Engineering Journal of the University of Qatar, Vol. 14, 2001, pp. 23-43

EFFECT OF PRODUCTION INDUCED STRESSES ON RESERVOIR PRODUCTIVITY

Musaed N. J. Al-Awad,
Petroleum Engineering Department
College of Engineering
King Saud University
P.O. Box 800 Riyadh 11421
Saudi Arabia
E-mail: malawwad@ksu.edu.sa

ABSTRACT

The importance of permeability sensitivity to the changes in pore pressure drop or effective overburden stress increase has been examined at laboratory using two types of rocks, sandstone and limestone. Whereas the experimental data were used as an input in the modified Darcy equation for single-phase steady-state flow through porous medium. The selected rocks were tested for triaxial compressive strength, permeability, x-ray diffraction, grain size distribution, stress-strain relationship and thin sections structure. The experimental work conducted in this study showed that the permeability of the tested rock samples was significantly influenced by the increase of effective overburden stress (i.e. pore fluid pressure drop). This result is supported by thin sections examination and stress-strain relationship, which have shown that pore structure was highly affected by the increase in the overburden stress. Therefore it is very important to include the effect of effective overburden stress increase (or pore fluid pressure drop) in any reservoir productivity prediction technique.

1. INTRODUCTION

One problem currently confronting petroleum engineers is the analysis of formation damage responsible for the reduced well productivity. The inelastic deformation of several rock materials (pore collapse) is one of the major reasons beyond the drop in reservoir productivity. 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. Changes in these forces at any time will result in changes in the in-situ stress-state. The consequence of the change in the in-situ stress-state is the variation in rock properties including porosity, permeability and mechanical properties. Mechanical and physical properties of subsurface rocks in the earth which are not subjected to tectonic forces are influenced by two basic stresses. These are grain-to-grain rock stress caused by the total weight of the overburden material and pore pressure of the interstitial fluids as shown in Fig. 1. The effective overburden stress (net confining pressure) acting on any plan through such rock is the resultant of the two stresses. Thus the reduction in the pore fluid pressure increases the net confining pressure as shown in the following equation [1]:

$$\sigma_e = \sigma_t - pp \tag{1}$$

where:

σ_e , σ_t = Effective and total overburden stresses respectively,
pp = Reservoir pore fluid pressure.

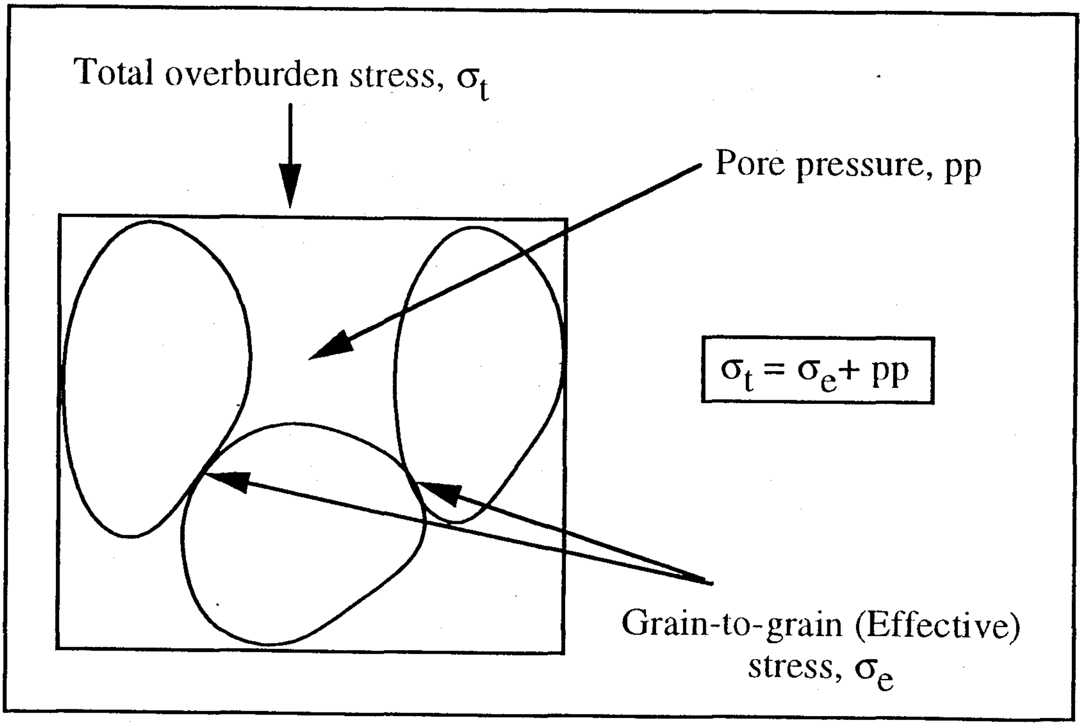


Fig. 1. Stresses acting on a fully sturated porous rock at depth.

A number of researchers have investigated the changes in reservoir rock porosity, compressibility, density, resistivity, permeability, relative permeability with changes in net confining pressure [2-24] and reservoir compaction [25-33]. The results all indicated that the permeability is reduced when the confining pressure is increased. The results for the effect of temperature increase on absolute permeability show much less consistency [16]. 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 as the confining pressure is increased (or the pore pressure is decreased).

2. EXPERIMENTAL WORK

Petropysical Properties and XRD Analysis

Two types of rocks (sandstone and limestone) were selected for this study. The first sample was sandstone, which is mainly composed of quartz. This sandstone is fine grained (100 to 600 μm) and red coloured due to the presence of iron oxides, poorly cemented and of high porosity and permeability. The second rock was limestone, which is mainly composed of calcite. This limestone rock is very fine grained and yellow in colour, very strong, highly cemented and has low porosity and permeability (see Figs. 2 and 3). These rock samples are microfractures free and their porosity and permeability are primary.

Mechanical Properties

A stiff compression machine equipped with a servo-controlled confining pressure system was used to measure the mechanical properties of the selected rocks. Tests were conducted according to the standard procedures outlined by the International Society of Rock Mechanics for samples preparation and testing procedures [34]. The performed tests include:

(i) Uniaxial compressive strength (UCS),
(ii) Triaxial compressive strength (TCS), and
(iii) Stress-strain relationship.

Furthermore, Mohr-Coulomb failure criterion was established for the tested rock samples.

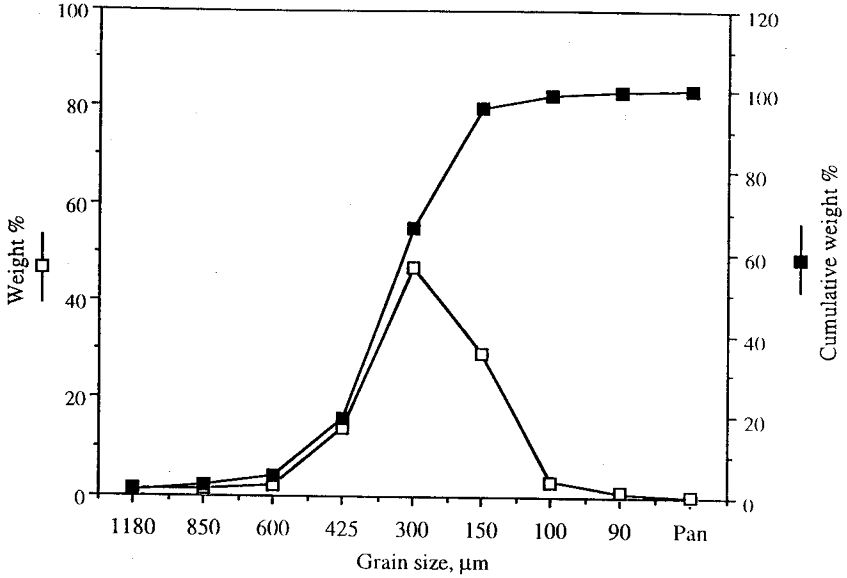


Fig. 2. Grain size distribution of the tested sandstone.

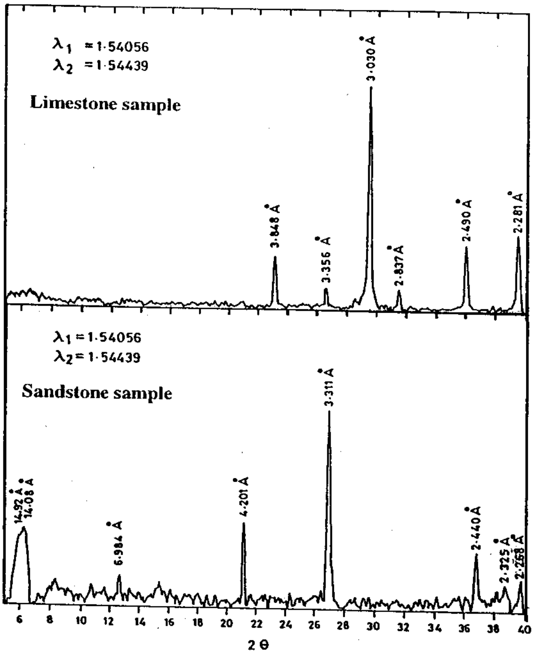


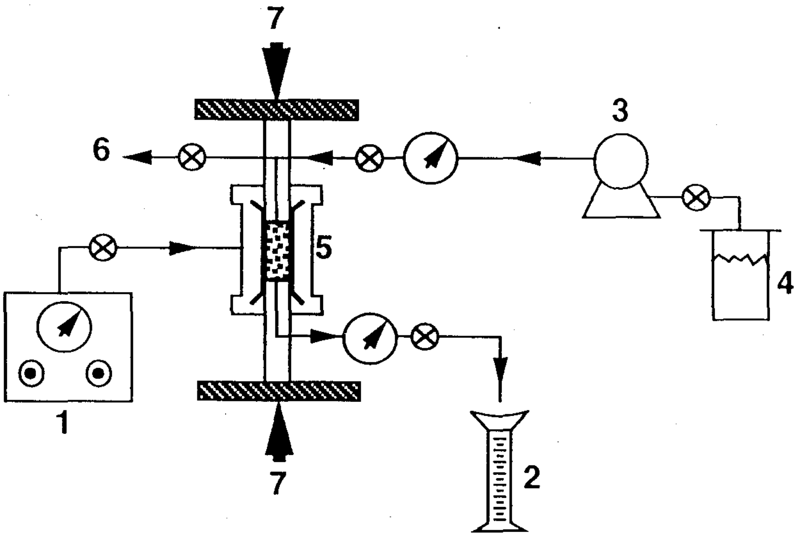
Fig. 3. X – ray diffractograms of the tested rock samples.

Thin Sections Examination

The ability to study rocks in thin sections greatly enhances understanding the changes in pore structure caused by the increase in overburden stress or the decrease in pore fluid pressure. A stereo microscope with a transmitted-light observation option was used in this study. Thin sections were prepared from rock samples (before and after testing) were sliced very thinly so that the contained minerals can transmit light. The analysis of thin sections provided information on the fabrics, textures, mineralogy and geochemistry of the chosen samples. In the preparation of thin section samples, sliced rock is placed in a vacuum desiccator and connected to a vacuum pump. After full evacuation of the rock sample, the sample is saturated with resin under vacuum (low pressure) to insure an excellent filling of the pore space with the resin. Then the sample is placed in an oven at 50 °C for 24 hours. The solid material can then be cut to a standard size then abraded using a lapping machine to produce a face which is as smooth and as flat as is possible. The sample is then mounted onto a glass slide using special glue such as Canada balsam. Finally the final thin section is produced by finishing the sample using a flat glass and carborundum of various sizes.

Permeability Measurement

A saturated cylindrical core sample (3.82 cm diameter and 8.80 cm length) 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 is therefore capable for applying independent axial and radial loads. There are two commonly methods can be applied to establish the relationship between pore pressure drop 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 value is reduced by a specific value (while the total 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 is reached. Then the total confining pressure 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 similar results because the increase in confining pressure has the same effect of 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. 4. In this work, the two cores (sandstone and limestone) were cut and their dimensions were measured, then saturated with 1% NaCl solution. After full saturation, the physical properties of these core samples were measured. 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 fluid flow through porous medium. The same procedure was applied when measuring the permeability-confining pressure (or pore fluid pressure) relationship.



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. 4. A schematic diagram of the permeability – stress experimental set -up

3. MATHEMATICAL MODELLING OF PERMEABILITY-STRESS RELATIONSHIP

Two expressions for the fluid flow can be derived: firstly, by neglecting permeability-pore pressure relationship assuming that the permeability remains constant at its initial undisturbed value [34]:

$$q = \frac{7.081\ k\ h\ \Delta pp}{\mu \ln\left(r_1 / r_2 \right)} \tag{2}$$

Secondly, taking into account permeability-pore pressure relationship[1]:

$$q = \frac{7.081\ h}{\mu \ln\left(r_1 / r_2 \right)} \left[a_o\, pp + \frac{a_1}{2} pp^2 + \frac{a_2}{3} pp^3 + \frac{a_3}{4} pp^4 + \ldots \right]_{pp_2}^{pp_1} \tag{3}$$

where:

r_1 and r_2 = Reservoir and the wellbore radii respectively, ft.
pp_1 and pp_2 = Initial and new pore fluid pressures respectively, psi.
k = Permeability, Darcy.
q = Flow rate, bbl/day.
h = Formation thickness, ft.
μ = Fluid viscosity, cp.
a_o , a_1 , ... = Correlation constants.
Δpp = Pressure drop, psi.

4. RESULTS AND DISCUSSION

In this study two rock samples were selected. The first one was limestone (carbonate) while the second was sandstone. The limestone is of very fine grains, yellow in color and very strong rock. The sandstone grain size distribution is shown in Fig. 2. This rock is fine-grained and very weak due to the lack of cementing material. XRD analysis has shown that the limestone is mainly composed of calcite and some silica while the sandstone is mainly composed of quartz, feldspar and iron oxides as shown in Fig. 3. In order to establish the relationship between pore pressure drop, overburden stress increase and permeability decrease, the mechanical properties of these rocks were measured. Fig. 5 shows the relationship between the confining pressure and the axial stress at failure for the tested rock samples. It can be seen that the uniaxial compressive strength of the limestone is 30 MPa. Whereas the uniaxial compressive strength of the sandstone sample was 6 MPa. It is clear that the tested limestone is 5 times stronger than the tested sandstone.

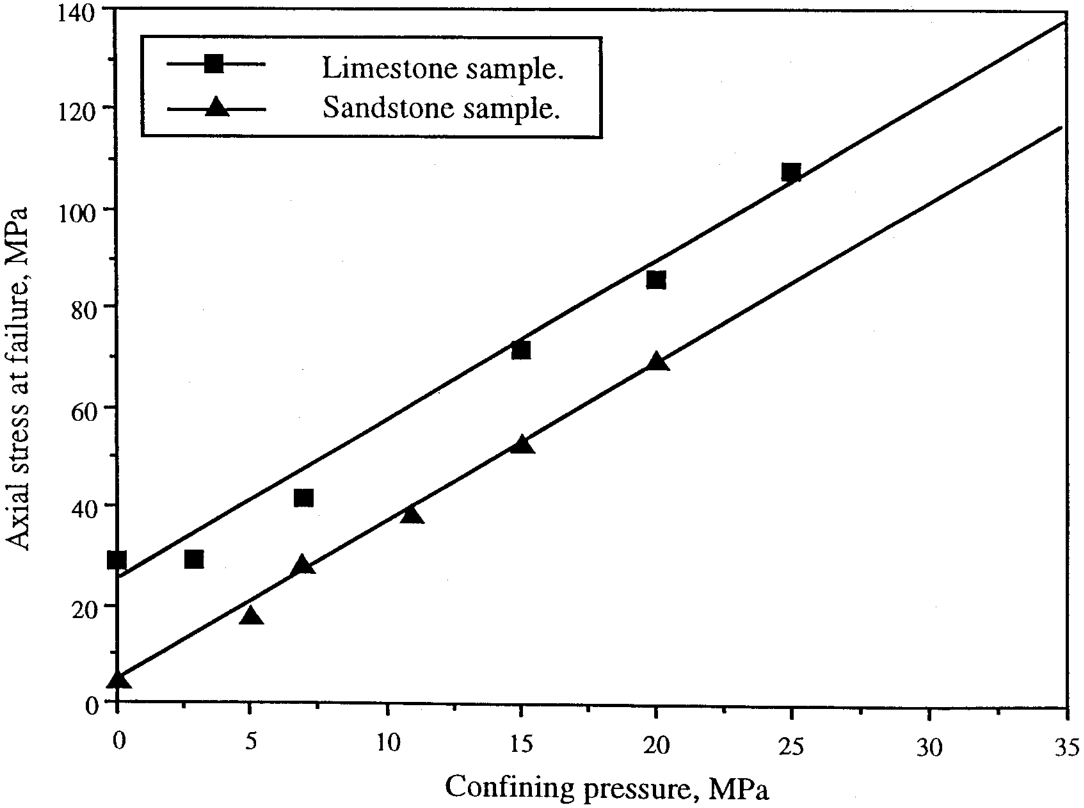


Fig. 5. Relationship between confining pressure and axial stress at failure for the tested rock samples.

Similar conclusion can be obtained from Figs. 6 and 7. These figures show the established Mohr-Coulomb failure criteria of the tested rock samples. The estimated apparent cohesion (a measure for the degree of cementing material strength) was 6 MPa for the limestone and 1.2 for the sandstone which yield the same ratio as that obtained from the uniaxial compressive strength. In order to establish the effect of applied stress on the deformation characteristics of the chosen rocks, the relationship between axial stress and axial displacement was established (in the elastic region, i.e. below the measured uniaxial compressive strength) for both rocks as shown in Figs, 8 and 9. From these relationships, it can be shown that the tested limestone returns to its initial state without any permanent deformations, whereas, the tested sandstone exhibited some permanent deformation after releasing the applied load with a magnitude of 0.0255 mm.

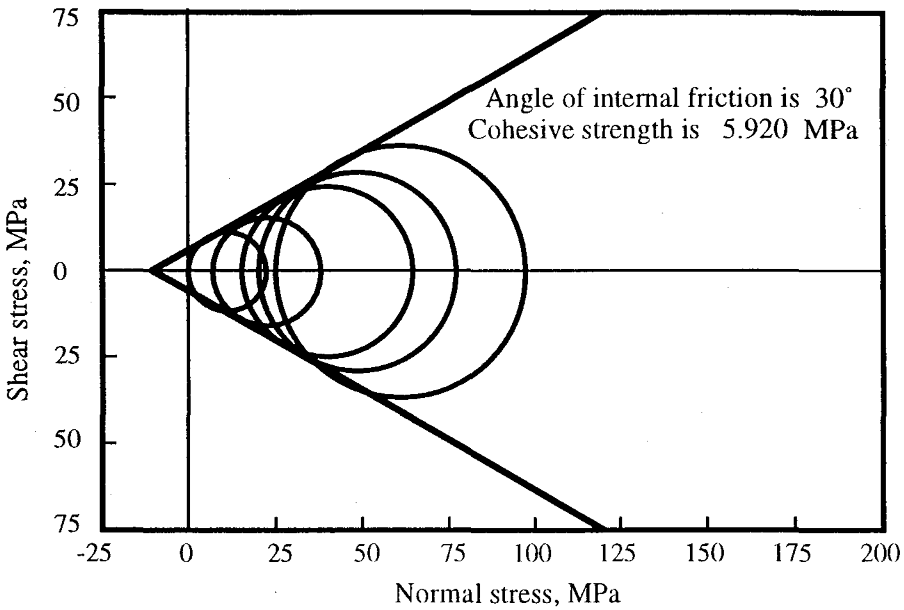


Fig. 6. Mohr – Coulomb failure criteria of the tested limestone.

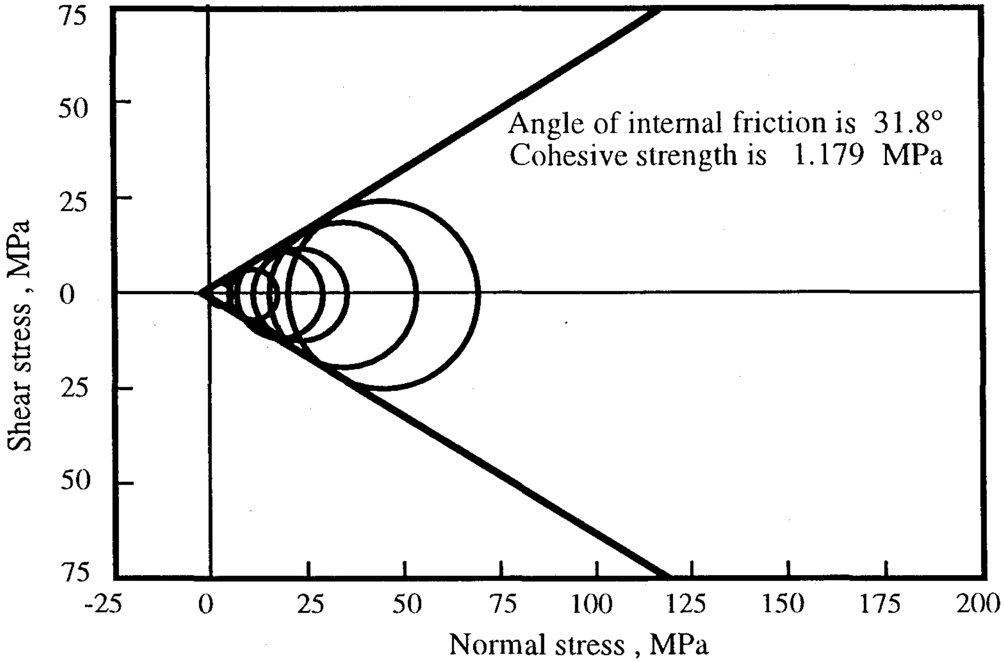


Fig. 7. Mohr – Coulomb failure criteria of the tested sandstone.

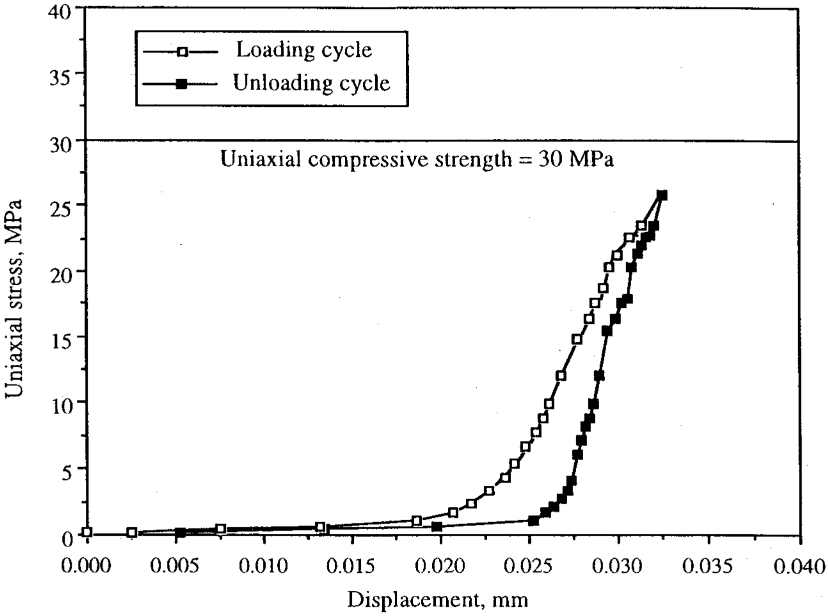


Fig. 8. Stress – strain relationship for the tested limestone.

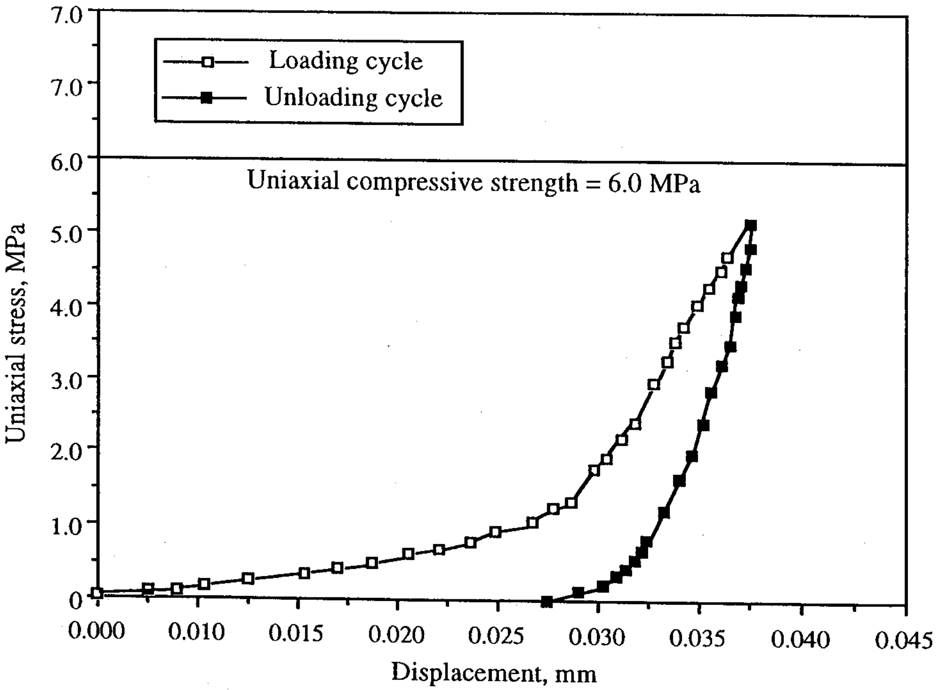
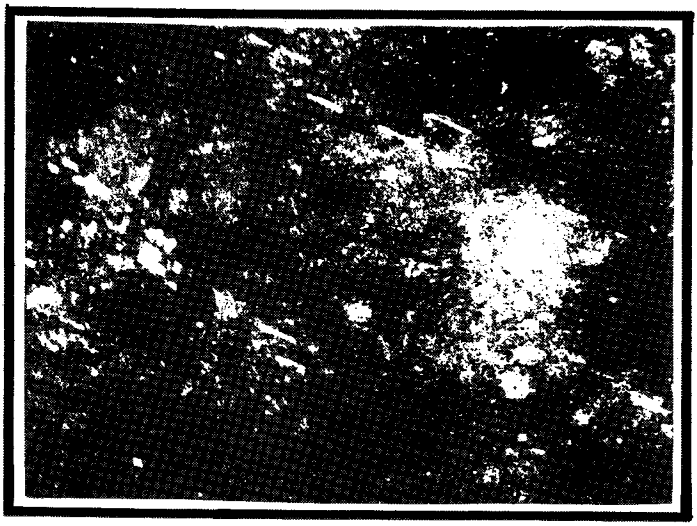


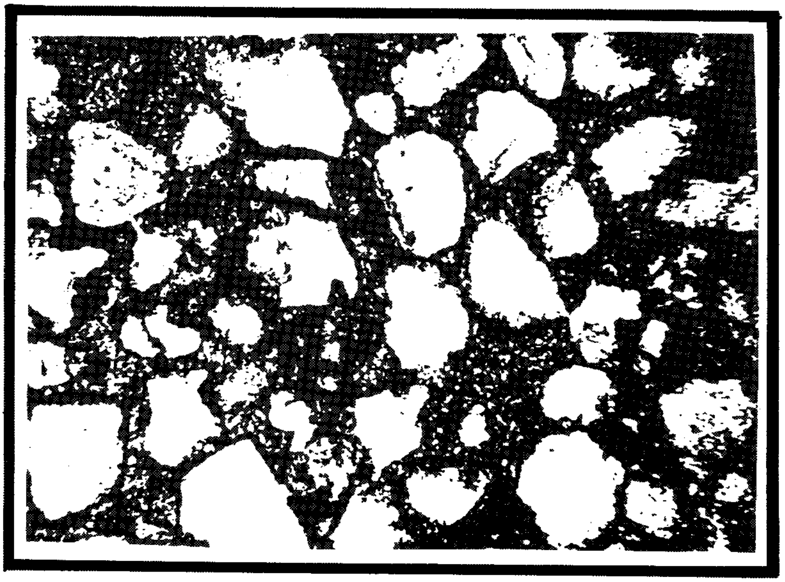
Fig. 9. Stress – strain relationship for the tested sandstone.

This permanent deformation is attributed to the breaking of some grains and/or the cementing material as shown in Figs. 10, 11, 12 and 13. The experimentally determined relationships between the absolute permeability and the total confining (overburden) pressure for the carbonate and the sandstone rock samples are shown in Figs. 14 and 15. These figures show the decrease in permeability with the increase in confining pressure. Also, it can be noticed that the carbonate rock sample had little decrease in permeability when compared to the decrease in the permeability of the sandstone sample. 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 [1]. Based on the experimental results shown in Figs. 14 and 15, correlations between the absolute permeability and the pore pressure drop were obtained for a hypothetical oil reservoir and the results are tabulated in Table 1 and plotted in Figs. 16 and 17. It was found that the tested limestone sample restore its initial permeability when the applied confining pressure (up to 25 MPa) was released indicating that this sample has no permanent reduction in permeability (pore collapse). Whereas, some permanent reduction in permeability was observed for the tested sandstone when the applied load (10.5 MPa) was released. 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 1 was used to predict the decrease in the hypothetical reservoir productivity due to pore fluid pressure drop. Two models where used in this analysis, the first is based on pore pressure (or overburden stress) independent permeability (Eq. 2) and the second is the pore pressure (or overburden stress) dependent permeability (Eq. 3) [1]. The results are plotted in Figs 18 and 19. It can be seen from these two figures that, when the reservoir pore fluid pressure is decreased, the productivity of the reservoir is also decreased for both rocks. Thus the assumption of pore pressure independent permeability will yield overestimated production rates.



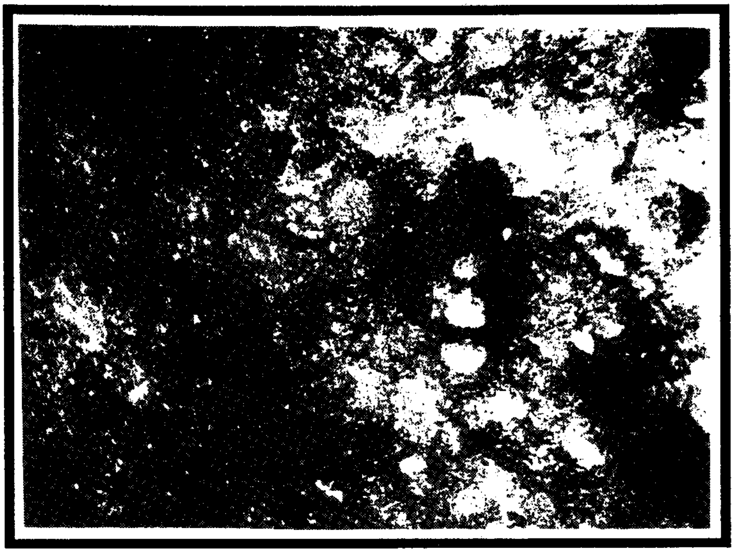
Colored photograph: (Orange color: matrix Red color: pores)
Black & White version: (White color: matrix Black color: pores)

Fig. 10. Pore structure of the tested limestone in its natural state magnified 40 times.



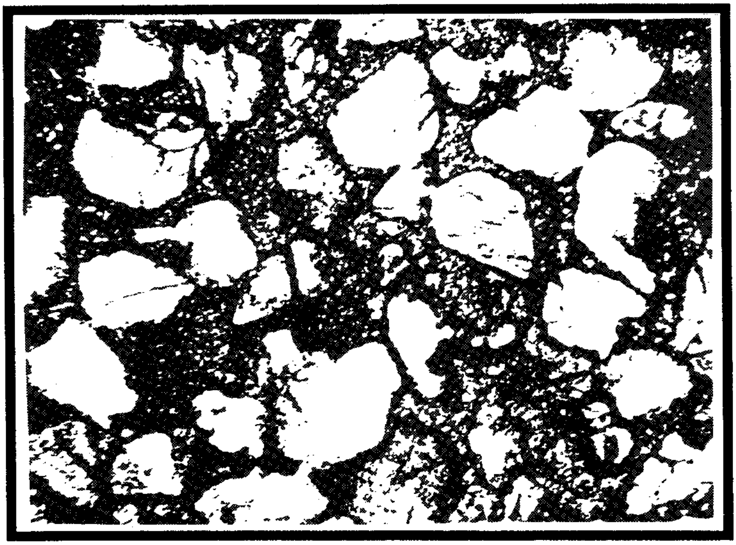
Colored photograph: (White color: grains Bronze color: pores)
Black & White version: (White color: grains Black color: pores)

Fig. 11. Pore structure of the tested sandstone in its natural state magnified 40 times



Colored photograph:	(Orange color:	matrix	Red color:	pores)
Black & White version:	(White color:	matrix	Black color:	pores)

Fig. 12. Pore structure of the tested limestone after loading at 65% of the uniaxial compressive strength value magnified 40 times.



Colored photograph:	(White color:	grains	Bronze color:	pores)
Black & White version:	(White color:	grains	Black color:	pores)

Fig. 13. Pore structure of the tested sandstone after loading at 65% of the uniaxial compressive strength value magnified 40 times.

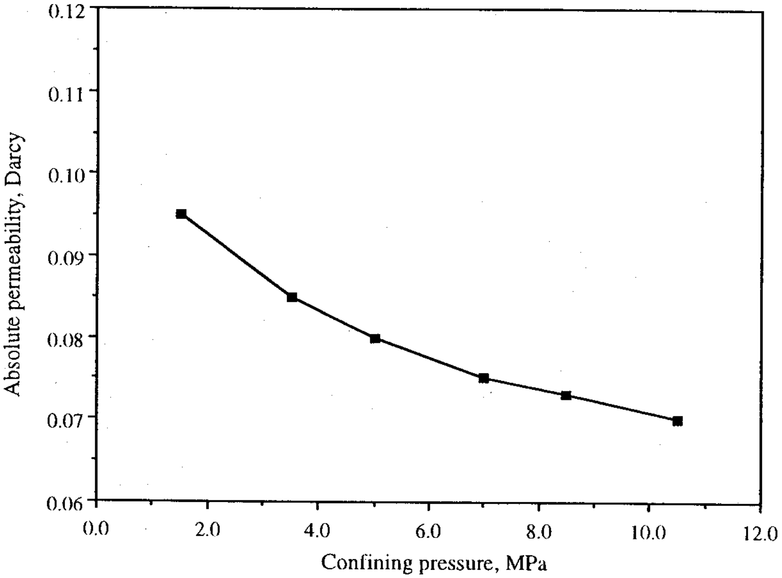


Fig. 14. Confining pressure – permeability relationship of the tested limestone.

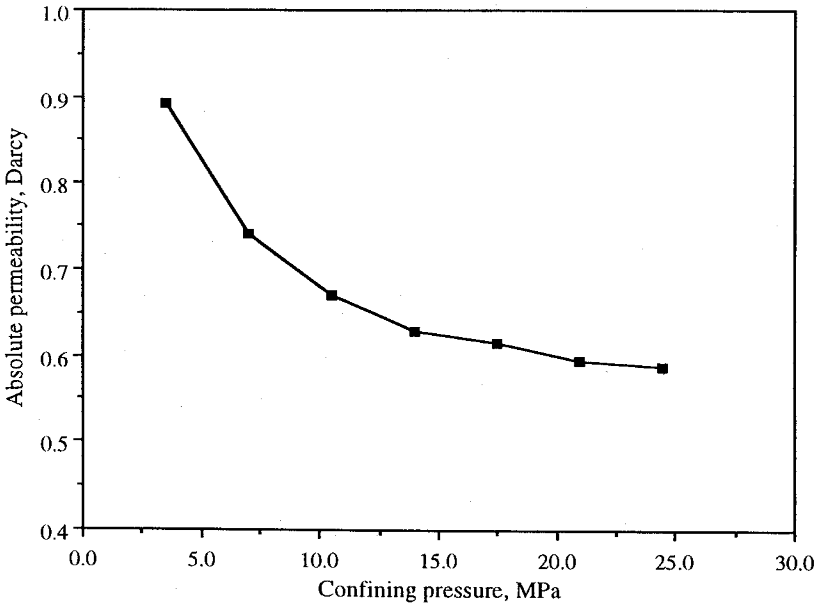


Fig. 15. Confining pressure – permeability relationship of the tested sandstone.

Table 1 Reservoir properties and pore pressure-permeability correlation data.

Sample	a_o	a_1	a_2	a_3	a_4	r^2
Limestone	-0.26407	6.7737e-2	-5.0858e-3	1.6511e-4	-1.8588e-6	1.0
Sandstone	0.58808	-1.4274e-3	1.2228e-3	-1.0962e-4	4.0210e-6	1.0

<u>Reservoir properties</u>

r_1/r_2 = 1000 ft. μ_o = 1.18 cp

h = 136 ft initial pore pressure (pp) = 25 MPa (1 MPa = 145 psi)

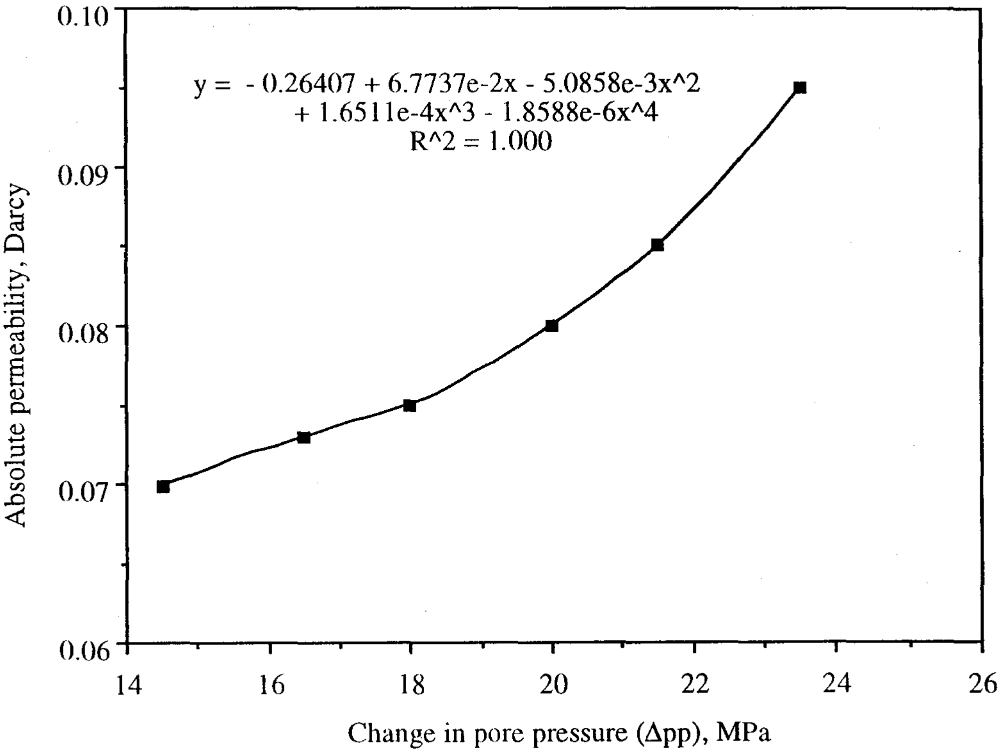


Fig. 16. Relationship between the change in pore pressure and absolute permeability for the tested limestone.

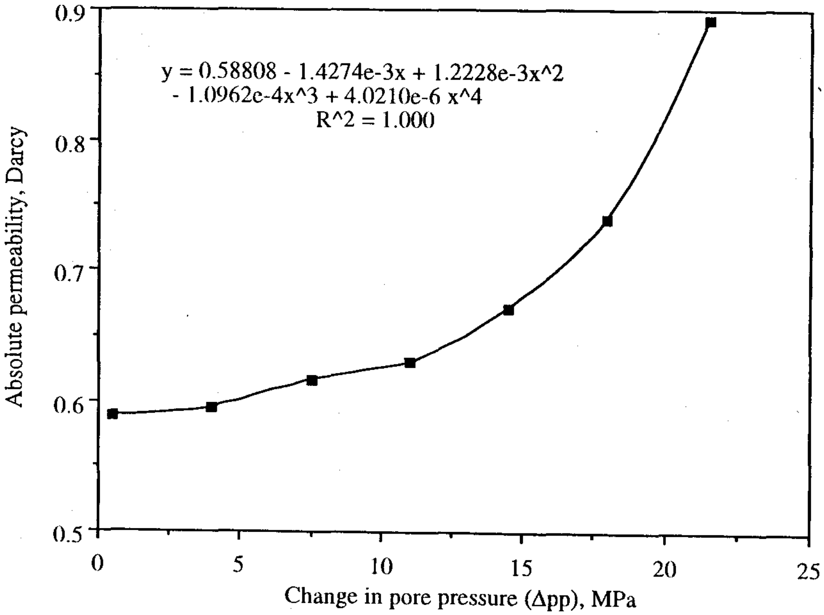


Fig. 17. Relationship between the change in pore pressure and absolute permeability for the tested sandstone.

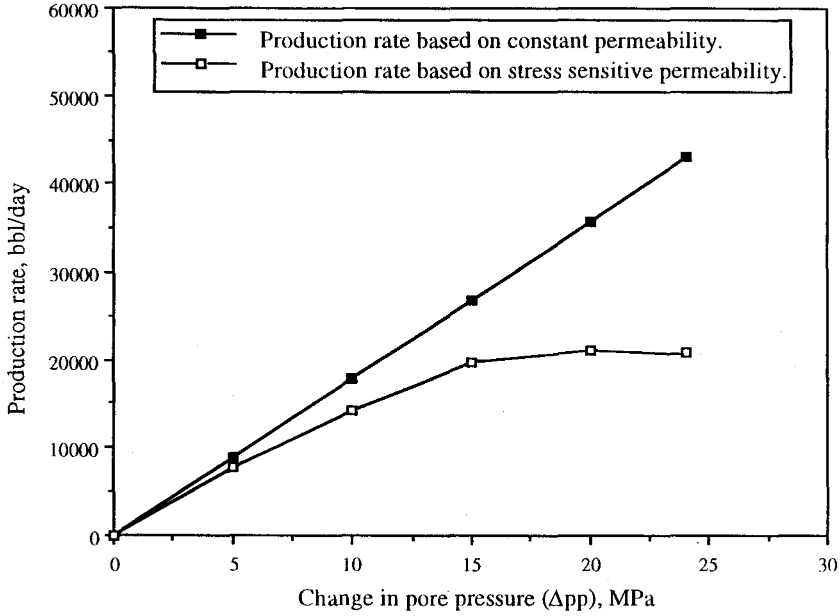


Fig. 18. Effect of pore pressure drop on the productivity of the tested limestone.

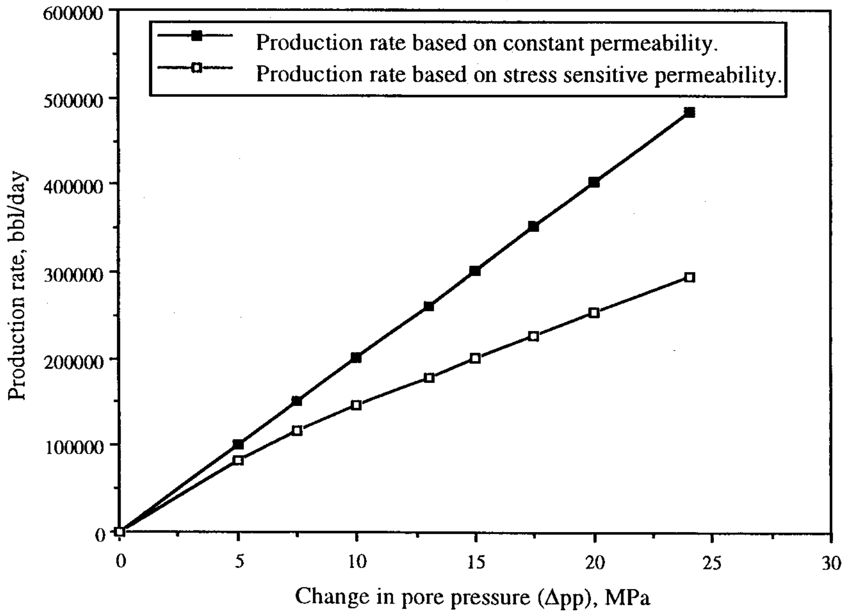


Fig. 19. Effect of pore pressure drop on the productivity of the tested sandstone.

5. CONCLUSIONS

1. The degree of reduction in rock permeability due to pore pressure drop (or effective overburden stress increase) is function of the rock initial porosity and permeability.
2. Calculations based on the elaborated model (Eq. 6) showed that the permeability reduction due to pore pressure drop significantly affect the productivity of the examined formations.
3. After the application of confining pressure up to 10.5 MPa, permanent reduction in permeability was observed for the tested sandstone, whereas no permanent reduction in the permeability was observed for the tested carbonate rock at a maximum confining pressure of 25 MPa.
4. Correct productivity estimation cannot be obtained until the permeability is expressed as a function of effective overburden pressure (i.e. the difference between the overburden pressure and the reservoir pore fluid pressure).

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

6. REFERENCES

1. **Musaed N. J. Al-Awad** : "Relationship between reservoir productivity and pore pressure drop." A paper considered for publication in KSU Journal, Engineering Sciences, Vol. 13, No. 1, 2000.

2. **Fatt I., Davis D.H.** and **La Habra** : "Reduction in permeability with overburden pressure." Petrol. Trans. AIME, pp. 329-329 (one page), Vol. 195, 1952.

3. **Fatt I.** : "The effect of overburden pressure on relative permeability." Petrol. Trans. AIME, pp. 325-326, Vol. 198, 1953.

4. **Hall, H. N.** : "Compressibility of reservoir rocks." Petrol. Trans. AIME, pp. 309-311, Vol. 198, 1953.

5. **Geertsma J.** : "The effect of fluid pressure decline on volume changes of porous rock." Petrol. Trans. AIME, pp. 210-331, 1957.

6. **Wyble, D.O.** : "Effect of applied pressure on conductivity, porosity and permeability of sandstones." Petrol. Trans. AIME No. 213, pp. 431-432, 1958.

7. **Fatt, I.** : "Pore volume compressibilities of sandstone reservoir rocks." Petrol. Trans. AIME, pp. 362-364, Vol. 201, 1958.

8. **Dobrynin, V. M.** : "Effect of overburden pressure on some properties of sandstones." Soc. Petrol. Engineers J., pp. 360-366, Vol. 12, December 1962.

9. **Ferrel, H. H., Felsenthal M.** and **Wolfe Jr. J. W.** : "Effect of overburden pressure on flow capacity in a deep oil reservoir." J. Petrol. Technol., pp. 962-966, Sept. 1962.

10. **Gray D.H. Fatt I.** and **Bergamini G.** : "The effect of stress on permeability of sandstone cores." SPE Journal., pp. 95-100, Vol. 3, No. 3 , June 1963.

11. **Juris, V., Heam, C.L., Donald, W.D.** and **Rhoades, V.W.** : "Effect of rock stress on gas production from low-permeability reservoirs." J. Petrol.

Technol., pp. 1161-1167, Vol. 23, No. 9, Sept. 1971.

12. **Rex, D. T. and Don, C.W.** : "Effect of overburden pressure and water saturation on gas permeability of tight sandstone cores." J. Petrol. Technol., pp. 120-124, Vol. 23 No. 2, Feb. 1971.

13. **Marek, B. F.:** "Permeability loss in depletion reservoirs." The 54th Annual Tech. Conf. and Exhib., Las Vegas, Sept. 23-26, 1979.

14. **Wel, K.K., Morrow, N.R. and Brower, K.R.** : "Effect of fluid confining pressure and temperature on absolute permeability of low permeability sandstones." SPE Formation Evaluation Journal, pp. 413-423, August 1986.

15. **Gobran, B. D., Brigham W.E. and Ramey Jr. H.J.** : "Absolute permeability as a function of confining pressure, pore pressure, and temperature." SPE Formation Evaluation J., pp.77-84, March 1987.

16. **Adnan, O.** : "Effect of brine concentration on permeability at elevated temperatures and pressures." J. Faculty of Engineering, Cairo University, pp. 269-291, Vol. 36, No. 1, 1989.

17. **Teufel, L.E., Rhett, D.W. and Farrell, H.E.** : "Effect of reservoir depletion and pore pressure drawdown on in-situ stress and deformation in the Ekofisk field, North Sea." Proceedings of the 32nd U.S. Symp. on Rock Mechanics, pp. 63-72, 1991.

18. **Smart, B.G.D., Tehrani, D.H., Olden, P.W.H. and Jin, M.:** "Results from reservoir depressurisation simulation incorporating phenomena revealed in a reactive reservoir analogue." pp. 155-161, Eurock 94, SPE/ISRM Conf. 29-31 Aug., 1994.

19. **Gutierrez, M., Tunbrige, L., Hansteen, H., Makurat, A., Barton, N., and Landa, G. H.,** : "Modelling of the compaction behaviour of fractured chalk." pp. 803-810, Eurock 94, SPE/ISRM Conf. 29-31 Aug., 1994.

20. **Amar, Z.H.B., Altunbay, M. and Barr, D.** : "Stress sensitivity in the Duland field-how it is related to productivity." SPE Paper No. 30092 presented at the European Formation Damage Control Conf., The Hague, The Netherlands, 15-16 May 1995.

21. **Al-Awad, M. N. J. and Alsayed, N. A.** : "Effect of drilling induced stresses on formation productivity." The Fifth International Conference on Mining,

Petroleum and Metallurgical Engineering, Suez Canal University, Suez, Egypt, pp. 71-84, Feb. 24-26, 1997.

22. **Azeemuddin, M., Roegiers, J.C., Suri, P.Z., Zaman, M.** and **Kukreti, A.R.** : "Stress dependent permeability measurements of rock in a triaxial cell." pp. 645-650, Proceedings of the 35th US Conf. in Rock Mechanics, Balkema, Rotterdam, Holland, 1995.

23. **Bearumen, S.** and **Tiab, D.** : "Effect of pore pressure on conductivity and permeability of fractured rocks." SPE Paper No. 35694, 66th SPE Western Region Meeting, USA, pp. 445-460, 1996.

24. **Plamer, I.** and **Mansouori, J.** : "How permeability depends on stress and pore pressure in coalbeds, a new model." SPE Paper No. 36737, SPE Annual Technical Conference and Exhibition, Denver, Colorado, pp. 557-564, 6-9 October 1996.

25. **Ruistuen, H., Teufel, L.W.** and **Rhett, D.** : "Influence of reservoir stress path on deformation and permeability of weakly cemented sandstone reservoirs." SPE Paper no. 36535, SPE Technical Conf. and Exhibition, Denver, Colorado, pp. 463-470, 6-9 October 1996.

26. **Chilingarian, G. V.** and **Rieke, H. H.** " Compaction of Argillaceous Sediments " pp. ٤٩-١٠٠ in Abnormal Formation pressures by W. H. Fertl,. Development in Petroleum Science ٢،٣٨٣pp.

27. **Chilingarian, G. V.** and **Rieke, H. H.** " Compaction of Argillaceous Sediments, Developments in Sedimentology ١٦, Elservier Publ. Co. ٤٥٠pp, ١٩٧٤.

28. **Chilingarian, G. V. ETAL**. " Carbonate Reservoir Characterization: A Geologic- Engineering Analysis. Developments in Petroleum Science ٣٠, ٦٣٩pp ١٩٩٢.

29. **Chilingarian, G. V. ETAL**. " Subsidence due to Fluid Withdrawal, " " Elsevier, 1996.

30. **Chilingarian, G. V. ETAL**. " Compaction of Coarse–Grained Sediments I, Developments in Sedimentology ١٨A, Elsevier Publ. Co. ٥٥٢ pp, ١٩٧٥.

31. **Chilingarian, G. V. ETAL**. " Compaction of Coarse–Grained Sediments II, Developments in Sedinentology ١٨B, ٨٠٨pp., ١٩٧٦.

32. **Chilingarian, G. V. ETAL**. " Subsidence. Due to Fluid Withdrawal, ٤٩٨ pp. Elsevier, ١٩٩٥.

33. **Chilingarian, G. V**. " Carbonate Reservoir Characterization: A Geologic–Engineering Analysis, Part II. Developments in Petroleum Science ٩٩٩ pp., ١٩٩٦.

34. **Jaeger J.C. and Cook N.G.W.** : "Fundamentals of Rock Mechanics." 3rd edition, Chapman and Hall, London, 1979, 593p.