Approximation of Time-Dependent Rock Compaction Effects in Reservoir Simulation

By

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A report submitted in partial fulfilment of the requirements for the MSc and/or the DIC.

September 2013
DECLARATION OF OWN WORK

I declare that this thesis *Approximation of Time-Dependent Rock Compaction Effects in Reservoir Simulation* is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

Signature:

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Approximation of Time-Dependent Rock Compaction Effects in Reservoir Simulation
Marianna Sinakova, Imperial College London

Abstract
Time-dependent rock compaction (creep) can be defined as continued deformation without change in stress. In petroleum reservoirs creep is manifested by delayed pore volume reduction. At present, common industry practice when dealing with more complex compaction behaviours is the use of either fully or partially coupled models, which provide the best possible simultaneous solution to fluid-flow and rock deformation equations. However, such models are expensive and difficult to implement.

Many of the world’s prolific reservoirs are comprised from weak, poorly-consolidated sandstones. Similarly to chalks, such sediments are likely to be prone to creep compaction. In the absence of a coupled geomechanical model, it is currently not possible for a reservoir engineer to model creep compaction in most mainstream simulation packages (Eclipse, Nexus, and IMEX). This makes it difficult to assess the additional compaction drive that could be gained from time-dependent compaction behaviour of weak rocks.

This paper provides the results of a sensitivity study performed using the Landmark VIP simulator, which has a built-in creep function capability. The mathematical model behind the way reservoir simulator models rock mechanics is analysed, and thorough analysis of all rock behaviours is presented. A sensitivity study on the creep function is performed and a framework for the approximation of the creep function in other simulation packages is proposed.

From the simulation study it was established that creep can provide between up to 31% extra pressure support. It was found that the amount of creep was sensitive to the depletion strategy of the field. Creep effects will be highest in reservoirs with larger pressure drawdowns and would be minimised by secondary recovery / pressure maintenance mechanisms.

Introduction
Reservoir simulation packages are used around the world as a basis for the prediction of reservoir productivity. Important business decisions are often based on the predictions from these simulation models. However, these predictions are only as good as the assumptions that go into building the models. These software packages are designed for solving complex fluid flow problems; however they often oversimplify other physical processes that might be on-going in the reservoir. One of such processes is rock compaction.

Rock compaction is modelled in the simulator based on the changes in the fluid pore pressure. However, in reality, rocks deform in a much more complex way, where stress history and path of each material is of great importance. In addition, most mainstream simulation packages do not allow for the time-dependent rock compaction to be modelled. At present, the best way to account for more complex behaviours is to construct a coupled-geomechanical model. Such models are expensive to build and require very long computational times; often making them unavailable for reservoir engineers to make improved predictions of the compaction drive in the reservoir. There is currently no cheaper and quicker alternative to the coupled
modelling that would allow an engineer to make a quick estimate of the potential magnitude of creep. Creep can be of significant importance in weak sandstone reservoirs (such as many Gulf of Mexico and Angola reservoirs). Failure to account for this potentially large effect could result in underestimation of the natural compaction drive and production profiles for the field.

The first objective of this study was to understand and evaluate the way in which mainstream reservoir simulation package VIP calculates creep compaction. The literature search has not revealed any other tools to calculate creep in a simulator alone and VIP appears to be the only commercially available package with a built-in creep function. A potential magnitude of additional pressure support due to creep was evaluated. The second (main) objective of this study was to propose a framework for approximating the creep effect calculated from VIP in other simulators (Nexus / Eclipse).

This report will provide a brief discussion of the three main rock deformation mechanisms (elastic compressibility, inelastic compaction and creep) and their effect on reservoir pressure and volumetric strain. It will then evaluate the sensitivity of the creep effect to production/ injection rates. Finally, a function will be proposed for approximating the observed creep effect in Nexus / Eclipse.

**Background Literature Review**

Creep is a well-known phenomenon in material science. Materials creep when undergoing change in stress (Dusseault and Fordham, 1993). The importance of time-dependent rock compaction for the petroleum industry was first established when dealing with surface subsidence in the chalk fields of the North Sea. Ekofisk field, which, after start-up of production in the mid seventies famously showed subsidence in the mid 1980-s, prompted a number of investigations into the reasons behind such costly foresight. Chin et al (1993) report that it was around the same time that the reservoir pressure decline in Ekofisk began to slow down to about 1/3 of the rate in the early 1980-s. It was then that the time-dependent compaction of weak sedimentary rocks was evaluated as a contributor to the chalk compaction drive. During this time, early coupled-geomechanical models were being developed to account for this behaviour.

Similarly to Ekofisk, BP’s Valhall field was experiencing subsidence and solids production problems. Coupled geomechanical models were improving, and to this day the common industry practice when dealing with more complex compaction behaviours is to develop either fully or partially coupled models (Pettersen and Golder Kristiansen, 2009). This approach is very expensive and time consuming, and thus not always studied for lower risk, weak sandstone reservoirs. In the recent years, numerous discoveries were made in weak, poorly consolidated sandstone reservoirs (Gulf of Mexico, Angola). Many of these discoveries lay in challenging deep water environments, making it important to learn from the mistakes made in the North Sea chalks and study the compaction behaviour of these weak sands.

Experimental work by Chase & Dietrich, 1989, showed that creep can have a significant effect on cumulative oil production. Whilst looking at the effect of water weakening, several authors (Papamichos et al, 1998; Rhett & Lord, 2001) experimentally proved that water weakened rocks exhibit time-dependent creep under most loading stresses. Schatz & Carroll, 1981, proposed a method of extrapolation of the short time results from a laboratory creep test to predict long-term, reservoir time-scale effect on porosity changes. The results suggested that for a poorly consolidated rock of 20% initial porosity, a loss of up to 2% could be achieved in between 1-30 years’ time. However, laboratory testing procedures are very time consuming and the results are not always trustworthy. Thus, more understanding is needed in the industry about the best practices for the estimation and measurement of creep.

Most of the published work on the creep compaction discussed above described the laboratory work that was carried out to understand this phenomenon. Then Pettersen and Golder Kristiansen (2009) proposed a pseudo material definition for the use with the conventional flow simulators. The computational time was significantly reduced when compared with the fully coupled geomechanical model, and a good match for pressure and oil recovery was achieved. This approach could provide a good alternative for the reservoirs where subsidence and uneven stress distribution within the reservoir are of concern. It is also most applicable to reservoirs where the fully coupled geomechanical model is available, as a means of reducing the computational time requirements. However, if a coupled model is not available, there is currently no approach proposed to approximate the effect of creep in reservoir simulation.

This paper will focus on the way the mainstream simulators compute rock compaction and propose a way to approximate the creep behaviour without the need for a fully coupled geomechanical simulator.

**Compaction Theory**

Creep can be reported as a function of the strain rate:
\[ \varepsilon^* = \frac{de}{dt} \quad \varepsilon^s = \frac{de}{dt} \]  

(1)

Where \( \varepsilon^* \) is the strain rate, \( \varepsilon \) is strain and \( t \) is time.

There are two main ways in which rocks respond to stress changes: instantaneous strain and time-dependent strain (creep). The instantaneous strain can be both elastic and inelastic (plastic), whereas creep is always an inelastic deformation mechanism. In other words, creep compaction is always irreversible.

The magnitude of the creep depends on individual material constants (taking into account degree of consolidation, porosity/permeability etc). The data used in this study comes from an overpressured sandstone in the Gulf of Mexico. It is representative of a weak, moderately consolidated rock with 22\% porosity. The results presented here are only valid for analogous fields, as creep parameters used in this model are specific to this rock texture. These creep model parameters can vary dramatically with change in porosity/texture/mineralogy of the rock. In high porosity, poorly consolidated rocks, creep deformation is thought to be achieved by an increase in grain packing density on loading (Dusseault and Fordham, 1993), accompanied by additional pore scale processes, such as micro-cracking and pressure solution.

Under the application of stress, the rocks first respond by instantaneous deformation. The instantaneous deformation of a rock can be described in three key stages:

1. Elastic Deformation
2. Inelastic Deformation
3. Plastic Deformation

As fluids are withdrawn from the reservoir, fluid pore pressure decreases, thus increasing the effective stress on the rock. Upon loading, the pore spaces are initially reduced by elastic deformation Figure 1 Curve A), causing the rocks to stiffen. On further loading the rocks reach their material specific threshold pressure, below which they cross into an inelastic deformation region. This is accompanied by a much large compressibility (Figure 1 Curve B). Curves A and B, which represent the decrease in pore-volume, can be called deflation curves.

If the stress regime changes (such as cessation of production/water injection) and the pressure is allowed to build-up in the reservoir, the rocks will respond via a different compaction path depending on their stress history. If the threshold pressure was never exceeded (only simple elastic deformation took place), the rocks will expand back on a deflation Curve A in Figure 1. This behaviour can be modelled in VIP using rock compressibility function (CR). A single value of elastic compressibility is provided for the simulator in this case.

In the case of inelastic deformation (threshold pressure was exceeded during depletion), the rapid compaction and hardening of the rocks during depletion results in the rock following a new, lower-compressibility compaction path during pressure rise (Figure 1 Curve C). This phenomenon is known as hysteresis. Curves C can be known as reflation curves. This behaviour can be modelled in VIP using tabulated compaction tables (CMT).

In addition to the instantaneous response, there exists a time-dependent deformation element in weak rocks. Following the initial instantaneous reaction to the change in stress, the rocks ‘relax’ or ‘creep’ until the new equilibrium state (for strain and pressure) is reached. The amount of time it takes for the rock to reach new equilibrium depends on how far away its initial strain is from the final equilibrium strain. This phenomenon is known as creep.

**The VIP Creep Model**

Mathematically, creep is a superposition in time function. At any given change in stress, there would be corresponding creep associated with it. In a typical laboratory creep test the stress is increased to a new value and then held constant for a period of time. Thus, the instantaneous and the creep part can be measured in a controlled environment. In the reservoir, the stress is never held constant. Rather, the stress is constantly being increased as the reservoir is depleted. Thus, at any time after the start of production, there is a superposition effect of creep from the earlier times.
In VIP, creep is modelled using a built-in creep function. Creep modifies the existing pore volume multipliers to a lower value, resulting in larger compaction. Without creep, the compaction in VIP can be calculated by accounting for the elastic and inelastic compaction in the following way:

\[
V^n_p = V^n_{\text{multi}} \left[ 1 + C_v^n (P^n - P_r) \right]
\]

(2)

Where \(V^n_{\text{multi}}\) is the multiplier from the compaction table representing the inelastic compaction data for the current time-step; and \(C_v^n\) is the elastic compressibility value. For detailed description of the mathematics of the additional creep effect in VIP refer to Table C-0 of Appendix C.

The input parameters for the VIP creep model are the following:

- **CREEP B (B)** - the reservoir rock rate constant; inversely proportional to the characteristic time constant of the material. This signifies the time needed for the rock to creep and reach its relaxed condition (day\(^{-1}\));
- **CREEP M (m)** - creep exponent, the long term reservoir compressibility;
- **CREEP C (C_\infty)** – the total rock compressibility at equilibrium state (psi\(^{-1}\)).

**Review of Available Data**

As mentioned previously, very little experimental creep data exists for sandstones. The model used here is of the form proposed by Landmark VIP (above), and thus it was necessary to evaluate the input parameters required for the simulation (B, \(C_\infty\) and m).

The data used in this study was taken from a deeply buried, poorly consolidated and over pressured deep-water reservoir in the Gulf of Mexico. Following standard compressibility testing, a report detailing the conversion to the input parameters for the VIP creep model was produced by a contracting company. A total of seven plug samples were available for analysis. This report will discuss the analysis of a single sample, which marks a starting point in understanding of the effect of different rock mechanics on reservoir pressure. Further samples can be analysed in the future to bracket the potential magnitudes.

The raw data is presented in Table 1.

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>Depth (ft)</th>
<th>B (day(^{-1}))</th>
<th>m</th>
<th>(C_\infty) (psi(^{-1}))</th>
<th>CR (psi(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>creep1</td>
<td>21,606.30</td>
<td>8.064×10(^{-3})</td>
<td>8.354</td>
<td>1.325×10(^{-6})</td>
<td>5.09×10(^{-6})</td>
</tr>
</tbody>
</table>

The data in Table 1 came from measurements taken during elastic deformation period only. This is supported from the plot of variation in stress (Figure 2) and strain (Figure 3) with time from the experimental work on the sample. Two hold periods were recorded and it can be seen from Figure 3 in particular that both periods came from the elastic deformation region. It can be seen that as soon as the sample entered inelastic behaviour (at a time of approximately 60 hours), the experiment was stopped. The change to the inelastic deformation can be observed from the rapid rate of change in strain in Figure 3. Due to this fact it can be expected that the creep parameters from Table 1 are underestimates of the overall compressibility that can be reached by the system. This is because the instantaneous strain in elastic deformation is low compared to that of inelastic.

Weak, poorly consolidated sands are very likely to deform inelastically during rapid production. It can be seen from Figure 2 that for this sample initial stress is approximately 3000 psi (after ramp-up). It can then be seen from Figure 2 that inelastic deformation for this sample commences at a stress of approximately 4500 psi. This means that the rocks enter into the inelastic compaction after pressure depletion of 1500 psi. Pressure depletion of such magnitude is possible, however it would be dependent on the depletion strategy. For this reason, it was important to include the inelastic deformation component into the model.
The challenging part of doing that was to express the ultimate compaction of the rocks in a realistic and meaningful way. Experimental work by Hathon and Myers (2011) formed the basis for the approach used in this project. In their study, Hathon and Myers analysed weak Gulf of Mexico sands and established a range of their ultimate compressibilities to lay between 28-85 microsips (2.8×10⁻⁵ - 8.48×10⁻⁵ psi⁻¹). Comparing these values with the CR value from Table 1, it can be seen that they are of an order of magnitude higher. Hathon and Myers analysed a number of sands, thus making those brackets meaningful for the representation of compressibility ranges of weak sands. This difference in magnitude is likely to be due to inelastic compaction not being measured in these creep experiments. For this reason, the ultimate compressibility would be added to the sample description by increasing the CR value by an order of magnitude (Table 2). Further information can be found in Table C-1 of Appendix C.

Another parameter that is dependent on the deformation behaviour is the creep equilibrium compressibility (C∞). From Table 1 it can be seen that the C∞/CR ratio=0.26. Similar ratio (0.35) is reported by Dudley et al (1998) from creep experiments on sands from several reservoirs in the Gulf of Mexico (Figure C-1 of Appendix C). Taking the average of the two sources, a ratio of C∞/CR= 0.3 is applied to the new ultimate compressibility value to obtain the value in Table 2.

### Table 2 Amended Laboratory Data For Creep Model

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>Depth (ft)</th>
<th>B (day⁻¹)</th>
<th>m</th>
<th>C∞ (psi⁻¹)</th>
<th>CR (psi⁻¹)</th>
<th>CMT (psi⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>creep1</td>
<td>21,606.30</td>
<td>8.064×10⁻³</td>
<td>8.354</td>
<td>1.325E-6</td>
<td>5.09×10⁻⁶</td>
<td>5.09×10⁻⁵</td>
</tr>
</tbody>
</table>

### Methodology

The analysis of rock compaction mechanisms was carried out using Landmark VIP simulation software. For this purpose, a simple homogeneous 1D mechanistic model was constructed (Figure 4). More detailed description of the model can be found in Figure C-2 of Appendix C. The workflow for the study is summarised below.

1. **Simple depletion model**

   This model was built with the purpose of isolating and comparing the behaviour of each of the deformation mechanisms (elastic, inelastic and creep). Thus, the model was built to represent the compression test – a short rapid depletion period (40 days at 2500 SM3/DAY) followed by a long shut-in period (1785 days). This represents an equivalent of a long creep test, where a stress is instantaneously increased on the rock and then kept constant. A long shut-in period was chosen to observe the effects of creep over a significant period of time, allowing for it to fully develop.

   Three behaviours were studied separately and then compared:
   a. Elastic compressibility only
   b. Elastic compressibility + Inelastic Compaction
   c. Elastic compressibility + Inelastic Compaction + Creep

   For the final case (case c), a sensitivity study was carried out to investigate the effect of production rate and depletion period length on the magnitude of creep. The model with the highest creep contribution was taken forward into the second study.

2. **Simple Injection Model**

   An injection well was added to the final depletion model case. In this model, the original depletion period was kept the same. However, the production well continued to produce until the end of simulation. At the time of the original well shut-in, the injection well would be brought on stream. A number of cases were run at different voidage replacement ratios:
   a. Voidage Replacement 1:1 (for production rate of 125 SM3/DAY)
   b. Voidage Replacement 1:1 (for production rate of 250 SM3/DAY)
   c. Voidage Replacement 2:1 (for production rate of 500 SM3/DAY)

   The cases were analysed for sensitivities to injection rates and the case with the largest creep magnitude was taken forward into the final stage of the project.

3. **Creep Approximation Function for Nexus**

   The final injection case was analysed for the behaviour of individual cells in the model. The model was broken into five
regions of similar cell behaviour. A representative cell was picked from each region (middle cell).

Differences in Pore Volumes changes between no creep and creep cases were analysed for representative cells. A number of multipliers were applied to the existing pore volumes to give the modified compaction table per region. A total of 5 modified compaction tables were added to the no creep data file.

4. **Nexus Model Testing**

An identical Nexus model was built and run with and without the modified compaction tables. The effect was compared and the differences in rock compaction calculations between the two simulators were compared.

**Results: Simple Depletion Model**

1. **Elastic compressibility only**

In the simplest case, only elastic compressibility is provided to the simulator in the initialisation section. As the reservoir is depleted, the effective stress on the rock is increased. This drives the pore volume reduction of magnitude equivalent to the rock compressibility of 5.096×10^{-6} psi^{-1}. There is a stable reduction in pore volume with time ( ), and linear reduction in PV with Pressure (Figure 7). A steady decline in pressure is observed, followed by a stabilisation of pressure after the shut-in of the well ( ). The pressure equilibrates at 4388.2 psi, giving a total pressure drop of 428.3 psi. The pore volume is reduced by 437.8 KRM3 (0.22% strain). This represents an over simplified case, by discarding other components of rock deformation that are very likely to be present in the reservoir.

**Table 4 Comparison Between Rock Functions**

<table>
<thead>
<tr>
<th>CMT</th>
<th>CR (psi^{-1})</th>
<th>Elastic compressibility only</th>
<th>Elastic compressibility + Inelastic Compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.09×10^{-6}</td>
<td>5.09×10^{-6}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>5.09×10^{-6}</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5 Elastic Pore Volume Change**

**Figure 6 Elastic Pressure Change**

**Figure 7 Pore Volume Change With Pressure**
2. Elastic compressibility + Inelastic Compaction

The inelastic part of compaction behaviour can be represented in VIP by enabling compaction tables (CMT, Table 3). Compaction table represents the ultimate compressibility of the system and its effect on reservoir pore volume under different pressure conditions. As discussed previously in the Data Review Section, the ultimate compressibility of this rock sample was calculated to be 5.09×10⁻⁵ psi⁻¹. The data is input via the pore volume multipliers (PVMULT) covering a depletion range of 2900 psi (to account for the full range of conditions). Additional inputs include transmissibility multipliers (TAMULT – areal transmissibility; and TVMULT – vertical transmissibility). Transmissibility multipliers can be added to represent changes in permeability with pressure / porosity change. In this study, no transmissibility changes are applied due to lack of experimental data, thus making the focus of this study on porosity change only.

Table 4 above shows the differences between the elastic only and current case in terms of input to the simulator. CMT Tables are specified in addition to the elastic compressibility value in the initialisation data. The effect of those values is multiplicative if both are specified (please refer to Table C-0 of Appendix C).

In the previous case, the amount of pore volume change during depletion was governed by one constant compressibility value. In the current case, the magnitude of compaction at a given pressure will differ according to the corresponding pore volume multiplier (as per Table 3).

Due to the multiplicative effect of the compaction table, much larger pore volume reduction occurs in the current case for the same depletion period (Figure 9). This is physically explained by a much quicker compaction rate due to switching from deflation curve A to B in Figure 1. Inelastic rock deformation results in 78% better pressure support to the reservoir (Figure 8). The increase in pressure is evaluated as a percentage of the pressure increase compared to the total depletion pressure drop. The same evaluation method will be used for all up-coming cases. For this case, the reservoir pore volume is varying with time, and thus it is no longer possible to approximate it with a single value of strain. The strains presented in Figure 9 are those at maximum and equilibrium conditions.

This behaviour can be explained by looking at the stress path undergone by the rocks. Referring to Figure 10, it can be seen that the shut-in period behaviour is dominated by hysteresis (as discussed earlier in Compaction Theory section of this report). Comparing Figure 10 and Figure 1, it can be seen that different compaction curves are followed during depletion and shut-in period.
Switching between the different compaction curves is induced by the equilibration process of the simulation model. Initially (at time=0 days in Figure 11), the model exists in equilibrium (all cells are at the same pore volume and pressure, hence there is no pressure gradient between any of the cells). During depletion, regions of different pressure are created in the model (time=40 days in Figure 11). Cells around the production well drop in pressure significantly more than cells on the edges of the model, introducing a pressure gradient into the model. Once the well is shut-in, the model begins to re-equilibrate towards an equilibrium state again. Thus, the model begins to get rid of the pressure gradients, increasing pressure in some cells (around the production well), and decreasing pressure in others (on the edges). As the pressure changes, so does the pore volume. In the elastic only case, all cells are readjusting at the same rate (equivalent to the elastic compressibility value of $5.09\times10^{-6}$ psi$^{-1}$). For this reason, no increase in pressure is seen after the shut-in of the well.

In the inelastic case, the cells are re-equilibrating in pressure at different rates due to the hysteresis effects discussed in the Compaction Theory section (Figure 1 and Figure 10). Cells around the production well undergo a larger pressure drop and enter an inelastic compaction behaviour (at higher compressibility). Cells on the edges of the model stay very close to the initial reservoir pressure, remaining in the elastic compaction behaviour. Therefore, during the re-equilibration process, the cells that have compacted inelastically reflate at lower compressibility (as per Figure 1 and Figure 10). This produces larger effect on pressure compared with the other cells, which continue to decrease in pressure despite having exceeded their compaction threshold. For this reason, a rise in pressure is observed following the shut-in of the well.

### 3. Elastic compressibility + Inelastic Compaction + Creep

As discussed previously in the Creep Model section of this report, Landmark VIP simulator provides a built-in creep function (see description in Table C-0 of Appendix C). The input parameter summary was discussed in the available data section of this report. The input was provided in the ARRAYS section of the VIP initialization data file in the format shown in Table 5. The creep function was added to the previously described case (comprising of elastic and inelastic behaviours). It can be seen from Figure 12 through to Figure 13 that similar trends in pore volume and pressure change were observed between the no creep and creep cases. However, creep provided an additional 0.03% pore volume reduction, giving an extra 6% pressure support to the reservoir. More detailed results can be found in Table C-2 of Appendix C.

### Table 5 VIP Creep Input

<table>
<thead>
<tr>
<th>Array</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CREEPB</td>
<td>CON</td>
</tr>
<tr>
<td>8.06E-03</td>
<td></td>
</tr>
<tr>
<td>CREEPC</td>
<td>CON</td>
</tr>
<tr>
<td>2.44E-04</td>
<td></td>
</tr>
<tr>
<td>CREEPM</td>
<td>CON</td>
</tr>
<tr>
<td>8.354</td>
<td></td>
</tr>
</tbody>
</table>

Figure 11 Pressure Gradient in the model

Figure 12 Creep Pore Volume Change

Figure 13 Creep Pressure Change
Creep Sensitivity Analysis: Depletion Rate

It was described previously in the Methodology section that the depletion model was built to represent the creep test (by applying almost instantaneous stress change on the rock and holding it constant for a period of time). Rapid depletion created a steep pressure gradient in the model between the edge and production well adjacent cells. In addition, the value of the creep parameter B \( (8.064 \times 10^{-3} \text{ day}^{-1}) \) gives the time needed for the rock to develop maximum creep effect as 124 days \( (\text{time}=\frac{1}{(8.064 \times 10^{-3})}) \). It can be noted from Figure 13 that the differences due to creep begin to appear at exactly 124 days. Therefore, no effects of creep are manifested during the depletion period (which is 40 days long), as it is not long enough for the given CREEP B parameter.

A number of cases were created to assess the influence of the model pressure gradient and depletion time on the creep magnitude. For each case, production rate and time were changed by an order of magnitude respectively to keep the overall fluids withdrawn constant. Overall simulation time was increased to 8000 days to accommodate longer depletion periods. More detailed description of all cases can be found in Table C-3 of Appendix C.

The key finding from this sensitivity study was that the model re-equilibrated at a lower pressure at slower depletion rates (Figure 14). This is shown by the lower final pressure in Creep 2 & 3 cases compared with Creep Original. In addition, the difference in equilibrium pressure between no creep and creep cases was relatively larger for slower depletion cases. In slower depletion models, creep effects were visible during the production period. This resulted in extra compaction drive providing the depleting reservoir with pressure support. Thus, the slower depletion models with creep arrived at the end of the depletion period at higher pressures than their respective no-creep models. These results suggest the high impact of creep in the areas of lower pressure gradient. Physically, this behaviour is explained by the fact that rocks compact (and hence creep) only upon the increase in vertical stress. It was previously discussed that cells around the production well increase in pressure during equilibration. Since the effective stress on those cells is decreasing, there is no further creep acting on them. At higher depletion rates, more cells around the producer drop in pressure, thus leaving fewer cells with creep acting during equilibration.

The creep function is governed by the time constant (CREEPB), despite being pressure dependent. Creep 3 case in Figure 14 shows that if the depletion period is long enough to allow for the superposition of all previous creep components, a maximum creep magnitude can be reached during the production period. Beyond that point, no further difference in creep will be

![Figure 14 Creep Rate Sensitivity 1](image_url)
observed during re-equilibration (shown by equal ΔP at both the end of depletion and at the end of equilibration for Creep 3 case). In such case, all of the creep effect is developed during depletion. If the length of the depletion period is increased further, no additional increase in creep magnitude is observed (see Creep 3 and Creep 4 cases in Figure 15). From Figure 15, this behavior can be seen as a rising pressure at the end of the depletion period for cases Creep Original, Creep 2 and Creep 3. There is no further pressure rise observed between cases Creep 3 and Creep 4 (both arrive at the end of depletion at the same pressure). Thus, for a given time constant, there exists a time when a maximum creep contribution is achieved.

![Average Reservoir Pressure](image)

**Figure 15 Creep Rate Sensitivity 2**

It would be desirable to perform a sensitivity analysis on the creep parameter CREEPB, as it governs the amount of time it takes for the full impact of creep to be seen. However, as it is a material specific constant, changing parameter B alone without changing the other creep material constants (C∞ and m) would not be physically correct. This sensitivity can be performed once more sand samples are analysed.

**Results: Simple Injection Model**

Water injection can be used to either maintain or increase reservoir pressure. From the previous results it was concluded that raising the reservoir pressure opposes the development of compaction due to creep. As water injection is a common method of secondary recovery in many weak sandstone reservoirs around the world, it was necessary to evaluate the effects of creep in the presence of pressure support.

‘Creep 3’ and ‘No Creep 3’ models were used as a basis for the addition of the injection into the model. The new injection model simulated a continuous depletion period at varied constant rates. Water injection was introduced into the model after 800 days of production. Injection was controlled by the 1:1 voidage replacement ratio for each case. Three different injection scenarios were evaluated. More details on the models can be found in Table C-4 of Appendix C.

As the water is injected into the model at high pressure, cells around the injection well increase in pressure. The rate of injection determines the speed at which the increase in pressure propagates to the adjacent cells. With time, more cells increase in pressure, thus leaving fewer cells with active creep compaction. In the high injection rate model, more cells exist at higher pressure at the end of the simulation when compared with the low rate model. Thus, the relative magnitude of the difference between the ‘No Creep’ and ‘Creep’ cases for the highest injection rate is smallest (Figure 16).

The magnitude of the difference between the ‘No Creep’ and ‘Creep’ is expressed as the difference in pressure between the two cases at the end of the simulation over the pressure rise following the start of water injection. All models begin water
injection at the same pressure (Figure 16). This provides a consistent way of measuring the difference due to creep when the pressure increase is changing with the water injection rate. Although that at high injection rates creep has the largest absolute pressure difference between the ‘No Creep’ and ‘Creep’ cases (41 psi), it also has the largest pressure increase in the No Creep Case (305 psi). As more cells are at a higher pressure in the high injection rate case (Figure 17), the overall creep effect is lowest. It can be seen from the lateral cell pressure graph in Figure 18 that the pressure gradients vary greatly amongst the three injection cases.

It can be concluded that creep can provide additional pressure support during water injection. Similarly to the depletion model results, creep has higher relative contribution to the pressure support in lower injection rate cases. Creep is sensitive to the pressure gradients in the field and the sweep efficiency of the water flood project. Results derived from the study of this rock sample show that the creep contribution to pressure support during water-flood project can be in the order of 9-31% (Figure 19).

![Figure 16 Pressure Change due to Injection](image)

![Figure 17 Model Pressure Gradients Visual](image)

![Figure 18 Model Pressure Gradients Plot](image)

![Figure 19 Creep Contribution Summary](image)
Results: Creep Approximation Function For Nexus

The approach for the approximation of the creep effect in Nexus proposed here involves the modification of the existing compaction tables. This represents the evolution of the pore volume with pressure. In the previous VIP models, one value of inelastic compressibility and one compaction table were provided (refer to Table 4). However, Figure 18 above showed that when creep is present under dynamic conditions, not all cells behave the same way. Under different rates, the same cell can also exhibit different deformation behaviour. Further analysis of the differences in cell response showed that it is possible to group cells into regions of similar pore volume - pressure behaviour (Figure 20 & Figure 21). It can be seen from Figure 21 that each region is defined by its own pressure gradient, and the same regions can be successfully applied to all three injection cases.

Each of the five regions was represented in the new test model by its own compaction (CMT) table. Each cell in the model was allocated a specified table as per Figure 20 and Table 6. For each of the new compaction regions, a middle cell was chosen as a basis for the generation of new pore volume multipliers. The process of generating the new inputs was as followed:

**Table 6 Compaction Regions Summary**

<table>
<thead>
<tr>
<th>From Cell</th>
<th>To Cell</th>
<th>Number of Cells in Region</th>
<th>Representative Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>REGION 1</td>
<td>1</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>REGION 2</td>
<td>13</td>
<td>27</td>
<td>25</td>
</tr>
<tr>
<td>REGION 3</td>
<td>40</td>
<td>21</td>
<td>50</td>
</tr>
<tr>
<td>REGION 4</td>
<td>63</td>
<td>6</td>
<td>64</td>
</tr>
<tr>
<td>REGION 5</td>
<td>67</td>
<td>33</td>
<td>83</td>
</tr>
</tbody>
</table>

**Figure 20 Compaction Regions**

**Figure 21 Compaction Regions' Cells**

**Step 1:** The original low injection model was used as a basis for generating the approximation function. Calculated pressures and pore volumes for each cell were requested as output from both ‘No Creep’ and ‘Creep’ cases. Table C-5 of Appendix C shows the sample output table for Cell X=6. Output tables were generated for each cell representative of a compaction region (cells listed in Table 6).

**Step 2:** Two new simulation cases were set up, each containing 5 new compaction regions. Model A contained pressure and pore volume multipliers from the original creep case (the only difference now being 5 compaction tables instead of one). Model B contained pressures from the original ‘No Creep’ model, but corresponding pore volumes from the original ‘Creep’ model. The resulting reservoir pressure trend (Figure C-3 of Appendix C) showed that Model A was overestimating the amount of creep compaction. Model B however, was underestimating it. The difference between the reservoir pressures of Models A & B was used to propose a number of adjustments to the pore volume multipliers.

**Step 3:** A number of multipliers were applied to the pore volumes from Model B (please refer to Table C-6 of Appendix C). The process was carried out for all 5 new compaction regions, generating 5 compaction tables. A new compaction table for Region 1 is shown in Table C-7 of Appendix C. Compaction tables for all other regions are of the same format.

The new tables were added to the original ‘No Creep’ VIP case and the results are presented in Figure 22 and Figure 23. A comparison is shown against the original model. The same methodology was applied to the high injection rate model. For both low and high injection rate cases the new function produced errors of less than 1.5% (refer to Table C-8 and Table C-9 of Appendix C for more information). This suggests that the function can be effectively applied to a range of operating conditions and/or different pressure regions.
It should be noted that VIP (and Nexus) do not allow for the hysteresis to be represented in the CMT Table. Therefore the effective reflation curve in Figure 1 is being set by the elastic behavior. Input requirement is such that the pressure values increase monotonically in the table (Table C-7 of Appendix C). This meant that only the depletion period was matched in the table, forming the basis for the successful representation of creep in the injection phase.

Results: Nexus Model Testing

The original VIP ‘No Creep’ model was converted to Nexus for the purpose of testing the creep approximation function. All static and dynamic parameters from the original VIP model were preserved. However, there is a fundamental difference in the way rock compaction is modelled in VIP and Nexus. In VIP, the effect of specifying both elastic and inelastic compressibilities simultaneously is multiplicative. In Nexus, either constant elastic compressibility value or the inelastic compaction tables can be specified (simultaneous use of both is not permitted). The magnitude of the elastic compressibility is small \(5.09 \times 10^{-6} \text{ psi}^{-1}\), therefore unlikely to have a large influence on the pore volume behaviour. For the purpose of testing the approximation function, the compaction table option in Nexus was selected.

Before applying the approximation function, the ‘No Creep’ models from VIP and Nexus were compared. Figure 24 shows that the resulting pressure response had significant differences. Despite VIP model having two multiplicative rock deformation mechanisms enabled, it had a larger pressure drop than Nexus for the same amount of fluids withdrawn. However, the key difference was in the amount of pressure rise following the start of water injection. Both models had the same compaction table enabled, yet showed a 20% difference in pressure response to equal volumes of water injected. It was beyond the scope of this project to dwell into the mathematical model behind Nexus’s rock compaction methods. Given the time constraints, the approximation function was applied to the ‘No Creep’ Nexus model shown in Figure 24. The results are shown in Figure 25.

It can be seen from Figure 25 that due to profound differences between the VIP and Nexus ‘No Creep’ models, it would not be meaningful to compare the results from Nexus creep approximation to the VIP creep model. The function was instead assessed on the per cent difference in final pressure between the ‘No Creep’ and ‘Creep’ cases. There was a 22% difference in final pressures between the VIP models, and 17% difference between the Nexus models. The results were able to show that the function could be used to mimic the magnitude of additional pressure rise with a 5% error. Such error is larger than desired and 4% larger than when the same function was tested in VIP (See Figure 22 & Figure 23).
Discussion

Results obtained from this study form a first step towards providing a way of representing time-dependent rock compaction in a main-stream simulator. At present, most simulators have limited capabilities when it comes to geomechanical modelling, thus the more complex rock mechanics are either simplified or omitted. Some of the world’s most prolific areas for recent and future hydrocarbon development are made up of poorly consolidated sandstone basins (such as Gulf of Mexico and Angola). The simpler rock deformation behaviours (elastic compressibility and inelastic compaction) are widely understood and implemented in most reservoir models. Uniaxial and triaxial compression tests are commonly commissioned to characterize instantaneous rock compaction in reservoirs. However, literature review showed that there is increasing interest in the time-dependent compaction in sandstones within the industry. Therefore, there is a growing demand for understanding of the potential magnitudes of creep, its sensitivities and whether it could be a significant contributor towards the long-term reservoir productivity.

The results presented here show between 4-31% additional reservoir pressure due to effects of creep. Such broad range of magnitudes shows that the effects of creep are very sensitive to the reservoir operating conditions (depletion rate, presence of pressure support, voidage replacement ratio for injection etc). Based on the findings presented in this report, it can be concluded that a continuous depletion period at high production rates would result in the largest additional creep effects. However, this is not a realistic reservoir development strategy. In most cases, such strategy would result in dropping the reservoir pressure below the bubble point very quickly, introducing problems for lifting the valuable hydrocarbons to the surface. Thus, it can be expected that in reality, lower effects would be observed.

Before concrete conclusions can be drawn from this study, it is important to acknowledge that there are a number of uncertainties within the results presented in this report. First, and perhaps the most important uncertainty comes from the data used for this study. It was mentioned in the data review section of the report that both creep hold periods during the laboratory experiment came from the period of elastic deformation only. The inelastic compaction would have initiated after 1500 psi pressure depletion. The reasons for the decision to stop the creep experiment without measuring the creep parameters during inelastic compaction are unknown. It could be that the depletion plan for the reservoir (from which the sample came) states that such large pressure depletion is unlikely to occur. It could also be due to financial reasons – laboratory time is expensive, and hence many creep tests last a couple of hours maximum.

However, it is unlikely that weak, poorly consolidated sandstone would only exhibit elastic behaviour. A review of a confidential internal geomechanics report for another poorly consolidated sandstone field showed that even for the samples with highest level of cement, inelastic compaction was activated well within the foreseeable operating pressures. This, together with the literature findings discussed in the data review section, formed the basis for the adjustment of compressibility parameters to reflect the inelastic compaction. However, other creep parameters (B and m) were left unchanged because those are material specific constants. More understanding is needed to know whether changes in overall compressibility of the system would affect parameters B and m and whether there is a relationship between them.

A second uncertainty is the fact that this study was performed on a homogeneous 1-D box model. Although this was the best way to investigate the way that creep is simulated, it can be expected that a different behaviour would be observed in full-field reservoir models. In reality, reservoir models can be very complex, often with multiple isolated pockets and varying rock quality across the model. This means that the creep parameters could be vastly different across the field. It is uncertain at this
stage whether the approximation function presented here would be the same for different creep parameters. If creep was a real concern for a particular reservoir, each compaction region would need to be modelled in a test model and the function verified to achieve meaningful results.

The third limitation is that it wouldn’t be possible to generate the modified compaction tables without the results from the VIP simulator. In this case, VIP results effectively permitted a pseudo-compaction curve to be calculated for different classes of cell pressure history. Creep is a superposition function, and pressure/ pore volume values at the next timestep depend on the previous values, thus it would be difficult to recreate this by hand in another software. If such method was generated, the approximation approach proposed here could be much more applicable to a wider range of reservoir simulation packages. Currently, the only other alternative to account for the time-dependent creep is to implement a fully coupled geomechanical model, which may not be economically feasible.

It was discussed previously that there are differences between the way VIP and Nexus calculate rock compaction. It would appear from the mathematical model that VIP can overestimate the amount of compaction by allowing both elastic and inelastic components to be multiplied together. This could be the reason for a higher final pressure in the VIP model in Figure 24. Similarly to Nexus, the Eclipse simulator doesn’t allow for the two components to be modelled at the same time. Eclipse also allows for the hysteresis to be represented in the compaction table in a very flexible way - something which isn’t available in VIP or Nexus. Therefore, slight difference between the models can be expected. These differences are due to the mathematical models behind the simulators. Thorough analysis of mathematics behind each one was beyond the scope of this project.

Finally, it is important to highlight that creep can have a negative effect on the reservoir performance. Increased compaction can result in permeability reduction (by the collapsing of the pores), which can create baffles / barriers to flow. This could have severe implications for the production / injection strategy. Therefore, despite the added benefit of an increased compaction drive, reservoir performance problems can be encountered in cases of severe creep.

**Conclusion**

The aim of this study was to assess if creep can provide a significant contribution to the compaction drive of the poorly consolidated reservoirs, thus providing extra pressure support to the reservoir. From the simulation study performed using data from Gulf of Mexico rock sample, it was established that creep can provide between 4-31% extra pressure support (compared to the elastic and inelastic compaction). It was found that the amount of creep was sensitive to the depletion strategy of the field. Creep effects will be highest in reservoirs with larger pressure drawdowns and would be minimised by secondary recovery / pressure maintenance mechanisms. Depending on the size of the reservoir and the pressure drawdown, accounting for creep compaction can impact business decisions for the long term field development planning. If 30% better pressure maintenance can be gained from compaction, more oil can be produced over time with lower need for artificial pressure support (all other parameters being equal). Most importantly, many weak sandstone reservoirs are found in challenging offshore environments (Gulf of Mexico, Angola). Platform space for drilling new wells is often limited and thus taking into account extra compaction from the start of the project could make valuable cost savings over the life of field.

Further work would be required until a better picture of the ranges of creep compaction magnitude can be compiled. Several key areas for necessary future work were identified from this project:

**Short term:**
1. Analysis of further sand samples from the same reservoir as the test sample. Available samples were taken from the same well at different depth, and exhibit a large variation in creep model parameters B, m and C∞. Thus, a relationship between rock quality, model parameters and creep effect can begin to be established.
2. Re-running the simulation model in VIP with disabled elastic compressibility option. This would, in theory, make the results comparable with those from Nexus / Eclipse.

**Long term:**
1. More frequent laboratory testing for creep for the weak sandstone reservoirs. Due to high costs associated with long-lasting laboratory tests, creep test is not performed as standard for the purpose of improving reservoir simulation model. However, this study showed that a large effect could be present due to creep, making a justified business case for future testing.
2. Designing a creep test to measure a hold period in the inelastic compaction behaviour. This would help to understand the ranges of ultimate creep compressibilities and whether those are affected by the elastic / inelastic deformation.
3. Addition of the creep function to other mainstream simulators. Much more understanding within the industry would be achieved by collective effort of reservoir engineers working on different weak reservoirs.
4. The results of this study to be compared against the prediction from the coupled-geomechanical model. This would help to understand the accuracy of the results from simulation model. Results from the coupled model could be used to improve the approximation function.
Nomenclature

A = mathematical operator in VIP Creep Model
CMT = Compaction Table in VIP / Nexus
CR (C_r) = elastic compressibility (psi -1 )
creep = Pore Volume multiplier from creep function
CREEP B (B) = the reservoir rock rate constant; inversely proportional to the characteristic time constant of the material. This signifies the time needed for the rock to creep and reach its’ relaxed condition (day-1);
CREEP M (m) - creep exponent, the long term reservoir compressibility;
C∞(CREEP C) = the total rock compressibility at equilibrium state (psi-1)
KRM3 = thousand reservoir cubic meters
n= nth timestep (current timestep)
t = time (days / years)
V_mult(PV) = Pore Volume multiplier at nth timestep (KRM3)
V_o = Initial Pore Volume (KRM3)
PV = Pore Volume (KRM3)
P = Pressure (psi or BAR)
ε = volumetric strain
ε* = volumetric strain rate

References

5. Eclipse Technical Description (2010) , Schlumberger
APPENDICES

Appendix A – Critical Literature Review Summary

SPE 51324 (1998)

Measuring Compaction and Compressibilities in Unconsolidated Reservoir Materials by Time-Scaling Creep

Authors: Dudley J.W., Myers M.T., Shew R.D., and Arasteh M.M

Contribution to the understanding of creep compaction modelling: (*)
Proposed a testing and analysis procedure for estimating compaction and compressibility that are independent of the duration of the laboratory test.

Objective of the paper:
To prove the time-scaling behaviour of unconsolidated sandstones and propose a way of interpolating the ultimate compressibility without the need for a long, expensive test.

Methodology used:
Laboratory testing: uniaxial constant lateral strain step increase and hold compaction tests. Three different apparatus were used, three different hold times (1.5 hours, 1 day and 1 week).

Analytical technique (power law model) based on the technique proposed by Jaurez-Badillo (1985). Key method was to assume that the test time was significantly smaller than the material characteristic time. This allowed for the fit with the proposed power law creep model.

Conclusion reached:
1. Weak sandstone exhibit time-scaling behaviour in the lab.
2. Creep strain during a constant stress increment can be described by a power law model. Thus it is possible to predict stress-strain time behaviour (from a short laboratory test to the life of field time scale) if material type curves are available.
Improved Compaction Modeling in Reservoir Simulation and Coupled Rock Mechanics/Flow Simulation, With Examples From the Valhall Field

Authors: Pettersen, Ø., and Golder Kristiansen, T.

Contribution to the understanding of creep compaction modelling: (*)
Not specifically about creep modelling, but improving the general compaction modelling in the reservoir simulator. Proposed a way of reducing the computational time required for the coupled model by reducing the number of iterative time steps. Resulting compaction field is comparable to the real one.

Objective of the paper:
To proposing a procedure for generating a pseudo material definition (from the fully coupled geomechanical model) that can be used in the flow simulator for better compaction prediction.

Methodology used:
Used a coupled model (VIPS2003 with Eclipse and VIP) to construct a framework for the following:
- Easy visualisation of areas of similar compaction behaviours. These areas were grouped together into pseudoregions
- Mathematical model allowing the simulator PV-curve to be validated against geomechanical predictions. The process allowed for discarding of irrelevant points from the unloading-reloading cycle

Conclusion reached:
1. It is possible to significantly reduce the computational time of a fully coupled geomechanical model by the creation of pseudo material regions.
2. The results obtained from this approximation provide a good match to fully coupled solution at a fraction of computational time requirement.
A Survey of the Production Time-Scale Compaction Behaviour of Unconsolidated Sands

Authors: Hathon, L.A., and Myers, M.T.

Contribution to the understanding of creep compaction modelling: (*)
This paper doesn’t discuss creep compaction. However, it compiled a survey of the compressibility ranges of unconsolidated sands. Ranking and discussion of main controls on the magnitude of compressibility was presented.

Objective of the paper:
To rank the important controls on the pore volume compressibility of unconsolidated sands.

Methodology used:
Sandstone samples from the Gulf of Mexico, Brazil, West Africa and Malaysia were analysed for the influence of stress history, grain size, framework mineralogy and overgrowth cement on the overall pore volume compressibility.

Conclusion reached:
1. Stress history is a primary control on pore volume compressibility.
2. As maximum effective stress increases, the magnitude of compressibility curve decreases.
Time-Dependent Behaviour of Rocks (n.d)

Authors: Dusseault, M.B and Fordham, C.J.

Contribution to the understanding of creep compaction modelling: (*)
A comprehensive book describing the fundamental laws, rheological models and creep testing procedures of different types of reservoir rocks.

Objective of the paper:
To provide a good understanding of mechanisms of creep.

Methodology used:
Each chapter discusses a separate topic: types of creep (steady-state, transient, tertiary), imperial laws, types of creep testing and laboratory creep test design.

Conclusion reached:
No specific conclusion but gives a fundamental understanding of creep.
### Appendix B – Milestones in Creep Compaction Study

<table>
<thead>
<tr>
<th>SPE Paper n°</th>
<th>Year</th>
<th>Title</th>
<th>Authors</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wiley Online Library Online ISBN: 9780470172766</td>
<td>1943</td>
<td>‘Theoretical Soil Mechanics’</td>
<td>K.Terzaghi</td>
<td>First book to systematically set forth fundamental aspects of soil mechanics theory and describe fully the theoretical behaviour of subsurface soils under the influence of internal and external forces.</td>
</tr>
<tr>
<td>IS-1989-022</td>
<td>1981</td>
<td>‘Creep compaction of porous rock’</td>
<td>M.M.Carroll, J.F.Schatz</td>
<td>First to propose a methodology for extending the theories of inelastic, time-dependent rock compaction to allow extrapolation of laboratory measurements to long field scale time frames.</td>
</tr>
<tr>
<td>14214</td>
<td>1988</td>
<td>‘Prediction of Reservoir Compaction and Surface Subsidence: Field Application of a New Model’</td>
<td>J.A. de Waal, R.M.M. Smits</td>
<td>First to propose the Rate-Type Compaction Model for unconsolidated sandstones</td>
</tr>
<tr>
<td>16389</td>
<td>1988</td>
<td>‘A Comparison Between the Pressure-Lag Model and the Rate-Type Model for the Prediction of Reservoir Compaction and Surface Subsidence’</td>
<td>J.A. de Waal, R.M.M. Smits</td>
<td>First to compare pressure-lag and rate-type compaction models, benchmark against field data and prove the superiority of the latter.</td>
</tr>
<tr>
<td>IS-1989-112</td>
<td>1989</td>
<td>‘Compaction and flow of porous rocks at depth’</td>
<td>M.E.Jones, M.J.Leddra</td>
<td>First to present the results of a large number of experiments to determine the nature of deformation behaviour of porous sedimentary rocks (stress path, failure criteria, elastic/plastic behaviour).</td>
</tr>
</tbody>
</table>
| 17415-PA     | 1989 | ‘Compaction Within the South Belridge Diatomite’                     | C.A. Chase Jr, J.K.Dietrich                 | 1. First to propose a way of including hysteresis of compaction to a full field simulation model  
2. First to find the detrimental effect of rebound on water flood operations. |
| 26647        | 1993 | ‘Application of Variable Formation Compressibility for Improved Reservoir Analysis’ | D.P.Yale, G.W.Nabor, J.A.Russell, H.D.Pham, M.Yousef | 1. First to produce extensive databases of formation compressibilities for consolidated, friable and unconsolidated reservoirs and produce type-curves for each case.  
2. First to propose Pore Volume FVF to be used in material balance and reservoir simulation to better estimate change in compressibility with reservoir pressure decline. |
| 47392        | 1993 | ‘The Role of Geomechanics in Reservoir Simulation’                   | M.Gutierrez, R.W.Lewis                     | First to produce a fully-coupled geomechanics and reservoir simulation model and show key prediction differences against conventional simulation model. |
| 47350        | 1998 | ‘Reservoir Stress Path: The Depletion and the Rebound’               | F.J.Santarelli, J.T.Tromvoll, M.Svennekjaer, R.Henriksen, R.K.Bratil | First to highlight the differences in irreversibility behaviour between core and field scale rock and to propose the rigid rock model to deal with this issue. |
| 51324        | 1998 | Measuring Compaction and Compressibilities in Unconsolidated Reservoir Materials by Time-Scaling Creep | J.W.Dudley, M.T. Myers, R.D.Shew, M.M.Aristeh | First to prove the time-scaling behaviour of unconsolidated sandstones and propose a way of interpolating the ultimate compressibility without the need for a long, expensive test. |
| 01-0121      | 2001 | ‘Water Weakening in sedimentary rocks’                              | D.W.Rhett, C.J.Lord                       | First to experimentally prove the requirement of chemically active water for water weakening process to occur. |
| 113003       | 2009 | Improved Compaction Modeling in Reservoir Simulation and Coupled Rock Mechanics/ Flow Simulation, With Examples From the Valhall Field | Ø. Pettersen, T.Golder Kristiansen,         | First to propose a pseudo material definition to significantly reduce the computational time required for a couple geomechanical model. |
Appendix C – Supplementary Materials

Table C-0 - VIP Creep Model Mathematics

\[
\begin{align*}
V_p^n &= \left[V_{\text{multi}} V_o [1 + C_r(P^n - P_o)]\right]^{(2)} = V_{\text{multi}}^n \times V_o^n \left[1 + C_r(P_n^{n+1} - P_o)\right]
\end{align*}
\]

With the creep function activated, the effect of creep is added to the previous compaction calculation:

\[
V_p^n = V_{\text{multi}} V_o [1 + C_r(P^n - P_o)] + \text{creep}^n
\]

(3)

Creep is a dynamic function, where the amount of pore volume reduction at the next time step will depend on the pressure at a previous timestep. Then the pore volume at a next time-step is:

\[
\begin{align*}
V_p^{n+1} &= V_{\text{multi}} V_o [1 + C_r(P^{n+1} - P_o)] + \text{creep}^n + \Delta \text{creep}^{n+1}
\end{align*}
\]

(4)

To allow for both increasing and decreasing pressures in model cells,

\[
\Delta \text{creep}^{n+1} = \alpha_{n+1} \frac{V_o B \Delta \text{I}^{n+1}}{\phi_o} e^{-\frac{x(V_m^{n+1} - V_p^{n+1})}{\Delta V_m^{n+1}}};
\]

(5)

And

\[
\Delta V_m^{n+1} \equiv V_m^{n+1} - V_m^n,
\]

(6)

\[
V_p^{n+1} = V_{\text{multi}} V_o [1 + C_r(P^{n+1} - P_o)] + V_o(C_r - C_r)(P^{n+1} - P_o);
\]

(7)

\[
\alpha_{n+1} = \begin{cases} 
-1, & \text{if } \Delta V_m^{n+1} > 0; \\
0, & \text{if } \Delta V_m^{n+1} \leq 0 \text{ and creep is irreversible} \\
+1 = -1, & \text{if } \Delta V_m^{n+1} > 0
\end{cases}
\]

(8)

At time zero, variable \( V_p^0 \) is equal to the initial pore volume. This variable must be updated whenever the direction of the volume change is altered, i.e.:

\[
V_m^n = V_p^n \text{ if } V_m^n > V_p^n \text{ and } V_p^n < V_m^n,
\]

(10)

\[
V_m^n = V_p^n \text{ if } V_m^n < V_p^n \text{ and } V_p^n > V_m^n
\]

(11)

It should be noted that the definition of \( V_m^n \) is modified to separate the creep volume from the volume change due to compaction. Finally, variable \( \text{creep}^n \) is the cumulative creep volume at the end of the nth timestep (due to superposition effects):

\[
\text{creep}^n = \frac{V_o B}{\phi_o} \sum_{k=1}^n \alpha_k e^{-\frac{x(V_m^{n+1} - V_p^{n+1})}{\Delta V_m^{n+1}}} \Delta t^k
\]

(12)

CREEP B - the reservoir rock rate constant; inversely proportional to the characteristic time constant of the material. This signifies the time needed for the rock to creep and reach its’ relaxed condition (day⁻¹);

CREEP M - creep exponent, the long term reservoir compressibility;

CREEP C – the total rock compressibility at equilibrium state (psi⁻¹).

These parameters relate to the model described above through expressing the changes in the form of derivatives:

\[
\frac{dV_p^{n+1}}{dP} = \frac{V_o [A + \Delta \text{creep}^{n+1} B(V_m^{n+1} - V_p^{n+1})(A + C_r - C_r)]}{1 + B \Delta \text{creep}^{n+1}}
\]

(13)
It can be seen from this table that the method followed in this study (for approximation of ultimate inelastic compressibility) gives meaningful results. The result – 51 µs – gives a mid-range value when compared against a database compiled by Hathon and Myers, 2011.

Dudley et al (1998) conducted creep experiments on several GoM reservoirs using different hold-times, and obtained the following plot. It can be seen from this plot that on average, creep strain is approximately 30% of the total instantaneous strain, regardless of the stress history and how strained the sample is at the time.
The model consists of 100 equal volume cells at the same depth and of initial pore volume $PV=2\times10^8$ RM each. Initial reservoir pressure is 332.3 BAR. The model is initially above bubble point and never drop below bubble point (to simplify material balance calculations between different cases).
Table C-2 Creep Effect Analysis

**FIELD PRESSURE BEHAVIOUR**

<table>
<thead>
<tr>
<th></th>
<th>Inelastic</th>
<th>With Creep</th>
<th>No creep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Pressure, Pi (psi)</td>
<td>4817.4626</td>
<td>4817.463</td>
<td></td>
</tr>
<tr>
<td>Lowest Pressure, Pmin (psi)</td>
<td>4726.362</td>
<td>4724.932</td>
<td></td>
</tr>
<tr>
<td>Equilibrium (final) Pressure Pf (psi)</td>
<td>4804.5257</td>
<td>4798.948</td>
<td></td>
</tr>
<tr>
<td>ΔP (Pi-Pf) (psi)</td>
<td>12.9369</td>
<td>18.51505</td>
<td></td>
</tr>
<tr>
<td>ΔP (Pi-Pmin) (psi)</td>
<td>91.1006</td>
<td>92.5303</td>
<td></td>
</tr>
<tr>
<td>ΔP (Pf-Pmin) (psi)</td>
<td>78.1637</td>
<td>74.01525</td>
<td></td>
</tr>
<tr>
<td>Pressure Rise after shut-in (psi)</td>
<td>78.1637</td>
<td>74.01525</td>
<td></td>
</tr>
<tr>
<td>Pressure Rise as % of total pressure drop</td>
<td>85.80</td>
<td>79.99</td>
<td></td>
</tr>
<tr>
<td>Difference due to creep (psi)</td>
<td></td>
<td>5.57815</td>
<td></td>
</tr>
<tr>
<td>Difference due to creep (%)</td>
<td></td>
<td>6.10</td>
<td></td>
</tr>
</tbody>
</table>

Table C-3 Summary of Depletion Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Depletion Rate (% of STOIIP)</td>
<td>6.27</td>
<td>0.63</td>
<td>0.31</td>
<td>0.25</td>
</tr>
<tr>
<td>No Creep 1</td>
<td>Creep 1</td>
<td>No Creep 2</td>
<td>Creep 2</td>
<td>No Creep 3</td>
</tr>
<tr>
<td>Oil Rate (SM3/DAY)</td>
<td>2500</td>
<td>250</td>
<td>125</td>
<td>100</td>
</tr>
<tr>
<td>Production Period (DAYS)</td>
<td>40</td>
<td>400</td>
<td>800</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table C-4 Summary of Injection Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Low Injection Rate</th>
<th>Medium Injection Rate</th>
<th>High Injection Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>at 0 days</td>
<td>Oil Production Rate (SM3/DAY)</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>Water Injection Rate (SM3/DAY)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>at 800 days</td>
<td>Oil Production Rate (SM3/DAY)</td>
<td>125</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>Water Injection Rate (SM3/DAY)</td>
<td>149.3</td>
<td>299.5</td>
</tr>
</tbody>
</table>

*Water Injection Set on Voidage Replacement Ratio of 1:1*
The table shows the following information for the Cell 6 (Compaction Region 1): Coordinate I (X), Coordinate J (Y), Coordinate K(Z), elapsed time (days), date, cell pressure (BAR), water saturation, Oil Saturation, minimum cell pressure (BAR), Pore Volume (KRM3) and PVMULT used by the simulator. Entries shaded in blue represent the depletion period. Cells shaded in white represent the injection (pressure increase) period. Only cells shaded in blue can be used for the creep approximation function.
Figure C-3 Comparison of Two Base Cases For Creep Approximation Function

Table C-6 Description of Multipliers for Creep Approximation Function

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>PVMULT Model A</th>
<th>PVMULT Model B</th>
<th>3.1</th>
<th>3.2</th>
<th>3.3</th>
<th>3.4</th>
<th>3.5 Final PVMULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>4765.7005</td>
<td>0.99769586</td>
<td>0.997816477</td>
<td>0.000120617</td>
<td>4.02057E-05</td>
<td>0.997776271</td>
<td>6.03085E-05</td>
<td>0.99783658</td>
</tr>
<tr>
<td>4774.734</td>
<td>0.99820297</td>
<td>0.998323648</td>
<td>0.000120678</td>
<td>4.02261E-05</td>
<td>0.998283422</td>
<td>6.03392E-05</td>
<td>0.998343761</td>
</tr>
<tr>
<td>4783.1585</td>
<td>0.998675625</td>
<td>0.99879636</td>
<td>0.000120736</td>
<td>4.02452E-05</td>
<td>0.998756115</td>
<td>6.03678E-05</td>
<td>0.998816483</td>
</tr>
<tr>
<td>4790.785</td>
<td>0.999103675</td>
<td>0.99924462</td>
<td>0.000120787</td>
<td>4.02624E-05</td>
<td>0.9991842</td>
<td>6.03936E-05</td>
<td>0.999244593</td>
</tr>
<tr>
<td>4797.354</td>
<td>0.9994725</td>
<td>0.999593332</td>
<td>0.000120832</td>
<td>4.02773E-05</td>
<td>0.999553055</td>
<td>6.04159E-05</td>
<td>0.99961347</td>
</tr>
<tr>
<td>4800.1235</td>
<td>0.999628205</td>
<td>0.999749056</td>
<td>0.000120851</td>
<td>4.02836E-05</td>
<td>0.999708772</td>
<td>6.04254E-05</td>
<td>0.999769197</td>
</tr>
<tr>
<td>4802.487</td>
<td>0.999760315</td>
<td>0.999881182</td>
<td>0.000120876</td>
<td>4.02889E-05</td>
<td>0.999840893</td>
<td>6.04333E-05</td>
<td>0.999901326</td>
</tr>
<tr>
<td>4804.343</td>
<td>0.999865235</td>
<td>0.999986114</td>
<td>0.000120879</td>
<td>4.02934E-05</td>
<td>0.999945821</td>
<td>6.04397E-05</td>
<td>1</td>
</tr>
<tr>
<td>4805.677</td>
<td>0.999939455</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4806.75</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Explanation of terms in Table C-6:

3.1 Difference in pore volume between PVMULT A and PVMULT B is taken.

3.2 Difference calculated in 3.1 is divided by 1/3 (Approximately the difference between PVMULTA and B pressures):

\[
\frac{(PVMULT A - PVMULT B)}{3}
\]

3.3 Values from 3.2 are subtracted from PVMULT B (to attempt to match PVMULTB to original creep cure):

PVMULT B - \[
\frac{(PVMULT A - PVMULT B)}{2}
\]

3.4 Difference calculated in 3.1 is divided by 1/2:

\[
\frac{(PVMULT A - PVMULT B)}{2}
\]

3.5 Values obtained from 3.4 are added to the values calculated from 3.3. This represents the final pore volume multipliers for the modified compaction table.
### Table C-7 Modified Compaction Table For Compaction Region 1

<table>
<thead>
<tr>
<th>CMT 1</th>
<th>P</th>
<th>PVMULT</th>
<th>TAMULT</th>
<th>TVMULT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>131.5</td>
<td>0.852</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>328.668</td>
<td>0.997031</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>328.67</td>
<td>0.997036</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>328.677</td>
<td>0.997037</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>328.688</td>
<td>0.997038</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>328.704</td>
<td>0.997039</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>328.723</td>
<td>0.997039</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>328.746</td>
<td>0.99704</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>328.771</td>
<td>0.997036</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>328.798</td>
<td>0.997576</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>328.826</td>
<td>0.998088</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>329.292</td>
<td>0.997354</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>329.873</td>
<td>0.998646</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>330.393</td>
<td>0.999055</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>330.852</td>
<td>0.999261</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>331.043</td>
<td>0.999454</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>331.133</td>
<td>0.99963</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>331.206</td>
<td>0.999783</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>331.334</td>
<td>0.999902</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>331.426</td>
<td>0.999974</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>331.478</td>
<td>0.99999</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>331.497</td>
<td>0.999997</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>331.499</td>
<td>0.999999</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>331.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table C-8 Approximation Function Analysis for Low Injection Rate

<table>
<thead>
<tr>
<th></th>
<th>Original Creep</th>
<th>Creep Approximation Function</th>
<th>Difference (CREEP- Approximation) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final depletion pressure (psi)</td>
<td>4726.28</td>
<td>4724.23</td>
<td>2.05</td>
</tr>
<tr>
<td>ΔP depletion (psi)</td>
<td>80.46</td>
<td>82.51</td>
<td>2.05</td>
</tr>
<tr>
<td>Final pressure (psi)</td>
<td>4793.94</td>
<td>4794.53</td>
<td>0.59</td>
</tr>
<tr>
<td>Pressure rise (psi)</td>
<td>67.66</td>
<td>70.30</td>
<td>2.64</td>
</tr>
</tbody>
</table>

| % of depletion | 84.09 | 85.20 | 1.11 |

### Table C-9 Approximation Function Analysis for High Injection Rate

<table>
<thead>
<tr>
<th></th>
<th>Original Creep</th>
<th>Creep Approximation Function</th>
<th>Difference (CREEP- Approximation) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final depletion pressure (psi)</td>
<td>4726.28</td>
<td>4725.79</td>
<td>0.49</td>
</tr>
<tr>
<td>ΔP depletion (psi)</td>
<td>80.46</td>
<td>80.95</td>
<td>0.49</td>
</tr>
<tr>
<td>Final pressure (psi)</td>
<td>5153.36</td>
<td>5160.16</td>
<td>6.79</td>
</tr>
<tr>
<td>Pressure rise (psi)</td>
<td>427.08</td>
<td>434.37</td>
<td>7.28</td>
</tr>
</tbody>
</table>

| % of depletion | 18.84 | 18.64 | 0.20 |