Chapter 8

A DEPRESSURIZATION CASE STUDY: PART II – PREDICTIVE SIMULATIONS, $S_{gc}$ CORRELATIONS AND COMPARATIVE LITERATURE SURVEY

8.1 Introduction

This chapter builds upon the fundamental framework developed in the previous chapter, which provided the following conclusions:

- the depressurisation-related processes of bubble nucleation and bubble growth could be expected to lead to a substantial reduction in pre-depletion oil saturation in Pilton;
- the short, tight nature of Pilton core meant that bubble growth in Pilton material was predicted to be highly dendritic and largely unaffected by buoyancy. Analytical considerations suggested that, under virgin conditions, gas structures would need to reach 4cm in height for gravity bias to become an issue (and 400cm in height for spontaneous bubble migration);
- spreading films of oil between gas and water encouraged continuous expulsion of oil from the system throughout the depressurisation;

However, a number of outstanding issues remain to be resolved and the base model is extended to examine additional sensitivities and results are compared with other experimental observations reported in the literature.
We begin in Section 2 of this chapter by presenting simulations looking at the impacts of \( S_{wi} \) and depletion rate on critical gas saturation, with a view to generating corresponding correlations. There is significant uncertainty associated with the estimation of fluid interfacial tensions. Small deviations of any one of the three IFTs from their base values could lead to a switch in the spreading characteristics of the oil during the depletion process. As seen from 2D simulations in the previous chapter, the implications of a switch from a spreading to a non-spreading system on oil recovery are considerable. Section 3 consequently discusses the results of extensive simulations of the sensitivity of critical gas saturation to \( \pm 10\% \) variations in all three interfacial tensions (\( \sigma_{go}, \sigma_{ow}, \sigma_{wg} \)) in both 2D and 3D networks. We then briefly return to the study of the impact of system size and buoyancy on critical gas saturation in section 4, this time using waterflooded Pilton systems, followed by a brief note on the definition of critical gas saturation itself. Section 5 examines the specific contribution of Pilton pore microstructure to its depletion behaviour via comparisons with networks characterised by pore size distribution (PSD) parameters that differ from those characterising the Pilton sample. Two new rock fabrics were considered: one a 3mD network representing a chalk sample and the other a 300mD network more characteristic of a clastic rock.

One characteristic of the Pilton field that have so far been neglected is the existence of fracture networks at the core scale. Although earlier focus had been on the mechanics of fluid discharge from the matrix surrounded by well-defined boundaries, departures from these results could be expected when the effects of high conductivity fractures are taken into account. To address this shortcoming, Section 6 provides an assessment of the impact of fractures and fracture spacing on the onset of gas flow and oil recovery. Simulations in this section, as well as in sections 4 and 5, utilise 2D networks. Section 7 presents a general procedure for estimating pertinent reservoir engineering parameters – critical gas saturation and relative permeability functions – that characterise macroscopic Pilton depressurization behaviour over a range of operating conditions. Finally, section 8 discusses the Pilton depletion within the context of other available depressurisation results (for example, those associated with the Brent field, other clastic media, and other North Sea chalks).

The chapter ends with a summary of key conclusions.
8.2 Sensitivity of $S_{gc}$ to Depletion Rate and Initial Water Saturation ($S_{wi}$)

The previous chapter has described a comprehensive anchoring procedure that was used to create a faithfully tuned network model analogue of the Pilton core used in the experiment. We are now ready to run a number of “what if” scenarios to derive correlations between important reservoir simulation parameters (critical gas saturation, relative permeability) and model variables such as initial water saturation, depletion rate, and length scale, fluid IFTs, pore network architecture and fractures. This section focuses on the investigation of the impact of depletion rate and $S_{wi}$ on the critical gas saturation. Table 8-1 summarises the properties of the anchored and history-matched Pilton 2D and 3D network surrogates used in these predictive simulation runs. All networks used in this section are 3D.

8.2.1 Impact of Depletion Rate on $S_{gc}$

Gas saturation is generally assumed to be critical when a sample spanning cluster is formed along the flow direction (although discontinuous gas fluxes can occur under large gravitational and/or viscous pressure gradients). The spanning cluster definition seems appropriate here given the predominance of capillary forces and the relatively high nucleation densities expected during Pilton depletion. The range of depletion rate (1.0psi/day – 200psi/day) was chosen to cover much of the observed range of values across a typical reservoir – from the near-well regions to the farthest reservoir boundaries.

Results

Experimental studies have repeatedly shown that nucleation density and critical gas saturation increase with an increase in depletion rate (Kennedy and Olson, 1952; Stewart et al., 1954; Berry, 1956; Handy, 1958; Moulu and Longeron, 1989; Kortekaas and Poelgeest, 1991; inter alia). Kennedy and Olson (1952) reported experimental observations which show nucleation density to be directly proportional to depletion rate. It is therefore striking to see that nucleation density changed only marginally as the depletion rate was varied over two orders of magnitude in Figure 8-1. However, two important features set apart the Pilton core – and by extension its numerical network
model analogue – from the porous media used in the experiments sited above. Whilst all the porous media used in the referenced papers were virgin and had permeabilities that ranged from 200mD to several Darcies (200mD for Stewart et al., 1954; 211mD for Moulu, 1988; 200 – 1900mD for Kortegas et al., 1991; Micromodels for Bora et al., 1997; Bead packs for Chateneva et al., 1959; and Crystal surfaces for Kennedy and Olson, 1952), the Pilton core was (i) waterflooded, and (ii) has an average permeability of approximately 0.271mD. Under virgin conditions and in high permeability media, diffusion occurs more rapidly and concentration gradients quickly flatten, decreasing local supersaturation and hindering further nucleation. In waterflooded and tight media, however, there are fewer and narrower channels for diffusive mass transport and therefore considerably more time is required for the system to equilibrate. This leads to higher degrees of local supersaturation that increases the potential for bubble nucleation. Unless depletion rates are set extremely low (less than 0.001psi/day, for example), ultra-low diffusion rates will suppress the effect of depletion rate on nucleation density in tight and waterflooded systems.

Figure 8-2 shows the predicted effect of depletion rate upon critical gas saturation in the Pilton sample – the correlation between depletion rate and critical gas saturation can be seen to be extremely weak. Varying the depletion rate over two orders of magnitude changed the overall nucleation density by less than 1.3% (232nuclei to 229nuclei), and the critical gas saturation from 0.19 @ 200psi/day to 0.17 @ 10psi/day. To understand these results we must go back to Figure 8-1.

Although the nucleation profiles in Figure 8-1 all eventually peak at more or less the same value, their respective rates of build-up varied with depletion rate, with nucleation rate decreasing as the depletion rate decreased. Within a system pressure range of 3045psia to 3020psia – the zone of the widest separation between nucleation profiles – the 200psi/day model had already achieved 80% activation, while in the 1psi/day model only 49% activation had been achieved at this point (see Figure 8-3). It was the initial rate of nuclei build up, especially during the first 250psia pressure drop, not the total number of bubbles that eventually nucleated, which ultimately determined the critical gas saturation for a given depletion rate. Now, in a progressive nucleation process, where crevices activate sequentially in time, bubbles that nucleate early have the potential to grow
faster because of less competition for dissolved gas. Those that nucleate later emerge in a much more gas impoverished oleic phase and the contribution of these newcomers to the overall depletion behaviour would be heavily outweighed by that from the larger, longer nucleated bubbles. The greater the fraction of the total number of nuclei activated early, the greater the overall impact on critical gas saturation. After the effects of the marginal differences in nucleation density have been accounted for, differential nucleation rates explain why very similar nucleation densities can gave rise to different critical gas saturations as the depletion rate was varied. Similar behaviour is shown in Figure 8-4 using a different random number seed for constructing the network.

*If the first set of realizations in Figure 8-2 were taken as representative of the general trend – having retained the same initialization parameters used in the history matching process – we can conclude that critical gas saturation decreases with a decrease in depletion rate but within only 2 percentage points. However, results from other realisations using different random number seeds (undertaken to test the robustness of the model) predict that, on average, critical gas saturation should remain essentially constant (\(S_{gc} \approx 20\%\)) for the Pilton sample over the full range of depletion rates considered (Figures 8-5 and 8-6).*

### 8.2.2 Impact of \(S_{wi}\) on \(S_{gc}\)

Fluid distributions in waterflooded reservoirs are far from homogeneous and large patches could have water saturations below or above the value used in the core depletion experiment. It is therefore useful to examine the degree to which reservoir simulation parameters would have to be tailored to cater for different regions of the reservoir characterised by different pre-depletion water saturations.

There are conflicting accounts of the effect of \(S_{wi}\) upon critical gas saturation in the depressurization literature. Whilst some authors (Kortekaas and Poelgeest, 1989) report that \(S_{gc}\) increases with \(S_{wi}\), others (Moulu and Longeron, 1989; Firoozabadi et al, 1992), maintain that the opposite is true. In the face of these contradicting claims, pore network modelling can provide a productive means for examining these issues from first principles.
A fixed depletion rate of 5psi/day was chosen for the $S_{wi}$ sensitivity study here. A number of simulations were performed at different initial water saturations – starting from a virgin scenario to a maximum of 0.65.

**Results**

Figure 8-7 confirms the results of the 2D scoping studies in Chapter 7 regarding the relationship between nucleation density and $S_{wi}$: viz. that nucleation density (in terms of the number of nuclei per initial oil volume) increases monotonically with increased $S_{wi}$. However, simulations show that this does not simply translate into a corresponding increase in $S_{gc}$ as $S_{wi}$ increases (Figure 8-8). *Indeed, $S_{gc}$ can be predicted to broadly decline with an increase in $S_{wi}$ ($S_{gc}$ varies from 27% – 17% as $S_{wi}$ is increased from 0% to 65%).*

Models with lower $S_{wi}$ naturally begin with a higher saturation of potentially displaceable oil, and since capillary forces were dominant and the nucleation density high, $S_{gc}$ increased with a decrease in $S_{wi}$.

As $S_{wi}$ was increased, however, there were two competing effects which acted to modify $S_{gc}$. Firstly, an increase in nucleation density (Figure 8-7) (which generally increases $S_{gc}$) and secondly, a reduction in oil connectivity (which slows diffusional mass transport and reduces the probability of gas cluster coalescence). These two mechanisms tend to offset one another and only through simulation can we predict which will win out. The results (Figure 8-8) show a small increase in $S_{gc}$ as $S_{wi}$ increased from 0.15 to 0.25, whilst further increase in $S_{wi}$ above 0.25 led to a progressive decrease in the bulk oil connectivity, choking off bubble coalescence and ultimately leading to a negative correlation between $S_{wi}$ and $S_{gc}$.

Despite the overall inverse relationship between $S_{gc}$ and $S_{wi}$, the oil recovery efficiency broadly increased as $S_{wi}$ increased (Figures 8-9), although Figures 8-9 & 8-10 show that this increase in oil recovery efficiency was most evident towards the end of the depletion process rather than in the early to intermediate stages.

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Table 8-1: Summary of network and fluid properties, and operating conditions. Sample porosity was matched by means of the pore volume pre-factor as described in Chapter Seven.
### Properties

<table>
<thead>
<tr>
<th></th>
<th>3D</th>
<th>2D</th>
</tr>
</thead>
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<tr>
<td>Initial Pressure, [psia]</td>
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<td></td>
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<tr>
<td>Final Pressure, [psia]</td>
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<td></td>
</tr>
<tr>
<td>Temperature, [°F]</td>
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<td></td>
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<tr>
<td>Gravity</td>
<td>Always on</td>
<td>Negligible</td>
</tr>
<tr>
<td>NX, NY, NZ</td>
<td>106, 23, 23</td>
<td>213, 47, 1</td>
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<tr>
<td>Total Core Pore Volume, [m³]</td>
<td>3.659E-05</td>
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<td>Model Volume, [m³]</td>
<td>1.496E-10</td>
<td>2.671E-11</td>
</tr>
<tr>
<td>Volume Pre-factor</td>
<td>49.87915916</td>
<td>73.52958371</td>
</tr>
<tr>
<td>Porosity [fraction]</td>
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<td></td>
</tr>
<tr>
<td>Pore length, [µm]</td>
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<td></td>
</tr>
<tr>
<td>Total Core Height, [cm]</td>
<td>15.397</td>
<td></td>
</tr>
<tr>
<td>Model height, [cm]</td>
<td>0.25</td>
<td>0.5</td>
</tr>
<tr>
<td>Model width, [cm]</td>
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<td>0.11</td>
</tr>
<tr>
<td>Buffer</td>
<td>Top 2 bond rows</td>
<td></td>
</tr>
<tr>
<td>Mean Pore Radius, [µm]</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>R_{min}, R_{max}, [µm]</td>
<td>0.002, 0.389</td>
<td></td>
</tr>
<tr>
<td>Gas Molar Weight, [kg/mol]</td>
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<td></td>
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<td>Gas Density at Std. Condition, [kg/m³]</td>
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<td></td>
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<td>Gas-Oil Diffusion Coefficient, [m²/sec]</td>
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<td></td>
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<tr>
<td>Gas-Water Diffusion Coefficient, [m²/sec]</td>
<td>1.00E-9</td>
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<tr>
<td>Gas-Water Interfacial Tension, [mN/m]</td>
<td>50.0</td>
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<td>Oil-Water Interfacial Tension, [mN/m]</td>
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<tr>
<td>Gas-Oil Interfacial Tension, [mN/m]</td>
<td>See Figure 8-11</td>
<td></td>
</tr>
<tr>
<td>Crevice Density [crevice/oil-filled pores]</td>
<td>1/500</td>
<td></td>
</tr>
<tr>
<td>Crevice Size Interval [m, m]</td>
<td>[1.0 × 10⁻⁹, 20.0 × 10⁻⁹]</td>
<td></td>
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<tr>
<td>Depletion rate, [psi/day]</td>
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<tr>
<td>S_{wi}, [fraction]</td>
<td>0.0 – 0.65</td>
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Figure 8-1: Sensitivity of the number of activated nuclei count to depletion rate.

Figure 8-2: Correlation of critical gas saturation with depletion rate. Red square represents $S_{gc}$ at the experimental rate ($S_{wi}=0.616$).

Figure 8-3: Percentage of the cumulative total bubbles nucleated for each depletion rate as a function of pressure. It shows nucleation rate increase with depletion rate.
Figure 8-4: Sensitivity of activated nuclei count to depletion rate for a different individual model realization.

Figure 8-5: Correlation of critical gas saturation with depletion rate at different model realizations.

Figure 8-6: Correlation of critical gas saturation with depletion rate including uncertainty bars. Red square represents $S_{gc}$ at the experimental rate ($S_{wi}$=0.616)
Figure 8-7: A monotonically increasing relationship between nucleation density and initial water saturation was observed.

Figure 8-8: Correlation of critical gas saturation with initial water saturation. Red square represents $S_{gc}$ at the experimental $S_{wi}$ (0.616)

Figure 8-9: Cumulative oil recovery factor profiles at different $S_{wi}$.
8.3 Sensitivity of $S_{gc}$ to Variations in GWIFT, GOIFT, and OWIFT under Different Operating Conditions

8.3.1 Introduction
Both 2D and 3D networks were used for the simulations in this section. For 2D networks, four values of $S_{wi}$ were considered (0, 0.10, 0.232, and 0.30) at three depletion rates (100, 10, 1psi/day) and for four representative combinations of ±10% variations in all three interfacial tensions from their base values. For 3D networks, five values of $S_{wi}$ were considered (0, 0.15, 0.45, 0.616, and 0.65) at two depletion rates (100, 10psi/day) and for four representative combinations of ±10% variations in all three interfacial tensions from their base values (note that depletions at 1psi/day in 3D systems are prohibitively time-consuming at present).

8.3.2 2D Simulations
Using 2D systems allows us to consider a wider range of sensitivities without introducing prohibitive CPU issues associated with large 3D simulations. Once the most influential parameters have been identified from these simulations, a number of targeted 3D runs are subsequently undertaken as reported later in this section.

The main network properties are as listed in Table 8-1. The equivalence of the experimental 3D $S_{wi}$ of 0.616 in a 2D system was calculated as 0.232 – this scaling was based upon a simplified analysis of the corresponding percolation thresholds of the 3D and 2D networks, see Table 8-2 for a brief explanation.
Figure 8-11: Gas-Oil interfacial tension as a function of pressure (reproduced).

Table 8-2: $S_{wi}$ values for 3D fractionally-wet networks and their 2D equivalents based on an analysis of 3D and 2D equivalent percolation saturations (NB in fractionally-wet networks, saturation corresponds to number percentage). 0.616* and 0.232* are the values corresponding to experiment and 2D analogue. $P_{th}^{3D} = 0.3$ and $P_{th}^{2D} = 0.6$ for a 3DZ of 5 and a 2DZ of 3.33, respectively. $P_{th}$ denotes percolation threshold. This process essentially aims to reproduce 3D oil phase connectivity in an equivalent 2D network.

<table>
<thead>
<tr>
<th>$S_{wi}$</th>
<th>$Soi$</th>
<th>$S_{oi}^{3D}$/$P_{th}^{3D}$</th>
<th>$S_{wi}$</th>
<th>$S_{oi}^{2D}$ = $S_{oi}^{3D}$/$P_{th}^{3D}$ * $P_{th}^{2D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.650</td>
<td>0.350</td>
<td>1.167</td>
<td>0.300</td>
<td>0.700</td>
</tr>
<tr>
<td>0.616*</td>
<td>0.384</td>
<td>1.280</td>
<td>0.232*</td>
<td>0.768</td>
</tr>
<tr>
<td>0.450</td>
<td>0.550</td>
<td>1.833</td>
<td>NA</td>
<td>1.100</td>
</tr>
<tr>
<td>0.150</td>
<td>0.850</td>
<td>2.833</td>
<td>NA</td>
<td>1.700</td>
</tr>
</tbody>
</table>

8.3.2.1 Impact of IFT departures from base case @ $S_{wi}$=0.232 and 100psi/day.

The first sensitivity addresses the impact of possible inaccuracies in the three interfacial tensions upon pore-scale mechanisms and subsequent gas evolution. A 10% variation in each interfacial tension was considered – note that this affects the time evolution of the oil spreading coefficient ($Cs=GWIFT-(GOIFT+OWIFT)$), which, in turn, affects the growth of the gaseous phase through the displacement of various oil-water, oil-gas, and water-gas interfaces. Figure 8-12 shows the variation of spreading coefficient ($Cs$) profiles with pressure for the 27 possible combinations of ±10% departures from the base values of GOIFT, OWIFT, and GWIFT, together with the base case curve. Note that no change in GOIFT, OWIFT, or GWIFT is expected to significantly affect the capillary-gravity force balance (presented later). Any small effect is likely to be dwarfed by the impact of changes in the sign of Cs at any point during the course of the depletion.
A subset of four Cs curves covering the full span of the Cs behaviours was selected for the simulations (Figure 8-13) and all simulations were initially carried out at a rate of 100psia/day (a high depletion rate used to expedite the sensitivity – lower rate depletions are reported later). The gas saturation profile (and the critical gas saturation, \( S_{gc} \)), showed a high sensitivity to Cs (Figures 8-14(a) and 8-15). Indeed, \( S_{gc} \) – defined provisionally here as the gas saturation at which the absolute slope of the saturation profile begins to decrease – decreased in proportion to the fraction of the pressure range characterised by a negative Cs (cross reference Figure 8-14(a) and Figure 8-12). Thus, the IFT combination \((\sigma_{go}, \sigma_{ow}, \sigma_{wg})=(+,+,\cdot)\) exhibited the lowest \( S_{gc} \), a value less than half that observed in the base case combination \((0,0,0)\). In order to test the relative importance of oil spreading behaviour and absolute IFT values, combination \((\sigma_{go}, \sigma_{ow}, \sigma_{wg})=(+,+,\cdot)\) was re-run whilst artificially maintaining a positive Cs throughout the depletion. Figure 8-14(b) conclusively shows that it was the change in the sign of Cs rather than the absolute IFT values that controlled the displacement process.

![Figure 8-12: Spreading coefficient profiles against pressure for the 26 combinations of ±10% variations from base values of GOIFT, OWIFT, and GWIFT, including the base case (0,0,0).](image-url)
Figure 8-13: A selection of five spreading coefficient profiles vs. pressure that samples the full range of possibilities in Figure 8-2.

Figure 8-14: Impact of Cs on saturation profile at $S_{wi}=0.232$ and 100psi/day. (a) Comparison of the selected five IFT combinations, (b) Impact of artificially maintaining a positive Cs for combination $(\sigma_{go}, \sigma_{ow}, \sigma_{wg}) = (+,+, -)$ throughout the pressure range.
8.3.2.2 Impact of $S_{wi}$ and IFT Variations @ 100psi/day

The (3D) $S_{wi}$ values to be investigated are listed in Table 8-2. By using our percolation threshold-based scaling approach, four approximately equivalent 2D $S_{wi}$ values were derived for use in the 2D networks – 0.30, 0.232, 0.10 and 0 – and 3 depletion rates were considered (100, 10, and 1psia/day). The $S_{wi} = 0.232$ case was chosen as the 2D equivalent of the (3D) experimental value (0.616).

At $S_{wi} = 0$, we have only two phases, oil and gas and so Cs does not play a role because it is a property of 3-phase systems only. Nevertheless, the result for $S_{wi} = 0$ confirmed our earlier observation that variations in GOIFT will by itself have no effect on $S_{gc}$ (Figure 8-16, top row). For $S_{wi} > 0$, however, Cs begins to have an impact on gas build-up – gas saturation is retarded in cases where the spreading coefficient becomes negative and this reduction is more pronounced at increasing $S_{wi}$ (reading down columns in Figure 8-16). The 2D sensitivity of $S_{gc}$ as a function of $S_{wi}$ and depletion rate is shown in the histograms of Figure 8-17.

8.3.2.3 Impact of Depletion Rate for varying IFT combinations

For the 2D Pilton system, decreasing depletion rate through three orders of magnitudes – from 100psi/day to 1psi/day – did not have a significant effect on gas evolution and $S_{gc}$ regardless of $S_{wi}$ (reading along rows in Figure 8-16, and see histograms in Figure 8-17). Nucleation density and nucleation rate decreased slightly with depletion rate (Figure...
8-18) but this was not sufficient to have a noticeable impact on the saturation profile. A change in depletion rate altered the spatial distribution of nuclei (Figure 8-19) and additional simulations using different random number seeds should ideally be run to reduce uncertainty in these 2D conclusions. However, the primary interest is in 3D predictions, and we will go on to discuss sensitivities in 3D Pilton analogues.

**Figure 8-16**: $S_g$ profile of 2D networks as a function of pressure for five different spreading coefficient profiles, at five $S_{wi}$ (initial water saturation) conditions, and for three depletion rates.
Figure 8-17: $S_{gc}$ (critical gas saturations) of 2D networks for five different spreading coefficient profiles at different $S_{wi}$ (initial water saturation) conditions for three depletion rates.

Figure 8-18: Sensitivity of nucleation profile to depletion rate at $S_{wi}=0.30$ and for a mostly positive Cs profile.
8.3.3 3D Simulations

2D networks have been used above to examine the sensitivity of $S_{gc}$ to changes in spreading coefficient by considering deviations of ±10% in GOIFT, OWIFT, and GWIFT from their baseline values. The results showed a strong sensitivity of $S_{gc}$ to changes in spreading coefficient profiles, with the IFT combination that displayed non-spreading behaviour through the entire depletion process (i.e. the combination (+,+,−), Figure 8-13), yielding the largest reduction in $S_{gc}$ from the base case for 0.232 (the 2D equivalent of the 0.616 $S_{wi}$ used in the experiment).

The result of the same sensitivities using history-matched 3D network surrogates of the Pilton core is presented next. All other network parameters are the same as those used with 2D networks as shown in Table 8-1.

8.3.3.1 Impact of Spreading Coefficient at Varying $S_{wi}$ and Depletion Rate

Figure 8-20 compares the impact of spreading coefficient on $S_g$ profiles at depletion rates of 100psi/day and 10psi/day, for five $S_{wi}$ values − 0, 0.15, 0.45, 0.616, and 0.65. It shows spreading coefficient to have far less impact on the overall gas evolution behaviour in 3D networks than in 2D networks. The greater pore connectivity in 3D networks allows growing bubbles to readily find alternative evolution pathways to the production buffer. This not just explains the relative insensitivity of the $S_g$ profiles to variations in spreading
coefficient but also accounts for the lower gas saturations in 3D networks compared to 2D networks of equivalent oil percolation thresholds.

A decrease in depletion rate from 100psi/day to 10psi/day perturbed the $S_{gc}$ hierarchy but the average $S_{gc}$ for all $S_{wi}$ values considered remained practically the same for both depletion rates (Figure 8-20 and Figure 8-21). Hence the impact of depletion rate was essentially negligible in both 2D and 3D simulations for all IFT combinations.

Although the response of $S_g$ profiles to changes in $C_s$ became more varied as $S_{wi}$ was increased, this response was by no means systematic – as can be clearly seen in Figure 8-21 (which shows histograms of $S_{gc}$ under the different simulation conditions). This is a markedly different response in comparison to 2D networks, which showed $S_{gc}$ for combination $(\sigma_{go}, \sigma_{ow}, \sigma_{wg})=(+,+,⁻)$ to be consistently below that obtained with any other IFT combination. Figure 8-22 shows the corresponding pore occupancy graphics at the end of depressurisation in waterflooded networks under the five spreading coefficient assumptions, together with the results from a virgin network for comparative purposes. The $S_{gc}$ values obtained from the 3D simulations — averaged over five IFT combinations for each depletion rate — corresponded closely to those found when using the baseline IFT values. Average $S_{gc}$ values ranged from 0.27 to 0.163 as $S_{wi}$ was increased from 0 to 0.65.
Figure 8-20: $S_g$ profile of 3D networks as a function of pressure for five different spreading coefficient profiles, at five $S_{wi}$ (initial water saturation) conditions, and for two depletion rates.
Figure 8-21: $S_{gc}$ (critical gas saturations) of 3D networks for five different spreading coefficient profiles at different $S_{wi}$ (initial water saturation) conditions for two depletion rates.
Figure 8-22: Saturation distributions at 1000psia for (a) A virgin 3D model, and (b) – (f) Waterflooded 3D models ($S_{wi}=0.616$) showing the impact of Cs profiles obtained by varying the three interfacial tensions ($\sigma_{go}, \sigma_{ow}, \sigma_{gw}$) by ±10% from the base values – (f) represents a model with original IFT values. The depletion rate was 10psi/day.

8.4 Impact of network height and gravity @ $S_{wi}=0.232$ and 100psi/day (2D Networks)

Although the impact of gravity was investigated in Chapter 7 (and used to examine the important issue of scale-dependence on gas growth), the models used were virgin models ($S_{wi}=0$) with a single instantaneous nucleation site close to the bottom of the network. Here, this earlier 2D work is extended by introducing waterflooded models containing a 2D water saturation that is topologically close to the 3D experimental value (i.e. $S_{wi}=0.232$ in 2D). Moreover, the gas growth is now driven via a realistic progressive nucleation mechanism instead of a simplified single-nucleus approach. Note that we are again using 2D analogues here in order to consider larger networks – very large 3D networks are not currently feasible at present due to the small pore sizes and pore lengths associated with the low permeability Pilton material.

In order to enable us to study the impact of system size on depletion behaviour, the gravitational constant ($g$) was increased by four orders of magnitude from the base case, in four steps – equivalent to scaling the network model to different heights ($1g \equiv 15.397\text{cm} ; 10g \equiv 153.97\text{cm} ; 100g \equiv 15.397\text{m} , 1000g \equiv 153.97\text{m} ; 10000g \equiv 1539.70\text{m}$). A
high depletion rate was used to expedite these results. One point to bear in mind when using gravity as a scaling parameter is that our concept of what a pore actually represents varies as the gravitational constant is increased. As $g$ increases, a "pore" in the base system becomes more representative of a pore ensemble or small gridblock. Nevertheless, some progress can still be made using this approach.

Gravity impacts the depletion process in two fundamental ways: firstly, by biasing the activation of nucleation sites (a natural consequence of the increase in hydrostatic pressure that comes with an increase in system height); and secondly, by biasing the growth of nucleated bubbles. The simulations predict that gas saturation at any given pressure to broadly decrease with an increase in effective gravity (or, equivalently, network height) (see Figures 8-23 and 8-24, which plot maximum Bond Number and gas saturation histories respectively). The effect of gravity growth bias can be seen at 100g – which is equivalent to increasing the height of the network to 1539.7cm (see Figure 8-24). At 1000g, spontaneous cluster migration can be deduced from the Bo (Bond number) plot, although this is not obvious from the pore occupancy graphics in Figure 8-25. Further increase in g, to 10000 times the base case, showed nucleation bias towards the upper part of the network accompanied by a clear transition in flow regime to a dispersive migratory regime. From the simulations we see that $S_{gc}$ is essentially scale-dependent (see Figure 8-24(b)), which raises some important issues when attempting to populate reservoir-scale models. Nevertheless, the results suggest that the impact of gravity on critical gas saturation should remain negligible in waterflooded Pilton material up to a height of approximately 15m.

![Figure 8-23: 2D Bomax (local maximum Bond number) profiles for different values of g at 100psi/day and $S_{wi}=0.232$.](image-url)
Figure 8-24: The impact of gravity constant (used as a scaling cipher) on (a) the 2D $S_g$ profile and (b) correlation of $S_{gc}$ and network height, at 100psi/day and $S_{wi}=0.232$.

Figure 8-25: Pore occupancy graphics at 1000psia for varying $g$ values at $S_{wi}=0.232$. Depletion rate was at 100psi/day.

8.4.1 Definition of $S_{gc}$ and the Impact of Various System Parameters

Throughout the depressurization case study plots of gas evolution (and hence oil production) as functions of pressure have been presented. However, no explicit indication of how the critical gas saturation values have been estimated was given and the snapshots presented earlier suggest that we need to take care when defining this important parameter.

One definition relates to the saturation at which a continuous interconnected gas phase first spans the porous medium – and even this may be direction-dependent if the evolution regime is gravity-biased. Figures 8-15 and 8-26 demonstrate the difficulty:
combinations \((\sigma_{go}, \sigma_{ow}, \sigma_{wg}) = (+, +, -)\) and \((\sigma_{go}, \sigma_{ow}, \sigma_{wg}) = (+, 0, -)\) (Figures 8-15(c) and Figures 8-15(d), respectively) both have non-zero gas fluxes exiting the system, yet no spanning gas cluster emerges in either. Similarly, cases where gravity or fractures are important are likely to produce gas at very low critical saturations. So how can we infer \(S_{gc}\) from our simulations? We return to the 2D results for some insight.

Figure 8-26 presents plots of cumulative gas production (i.e. gas leaving the top of the system and immediately removed from the upper buffer) as functions of gas saturation within the entire network for (a) a variety of IFT values, and (b) different gravitational constants (i.e. length scales). These plots exhibit asymptotic behaviour that is a useful diagnostic of critical gas. For the IFT sensitivities, Figure 8-26(a), the vertical asymptotes in the cumulative gas production represent either: 1) the point of formation of a sample spanning cluster (top-to-bottom), or 2) the point at which thermodynamic shrinkage rather than diffusive mass transfer becomes the main driver of gaseous growth. Figure 8-26(a) confirms our earlier deduction (from 2D networks) that the largest reduction in critical gas saturation from the standard base case would be achieved when the IFT combination results in a negative \(C_s\) throughout the depletion process, see IFT combination \((+, +, -)\) in Figure 8-13. In Figure 8-26(b), for 1000g and above, gas becomes increasingly more mobile and the flow becomes increasingly discontinuous – no spanning clusters form. For such migratory cases, \(S_{gc}\) may be better defined as the saturation at first production: this would give very low \(S_{gc}\) values that may even approach zero in some cases.

Figure 8-26: Estimating 2D critical gas saturation using the cumulative gas production for (A) Four combinations of departures of GWIFT, OWIFT and GOIFT from their base values, including the base case“\((0,0,0)\)”, (B) A changing gravitational force or model size. \(S_{wi}=0.232\) and depletion rate at 100psi/day.
8.5 Impact of Fractures

There is particular interest in identifying the depletion conditions that could give rise to a low critical gas saturation (less than 0.10, say). To a large extent, this value depends upon the definition used – are we interested in a sample-spanning, connected gaseous phase or should we accept critical gas saturation to have been reached as soon as any non-zero (and possibly disconnected) gas flux has exited the system. This issue has been fully discussed in the previous section; here we will see how discontinuous gas fluxes can easily arise in fractured systems.

To model simple vertical fractures in the 2D network model, bonds on either side of the lateral boundaries were assigned capillary radii approximately 5000 times larger than the average in the matrix (i.e. $R_{\text{fracture}} \approx 1150 \mu m$). These ‘fractures’, were initially assumed to be 100% saturated with oil. As a first approximation, the fracture bonds were simply assigned volumes equal to the average volume of a matrix bond and fracture volumes were not used in the calculation of the network saturations (in effect, the large fracture radius defines its low capillary entry pressure but fracture volume remains small). Assigning fracture pores a volume proportional to the square of their mean capillary size would result in a fracture volume several orders of magnitude larger than the connected matrix block and this initially led to numerical issues. Each fracture pore was consequently assigned a volume of an average matrix pore as the simplest initial assumption – realistic fracture volumes were considered later. Diffusive mass transfer between fracture and matrix was also disabled initially.

8.5.1 Depletion in Vertically-Fractured Pilton Networks @ $S_{\text{wi}}=0.232$ and 100psi/day

Figures 8-27 and 8-28 show that, despite the continuous loss of free gas to the high conductivity fractures, some build-up of gas can still occur within the matrix itself. Once gas enters the fractures, it immediately migrates towards the outlet at the top of the system and is then produced. The presence of the fractures ultimately retarded the build-up of gas within the matrix (Figure 8-27a) as gas mobility accelerates (Figure 8-27b), leading to a substantial reduction in $S_{gc}$ – from 0.57 to 0.22. Moreover, final gas saturation within the matrix is effectively halved in the presence of vertical lateral fractures.
Chapter 8 – A Depressurization Case Study: Part II

8.5.2 Fracture Fluid and Fracture Orientation

The inclusion of oil-filled vertical fractures in the network has been shown to decrease the $S_{gc}$ and to approximately halve the final gas saturation within the matrix. In this section, we will consider an additional fracture configuration and also investigate the impact of fracture pore occupancy upon gas evolution and oil recovery. The new fracture configuration is slanted, running diagonally in the plane of the 2D model (as depicted in the graphics of Figures 8-29 and 8-30).

Figure 8-31(a) shows that an oil-filled diagonal fracture behaves in a manner similar to the lateral fractures, once again reducing final gas saturation by 50% when compared to a fracture-free (uniform) network. Moreover, the impact of filling fractures with water
rather than oil did not have any noticeable effect on the gas saturation profile for both vertical and diagonal fracture systems (Figures 8-31b and Figure 8-32).

Figure 8-29: Saturation distributions at 1000psia showing the impact of (b) Two lateral, and (c) One diagonal oil-filled fractures for $S_{wi}=0.232$ and a depletion rate of 100psi/day.

Figure 8-30: Saturation distributions at 1000psia showing the impact of (a) a fracture free network, (b) Two lateral, and (c) One diagonal water-filled fractures for $S_{wi}=0.232$ and a depletion rate of 100psi/day.
8.5.3 Fracture Aperture Size and Fracture-Matrix Coupling

In the foregoing section, fractures were modelled simply by assigning a large capillary entry radius to a subset of bonds within the original matrix network. However, fracture bonds were assigned volumes corresponding to matrix pores. We now go on to model fractures more realistically by assigning volumes that are more representative of those seen in reality. Fractures are now given a physical width corresponding to 4 pore lengths and are now effectively permeable strips within the matrix. The new fractures are assigned a porosity of 70% for convenience - i.e. the pore volume of fracture bonds divided by the bulk volume of fracture is 0.7. Moreover, diffusive mass transfer between fracture and matrix is now enabled. Due to the relatively large aperture size of the fractures, the redistribution of dissolved gas *within* the fracture itself is assumed to occur instantaneously and the dissolved gas concentration in each fracture pore after a diffusion loop is set equal to the average concentration over all fracture pores. To further reduce complexity, any gas entering a fracture pore, whether during growth or migration, is immediately produced in all scenarios – the effect of this simplification is minimal for
both fracture configurations (result not shown here). Henceforth all fractures are considered to be water-filled at the start of depressurisation.

**Results**

Results showed that assigning the fractures a substantial volume decreased the final gas saturation within the matrix by only 2 percentage points for the diagonal fracture, whilst for the vertical fractures the effect was negligible, see Figure 8-33. In addition, turning on fracture-matrix diffusion for networks containing these new fractures decreased the rate of gas build-up for both fracture configurations, but once again the final gas saturations remained largely unchanged, Figure 8-33. Comparisons between nucleation profiles of models with and without fracture-matrix diffusion (Figure 8-34) would suggest that these differences in build-up profiles are primarily due to the loss of gas to the water-filled fractures. Note that the later sharp rise of the nucleation profiles was due to nucleation in some pores repeatedly made active sites by cycles of invasion and imbibition events that accompany migration – this point will be elaborated upon in the next section.

Figure 8-35 shows that, when fracture-matrix diffusion was turned off, the $S_g$ profile in the diagonally fractured system was always lower than that in the network bounded by 2 parallel vertical fractures – the difference between the two increased slightly when fracture pores were assigned large volumes. When fracture-matrix diffusion was turned on, however, the $S_g$ profiles overlap during most of the depletion and only diverge at around 1800psia, resulting in the final saturation for the vertically fractured model being approximately 4 percentage points higher than that from the diagonally fractured network, Figure 8-36. Figures 8-37 and 8-38 show comparisons of final phase distributions in networks with diagonal and vertical fractures with different properties.

![Figure 8-33: Saturation profiles based on different properties of (a) Two lateral fractures, and (b) One diagonal fracture. Volumless implies extremely low porosity.](image-url)
Figure 8-34: Nucleation profiles based on different properties of (a) Two lateral fractures, and (b) One diagonal fracture.

Figure 8-35: Comparisons of the impact of 2 parallel vertical fractures and one diagonal fracture, with fracture assumed (a) Volumeless, and (b) Porous

Figure 8-36: Comparisons of the impact of 2 parallel vertical fractures and one diagonal fracture, with active fracture-matrix mass transfer.
8.5.4 Fracture spacing

The presence of fractures has been shown to suppress the build-up of gas, primarily by inhibiting the growth of those gas clusters which come into direct contact with the fracture network. This suggests that if a larger proportion of the gas clusters could be prevented or delayed from making contact with fractures by keeping the fractures farther apart, then the impact of fractures on gas build-up could be mitigated. To test this,
simulations have been performed with networks of varying widths, each incorporating two bounding vertical fractures as shown in Figure 8-39. In order to isolate the true contribution of the fractures as the model width was increased, a second set of simulations were performed using fracture-free networks that possess identical dimensions as networks which incorporate fractures.

**Results**

Figure 8-40 shows that increasing the spacing between fractures reduced their impact on the $S_g$. As fracture spacing increased, $S_{gc}$ (based on the asymptotic bulk production definition) tended to approach the values observed in the corresponding non-fractured models. Note that in increasing the fracture spacing, the model size was also increased and this means that boundary processes become less influential on the overall system behaviour, at least initially. As fracture spacing increased, a greater fraction of the nucleation occurred farther away from the fractures and the bubbles could then grow larger and over a wider depletion range before making contact with the high conductivity fractures, thus allowing gas to build-up in the network.

![Figure 8-39: The effect of fracture spacing on gas saturation distribution after depleting down to 1000psia. Gas (white) was produced predominantly through the fractures in the form of discontinuous migrating clusters.](image-url)
To summarise the findings related to fractured networks, simulations suggest that $S_{gc}$ could be decreased by 25% to 60% by coupling conductive fractures with the matrix blocks. The main contribution of fractures to the Pilton depletion is as a high-conductivity bypass mechanism that allows evolved gas to be produced more readily compared to an un-fractured system. The orientation of the fracture does not seem to be very important and nor do the assumptions made about fracture phase occupancy and fracture volume, as variations in $S_{gc}$ as a result of using volumeless fractures or disabling matrix-fracture diffusion is limited to a few percentage points. However, fracture spacing was observed to have a large effect – the farther apart the fractures are the lesser the impact on the $S_{gc}$.

8.6 Comparison of Pilton Behaviour with Two Network Models Constructed from Alternative PSD data

The two most characteristic features of solution gas drive within the laboratory-scale Pilton sample are the absence of flow bias by gravity and the insensitivity of the process to changes in depletion rate. Both are primarily controlled by the nature of the Pilton pore size distribution (PSD), specifically the small size of the average pore. Therefore, in spite of the comparatively low GOIFT, capillary forces dominate the displacement process in the presence of gravitational forces during gas liberation. The PSD function in the Pilton core appears to be unimodal but there is sufficient variation in pore size ($R_{max}=0.32\mu m$, $R_{min}=0.002\mu m$) to generate a highly heterogeneous capillary pressure field, which might promote more tortuous gas growth patterns. Furthermore, the small pore sizes retard...
dissolved gas transport through molecular diffusion – the process that drives re-equilibration of dissolved concentrations during depressurisation – and so only extremely low depletion rates (<<1psi/day) could be expected to result in any significant reduction in the $S_{gc}$ values reported here.

In order to highlight the importance of the Pilton rock fabric to depletion behaviour, simulations using networks that possess rather different PSD properties are now presented. The simulations are performed using the same fluid properties, depletion rates and initial water saturation distributions as were used for the earlier runs.

### 8.6.1 Simulation Details

Simulations have been performed on two new network configurations, one a low permeability network (K=3mD) typical of chalk samples (by virtue of permeability and PSD) and the other a higher permeability network (K=300mD) more representative of clastics. The results obtained with these new networks are compared with those obtained from identical simulations performed on Pilton core network model surrogates. 2D networks have been used here. Table 8-3 compares the network parameters of the two new networks with those of the Pilton network. The PSD in Pilton has already been determined to be unimodel and obeys a power law distribution. For the new networks, truncated normal pore size distributions have been adopted:

$$f(r) = N(R_{max} - r)(r - R_{min})Exp\left[-\frac{(r-\bar{r})^2}{2\sigma^2}\right], R_{min} < r < R_{max} \quad (8-1)$$

Where, $R_{min}$ and $R_{max}$ are the minimum and maximum radii of the pore size distributions, $\bar{r}$ and $\sigma$ are pore size distribution parameters, $N$ is a normalization pre-factor, $\nu$ is the pore volume exponent with the assumption that:

$$\begin{align*}
V_{pore} &= C\nu^\nu L 10^{(6\nu-12)} \\
\nu &\in [0,3]
\end{align*} \quad (8-2)$$
Where, \( C \) is a volumetric pre-factor, \( L \) the pore length, \( r \) the capillary entry radius of the pore and \( \nu \) the pore volume exponent. For \( \nu=2 \) and \( C=\pi \), this reduces to the volume of a simple cylinder.

The two pore size distributions are shown in Figure 8-41. The choice of the parameters in Table 8-3 was informed by data from Firoozabadi et al, 1992 and from previous work on depressurization processes in chalk carried out by Bondino and McDougall (2005).

A progressive nucleation mechanism was used in all models and no predetermined nucleation density was specified. An assumption of identical crevice densities in all three networks is made and also note that the gravitational constant in each network has been adjusted so that, irrespective of the absolute size of the network (which varies due to differences in pore length), a gravity gradient equivalent to that operating in the experimental core was imposed. Each simulation is thus run at the same Bond Number, which effectively scales each network to 15.3cm in height. The choice of pore length for each network was guided by the work of Bondino and McDougall (2005).

![Figure 8-41: Comparison of the pore size distributions [normalized] of the Pilton surrogate (a), with those of (b) the 3mD, and (c) the 300mD, alternate samples.](image)

| Table 8-3: Comparison of Pilton network parameters with those of the two new networks |
|----------------------------------|-----------------|-----------------|-----------------|
| \( K, \text{ mD} \)             | Pilton          | LOW K           | HIGH K          |
| \( \Phi, \% \)                  | 0.234           | 3.0             | 300.0           |
| \( R_{\text{min}}, \mu m \)    | 0.002           | 0.05            | 5.0             |
| \( R_{\text{max}}, \mu m \)    | 0.387           | 1.2             | 36.0            |
| \( \bar{r}, \mu m \)           | 0.1             | 1.5             |
| \( \sigma, \mu m \)            | 0.25            | 12.0            |
| \( \nu \)                      | 0.7             | 0.01            | 0.9             |
| \( Z \)                        | 5               | 5.8             | 6               |
| \( L, \mu m \)                 | 23.4            | 46.8            | 345.0           |
8.6.2 Impact of network fabric on gas saturation at varying depletion rates

The sensitivity of the gas saturation ($S_g$) profile to changes in depletion rate – in the range 1psi/day - 100psi/day – is shown for all three networks in Figure 8-42. The corresponding plots of nucleation count are shown in Figure 8-43. A far higher gas saturation can be observed developing in the un-fractured Pilton network compared to the other two systems, with final recovery being 50% greater.

Whilst a change in the depletion rate altered the bubble nucleation distribution, the overall effect on $S_g$ was neither significant nor systematic for any given system. For the 300mD network, Figure 8-43(iii) shows that during the initial stages of depletion the rate of nucleation decreased with decrease in depletion rate, whilst at later depletion stages sharp increases in nucleation rate occurred which raised the final nucleation count in a manner uncorrelated with the depletion rate. From the Bond number plots in Figure 8-44 we see that the gravity gradient in the 300mD network was sufficiently strong to cause spontaneous migration of gas structures. During migration, oil re-imbibes part of the migrating gas clusters and thereby creates new oil-filled pores. If these re-imbibed pores contain active nucleation sites then, given the right local supersaturation conditions, new gas nuclei may form and begin to initiate new gas structures. When these gas pores are re-imbibed again during a subsequent migration event, they could once more act as nucleation sites. The recurrent nucleation within the same pores explains the rapid build-up of nucleation count towards the end of the depletion process in the 300mD network as shown in Figure 8-43(iii).

![Graphs](image_url)

Figure 8-42: Comparison of the impact of network fabric on the sensitivity of $S_g$ to depletion rate for i) Pilton, ii) 3mD, and iii) 300mD networks, at $S_{wi} = 0.232$. 

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Figure 8-43: Comparison of the impact of network fabric on the sensitivity of nucleation count to depletion rate for i) Pilton, ii) 3mD, and iii) 300mD networks, at $S_{wi} = 0.232$.

Figure 8-44: The impact of rock fabric on the microscopic Bond number

The gas saturation profiles and the critical gas saturation ($S_{gc}$) varied with network permeability at the three depletion rates considered, Figure 8-45 and Figure 8-46. The 2D Pilton network yielded the highest $S_{gc}$ (0.57) followed by the 3mD network (0.37) and lastly the 300mD network (0.32). Note that $S_{gc}$ is defined here as the saturation at the start of bulk gas production, as illustrated in Figure 8-46.

Whilst the higher $S_{gc}$ in the Pilton network relative to the 300mD network could be explained by the comparatively larger Bond number in the 300mD network (Figure 8-44), the discrepancy in Bond number between the Pilton network and the 3mD network is insufficient to account for the higher $S_{gc}$ in the Pilton network relative to the 3mD network. A comparison of the nucleation counts among the three networks in Figure 8-47 shows nucleation count in the Pilton network to be the fewest over the three depletion rates, although the difference between the Pilton and 3mD cases is small. Hence, it may be infer that the discrepancy in $S_{gc}$ between the Pilton and the 3mD networks can only be accounted for from the differences between network architectures as represented by the
network parameters in Table 8-3. Figure 8-48 shows the final phase occupancy graphics at the end of depressurization for the three networks at a depletion rate of 10psi/day.

Figure 8-45: Comparison of the impact of network fabric on $S_g$ at varying depletion rates of: (1) 100psi/day, (2) 10psi/day, and (3) 1psi/day

Figure 8-46: Comparison of the plots of normalised cumulative gas production vs. gas saturation for the Pilton, 3mD, and the 300mD networks at 1psi/day. Normalization was performed by dividing the instantaneous cumulative gas production by the total amount of produced gas at the end of depletion so that production behavior from networks of different volumetric capacities could be compared. Arrows correspond to $S_{gc}$.

Figure 8-47: Comparison of the impact of network fabric on nucleation at varying depletion rates of (1) 100psi/day, (2) 10psi/day, and (3) 1psi/day.
Figure 8-48: Saturation distributions at 1000psi showing the impact of rock fabrics of (a) Pilton, (b) a 3mD network, and (c) a 300mD network for $S_{wi}=0.232$ and a depletion rate of 100psi/day. Note that the differences in $S_g$ observable in the pore occupancy graphics here do not match up precisely with the differences in the actual computed $S_g$ between the three rocks (Figure 8-49). This is partly due to the limitation of the graphics software used but it is primarily due to the varying displacement efficiencies achieved in the different rock types. The gas clusters in Pilton, (a), is for example more compact than in the other two rock types – the clusters in 3mD, (b), and 300mD, (c), appear more interspersed with oil and water.

**8.6.3 The Effect of Buoyancy Forces in the Three Systems**

A similar hierarchy of $S_{gc}$ among the three networks was obtained even when gravity was turned off – 0.55, 0.42, and 0.42 for the Pilton, 3mD, and 300mD networks respectively, for a depletion rate of 1psi/day (Figure 8-49). Figures 8-50, 8-51, and 8-52 show comparisons of saturation and nucleation profiles for the three network configurations under zero gravity forces. The similarities of the trends between Figure 8-42 and Figure 8-50 and between Figure 8-45 and Figure 8-51 are clear. Comparison of Figure 8-47 and Figure 8-52 reveals that the non-migratory, capillary dominated regime that prevailed in the 300mD network when gravity was disabled removed the rapid increase of the nucleation count in the last stages of depressurisation.
Figure 8-49: Comparison of the plots of normalised cumulative gas production vs. gas saturation for the Pilton, 3mD, and the 300mD networks at 1psi/day, under no gravity forces.

Figure 8-50: Comparison of the impact of network fabric on the sensitivity of $S_g$ to depletion rate for (i) Pilton, (ii) 3mD, and (iii) 300mD networks, at $S_{wi} = 0.232$, under no gravity forces.

Figure 8-51: Comparison of the impact of network fabric on $S_g$ at varying depletion rates of: 1)100psi/day, 2) 10psi/day, and 3) 1psi/day, under no gravity forces.

Figure 8-52: Comparison of the impact of network fabric on nucleation at varying depletion rates of 1)100psi/day, 2) 10psi/day, and 3) 1psi/day, under no gravity forces.
It is interesting that depressurisation using three characteristic pore sizes that spanned three orders of magnitude should all be relatively insensitive to changes in depletion rate over three orders of magnitude, 100 – 1psi/day. This insensitivity to depletion rate probably reflects the almost instantaneous nature of bubble nucleation, driven by the low GOIFT at the high initial system pressure, and also the assumption of identical crevice densities in all three networks. Nevertheless, these results demonstrate the significance of the contribution of the Pilton rock matrix architecture to the relatively high \( S_{gc} \) and endpoint gas saturation during Pilton core depressurization.

### 8.7 A generalized correlation function for \( S_{gc} \) and Calculation of Steady-state \( K_r \) curves

Simulations of the sensitivity of depletion behaviour to some key system parameters (\( S_{wi} \), depletion rate, system scale, and fracture spacing) have yielded single-variable correlations between each of the parameters and the \( S_{gc} \). Each of these single-variable correlations has been derived using base assumptions that may not correspond to the exact conditions in the field. For example, the \( S_{gc} \) vs. \( S_{wi} \) correlation in Figure 8-8 was derived under the assumption of a depletion rate of 5psi/day, using a fracture-free network with a scaled height equivalent to that of the experimental core. Given that wide deviations from these assumed conditions are likely to be encountered, the slope of the \( S_{gc} \) vs. \( S_{wi} \) curve must be shifted accordingly. A method for approximating \( S_{gc} \) under conditions with combination of system parameters that have no direct correspondence with any of the conditions considered so far is described below.

For each single-variable correlation of \( S_{gc} \) (with \( S_{wi} \), depletion rate, system scale, or fracture spacing), a normalised equivalent is constructed as shown in Figure 8-53. Given a set of operating conditions (\( S_{wi} \), depletion rate, system scale, fracture spacing), an effective critical gas saturation (\( S_{gc}^{\text{Effective}} \)) can be found as follows:

1. Read off the corresponding normalised \( S_{gc} \) factors from the matching graphs in Figure 8-53
2. Use these factors to calculate the effective \( S_{gc} \) as

\[
(S_{gc})^{\text{Effective}} = (S_{gc})^{\text{Exp.}} \times f_{Drate} \times f_{Swi} \times f_{fracture} \times f_{scale}
\]  

(8-3)

where, \((S_{gc})^{\text{Exp.}}\) is the \( S_{gc} \) at experimental conditions
8.7.1 Steady-State Relative Permeability Calculations

For completeness, we now explore the implications of our foregoing analysis of Pilton depletion behavior on the calculation of steady-state gas and oil relative permeability ($K_r$) functions under varying operating conditions.

8.7.1.1 Impact of $S_{wi}$ on $K_r$ curves

All simulations here were performed at a depletion rate of 10psi/day.

$K_r$ at $S_{wi}$=0.0

Figure 8-54(a, c) shows that $K_{rg}$ was significantly lower than $K_{ro}$ throughout the depletion process: the increase in $S_g$ after the formation of a network-spanning ‘gas cluster backbone’ did not sufficiently alter the effective gas permeability. After the critical gas saturation was reached, the bulk of the gas coming out of solution passed out of the network via the network spanning cluster and the size of this cluster hardly changed after
it was formed. There was some increase in the total gas saturation in the network post-$S_{gc}$ but not all of the expanding gas clusters were connected to the network-spanning cluster and therefore did not have an effect on the $K_r$.

**$K_r$ at Experimental $S_{wi}$ ($=0.616$)**

Figure 8-54(b, d) indicates that even before the formation of a network spanning cluster, the oil saturation in the waterflooded network had fallen below its bulk percolation threshold, and hence for a short depletion interval, both steady-state $K_{rg}$ and $K_{ro}$ were zero. Despite the absence of a network-spanning oil cluster, oil will however continue to be displaced from the network in two ways: (a) via untrapped bulk oil clusters with direct escape route to the outlet (for both spreading and non-spreading oil), and (b) through network-wide thin films for spreading oil. See Figure 8-55 for an extended illustration using a 2D network.

**$K_r$ at varying $S_{wi}$**

The slopes of the $K_{rg}$ and $K_{ro}$ curves were largely insensitive to $S_{wi}$ although $S_{gc}$ varied significantly (as already discussed in section one of this chapter) with change in $S_{wi}$ (Figure 8-56). Figure 8-56 also shows that $K_{ro}$ was non-zero throughout the depletion process for $S_{wi}$ up to 0.45. From an $S_{wi}$ of 0.61 and above, $K_{ro}$ was predicted to fall to zero at progressively lower $S_{g}$ values in the course of the depletion process.

**8.7.1.2 Impact of Depletion rate on $K_r$ curves**

Simulations here were carried out at virgin conditions and at $S_{wi}$ of 0.616. The $K_r$ curves were unaffected by changes in depletion rate (Figure 8-57). This is consistent with previous observations of the impact of depletion rate on the Pilton core behaviour.

**8.7.1.3 Characteristic $K_r$ curves for varying operating conditions**

Once again, the $S_{wi}$ values used in Figure 8-56 only apply to a select number of points among the wide range of possible conditions that could be encountered. Since these $K_r$ curves display broadly similar slopes regardless of $S_{wi}$, $K_r$ curves corresponding to $S_{wi}$ values intermediate between the curves shown in Figure 8-56 – and generally for a wider range of depletion rates, system scales, and fracture densities – can be approximated by selecting a $K_r$ curve in Figure 8-56 that best characterise the operating condition of
interest and whilst shifting the endpoints ($S_{gc}$ and $S_{or}$ = oil saturation at $K_{ro} = 0$) accordingly. For example, at $S_w=0.40$ adjust the endpoints of the curves corresponding to $S_{wi}=0.45$, whilst at $S_w=0.10$ adjust the endpoints of the curves corresponding to $S_{wi}=0.15$, etc.

With respect to $K_{rg}$, the adjustment of its endpoint (i.e. $S_{gc}$) would be as outlined at the onset of this section. An analogous adjustment could be made for $S_{or}$ with respect to the right endpoint of the $K_{ro}$ curves using a topological argument. The average $S_{or}$ for simulations at $S_w=0.616$ and at $S_w=0.65$ was 0.30 (Figure 8-58). This may be considered the oil percolation threshold and, as Figure 8-58 suggests, should be approximately the same regardless of $S_{wi}$ (this is consistent with the mixed-wet wettability assumption). Thus, $K_{ro}$ is zero (oil becomes non-network spanning) if $S_o > 0.30$ for all $S_{wi}$.

![Figure 8-54: Gas and oil steady-state $K_r$ curves for virgin (a, c) and waterflooded (b, d) systems, plotted on Cartesian (a, b) and semi-log (c, d) graphs.](image-url)
Figure 8-55: A schematic illustration of the implications of the spanning cluster definition of $S_{gc}$ to the calculation of steady-state $K_r$.

$S_{wi} = 0.0 - 0.65$

Cartesian

Semi-log plot

Figure 8-56: The impact of varying $S_{wi}$ on gas and oil steady-state $K_r$ curves on (a) Cartesian, and (b) semi-log graphs.
Figure 8-57: Gas and oil steady-state $K_r$ curves at varying depletion rates for virgin (a, c) and waterflooded (b, d) systems, plotted on Cartesian (a, b) and semi-log (c, d) graphs.

Figure 8-58: A weak sensitivity of the slope of the $K_{ro}$ curve to varying $S_{wi}$. A convergence of $S_o$ to a common point (at $S_o=0.30$) may be inferred from the figure although $K_{ro}$ reached zero only for $S_{wi}=0.616$ and above.
8.8 Survey of Depressurization Literature in the Light of Experimental and Simulation Results of Pilton.

There are many variables related to rock and fluid properties, and a wide range of operational parameters that impact – in isolation or in various combinations – the efficiency of a solution gas drive process. One of the main outcomes from a solution gas drive experiment is an inference of the critical gas saturation. Values of $S_{gc}$ reported based on experiments on reservoir core samples vary between 0.06 (Firoozabadi et al., 1992) to 0.27 (Madaoui, 1975) and the dependence of $S_{gc}$ on depletion rate, interfacial tension, initial water saturation, oil viscosity, and system size have been widely studied. While these efforts have provided valuable insights into the nature of the individual mechanisms involved – bubble nucleation and growth, the nature of non-equilibrium mass transfer processes, etc. – there is as yet no unifying theory that unambiguously explains the results of the wide range of experimental observations reported in the literature.

Differences in data acquisition and interpretation techniques, and a general lack of clarity about the fundamental processes involved have often resulted in mutually exclusive explanations of the same phenomena. Thus, there is a prevailing opinion that each depressurisation study is unique. This survey attempts to place the Pilton depletion behaviour in a larger context with the help of some relevant published results of experimental depressurisation studies.

**Pilton Depletion Characteristics:** The $S_{gc}$ obtained by 3D network simulations using models anchored to the Pilton sample ranged from 0.27 to 0.17 as $S_{wi}$ was increased from 0 to 0.65. $S_{gc}$ was relatively insensitive to changes in depletion rate from 200psi/day to 5psi/day but $S_{gc}$ increased with decreasing $S_{wi}$. The Pilton core has a permeability of 0.234mD and the minimum GOIFT for the fluid system was estimated at 1.8mN/m. Table 8-4 gives a summary of a range of $S_{gc}$ values obtained by conducting depletion experiments on rock samples with absolute permeability, $S_{wi}$, and depletion rates in the ranges 0.04 – 2060mD, 0 – 0.73, and 0.44 – 172800psid/day, respectively.
### Table 8-4: Summary of selected depressurization data from literature

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>K, mD</th>
<th>$S_{gc}$ fraction</th>
<th>DP Rate, psi/day</th>
<th>$S_{gc}$ vs. DP Rate</th>
<th>$S_{wi}$, fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petersen et al (Brent Group, Statfjord Field)</td>
<td>2004</td>
<td>990</td>
<td>0.064 – 0.122</td>
<td>115 - 731</td>
<td>increase with</td>
<td>0.179 -</td>
</tr>
<tr>
<td>Petersen et al (Brent Group, Statfjord Field)</td>
<td>2004</td>
<td>711</td>
<td>0.134</td>
<td>115 - 731</td>
<td>increase with</td>
<td>0.173 -</td>
</tr>
<tr>
<td>Drummond (South Brae Field - North Sea)</td>
<td>2001</td>
<td>292</td>
<td>0.025</td>
<td>99</td>
<td>-</td>
<td>0.23</td>
</tr>
<tr>
<td>Egermann and Vizika</td>
<td>2001</td>
<td>3.2</td>
<td>0.24</td>
<td>2304</td>
<td>increase with</td>
<td>0.55</td>
</tr>
<tr>
<td>Naylor et al (Miller Field)</td>
<td>2001</td>
<td>27</td>
<td>0.21</td>
<td>765</td>
<td>-</td>
<td>0.52</td>
</tr>
<tr>
<td>Naylor et al (Miller Field)</td>
<td>2001</td>
<td>492.5</td>
<td>0.06 – 0.16</td>
<td>89 - 26</td>
<td>increase with</td>
<td>0.70 - 0.73</td>
</tr>
<tr>
<td>Sahni et al</td>
<td>2001</td>
<td>2000, 2060</td>
<td>0.06 – 0.11</td>
<td>increase with</td>
<td></td>
<td>0.0213</td>
</tr>
<tr>
<td>Kumar et al</td>
<td>2000</td>
<td>1250, 1180</td>
<td>0.03 - 0.07</td>
<td>increase with</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kamath and Boyer</td>
<td>1995</td>
<td>0.1</td>
<td>0.10</td>
<td>20</td>
<td>non-monotonic</td>
<td></td>
</tr>
<tr>
<td>Kamath and Boyer</td>
<td>1995</td>
<td>0.04</td>
<td>0.10</td>
<td>20 - 100</td>
<td>non-monotonic</td>
<td>0</td>
</tr>
<tr>
<td>Firoozabadi et al (Berea)</td>
<td>1992</td>
<td>605</td>
<td>0.011 - 0.02</td>
<td>increase with</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Firoozabadi et al (Chalk)</td>
<td>1992</td>
<td>2.7</td>
<td>0.006 – 0.012</td>
<td>increase with</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Kortekaas and van Poelgeest (Brent)</td>
<td>1991</td>
<td>230 - 1900</td>
<td>0.04 – 0.08</td>
<td>10 - 230</td>
<td>increase with</td>
<td></td>
</tr>
<tr>
<td>Kortekaas and van Poelgeest (Brent)</td>
<td>1991</td>
<td>200 - 1100</td>
<td>0.07 – 0.10</td>
<td>10 - 230</td>
<td>increase with</td>
<td></td>
</tr>
<tr>
<td>Moulu (St Maximin limestone)</td>
<td>1989</td>
<td>211.10</td>
<td>0.066 – 0.12</td>
<td>0.44 – 72.5</td>
<td>increase with</td>
<td></td>
</tr>
<tr>
<td>Madaoui</td>
<td>1975</td>
<td>4.44</td>
<td>0.264</td>
<td>0.78 to 170</td>
<td>increase with</td>
<td></td>
</tr>
<tr>
<td>Handy</td>
<td>1958</td>
<td>7.41</td>
<td>0.05 – 0.16</td>
<td>172800</td>
<td>increase with</td>
<td></td>
</tr>
</tbody>
</table>

8.8.1 Impact of Capillary Radius or Permeability

The correlation between $S_{gc}$ and permeability has not been firmly established and some authors (Kortekaas and van Poelgeest, 1991) have thrown serious doubt on whether such a correlation exists at all. However, in Table 8-4 – except for the data of Firoozabadi et al (1992) – the high $S_{gc}$ values tend to correspond to cores with the lowest permeability although in a somewhat non-linear way. In making this assessment, however, we have ignored the effect of depletion rate (which differs from case to case). One of the highest $S_{gc}$ values recorded in Table 8-4 (0.24) was obtained from a 3.2mD Palatinat sandstone core. This apparent trend is in line with our interpretation of the relatively high Pilton $S_{gc}$ values, which suggests that the small average pore radius led to rapid nucleation of embryonic bubbles and a highly dendritic bubble growth pattern largely unbiased by gravity forces.
8.8.2 Impact of IFT and Contact angle

Based on a series of experiments on a connate-water saturated 550mD core from the Brent field, Kortekaas and van Poelgeest (1991) observed two effects of a change in IFT on the depressurisation process: an increase in IFT within a low IFT range led to a decrease in the rate of gas saturation build up, which in turn led to a decrease in $S_{gc}$, whilst the opposite effect was observed at a higher IFT range. As IFT was increased from 0.1mN/m to 0.25mN/m $S_{gc}$ decreased from 0.185 to 0.165, but an increased in IFT from 1mN/m to 5mN/m to an *increase* in $S_{gc}$ from 0.12 to 0.14. Similar results have been reported by Mackay et al (1998) from experiments conducted on micromodels. The accepted explanation for this phenomenon is based on the energy balance principle. A decrease in IFT lowers the energy threshold for the formation of a new interface and bubbles therefore nucleate more rapidly. At very low IFTs bubble nucleation may even become instantaneous, needing only a very low supersaturation to occur. However, this cannot explain the non-monotonic behaviour reported by Kortekaas and van Poelgeest (1991), gravity bias might also have played an important role (especially in the high permeability media considered in these experiments). Note that the low IFT of the Pilton fluid system – especially at the early stages of depletion, provides a perfect condition for high nucleation density which could subsequently lead to a high $S_{gc}$.

Figure 8-59 reproduces results of micromodel experiments of Dominguez et al. (2000) and clearly shows the impact of contact angle (or wettability) on nucleation density – bubble density increased as contact angle increases. Unfortunately, wettability is seldom taken into account when interpreting depletion experiments.

Figure 8-59: Gas cluster distributions in a micromodel for various wettability (from Dominguez et al., 2000): The number of growth sites decreases with the wettability. The results were obtained for $DP/DP_{sat} = 0.63$ and $\theta =0$ rad (a), $\theta =0.66$ rad (b) and $\theta =0.82$ rad (c).
8.8.3 Impact of Depletion Rate

An increase in depletion rate is generally known to increase bubble density which will in turn lead to an increase in $S_{gc}$. However, the data of Kamath and Boyer (1995) and that of Madaoui (1975) in Table 8-4 showed otherwise. For the two Colton sandstone cores used by Kamath and Boyer (1995), increasing the depletion rate from 20psi/day to 100psi/day had no effect on the $S_{gc}$. It is interesting that both Colton sandstone cores have permeabilities of a similar order of magnitude as the Pilton core (the cores are in fact less permeable than the Pilton core). The results of Kamath and Boyer (1995) support the conclusion that tight cores may require far larger time scales for equilibration to occur and this means that extremely low depletion rates are needed to reduce the $S_{gc}$ from the values achieved at typical laboratory depletion rates – a behaviour that has been repeatedly observed with respect to the Pilton core.

8.8.4 Impact of $S_{wi}$

Data on the impact of $S_{wi}$ on $S_{gc}$ do not show a clear trend. Kortekaas and van Poelgeest (1991) reported a doubling of critical gas saturation from $< 0.04$ to $0.05$ – $0.08$ as $S_{wi}$ was changed from virgin to watered-out conditions for three sandstone core samples (230mD, 550mD, and 1900mD) obtained from a Brent Group reservoir, while for two other samples (200mD and 1100mD, obtained from another Brent Group reservoir) an increase in $S_{wi}$ had a negligible effect on $S_{gc}$ – stabilised between 0.07 and 0.10 for virgin and watered-out samples. The differences in the trends of $S_{wi}$ and $S_{gc}$ between the two reservoirs were assumed to result from the differences in the mineralogical and morphological properties of the reservoir rocks. The two reservoirs were shown to have quite different clay structures, with one reservoir containing kaolinite-like sharp-edged booklets which could form preferred sites for bubble nucleation. The data of Peterson et al (2004) showed a consistent decrease in $S_{gc}$ as $S_{wi}$ increased over a range of depletion rates for two core samples (990mD and 711mD) obtained from the Statfjord field in the North Sea. With respect to the Pilton behaviour, while the $S_{gc}$ decreased gradually as $S_{wi}$ was increased, both nucleation density (expressed as number of bubbles per volume of pore space) and the oil recovery efficiency (expressed a fraction of the pre-depletion oil produced) increased as $S_{wi}$ increased.
8.9 Chapter Summary and Conclusions

This chapter has analysed the results of a range of pore-scale simulations performed with the history-matched network model analogue of the Pilton core developed in the previous chapter. The goal was to better characterize the uncertainties associated with the determination of $S_{gc}$ and relative permeabilities under changing operating conditions. Additionally, a literature survey was presented that discussed the Pilton results in the context of other published depressurisation experiments, particularly those conducted with samples from North Sea reservoirs.

The main conclusions are as follows:

- Decreasing depletion rate through three orders of magnitudes – from 100psi/day to 1psi/day for 2D networks and from 100psi/day to 5psi/day for 3D networks – did not have a significant effect on gas evolution and $S_{gc}$, regardless of $S_{wi}$. Results from several realizations, using different random seeds – undertaken to test the robustness of the model – predict that critical gas saturation should remain essentially constant ($S_{gc} \approx 20\%$ at $S_{wi}$ of 0.616) for the Pilton sample over the full range of depletion rates considered. The two most plausible reasons for this behaviour are: (a) the extremely low equilibration rates imposed by the small pore sizes, and (b) the high bubble density facilitated by the low GOIFT at initial conditions.

- Nucleation density (in terms of the number of nuclei per initial oil volume) increased monotonically as $S_{wi}$ increased: large $S_{wi}$ effectively restricted diffusive mass transport, increased the local supersaturation and led to even higher bubble densities. This, however, did not simply translate into a corresponding increase in $S_{gc}$ as $S_{wi}$ was increased. $S_{gc}$ broadly declined with an increase in $S_{wi}$ ($S_{gc}$ varied from 0.27 – 0.17 as $S_{wi}$ was increased from 0 to 0.65). Although critical gas saturation was found to be lower at larger values of $S_{wi}$, the oil recovery factor at the end of depletion increased with $S_{wi}$. Hence, depressurization as a recovery mechanism in chalk was predicted to approach its full potential in highly waterflooded systems.
• The principal effect of varying all three IFTs by ±10% in any combination on the displacement mechanism was the alteration of the spreading coefficient (Cs). The spreading coefficient was found to have far less impact on the overall gas evolution behaviour in 3D networks than in 2D networks – the topology of 3D networks counteracted the effect of varying Cs in a somewhat chaotic fashion. For 2D networks, $S_{gc}$ decreased in proportion to the fraction of the pressure range characterised by a negative Cs, and the IFT combination $(\sigma_{go}, \sigma_{ow}, \sigma_{wg})=(+,+,−)$ exhibited the lowest $S_{gc}$, a value 50% less than that observed in the base case combination (0,0,0). The $S_{gc}$ values obtained from the 3D simulations — averaged over five IFT combinations for each depletion rate — corresponded closely to those found for the base IFT combination. Average $S_{gc}$ values ranged from 0.27 to 0.16 as $S_{wi}$ was increased from 0 to 0.65.

• Gas saturation at any given pressure was found to broadly decrease with an increase in effective gravity (or, equivalently, network height). Thus $S_{gc}$ was essentially scale-dependent, which raises some important issues when attempting to populate reservoir-scale models. Nevertheless, simulation results suggest that the impact of gravity on critical gas saturation should remain negligible in waterflooded Pilton material up to a height of approximately 15m.

• The impact of rock fabric on Pilton behaviour was found to be significant. Compared to the two new rock fabrics considered – one a 3mD network representative of a chalk sample and the other 300mD network more characteristic of clastic rocks – far higher gas saturation was observed developing in the Pilton network compared to the other two systems, with final recovery being 50% greater. The $S_{gc}$ calculated for the alternative 3mD and 300mD networks were less than that observed for the Pilton network by 35% and 42%, respectively.

• The presence of fractures in the network, regardless of orientation or resident fluid type, was found to reduce $S_{gc}$ to about 20% to 60% of the values observed in fracture-free networks – the magnitude of change in $S_{gc}$ being dependent on the fracture spacing, the greater the spacing the lesser the $S_{gc}$ difference between
fractured and fracture-free networks. Fractures acted as high conductivity channels through which gas bubbles evolving from any point within the network are withdrawn almost instantaneously under buoyancy forces and are immediately produced. Variations in $S_{gc}$ as a result of using volumeless fractures or disabling matrix-fracture diffusion is limited to a few percentage points and $S_{gc}$ profiles from simulations with and without fracture-matrix diffusion overlap during the majority of the depletion and only began to diverge at around 1800psia.

- The main contribution of fractures to the Pilton depletion was as a high-conductivity bypass mechanism that allowed evolved gas to be produced more readily compared to an un-fractured system. The $S_{gc}$ obtained using fractured networks may be closer to the ‘true’ value needed for simulations involving 3D reservoirs models.

- A generalised correlation function has been developed which can be used to estimate $S_{gc}$ for a wide range of different operating conditions.

- The gas relative permeability ($K_{rg}$) for Pilton was predicted to be extremely low regardless of $S_{wi}$. The slopes of both the $K_{rg}$ and the $K_{ro}$ (oil relative permeability) were found to be insensitive to both $S_{wi}$ and depletion rate.

- In comparison to the surveyed published data on North Sea rocks that have been used in depressurization experiments, the properties of the Pilton core are unique. While the Pilton core has a permeability of about 0.23mD, permeability of North Sea rocks used in reported depressurization experiments ranged between 27mD (from the Miller field – Naylor et al, 2001) and 1900mD (from the Brent reservoir – Kortekaas and van Poelgeest, 1991). Literature $S_{gc}$ data for samples from the North Sea ranged between 0.025 (Drummond, 2001) and 0.21 (Naylor et al, 2001), although $S_{gc}$ of up 0.27 have been observed with non-North Sea rocks (Madaoui, 1975). These values may be contrasted with $S_{gc}$ values in the range 0.17 – 0.27 for $S_{wi}$ values ranging between 0 and 0.65 for the Pilton network. With a few exceptions, the highest literature $S_{gc}$ values corresponded to the lowest
permeability rocks. Apparent insensitivity of the depressurization process to changes in depletion rate was also reported for these tight rocks (Kamath and Boyer, 1995; Madaoui, 1975). All evidence so far indicate that given the pore microstructure, the instantaneous bubble nucleation mechanism, and the negligible impact of depletion rate on the Pilton depressurization process, the high $S_{gc}$ observed for Pilton (averaging 0.20 for an $S_{wi}$ of 0.61) was not particularly exceptional and similar examples could be found in the literature.