STRESS VARIABILITY AROUND LARGE STRUCTURAL FEATURES AND ITS IMPACT ON PERMEABILITY FOR COUPLED MODELLING SIMULATIONS

Ta Quoc Dung(1), **Suzanne Hunt**(2)
(1) University of Technology, VNU-HCM
(2) Australian School of Petroleum

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ABSTRACT: *A clear understanding of rock stress and its effect on permeability is important in a coupled simulation where fluid production causes a significant increase in the effective stress within a reservoir. Changing the in-situ rock stress state can alter the reservoir properties. As a result, porosity and permeability could be affected due to the rearrangement of rock particles and the redistribution of sensitive pore structures.*

It is known that permeability is more sensitive to stress changes than porosity. Permeability reduction can range between 10% and 30% as reported in previous publications, this is within the elastic range of the material under investigation. Once the material reaches its yield strength a dramatic increase in permeability can then occur or further reduction depending on the mode of failure of the rock type in question. This study reports on permeability reduction under increasing stress (within the elastic range) for a number of rock types, the samples tested are from the Cooper Basin of South Australia; the standard Berea Sandstone is included for validation purposes. The results are used within a newly developed finite element coupled code in order to estimate permeability sensitivity to stress changes for predicting compaction and subsidence effects for a cylindrical wellbore model.

Furthermore, understanding rock mass stress away from the borehole is a major obstacle in the exploration and development of hydrocarbons. It is standard practice in the petroleum industry to use drilling data to determine the orientation and estimate the magnitudes of principal stresses at depth. However, field observations indicate that the orientation of the principal stresses is often locally perturbed by and around discontinuities, such as faults or formation boundaries (Kattenhorn et al., 2000; Maerten et al., 2002). Numerical stress methods have been successfully employed to model the effect of displacing faults on the surrounding rock mass. 3D distinct element code has been used to show how displacing faults generate stress variation in 3D about a fault plane (Camac et al., 2004), verified with field observations. In this work consideration is made of this variability and its effect on wellbore subsidence and compaction models. A series of models were run which incorporate the stress variability expected around an example fault under normal stress field conditions. The models show that the initial stress state conditions associated with a fault give rise to a variation in the stress path during reservoir production and resultant permeability changes are measured. The extent of the influence of lateral changes around large-scale structural features is thereby assessed and the work demonstrates the importance of incorporating this initial stress variability for production purposes.

1.INTRODUCTION

Understanding stress sensitive permeability has been of wide interest to the petroleum engineering, geothermal energy and hydrogeological disciplines where coupled rock and fluid behavior are now being incorporated into reservoir simulations. Of particular importance to the petroleum industry is the ability to accurately model and subsequently predict rock and fluid behavior during hydrocarbon production, which can lead to the accurate prediction of reservoir compaction and near surface subsidence problems. Previously Ta & Hunt (2005) presented a finite element model for evaluating compaction and subsidence for a radial well bore model. This work aims to address the issue of stress sensitive permeability and incorporate this effect as well as influence of stress perturbation due to a discontinuity

2.SENSITIVITY OF PERMEABILITY TO STRESS PERTURBATION AND INFLUENCE OF A DISCONTINUITY ON PERMEABILITY

In the past, several authors have used a variety of laboratory based testing procedures to measure permeability under in situ stress conditions. Some of the earliest work relating to sensitivity of permeability due to stress variation was presented analytically in which permeability measurements were conducted for gas well testing (Vairogs et al., 1971). Skin values for the gas well tests were found to vary as permeability decreased during production, resulting from the enhanced permeability reduction near the wellbore, the inclusion of stress sensitive permeability effects altered the welltest analysis significantly. Most authors reached the conclusion that permeability is reduced from 10% to 30% when confining stress was increased in a range of 1000psi to 8000psi (Holt, 1990; Warpinski & Teufel, 1992). Further results showed that the reduction of permeability in low permeability core is greater than reduction of permeability in high permeability core (Vairogs & Rhoades, 1973), implying that only certain rock types demonstrate significant stress sensitive permeability. Consequently, reduction of permeability is dependent on lithology (John et al., 1998) which varies for each specific oil field. Some work has been done in characterizing stress sensitivity of various rock types, but no absolute method has been found to determine where a cut-off occurs. Certainly it is generally considered important to incorporate stress sensitive permeability for tight gas reservoirs where the permeability value is dominant factor for investigating the behaviors of fluid flow. A thorough review of hydro-mechanical testing procedures was carried out by Heiland (2003) where three laboratory procedures are described. In most cases decrease in permeability occurred with increasing stress. One exception to this where dilatancy leading to brittle failure occurs under triaxial conditions in which high shear stresses are acting only then can increased stress give rise to increased permeability.

The influence of temperature on permeability was also incorporated in searching the reduction of permeability in reservoir by Gobran et al (1987). This research investigated absolute permeability as a function of confining pressure, pore pressure and temperature reaching the conclusion, that permeability was independent of temperature, but was a linear function of confining pressure.

Jelmert et al (2000) investigated correlations between permeability and effective stress, reviewing power-law relationships and stating that straight-line correlations were inappropriate as opposed to polynomial fits to averaged core data. Warpinski & Teufel (1992) had previously fitted polynomial equations to experimental results. The reduction of permeability with effective stress increase is discussed further and mathematical relationships are summarised by Nathenson (1999).

A number of field studies relating to compaction and subsidence in the North Sea have also shown that permeability changes during production significantly influenced the stress path of the reservoir (Economides et al., 1994; Rhett & Teufel, 1992). Consequently, there is no doubt that the constant permeability values assumed in conventional reservoir simulation may result in considerable errors. Ambastha & Meng (1996) presented alternative one-two parameter models to calculate a permeability modulus that can be applied to produce a more accurate transient analysis in conventional fluid equations. Although these models look promising, the authors did not discuss the correlation between the reduction of well pressure and effective stress resulting in reduction of permeability. The investigation of the influence of the stress path under varying reservoir conditions was discussed by Mashiur & Teufel (1996). Importantly the results presented, demonstrated that sensitivity of permeability due to stress perturbation was not only dependent on effective stress but also on the size, geometry and other reservoir properties (i.e. reservoir boundary conditions). These experimental results on stress sensitivity demonstrated that the maximum permeability direction is parallel to the maximum principal stress and the magnitude of permeability anisotropy increases for lower stress paths. To deal numerically with the stress sensitive permeability problem, Mashiur & Teufel also used the finite element method that is more rigorous in solving the stress and fluid flow equations simultaneously. It is certain that permeability is a function of effective stress. In turn, production conditions will directly influence the reservoir condition where effective stress is one of the most important properties. In a detailed break-down of the numerical modeling methodology for permeability variation within a producing reservoir, Osorio et al. (1997) showed that the most sensitive stress permeability happens near the wellbore and within the production zone and decreases far from wellbore where the change of the local effective stress in this area is insignificant. Osorio et al. also incorporated the stress-permeability relationship into his model by incorporating generic relationships for shear modulus, bulk compressibility, and permeability against effective stress.

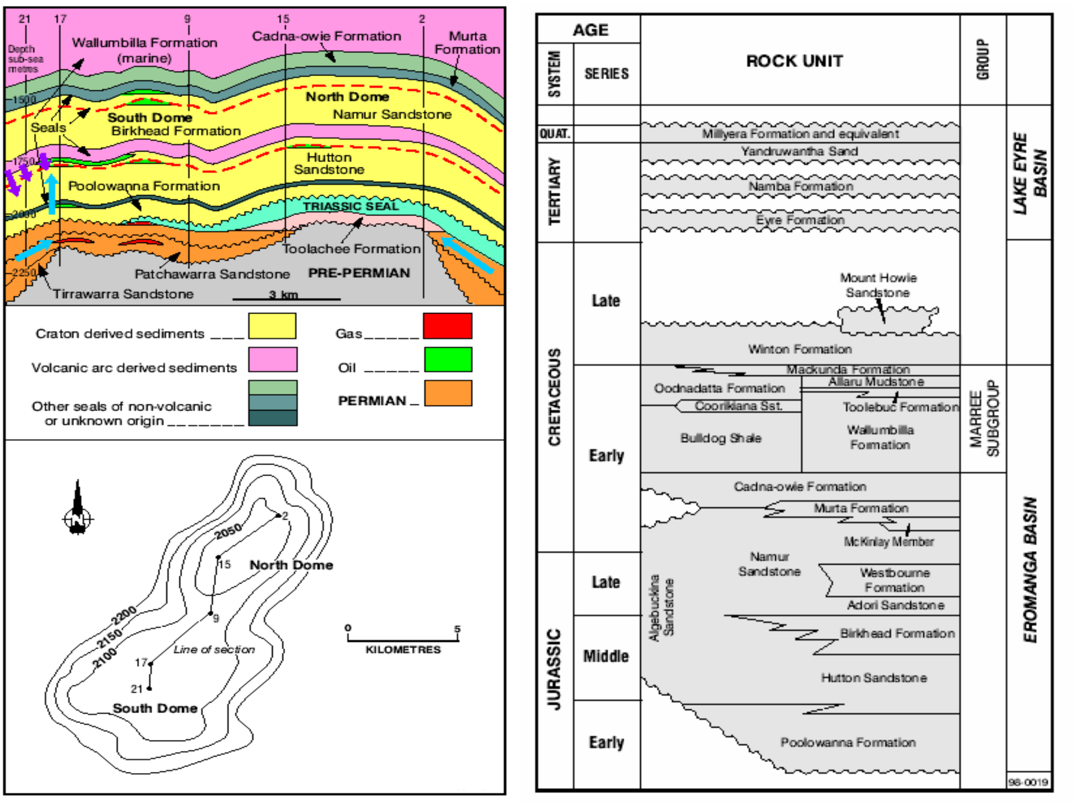

Fig. 1. Stratigraphy summary of Eromanga Basin (Boreham & Hill, 1998)

To investigate the influence of increasing effective stress and a discontinuity to stress perturbation on permeability, the Eromanga-Cooper Basins were used as case example (Fig. 1). These fields are located in central and eastern Australia. The saucer-shaped Eromanga Basin extends over one million square kilometers in Queensland, New South Wales, South Australia, and the southeast of the Northern Territory. The Eromanga-Cooper Basins is overlain by the Lake Eyre Basin, a succession of Tertiary and Quaternary age sediments occurring extensively throughout central Australia. These sediments are gently folded in some areas and contain a succession of extensive sandstone formations that serve as oil reservoirs and regional aquifers. The majority of oil producing reservoirs in the Eromanga-Cooper Basins is classified as 'water drive' reservoirs. Oil pools are usually found in formations that also contain considerable quantities of water. As a result of the differing physical properties of oil and water, over time the oil tends to 'float' to the surface and sit above the water. These formations usually exist under pressure so when they are accessed by drilling a borehole the oil will flow to the surface. Theoretically, fault system usually is consistently parallel S_{Hmax} orientation (Fig. 2). However, field observed data in Eromanga-Cooper Basin showed that the degree to which the stress field is perturbed relates to the contrast in geomechanical properties at the interface (Camac et al., 2004; Reynolds et al., 2005). Stress perturbations also occur as a result of slip on preexisting faults in rocks with homogenous elastic properties. In this situation, the stress perturbations are greatest at the tips of the discontinuity and can vary as a result of factors such as the differential stress magnitude, fault models, the friction coefficient on the discontinuity and the strike of the discontinuity relative to the far-field stress.

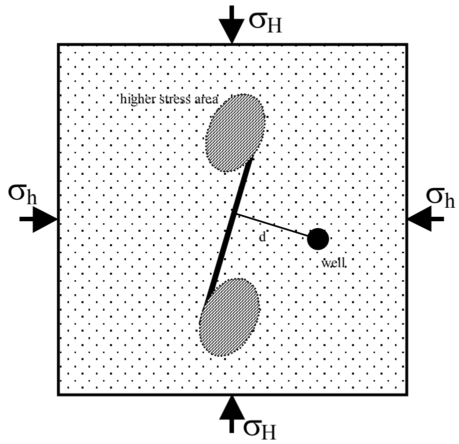

Fig. 2. Stress perturbation around the tip of fracture

It is also noted that when fluid is withdrawn from the reservoir, the in-situ stress will be changed. In turn, due to stress perturbation at the discontinuity, a change in the hydrocarbon production will occur. This situation should be considered seriously at the point that stress changes associated with depletion are complicated in compaction reservoir under pore pressure point of view (Ta & Hunt, 2005). In considering the influence of a discontinuity, the minimum stress-depletion response in the region of active normal faulting may be expressed (Addis et al., 1996) as following

$$\delta\sigma_3 = \delta P_p\left(1 - \nu\left(K_p + 1\right)\right)$$

$$\delta\sigma_3=\delta P_p(2\sin\phi/(1+\sin\phi))$$

This equation is suitably applied for the Eromanga-Cooper Basins because the minimum stress acts on the fault plane. According to Addis et al.'s theory, it means that $\nu>(1-\sin\phi)/2$.

Where: ϕ-fault friction angle or angle of internal friction;σ-principle stress; P_p-pore pressure and ν-poison ratio.

3.TEST EQUIPMENT AND EXPERIMENTAL DESIGN

The experiments to determine the stress sensitive reservoir properties were performed using a LP401 permeameter and helium porosimeter for measurement of porosity and permeability. Overburden pressure was applied on the core surface covered around by the sleeve in core holder. In this paper, the effective maximum stress is difference between the external applied stress and average fluid pressure.

Only limited work was undertaken on the reservoir unit porosity–permeability trends in the Eromanga-Cooper basins. The most significant observation is that there is no simple relationship or adequate models for estimating the reservoir quality with depth in the Coope-Eromanga basins (Table 1). Consequently, a simplified relationship was used in order to demonstrate the stress permeability effect in this compaction study. A standard core sample was tested to compare the laboratory relationship with the field relationship that is for permeability and overburden pressure as shown in Figure 3. The absolute radial permeability values ranged from about 0.2mD to 18mD and they decreased in virtually all samples as a function of increasing effective overburden stress. Figure 3 shows a compilation of all permeability data for the Eromanga Basin, normalised with respect to the first permeability measurement at about 145psi effective vertical stress. The normalized permeability range shows a maximum permeability reduction for the Namur, Hutton and Murta formations of 30%. In the other hand, the normalized permeability for the Poolowanna and Birkhead formations decreased only 10%. This agrees with that observed in the laboratory literature studies previously reviewed. The variation in the degree of change between differing lithologies is attributed to variation in composition and microstructure between individual samples from various formations.

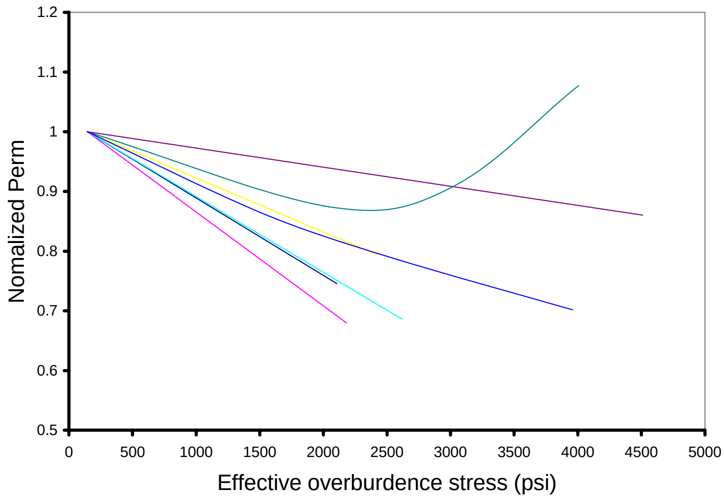

Fig. 3. Normalized permeability as a function of effective overburden stress for Eromanga Basin. Core 1 and core 2 are the Berea Sandstone used for comparative purpose.

The trend of the data indicates a more or less linear decrease of permeability with increasing effective overburden stress. For fitting a relationship to the overburden pressure, the permeability and the empirical equation; a polynomial equation (Jelmert et al., 2000; Morton, 1989) can be applied for estimating the overburden permeability for the Cooper Basin (Table 1).

Table 1. Porosity and permeability at ambient conditions (AC) and overburden condition (OC) in the Cooper Basin

Formation	Depth (m)	Press (psi) AC	Porosity (%) AC	Perm (md) AC	Press (psi) OC	Porosity (%) OC	Perm (md) OC
Cuddapan	2663	1000	9.2	1.58	3861.35	8.74	1.054
Tinchoo	2497	1000	11.9	26.1	3620.65	11.305	18.459
Wimma	2157	1000	10	0.926	3127.65	9.5	0.471
Paning	2173	1000	11.6	1.98	3150.85	11.02	1.328
Callamurra	2465	1000	9.7	0.62	3574.25	9.215	0.252
Toolachee	2180	1000	12.4	3.363	3161	11.78	2.280
Daralingie	2424	1000	9.7	0.397	3514.8	9.215	0.125
Epsilon	2409	1000	9.1	0.68	3493.05	8.645	0.291
Patchawarra	2463	1000	10.5	0.933	3571.35	9.975	0.476
Tirrawarra	2643	1000	11.1	1.59	3832.35	10.545	1.061
Merrimelia	2990	1000	7.7	0.109	4335.5	7.315	0.017

4.SUBSIDENCE PREDICTION

This study then analyses the impact of assigning different initial permeability to a coupled wellbore production model. Table 2 shows the values selected for a reservoir simulated using the symmetric well model in the Eromanga-Cooper basins. The emphasis is to simulate the effect permeability variation can have on subsidence and compaction estimates for the oil reservoir within the radial model (Fig. 4).

Table 2. Material properties of reservoir in the simulation

Material properties	Symbol	Values	Field unit
Initial porosity	ϕ_i	0.15	-
Poison's ratio	ν	0.25	-
Initial permeability	k_i	30	mD
Young modulus	E	5.6 E6	psi
Fluid compressibility	C_f	15.E-06	psi^{-1}
Solid compressibility	C_s	7.0E-06	psi^{-1}
Initial pressure	P_i	5000	psi
Production zone	N/A	1400-1800	ft
Well radius	r_w	0.5	ft
External boundary	R	7932	ft
Depth	z	4798	ft

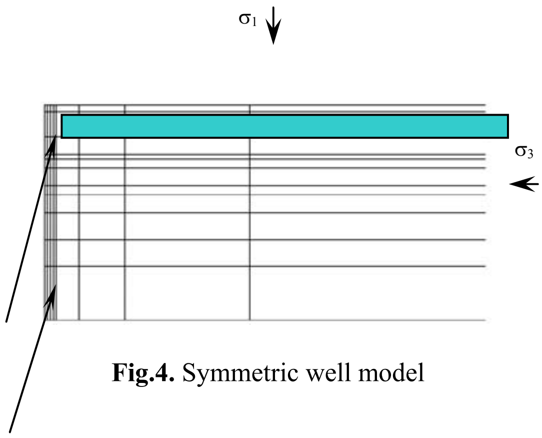

Fig.4. Symmetric well model

The reservoir in this model is assumed to be thin related to the depth, the perforated zone and a field scale example as shown in Figure 4. Oil production is simulated over a 200-day period. In this model, the well of radius r_w is producing a single-phase fluid at a constant rate q, from a saturated reservoir. The reservoir is assumed to be homogeneous and isotropic, with a boundary being restrained from any radial displacement at the producing wellbore, but allowing free displacement in the vertical direction. The study looks at the concept of introducing a large structural feature which will laterally give rise to a perturbation in the local stress field that will in turn influence the evolving reservoir permeability and final subsidence. Due to boundary condition that is being restrained from any vertical and horizontal displacement far from wellbore, the subsidence at the external boundary equals zero. This effect could increase significantly in the area around the wellbore where pore pressure is at a minimum. At a distance far from the wellbore, this influence will decrease and reach the initial value. The coupled model analysis is written using the Matlab programming environment and solves problems involving fluid flow through a saturated elastic porous medium under transient condition. Mechanical properties derived directly from core data were averaged for the purposes of the reservoir simulation.

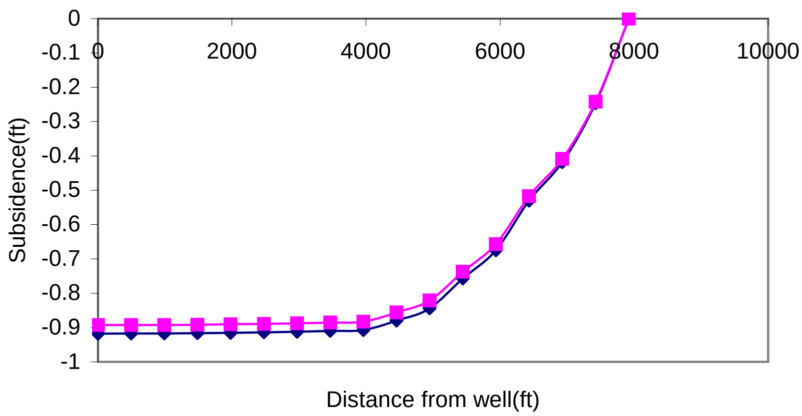

Fig.5. Subsidence variation between conventional permeability (permeability fixed throughout model run) and stress sensitive permeability (permeability permitted to vary throughout model run) models after 200 days of production (kI = 30md, ϕI = 0.15).

Figure 5 shows subsidence of the reservoir during fluid production for the conventional and the stress coupled permeability models with an initial porosity of 15%. The subsidence varied between 0.9ft and 0.95ft for the models run over a 200-day period, respectively. Consequently, it is evident that stress sensitive permeability has an increased effect on the subsidence magnitude.

A simulation of reservoir depletion was also run for different stress sensitive models by applying the same initial conditions for fluid production. Figure 6 presented below shows the influence of a discontinuity on possible lateral subsidence variation resulting in three models with different initial stress perturbation at the boundary such as faults or fracture. This is done in order to assess sensitivity for a stress sensitive reservoir to possible variation in stress caused by heterogeneity. It can be seen that the subsidence varies significantly from nearly 0.91ft to 0.95 ft over a 200-day simulation run. The results suggest that an increase in stress due to a large feature could lead to a significant variability in the coupled model runs. Moreover, because the deformation increased in the near wellbore region, rock properties are expected to change inelastically. Consequently, petrophysical parameters including permeability and porosity behaviors will be further complicated. So, detailed more qualitative calculation investigations are required in future within this plastic regime.

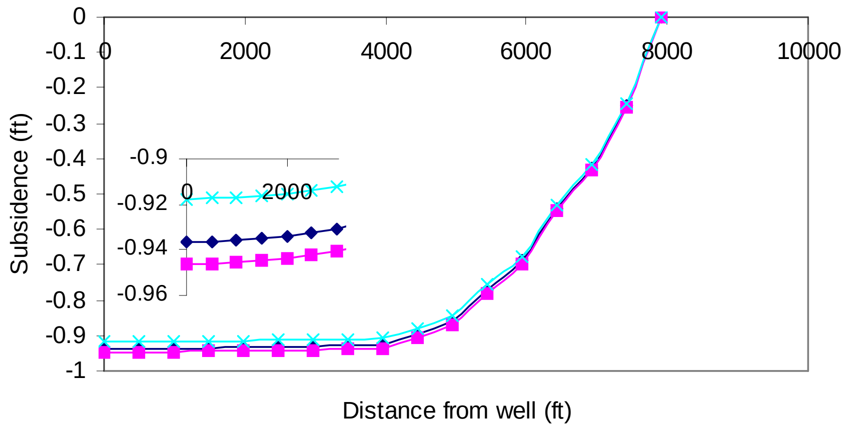

Fig. 6. Influence of large structure on subsidence, Δσ3 is the variation in the predicted applied horizontal stress possible around a discontinuity such as a fault (applied in the stress sensitive permeability models after 200days with kI=30md, ϕI=0.15).

5.CONCLUSION

The relationship between the permeability and the stress state as caused by depth and lateral changes incurred around large structural features such as discontinuities have been reviewed and studied. Particularly, it can be concluded that the permeability in the deforming reservoir is stress dependent and this influence is expected to be more significant in the near wellbore region, as the effective stress is largest during production and well-testing studies. However, in most calculations used by commercial software the permeability is applied as a constant.

The selections of fault models, fault friction, friction internal angle and Poisson's ratio are very important to assess the influence of discontinuity on the reservoir compaction and subsidence because it can cause a significantly change in the stress regime.

The permeability in Eromanga–Cooper Basins in this study decreased by 5% to 10% of the initial permeability with every 1000psi decrease of the reservoir fluid pressure. Most experimental results are in agreement with the literature data of compaction/permeability experiments (David & Crawford, 1998) but disagree with the data of Rhett & Teufel (1992), who showed that permeability can be increased during the uniaxial compaction of reservoir sandstone. The observation of increasing permeability is only matched when sample two of the Berea Sandstone core is at failure and generates more fissures.

Potential subsidence in the Eromanga-Cooper Basins is considered in this work and is an issue of theoretical future research.

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NGHIÊN CỨU SỰ BIẾN THIÊN TRƯỜNG ỨNG SUẤT XUNG QUANH CÁC CẤU TRÚC ĐỊA CHẤT VÀ TÁC ĐỘNG CỦA THAY ĐỔI TRƯỜNG ỨNG SUẤT TỚI ĐỘ THẤM TRONG MÔ PHỎNG TÍCH HỢP

Tạ Quốc Dũng(1), Suzanne Hunt(2)
(1) Trường Đại học Bách khoa, ĐHQG-HCM
(2) Trường Dầu khí Australia

TÓM TẮT: *Trường ứng suất của vỉa và sự thay đổi ứng suất tại chỗ do khai thác dầu khí có thể làm thay đổi tính chất vỉa như độ thấm và độ rỗng do có sự phân bố lại cấu trúc lỗ rỗng. Các nghiên cứu trước đây đã chỉ ra sự thay đổi của độ thấm nhạy hơn so với sự thay đổi độ rỗng khi ứng suất hữu hiệu tăng lên. Nghiên cứu của các tác giả đã chỉ ra qui luật thay đổi độ thấm trên nhiều mẫu từ bồn trũng Cooper, Úc và mẫu chuẩn cát kết Berea. Kết quả thí nghiệm được sử dụng làm dữ liệu đầu vào trong mô hình phần tử hữu hạn để dự báo sụt lún và cố kết tại bồn trũng Cooper. Mô hình tính toán cũng chỉ ra rằng trạng thái ứng suất ban đầu của vỉa kết hợp với các mô hình đứt gẫy sẽ dẫn đến thay đổi trạng thái ứng suất (stress path) và kết quả là độ thấm của vỉa thay đổi khi khai thác dầu khí.*

Từ khóa: *Độ thấm, trường ứng suất, đứt gẫy.*

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