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Relationship between Reservoir Productivity and Pore Pressure Drop

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Abstract. The significance of permeability sensitivity to changes in pore pressure (i.e., to change in effective overburden stress) has been examined by modifying Darcy law for radial single-phase steady state flow. The elaborate model accounts for pore pressure drop and permeability reduction due to reservoir compaction. Three Saudi oil reservoir rock samples as well as Berea sandstone were tested for their physical properties. All of these cores were free of microfractures. Furthermore, using 1% NaCl aqueous solution, relationship between the overburden pressure and absolute permeability of these samples were determined at several levels of confining pressure at which the permeability was calculated. These tests were performed to establish the effect of reservoir depressurization on reservoir rock permeability.

The experimental work performed in this study showed that reservoir rocks of high initial porosity and permeability are highly affected by reservoir (pore) pressure drop and resulting increase in the effective stress. For example, the production rate from sandstone sample N3 decreased 25% of its initial value when the pore pressure decreased by 25% of its initial value, whereas the production rate from carbonate sample N4 decreased 8% for the same pore pressure decrease. Moreover, it was observed that the reservoir rock permeability under in-situ conditions strongly depends on its initial porosity and permeability values. This study suggests that a severe error in productivity predictions can result on assuming that the formation permeability at depth is independent of the effective stress. Because the increase in the effective stress decreases porosity which, in turn, changes permeability.

Introduction

The state of stress acting at a subsurface rock is assumed to be a complex combination of forces. These forces could be due to gravitational, mechanical or chemical origin. Change in these forces at any time will result in change in the in-situ stress state. The consequences of the change in the in-situ stress state is the change in rock properties including porosity, permeability and mechanical properties. Mechanical and physical properties of the subsurface rocks in the earth which are not subjected to tectonic forces are influenced by two basic stresses. These are: the total overburden stress is supported by grain-to-grain stress and pore pressure (Fig. 1) and the relationship between these stresses can be written as follows:

$$s_e = s_t - Pp \qquad (1)$$

where:

s_e = Effective overburden stress,
s_t = Total overburden stress and
Pp = Reservoir pore fluid pressure.

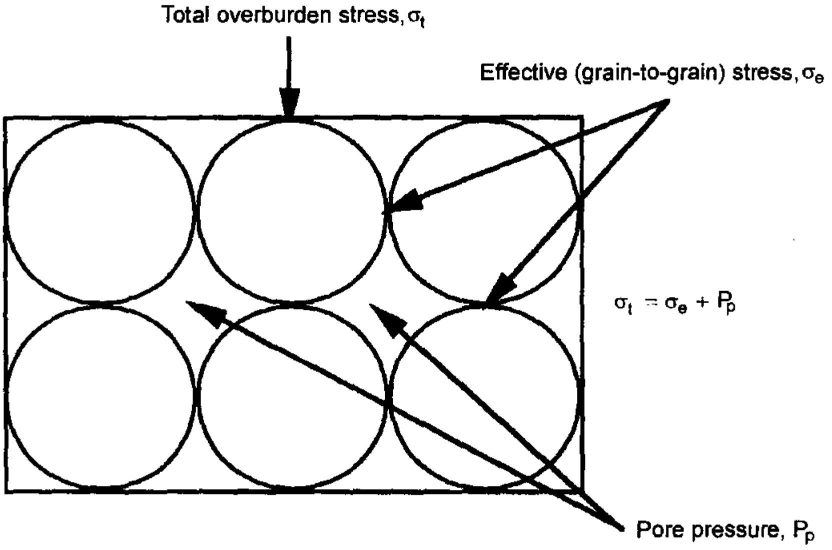


Fig. 1. Stresses acting on a fully saturated porous rock system at depth.

The net confining pressure (or effective overburden stress) acting on any plane through such rock is the resultant of the two stresses. Thus the reduction in the pore pressure increases the net confining pressure. A number of researchers have investigated the changes in reservoir rock porosity, compressibility, density, resistivity, permeability and relative permeability with changes in effective confining pressure as well as reservoir compaction [1-31]. The results all indicated that the permeability is reduced when the net confining pressure is increased. The results for the effect of temperature increase on absolute permeability show much less consistency. Permeability ratio is defined as the permeability at some confining pressure divided by the permeability at a reference confining pressure. It has been common practice with previous investigators to plot permeability ratio versus net confining pressure. These curves are of an exponential type, with the permeability ratio decreasing rapidly with increasing confining pressure (or decreasing pore pressure). The aim of this study is to experimentally investigate the effect of overburden stress on the absolute permeability of three types of reservoir rocks obtained from Saudi oil fields as well as Berea sandstone. Furthermore, the experimental findings were used as input in the modified Darcy law for radial single phase steady state flow and the resultant model (Eq. 6) was used to predict the magnitude of decrease in petroleum reservoirs productivities.

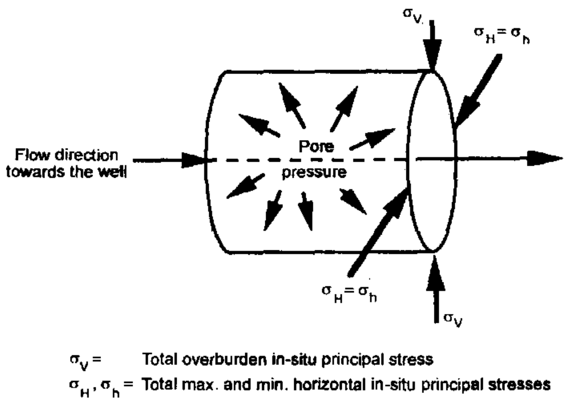
The Principle of effective overburden stress

By convention the in-situ stress acting at a point is often considered in terms of three mutually perpendicular principal stress directions. The principal stresses are the stresses acting on three orthogonal directions. The principal stresses are termed σ_V the vertical (or overburden) principal in-situ stress, σ_H the maximum horizontal principle in-situ stress and σ_h the minimum horizontal principal in-situ stress. Pore pressure (Pp) is an important parameter in any rock mechanics study of porous, fluid-filled rock system (Fig. 2). The pore fluid will carry part of the total stresses applied to the system, relieving the rock matrix from part of the load. Thus, the principle of effective stress is introduced [32]. The effective confining pressure is calculated by subtracting the pore pressure magnitude (Pp) from the total confining pressure as shown in Eq.1.

Experimental Set-up and Testing Procedure

A saturated cylindrical core sample is loaded into Hoek cell and the axial load is applied to the flat sample ends using a stiff compression tester. The radial load (confining pressure) is generated using an automatically controlled constant pressure pump. The cell, therefore, is capable of applying independent axial and radial loads on the core. There are two commonly used methods to establish the relationship between pore pressure depletion and the resulting decrease in porosity and permeability. In the first method, the sample is brought to the in-situ conditions and left for a while to equilibrate under such conditions. Then the pore pressure is reduced by a specific value (while the confining pressure is kept constant) and the sample permeability is measured using a liquid permeameter. In the second technique, the sample is loaded axially and radially until the in-situ conditions are reached. Then the confining pressure (total overburden load) is increased while keeping the pore pressure and axial load constant. The liquid permeability is then measured for each increasing interval. It should be noticed that both of the experimental procedures yield identical results because the increase in confining pressure has the same effect as the decrease in pore pressure which can be easily seen in the effective stress relationship (Eq. 1). In this study the second technique was applied using the experimental set-up shown in Fig. 3. In this work, the four cores were cut and their dimensions were measured, then saturated with 1% NaCl solution. After full saturation, the physical properties of the four core samples were measured (Table 1). The permeability of the rock samples was measured using a steady state liquid permeameter. This was done by forcing an aqueous solution (1% NaCl) of known viscosity through a core plug of known cross sectional area and length. Pressure and flow rate of liquid through the sample were measured and initial permeability was calculated using Darcy law for single phase steady state flow. The same procedure was applied when measuring the permeability-stress relationship.

(a) In-situ stresses configuration



(b) Laboratory stresses configuration

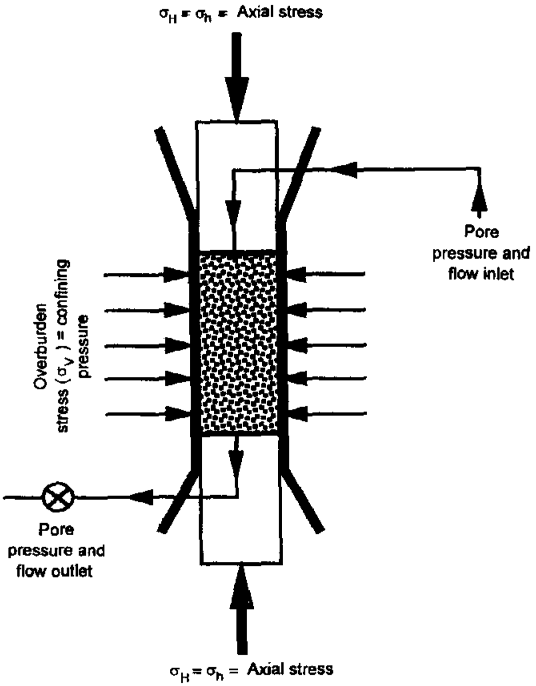
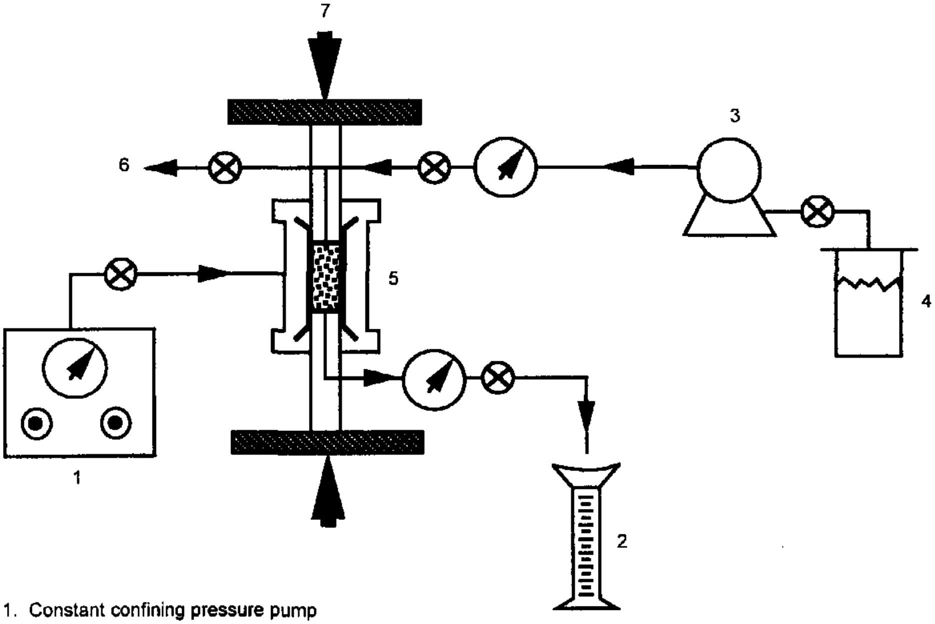


Fig. 2. Schematic diagrams showing the transformation of the in-situ stress state for application in laboratory testing.



1. Constant confining pressure pump
2. Sample collector
3. Constant rate pump
4. Fluid container
5. Hoek cell containing test sample
6. Vacuum pump
7. Stiff compression tester

Fig. 3. A schematic diagram of the permeability-stress experimental set-up.

Table 1. Physical properties of the tested core samples

Core no.	Type	Diameter, cm	Length, cm	Dry weight, g	Pore volume, cc	Porosity, %	Initial absolute permeability, Darcy
N1	Berea sandstone	3.82	8.80	204	21	20.7	0.2186
N2	Saudi sandstone	3.82	8.80	165	19	23.3	0.4030
N3	Saudi sandstone	3.82	8.80	169	16	18.6	0.6930
N4	Saudi carbonate	3.82	8.80	203	10.5	11.6	0.1900

Formulation of the Coupled Stress-Fluid Flow Equation

Darcy law for radial single phase steady state flow through porous media can be written as follows:

$$v = \frac{q}{A} = -1.127 \frac{k}{\mu} \frac{dp}{dr} \tag{2}$$

where:

v = Apparent velocity, ft/sec.
k = Permeability or constant of proportionality, Darcy.
r = Radial distance, ft.
A = Cross sectional area, ft^2.
q = Flow rate, bbl/day.
P = Driving pressure, psi.

Based on the experimental work, the characterisation of permeability to the decrease in pore pressure can be expressed as follows:

$$k = a_0 + a_1 P_p + a_2 P_p^2 + a_3 P_p^3 + \ldots \tag{3}$$

On integrating Eq. 2, it can be rewritten as follows:

$$\int_{r_1}^{r_2} \left[\frac{q}{2\pi r h} \right] dr = \frac{1.127}{\mu} \int_{P_{p1}}^{P_{p2}} \left[a_0 + a_1 P_p + a_2 P_p^2 + a_3 P_p^3 + \ldots \right] dp \tag{4}$$

Therefore, two expressions for the fluid flow can be derived: firstly, by neglecting permeability-pore pressure relationship assuming the permeability will remain constant at its initial undisturbed value:

$$q = \frac{7.081 k h \Delta P_p}{\mu \ln\left({r_1}/{r_2} \right)} \tag{5}$$

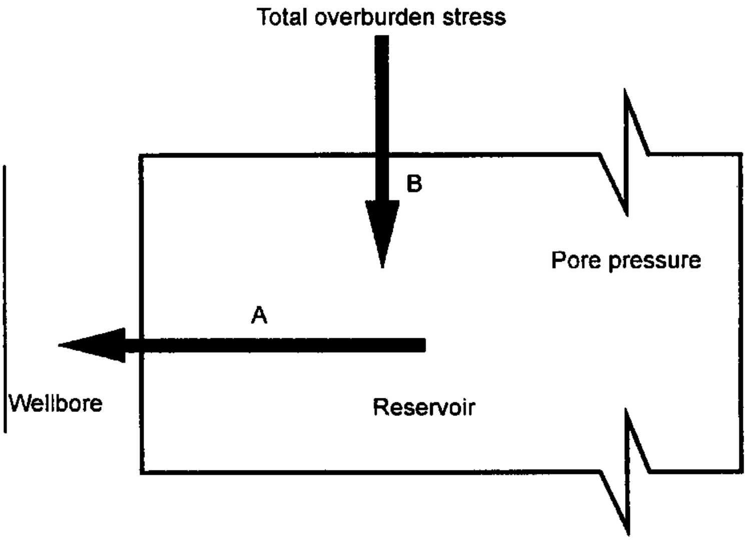
Secondly, taking into account permeability-pore pressure relationship:

$$q = \frac{7.081 h \Delta P_p}{\mu \ln\left({r_1}/{r_2} \right)} \left[a_0 P_p + \frac{a_1}{2} P_p^2 + \frac{a_2}{3} P_p^3 + \frac{a_3}{4} P_p^4 + \ldots \right]_{P_{p2}}^{P_{p1}} \tag{6}$$

where:

r_1 and r_2 = Reservoir and the wellbore radii respectively, ft.
Pp_1 and Pp_2 = Far and near wellbore pore pressures respectively, psi.

Thus, there are two forces governing the flow of fluids in the petroleum reservoir firstly, the difference between the wellbore pressure and the average reservoir pore fluids pressure, and secondly, the difference between the overburden stress and the average reservoir pore fluids pressure (Fig. 4). The fist force is a flow driving force, which tends to increase the amount of produced fluids, whereas the second one is an obstructing force causing a reduction in the amount of produced fluids by reducing the porosity and, consequently, the permeability of the reservoir rock.



A: Flow driving force resulting from the pressure difference between the average reservoir pore fluid pressure and the wellbore pressure.

B: Flow obstructing force resulting from the difference between the total overburden stress and the reservoir average pore fluid pressure.

Fig. 4. Forces affecting the production rate from oil and gas reservoirs.

Results and Discussion

The relationship between the absolute permeability and the total confining (overburden) pressure was experimentally determined for three sandstones and a carbonate reservoir rock samples as shown in Figs. 5 and 6. These figures show the decrease in permeability with the increase in the total confining (overburden) pressure. Also, it can be noticed that the carbonate core sample had little decrease in permeability when compared to the decrease in the permeability of the sandstone cores. This difference in permeability reduction can be attributed to the difference in the initial porosity and permeability of the two rocks. This reduction in permeability was appreciable for the first thousands of psi's but decrease with further increase in the overburden pressure. The amount of reduction in permeability was found to be function of the initial porosity and permeability of these cores as shown in Fig. 7. Based on the experimental results shown in Figs. 5 and 6, correlations between the absolute permeability and the pore pressure drop were obtained and tabulated in Table 2. It was found that all the tested core samples restore their initial permeability when the applied confining pressure is released from 5000 psi to its initial value of 500 psi indicating that these samples had no permanent reduction in permeability (pore collapse). If any rock sample is loaded above its yield strength, a permanent reduction in permeability will be the result due to pore collapse. It must be kept in mind that the loss of permeability due to pore collapse may not be restored by acidizing, fracturing or other well stimulation techniques [12]. The correlation data presented in Table 2 was used to predict the decrease in reservoir productivity due to pore pressure drop. Two models were used in this analysis: the first based on pore pressure independent permeability (Eq. 5) and the second is the pore pressure dependent permeability (Eq. 6). The results are shown in Figs. 8 through 12. It was found that if the reservoir pore pressure is decreased by 25% of its initial value the productivity will decrease by 8%, 13%, 25% and 3% for samples N1, N2, N3 and N4, respectively. Thus, the assumption that permeability is independent of pore pressure will yield overestimated production rates.

Table 2. Reservoir and pore pressure-absolute permeability correlation data

Sample	a_0	a_1	a_2	a_3	a_4	Correlation coefficient r^2
N1	184.22	-3.9376E-2	3.3863E-5	-1.0157E-8	1.2494E-12	1.00
N2	291.4	-6.8215E-2	6.9138E-5	-2.4894E-8	3.6804E-12	1.00
N3	411.77	-7.0419E-2	9.2765E-5	-4.2348E-8	7.713E-12	1.00
N4	129.53	2.1997E-3	-2.0434E-6	1.7491E-9	-2.5494E-13	1.00

Input data:

r_1/r_2 = 1000 ft.
μ_o = 1.18 cp.
h = 136 ft.
Initial Pp = 3630 psi.

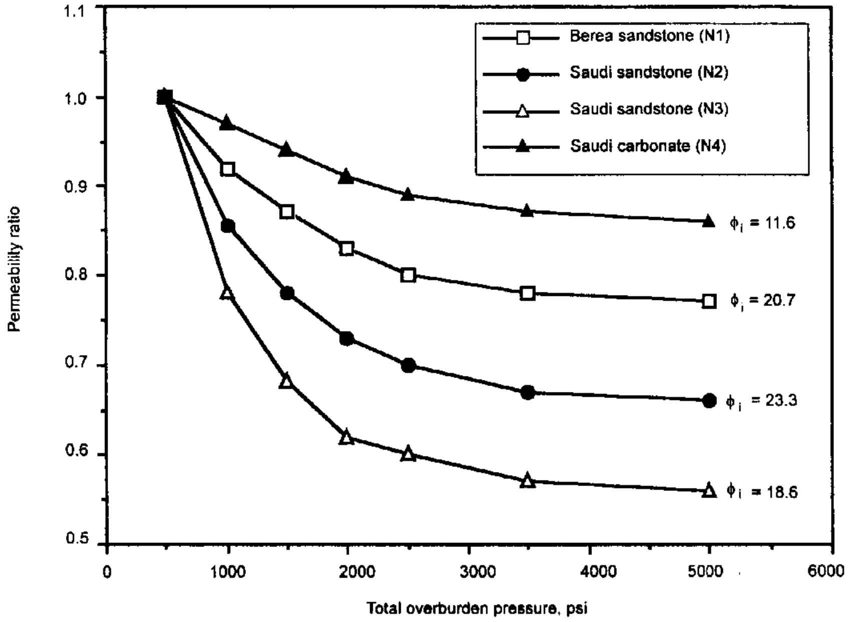


Fig. 5. Reduction of absolute permeability with total overburden pressure. Permeability ratio = Permeability at pressure / initial permeability.

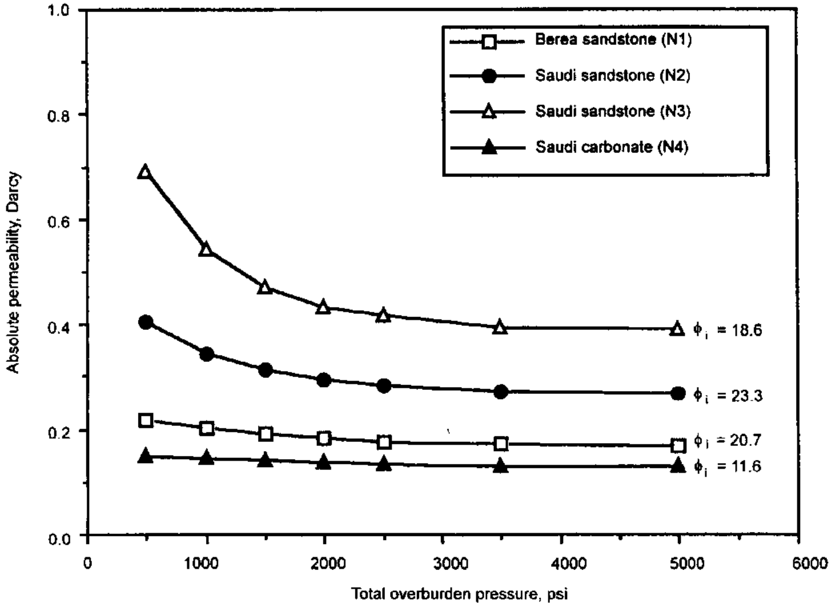


Fig. 6. Reduction of absolute permeability with total overburden pressure.

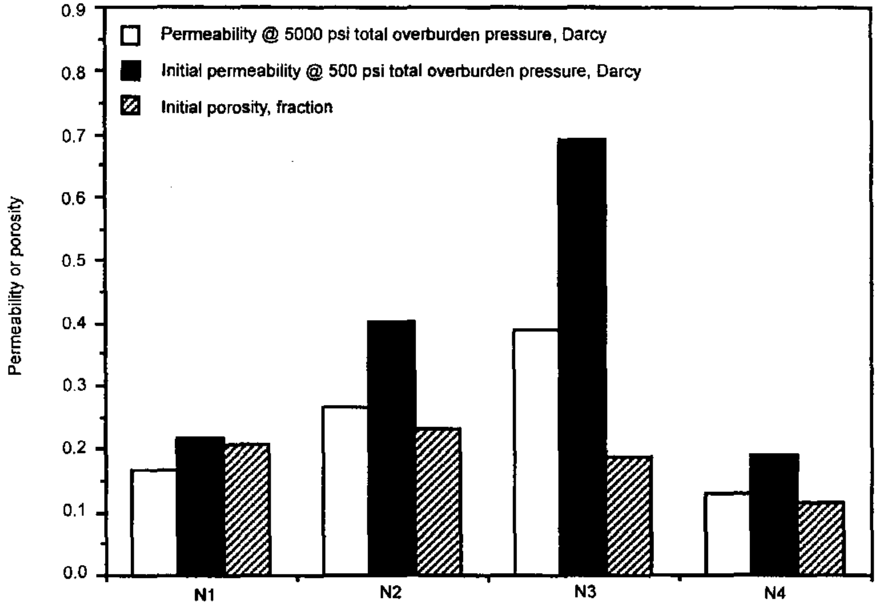


Fig. 7. Relationship between stress-reduced permeability, initial permeability, and initial porosity values.

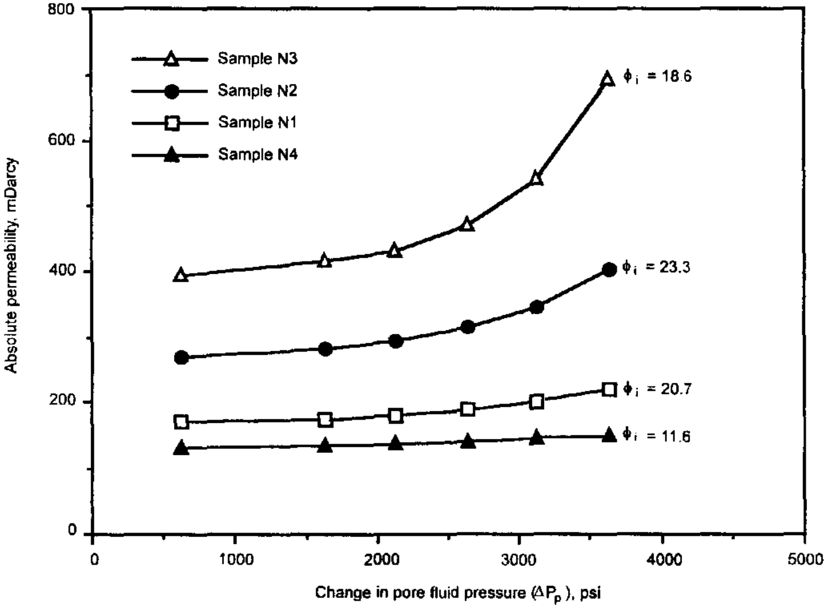


Fig. 8. Absolute permeability - pore pressure drop relationship for the tested samples (initial pore pressure (Ppi = 3630 psi).

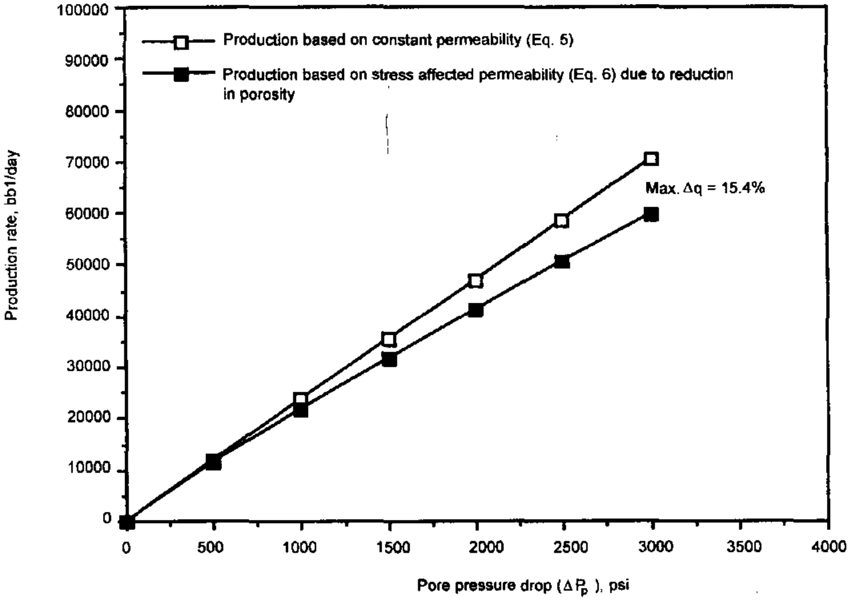


Fig. 9. Effect of pore pressure drop on formation productivity for sample N1.

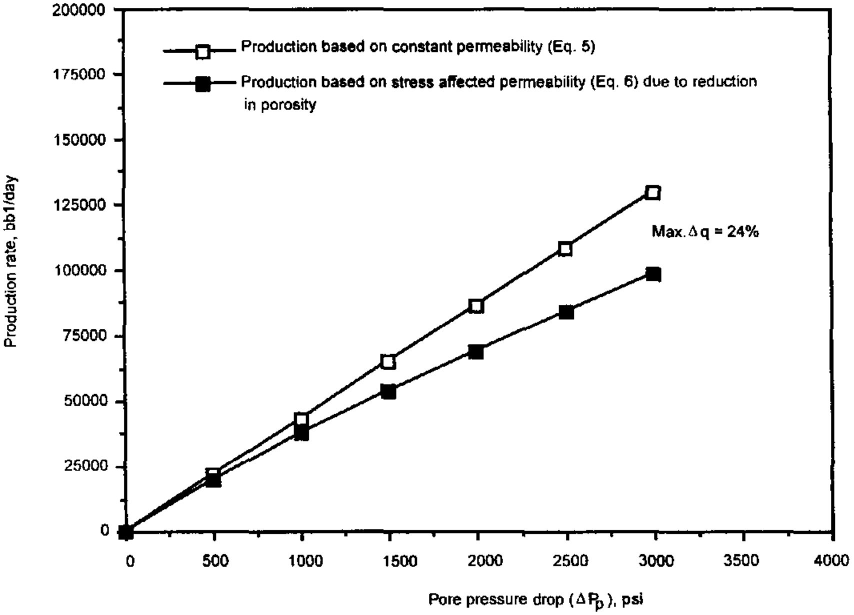


Fig. 10. Effect of pore pressure drop on formation productivity for sample N2.

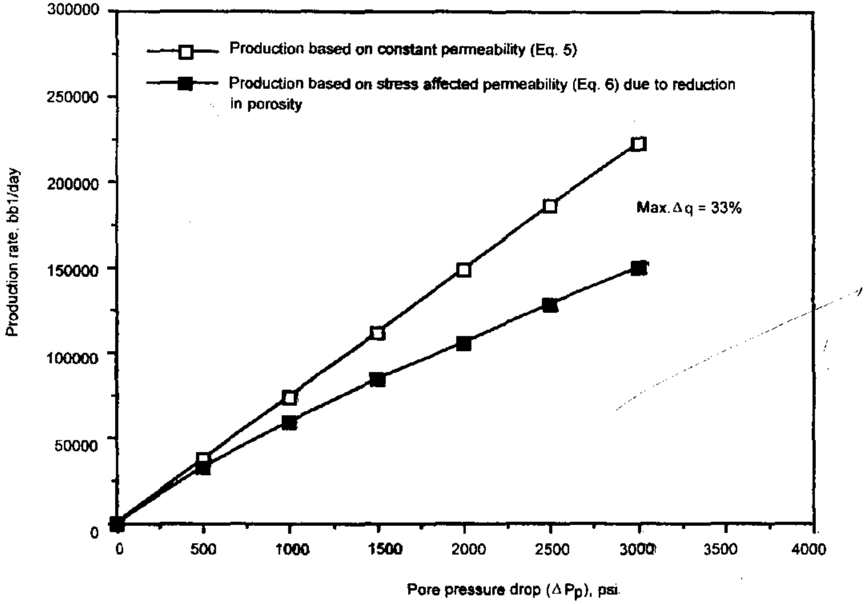


Fig. 11. Effect of pore pressure drop on formation productivity for sample N3.

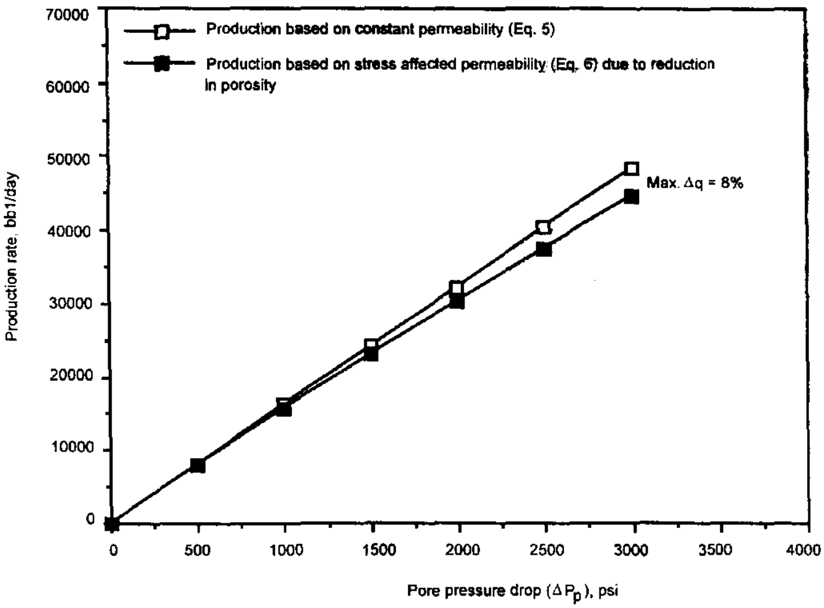


Fig. 12. Effect of pore pressure drop on formation productivity for sample N4.

Conclusion

1. The effect of effective overburden stress increase due to pore pressure drop was incorporated into Darcy law for single-phase steady state radial flow.

2. Rocks having high initial porosity and permeability are affected by effective overburden stress increase caused by pore pressure drop much more than those rocks having low initial porosity and permeability.

3. Calculations based on the elaborated model (Eq. 6) showed the permeability reduction due to pore pressure drop could significantly affect the productivity of the examined formations.

4. There was no permanent permeability decrease of the tested rock samples due to the increase in the applied confining pressure up to 5000 psi.

5. The absolute permeability is a variable in all fluid flow equations; thus, for correct productivity estimation the permeability must be expressed in these equations as a function of effective overburden pressure (the difference between the overburden pressure and the reservoir pore fluid pressure).

6. Accurate permeability-effective stress relationship can be determined using a triaxial compression equipment capable to generate pore pressure, and axial and radial stresses.

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العلاقة بين الإنتاجية والانخفاض في الضغط المسامي لسوائل المكامن البترولية

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(قدم للنشر في ١٩٩٩/٠٢/١٤، وقبل للنشر في ٢٠٠٠/٠٢/٢٩)

ملخص البحث. تم في هذا البحث دراسة أهمية التغير في نفاذية صخور المكامن البترولية نتيجة الانخفاض في الضغط المسامي لسوائل تلك المكامن (أي التغير في الإجهاد الرأسي المؤثر) وذلك بتطوير قانون دارسي للسريان القطري لسائل واحد في حالة الاستقرار. إن قانون دارسي المطوّر يأخذ في الاعتبار الانخفاض في الضغط المسامي لسوائل المكمن والتغير في مسامية صخور المكمن الناتج عن ذلك الانخفاض.

تم قياس الخواص البتروفيزيقية لثلاثة عينات مأخوذة من مكامن النفط السعودية بالإضافة إلى صخر بيريا الرملي. ووجد أن تلك العينات خالية من الكسور والتشققات المجهرية. بعد ذلك تم قياس النفاذية المطلقة لتلك العينات وذلك بحقن محلول ماء مالح يحتوي على كلوريد الصوديوم بتركيز ١٪ تحت عدة مستويات من الضغط الحاصر. إن الهدف من تلك القياسات المعملية هو دراسة أهمية التغير في نفاذية صخور المكامن البترولية نتيجة الانخفاض في الضغط المسامي لسوائل تلك المكامن.

أظهرت النتائج المعملية التي أجريت في هذه الدراسة أن مسامية صخور المكامن ذات درجات مسامية ونفاذية أوليتين عاليتين تنخفض بشكل أكبر بكثير نتيجة الزيادة في الإجهاد الرأسي المؤثر من صخور المكامن ذات درجات مسامية ونفاذية أوليتين منخفضتين. على سبيل المثال، إن معدل الإنتاج من عينة الصخر الرملي رقم ٣ قد انخفض بنسبة ٢٥٪ عندما نقص الضغط المسامي بنفس النسبة عن قيمته الأولية بينما نقص معدل الإنتاج من عينة الصخر الجيري رقم ٤ بنسبة ٨٪ عندما نقص الضغط المسامي نسبة ٢٥٪ عن قيمته الأولية. ووجد أن الانخفاض في نفاذية تلك العينات الصخرية يتناسب طرديا مع القيم الأولية لمساميتها الأولية ونفاذيتها.

إن هذه الدراسة تؤكد على أن خطأ كبير سيحدث في تقدير إنتاجية المكامن البترولية عند افتراض عدم وجود علاقة بين الإجهاد الرأسي المؤثر ومسامية صخور تلك المكامن وذلك لأن الزيادة في الإجهاد الرأسي المؤثر ستقلل من النفاذية والمسامية.