lower decrease of permeability which is attributed to the elastic deformation of the pores. The third phase is important but has been less studied in the literature. During this phase, the permeability evolution results from two opposing mechanisms. The first mechanism consists in the closure of microcracks together with pore collapse. This mechanism can be associated with a significant production of solid particles. It induces a reduction of the pore area opened to the fluid flow and hence a permeability reduction. The second mechanism corresponds to the propagation of existing microcracks. This mechanism creates more flow paths and thus induces an increase of the permeability.

In order to better understand the phenomena, strains and monophasic permeability changes have been simultaneously measured during experiments performed on a Vosges sandstone. Several loading paths have been investigated together with several pore pressure and confining pressure levels. The results are analyzed in order to evidence the influence of the effective mean stress p' and the influence of the deviatoric stress q.

2. EXPERIMENTAL PROCEDURES

a) Rock selection

The " Vosges Vosgian " sandstone was selected for three main reasons. Firstly, 80 % of the reservoirs are sandstone reservoirs and they contribute to 60% of world oil reserves (*Cossé*). Secondly, the behavior of crack dominated rocks has been much studied - see for instance Walsh (*Walsh*) - and the acquired knowledge appears to be satisfactory in this area. It was thus considered that our research should be focused on a porous sandstone which behavior could be studied beyond the elastic domain. Finally, many lab works have been performed using this sandstone which allows to compare our results to previously published data.

b) Experimental procedures

There are two basic methods to measure permeability (Bernabé *et al.* , Read *et al.*). The first one is the pressure pulse method. It is used for very low permeability rocks. The fluid pressure is increased at the core inlet by a pressure pulse. From the transit time of the pore pressure pulse through the core, the permeability can be computed. The second method is the equilibrium state method. It is usually used for rocks having a permeability greater than 10^{-3} mD.

The equilibrium state method was thus used in our experiments. It is similar to Darcy's method. The differential pressure between the inlet and the outlet of the core is measured under constant flow rate (Q) conditions. Given the core inlet area S, the core length L and the fluide dynamic viscosity μ for a given temperature and a given fluid pressure, the permeability can be determined from Darcy's law *(Darcy)* :

$$k = -\frac{\mu Q L}{S \Delta p}$$

Oil was used as a saturating fluid in our experiments. This minimizes physico-chemical interactions between the saturating fluid and the rock. However, it is of interest to note that viscosity varies as a function of pressure and temperature. These changes had to be characterized.

Saturating fluid viscosity as a function of pressure and temperature

Viscosity changes have been plotted in Figure 2 for the fluid used in our experiments. Since temperature

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is more or less constant in our lab, the most important parameter was the pressure. In our experiments, the pore pressure has been changed in the range [5–35 MPa].

For this type of investigation, very few work has been devoted to the influence of pressure on viscosity while, under certain circumstances, we found it to be the major factor for pressure drop determination.

c) Experimental set-up

The experimental set-up consists of 3 parts (see Figure 3) : a) a triaxial cell ; b) a pressure circuit including a differential pressure transducer, tubings and 3 pumps allowing pressure or flow regulation ; c) an automatic system for loading control and data acquisition. This set-up allows pore and confining pressure control, together with strain and permeability measurements.

d) Preparing the cores

The cores are 40 mm in diameter and 80 mm in height. They were cored perpendicular to the bedding in a cubic bloc 500 mm long. After surfacing, the samples are scanned in an X-Ray computed tomography scanner in order to spot any petrographic defect (crack for instance) that could hamper permeability and strain measurements. Some core properties have been measured, mainly the matrix density, velocities and porosity. Note that the porosity is very homogeneous with a mean value of 19.5% and a standard deviation of 0.4%. The selected samples are then prepared. Strain gauges (3 horizontal and 3 vertical gauges) are glued and the cores are coated with a rubber sleeve.

e) Experimental procedure

The core thus prepared is set vertically in the triaxial cell. Porous plates are set on both ends to ensure a better flow distribution. The sample is then saturated using the hydraulic device previously described. The vertical loading is mechanically applied and automatically controlled. The confining pressure is applied and controlled through one of the 3 pumps. In parallel, pore pressure is applied and controlled through one of the 2 remaining pumps up to the selected pressure level. The stress increase rate is 0.1 MPa/min for isotropic loading and 0.5 MPa/min otherwise. After stabilizing, the permeability is measured in 2 ways. A flow rate is set at the core inlet while maintaining the pressure constant at the outlet. The inlet permeability is thus determined. Conversely a flow rate is set at the core outlet while maintaining the pressure constant at the inlet face. The outlet permeability is thus determined. The permeability is obtained as the mean value of the 2 measurements. This procedure avoids plugging of the pore throats by fines (*Khilar and Fogler*) and allows duplicating each measurement under identical conditions.

f) Preliminary tests

Preliminary tests are necessary in order to better define experimental parameters such as flow rate and injection time. The tests performed indicated that the optimal flow rate was in the range of 1.5 to 3 cm^3/min. The injection time was set at 3 min. For this sandstone, the stabilization of the differential pressure is obtained after about 1 minute (see Figure 4).

The differential pressure is thus obtained as the mean value of the pressure difference measured during the last 2 minutes. The applicability of Darcy's law has been thoroughly checked for numerous loading paths. Repeated measurements under similar conditions led to a variation of 5% which represent the experimental error. Finally we compared permeability measurements with gas (air) and with oil for 2 samples. The obtained values are 800 mD for the measurements performed with air and 650 mD for the

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measurements performed with oil. This indicates that the procedure used for oil saturation is good.

g) Tests performed

Permeability and strains are measured during the tests. The experimental parameters that control these variables are the vertical stress, the confining pressure and the pore pressure. In order to analyze the results from a mechanical viewpoint, these parameters have been varied according to given stress paths. Four types of tests have been performed : a) isotropic loading - this phase is performed before any other loading path ; b) uniaxial compression with constant confining pressure at different pore pressure levels (UCC) - see Table 1 ; c) Proportional loading with a constant pore pressure equal to 5 MPa (PRL)- vertical and horizontal stress loading are proportional, the effective stress ratio $\Delta\sigma'_h / \Delta\sigma'_v = K$ has been set equal to 0.1 and 0.2 ; d) constant mean stress $p = (\sigma_v + 2\ \sigma_h)/3$, with a constant pore pressure equal to 5 MPa (CMS).

3. EXPERIMENTAL RESULTS : ANALYSIS AND COMMENTS

Measurements performed on each core under identical conditions - Pc= 10 MPa, Pp = 5 MPa - lead to very similar values of permeability. About 80% of the tested samples have a permeability in the range of 320 to 460 mD (see Figure 5). These homogeneous results stem from the initial choice of the rock together with the screening based on CT-Scan results. The core set is thus very homogeneous from the petrophysics standpoint (porosity and permeability). This facilitated the comparison between experiments and hence the analysis.

The numerous measurements performed during the isotropic phase that precedes the deviatoric phase allowed calculation of David's (*David*) γ coefficient. This coefficient corresponds to the slope of the $\ln k/k_o$ v.s. $p'-p'_o$ plot. K_o is the initial permeability under isotropic conditions, p' is the Terzaghi effective mean stress and p'_o its initial value. The mean value obtained for γ ($\gamma = 0.004$ MPa^{-1}, Figure 6) is in the range of values obtained by Yale (*Yale*) (0.0014 – 0.02 MPa^{-1}) for sandstones having similar porosities.

In Figure 7, results obtained for uniaxial compression tests (UCC) with a constant pore pressure of 5 MPa are sorted according to the confining pressure applied. The higher the confining stress, the higher is the final decrease of permeability. These results are in agreement with previous results obtained by Teufel (*Teufel*) with pre-fractured Coconino sandstone and with results obtained by Krishnan *et al.* (Krishnan *et al.*) with Alter sandstone having a weak cementation.

Plotting the same results as a function of the deviatoric stress leads to a single curve thus evidencing a $k/k_o= f(q)$ curve (figure 8). Further results obtained for a 15 MPa pore pressure are in agreement with these ones thus confirming the $k/k_o = f(q)$ trend. However a more careful examination of the 2 sets of results, by plotting both of them in the same plot, show a slight difference (figure 9). The permeability decrease for a 5 MPa pore pressure is slightly less than the one obtained for a 15 MPa pore pressure. In fact, when plotting all our results in this plot, the obtained curves range within these 2 sets. Hence the deviatoric stress has a predominant role and lead to a good estimate of the permeability variation but the pore pressure cannot be neglected nor the mean effective stress.

In any case the evolution of the permeability is always characterized by a 2 steps evolution. In the first step the permeability decreases slowly - less than 6%. It then decreases after a threshold more rapidly, the permeability reduction being as high as 60% in some cases - proportional loading with K=0.1. The

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permeability changes thresholds of all the experiments have been plotted in a p'-q plot (Figure 10). A criterion for the permeability behavior is thus evidenced. Within the domain limited by the criterion, the permeability variation is low or even nil. Outside the domain, a significant variation is observed. In the same p'-q plot we plotted the damage criterion and the failure envelope. The damage threshold is defined as the point where Young's modulus and the shear modulus decrease. It can be observed in Figure 10 that the permeability criterion is lower than the damage criterion. Both tend towards similar values when the mean stress decreases.

The permeability reduction rate (r_k) is constant after the permeability threshold. Analyzing the results indicate that this rate is always the same for a given stress path independently of the level of the stresses.

In Figure 11 we plotted r_k as a function of the slope s_{sp} that characterizes the stress path in the p'-q plot. It shows that the permeability reduction rate increases when the stress path moves towards the isotropic loading. As a matter of fact, when the stress path is dominated by the increase of the deviator, the dilatancy tends to counter-balance the permeability reduction. These results are in agreement with results obtained by Rhett and Teufel (*Rhett et Teufel*) and validate the hypothesis made by Krishnan (Krishnan *et al.*), who assumed "path dependency of the material under permeability measurement".

4. CONCLUSIONS

1. We evidenced a criterion in the p'-q plot for permeability changes. Within the domain limited by the criterion, the permeability variation is low or even nil. Outside the domain, a significant variation is observed. Experiments on similar rocks would be necessary to confirm these results.
2. The permeability criterion is below the damage threshold. This results has to be confirmed by performing more experiments with strain measurements.
3. Outside the domain defined by the permeability criterion, a unique permeability reduction rate is obtained for a given stress path. The more deviatoric the stress path, the lower is the reduction of the permeability. Conversely, the more isotropic the stress path, the higher is the permeability reduction.

FIGURES

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Paper 037, Figure 1.

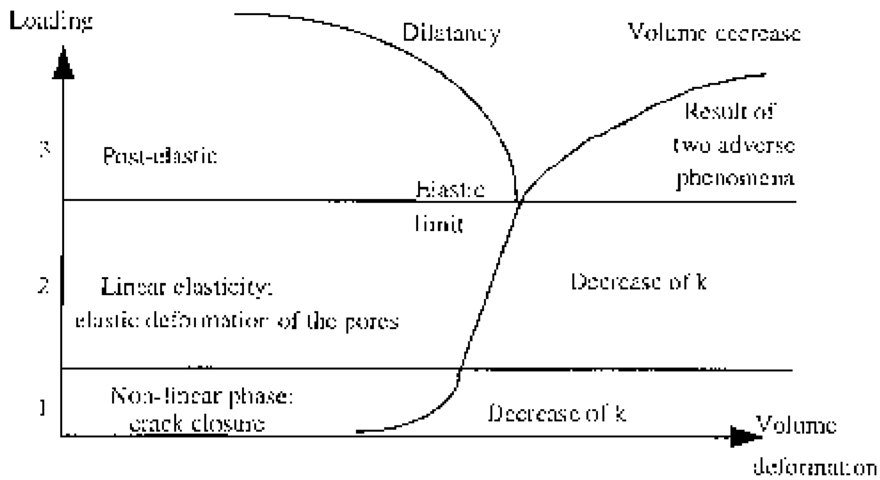

Figure 1. Evolution of permeability during loading

Paper 037, Figure 2.

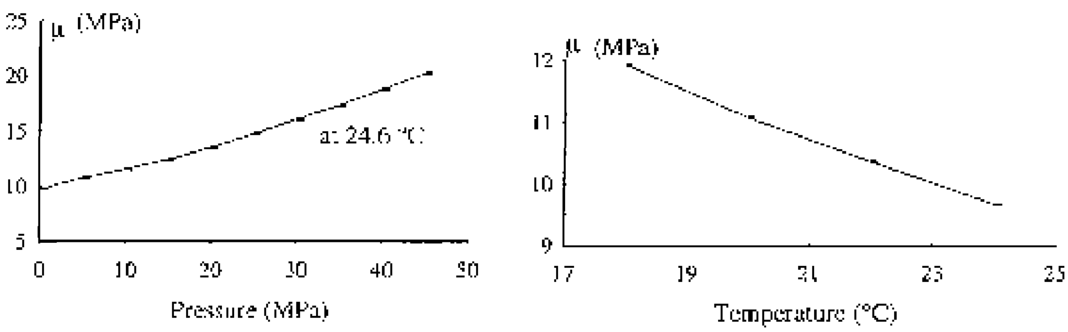

Figure 2. Influence of pressure and temperature on oil dynamic viscosity

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Paper 037, Figure 3.

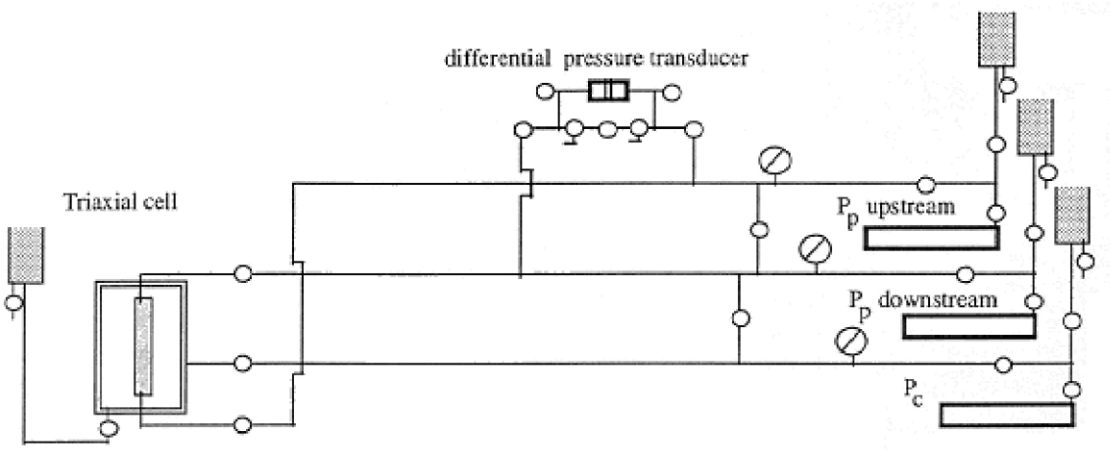

Figure 3. Experimental set-up

Paper 037, Figure 4.

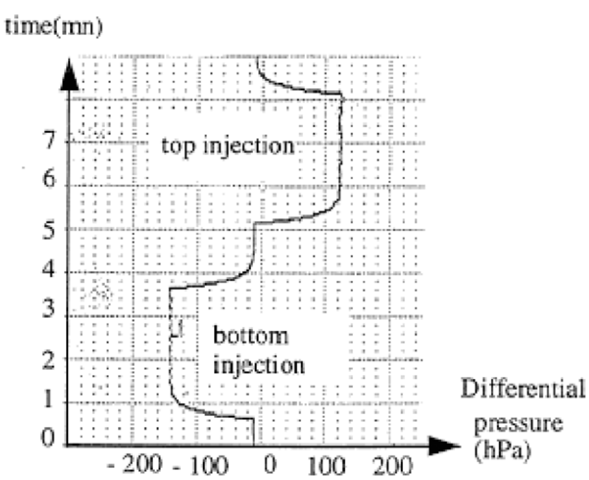

Figure 4. Evolution of ΔP during permeability measurement

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Paper 037, Figure 5.

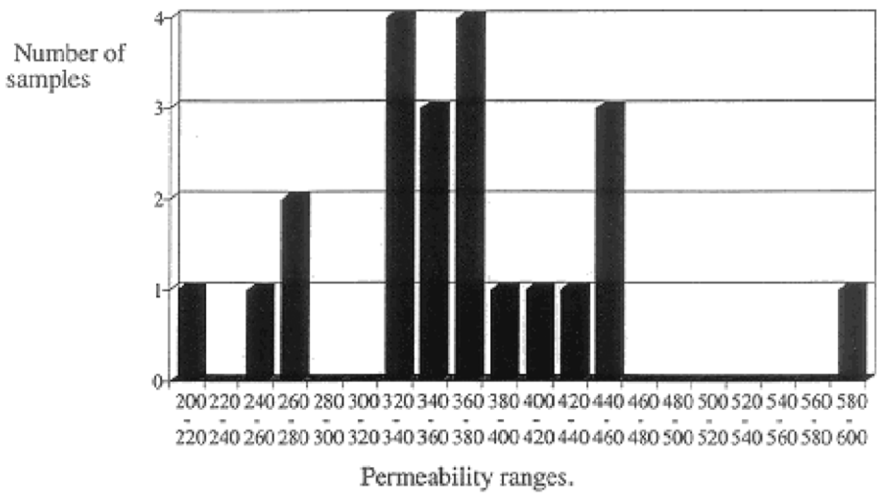

Figure 5. Permeability under 10 MPa isotropic stress

Paper 037, Figure 6.

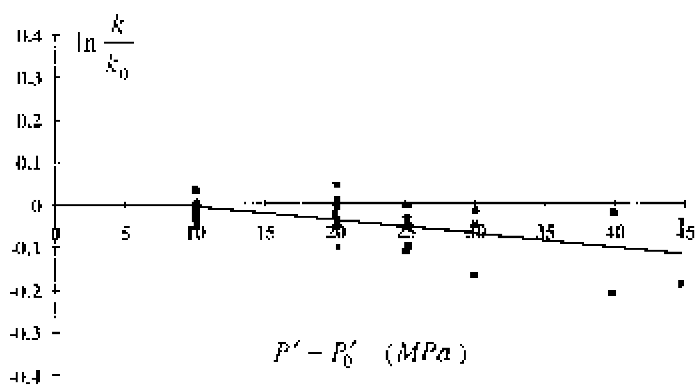

Figure 6. k measurement under isotropic stress at constant P_p

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Paper 037, Figure 7.

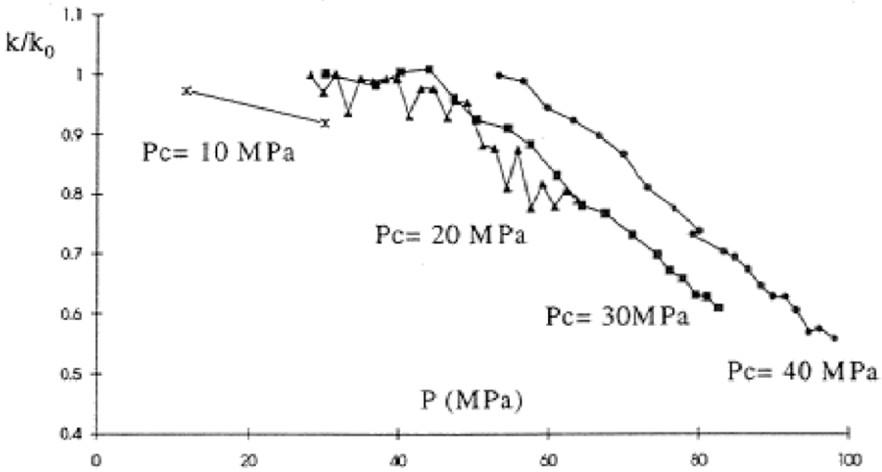

Figure 7. Vertical loading at constant confining stress and P_p= 5 MPa

Paper 037, Figure 8.

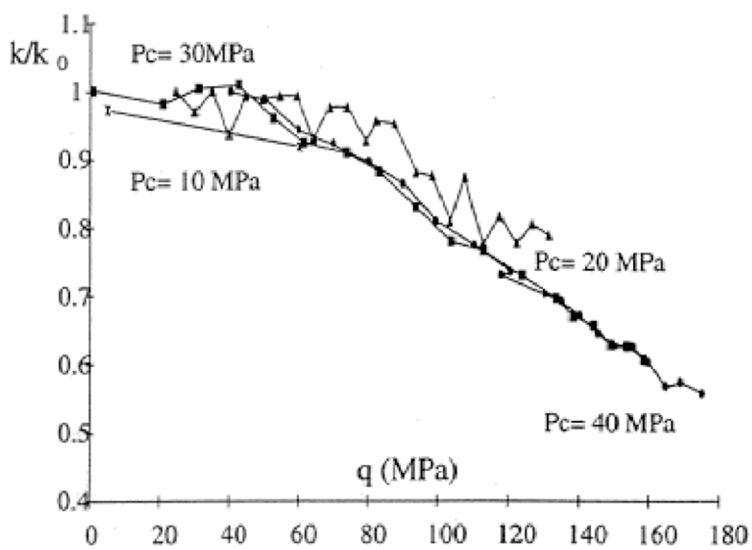

Figure 8. Vertical loading at constant confining stress and P_p = 5 MPa

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Paper 037, Figure 9.

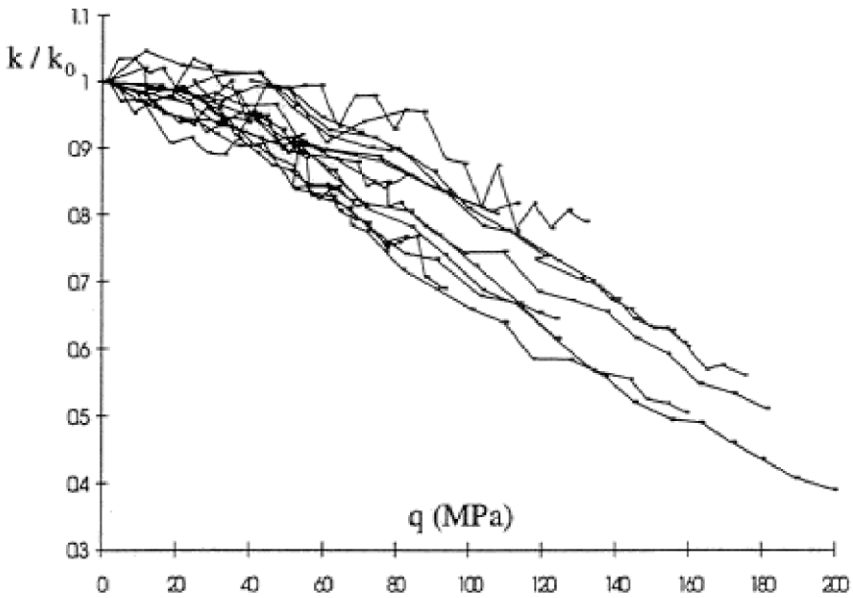

Figure 9. Permeability of the Vosges sandstone along various stress paths (UCC, PRL and CMS)

Paper 037, Figure 10.

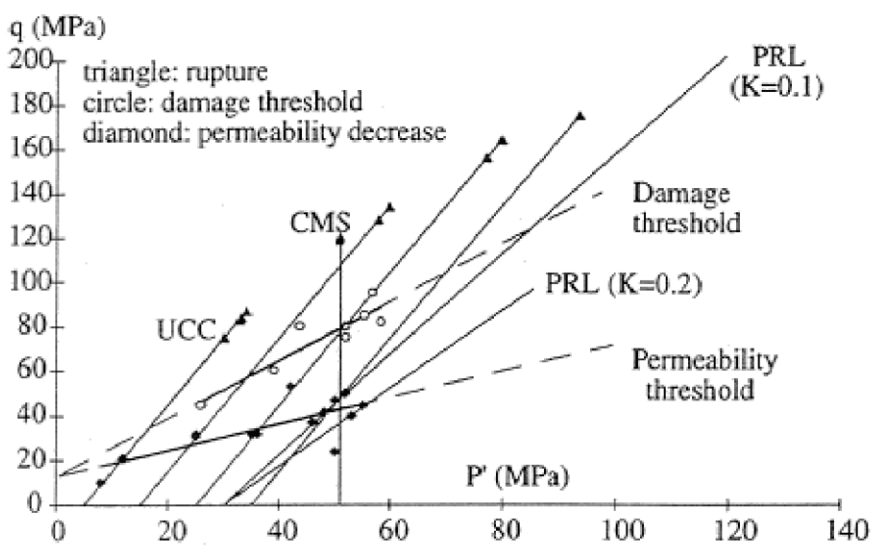

Figure 10. Mechanical and petrophysical threshold for various loading paths

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Paper 037, Figure 11.

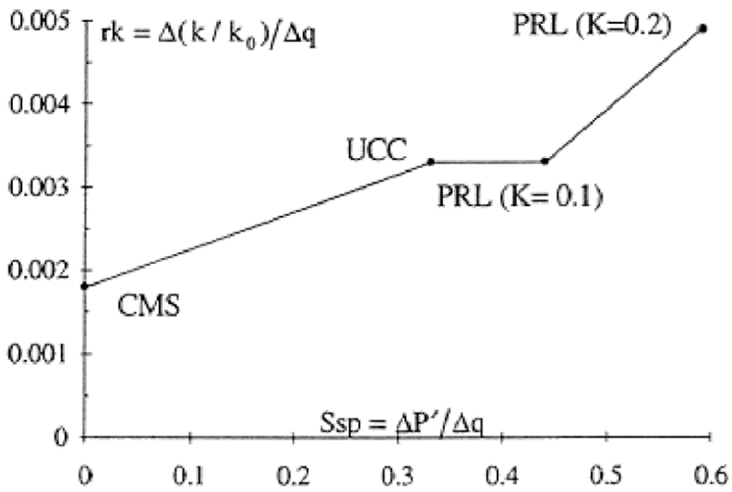

Figure 11. Influence of the stress path on the permeability reduction rate

TABLES

Paper 037, Table 1.

Table 1 : UCC tests

confining pressure	pore pressure
Pc= 10, 20, 30, 40 MPa	Pp= 5 MPa.
Pc= 20, 30 , 40 MPa	Pp= 15 MPa.
Pc= 30 , 40 MPa	Pp= 25 MPa
Pc= 40 MPa	Pp= 35 MPa

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