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Depressurization as an Effective IOR Strategy

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التقليل من الضغط كإستراتيجية مؤثرة للاسترداد الإضافي

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يتم الآن ضمن عمليات الاسترداد الإضافي تبني طريقة تخفيض ضغط المكمن كأفضل تقنية من المنظور الاقتصادي بعدة مكامن فتاتية.
حددت أعمال سابقة على تحليل الإجهاد بالمكمن بوضوح العلاقة المعقدة بين خواص انسياب المكمن وإجهاد المكمن المؤثر والسائد.
تقدم هذه الورقة نتائج دراسات استهلت بجامعة روبرت جوردون في الأعوام القليلة الماضية وأكدت هذه الدراسة نتائج دراسات سابقة عديدة تنص على وجود علاقة معقدة بين خصائص انسياب المكمن والإجهاد السائد المؤثر. وأكدت النتائج أيضا وبقوة أن كفاءة فاعلية انسياب المكمن ومعامل الاسترداد هما دالة نفاذية المكمن الأولية، ومعامل جودة الخزان ومسار الإجهاد.
لقد بينت دراسات النفاذية حتى الآن أن تأثير مسار الإجهاد على فاعلية الانسياب ومعامل الاسترداد يعتمد على معامل جودة الخزان وعلى ما يسمى بمؤشر جودة الخزان والذي تم تعريفه بأنه المعامل الوحيد الذي يشمل المزايا الجيولوجية للنسيج والمحتوى المعدني في تمييز سحنات الفراغات الهندسية والتي تعرف بالوحدات الهيدروليكية.
يمثل مسار الإجهاد تباين شدة الإجهاد بالمكمن، وتم إجراء بعض التحاليل باستعمال مجموعة من المعلومات الحقلية التي يمكن استعمال نتائجها في تطوير وأخذ قرار يخص اختيار المكمن الأمثل وظروف العمل المناسبة وبما يضمن تحسن في الاسترداد الإضافي.

Abstract: *Reservoir depressurization is now being adopted as the most economic improved oil recovery (IOR) technique in many clastic reservoirs. Early work on reservoir stress analysis has clearly identified a complex relationship between the reservoir flow properties and the prevailing reservoir effective stress.*

This paper presents the results of studies initiated at The Robert Gordon University over the last few years. These results have confirmed a number of previous studies that there is a complex relationship between reservoir flow properties and the prevailing effective stress. The results have confirmed that the reservoir flow efficiency and the recovery factor are both strongly a function of the initial reservoir permeability, Reservoir Quality Index (RQI) and the stress path.

Preliminary studies to date have indicated that the effect of the stress path on flow efficiency and recovery factor depend on the RQI and the so-called Flow Zone Indicator (FZI) defined to be a unique parameter that incorporates the geological attributes of texture and mineralogy in the discrimination of pore geometrical facies known as hydraulic units. The Stress Path represents the

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magnitude of stress anisotropy in a reservoir. Stochastic analysis have been carried out using a variety of field data the results of which can be used to develop a decision for optimum reservoir candidate selection and operating condition required to guarantee improved oil recovery.

INTRODUCTION

Depressurization has long been identified as one of the strategies for enhanced oil recovery especially in mature, depleted reservoirs.

Generally during depressurization, the reservoir pressure drops to release solution gas and mobilize trapped or by-passed oil. The flowing bottom hole pressure can also be reduced to create the necessary drawdown for improved inflow efficiency.

Depressurization itself can generally be achieved by withdrawing large volumes of liquid and free gas from the reservoir. This technique includes[1,2]:

1. Use of gas lift, for example, in mid-flank oil wells to maximize off take.
2. Depressurization of aquifer via ESP water off-take to maintain required pressure depletion rate
3. Under balanced drilling

Irrespective of the technique used, it is believed that during depressurization the reduction in the pore pressure profile will alter the effective stress in the rock matrix the magnitude of which will depend on the type of reservoir. For an HP-HT reservoir in offshore environment, this reduction may be drastic in the initial transient stage[5]. This will induce changes in pore structure and pore volume thereby causing permeability changes. Early work on reservoir stress analysis has clearly identified a complex relationship between the reservoir flow properties and the prevailing reservoir effective stress. The effective reservoir stress is here defined as the difference between the externally applied overburden stress and the internal stress created by the pore fluid pressure. The level of depressurization will no doubt affect the rate of pore pressure decline.

Recent studies initiated at The Robert Gordon University over the last few years [6] on the effect of depressurization on unconsolidated reservoirs has confirmed a number of previous studies by Amaefule *et al* [7], Ottesen *et al* [8] among others [9-11], that there is a complex relationship between reservoir flow properties and the prevailing effective stress. The results have confirmed that the reservoir flow efficiency and recovery factor are strongly a function of the initial reservoir permeability, Reservoir Quality Index (RQI) and the stress path.

A parallel work on UBD indicated that the productivity improvement in UBD-drilled wells is more complex than just mere reduction in formation damage/skin. The studies have indicated that the productivity improvement mechanism in UBD might be akin to ''transient'' or rapid depressurization mechanism[12].

EFFECT OF STRESS

Preliminary studies to date have indicated that the effect of the stress path on flow efficiency and recovery factor depend on the RQI and the so-called Flow Zone Indicator [FZI] defined by Amaefule *et al.* [7] to be a unique parameter that incorporates the geological attributes of texture and mineralogy in the discrimination of pore geometrical facies known as hydraulic units. The early work by Amaefule has indicated that the FZI for the Niger Delta ranged between 0.3 to 11. This may need to be confirmed for the deep offshore where the overburden stress will be a lot higher.

The Stress Path represents the magnitude of stress anisotropy in a reservoir. It is defined as the ratio of the changes in effective horizontal stress and the changes in effective overburden stress.

The stress path K_{sp} is defined mathematically as:

$$K_{sp} = \frac{\Delta\sigma_H}{\Delta\sigma_{OB}} \tag{1}$$

$\Delta\sigma_H$ = Change in effective horizontal stress
$\Delta\sigma_{OB}$ = Change in effective overburden stress

The model for predicting the vertical stress for Offshore Niger Delta was derived by Ottesen *et al* [8] as:

$$\sigma_{OB} = 0.374D^{1.0984} - 10.7 \tag{2}$$

$[\sigma_{OB}]$ = psi
D = True vertical depth, ft

Likewise, the horizontal stresses can be derived as:

$$\sigma_{H\max} = 0.1807D^{1.1650}$$
$$\sigma_{H\min} = 0.1779D^{1.15865} \tag{3}$$

The Reservoir Quality Index is a unique property of any reservoir that takes into account the impact of the effective stress on reservoir flow properties [Porosity and permeability]. It can be obtained mathematically as [7-9]:

$$RQI = 0.0314\sqrt{\frac{k}{\phi}} \tag{4}$$

The FZI can be computed from a log-log plot of RQI vs. normalized porosity index (φ_z)

$$\varphi_z = \frac{\phi}{1-\phi} \tag{5}$$

In order to define the relationship between the reservoir flow properties and effective stress, attempts have been made to develop a semi-empirical correlation using a combination of database from Niger Delta and offshore locations in the North Sea and Dulang Field[9] in Malaysia. The resulting correlation is given as:

$$\frac{k}{k_i} = A + [B * \sigma] - [C * \sigma * K_{sp}] + [D * \sigma * FZI] \tag{6}$$

A, B, C, and D = Empirical constants
σ ?= Effective stress, psi
k_i = initial permeability, mD
k = effective permeability, mD
K_{sp} = Stress path
FZI = Flow zone indicator, mD

EFFECT ON RECOVERY FACTOR

Some basic equations for recovery factor [RF] are as follows[13]:

1. Recovery Factor for Gas Drive Reservoir

$$RF = 0.41815\left[\frac{\varphi(1-S_w)}{\mu_{OB}}\right]^{0.1611} * \left[\frac{10^{-3}k}{\mu_{OB}}\right]^{0.0979} * [S_w]^{0.3722} * \left[\frac{P_b}{P_a}\right]^{0.1741} \tag{7}$$

2. Recovery Factor for Water Drive Reservoirs

$$RF = 0.549\left[\frac{\varphi(1-S_w)}{B_{Oi}}\right]^{0.0422} * \left[\frac{10^{-3}k\mu_{wi}}{\mu_{Oi}}\right]^{0.0979} * [S_w]^{-0.1903} * \left[\frac{P_i}{P_a}\right]^{-0.2159} \tag{8}$$

Where:

φ = Porosity;
k = Effective permeability
$k\mu_{wi}$ = connate water viscosity at irreducible water saturation level
μ_{OB} = Fluid viscosity at bubble point condition
B_{oi} = Formation volume factor at initial reservoir pressure P_i
S_w = Connate water saturation
P_b = Bubble point pressure
P_a = Ambient pressure

As can be observed from equations 7 and 8, any increase in permeability can be said to normally lead to a corresponding increase in recovery factor. Therefore for situations where the increase in effective stress leads to a corresponding increase in permeability, there will be an increase in productivity and recovery.

RESULTS

Figures 1, 2 and 3 show that whilst some reservoirs, appear to indicate an increase in reservoir flow efficiency and RF, others indicate no change and sometime outright decrease in recovery factor.

Figure 1 indicates clearly that for FZI greater than 5 the flow efficiency appears to increase with increase in the effective stress. This also leads, as expected, to a corresponding increase in recovery factor for the same FZI range, (Fig 2). This increase in RF however appears to be more pronounced in the low permeability sands than in the high permeability ones, as shown in Figure 3. On the other hand, the recovery factor appears to increase with decrease in stress path especially for stress paths less than 0.5.

These results appear to indicate therefore that the level of effective stress or drawdown and therefore the stress path will have an effect on reservoir performance depending on the type of reservoir. Therefore for sustainable improvement in

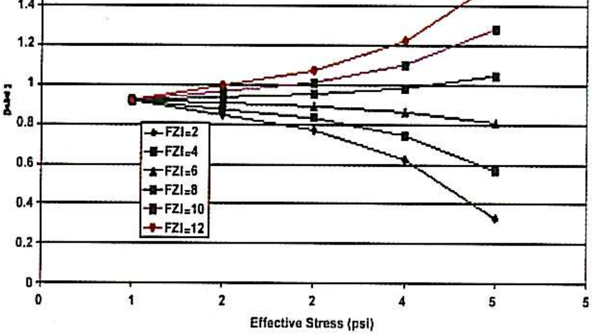

Fig. 1. Effect of stress on permeability.

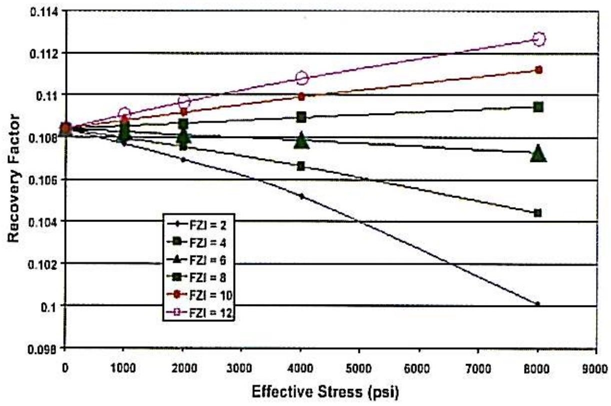

Fig. 2. Recovery factor as a function of effective stress.

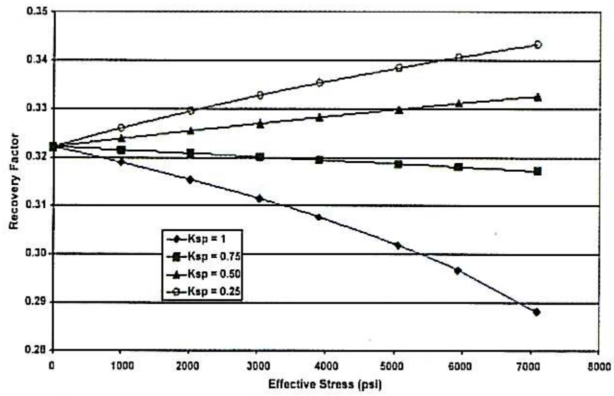

Fig. 3. Effect of stress path on recovery factor.

productivity, it may be logical to say that there must be an optimum level of effective stress or drawdown if productivity improvement is to be sustained over a long period. The same can also be said for under-balanced drilling condition where transient depressurization appears to be taking place during drilling[12]. The studies on UBD are still in their preliminary stages and more extensive studies are required to develop a comprehensive strategy for under-balanced drilling.

CONCLUSIONS

In this paper attempts have been made to present the effect of depressurization and corresponding change in effective stress on recovery factor. The main conclusions are:

1. Depressurization and therefore change in effective stress has a mixed effect on recovery factor depending on the RQI [and thus the type of reservoir], the initial reservoir permeability, type of completion and stress path.
2. Increase in effective stress leads to a higher RF in low permeability reservoirs than it does in higher permeability sands.
3. The increase in RF is limited to FZI greater than 5 and stress path less than 0.5.
4. For lower FZI and stress path higher than 0.5, the RF appears to decrease.
5. Effective reservoir characterization studies are essential to a successful depressurization as an effective IOR strategy

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