Chapter 9

CONCLUSIONS, SIGNIFICANCE OF RESEARCH, AND RECOMMENDATIONS FOR FUTURE WORK

9.1 Introduction

This work has been motivated by the need for a rigorous theoretical foundation for the analysis of interface instabilities associated with gas flow in liquid-filled porous media, with particular emphasis on CO_2 migration in brine and gas evolution during depressurization in hydrocarbon-saturated rocks. A survey of current literature on the subject reveals conspicuous knowledge gaps which contemporary experimental techniques or standard numerical approaches using the Darcian description have been unable to successfully bridge. As a consequence, this thesis reports on the development of a pore network model of multiphase flow in porous media and its use to analyse and explain a variety of gas flow phenomena in terms of the interactions between capillary, gravity, and viscous forces and the pore structure. The model has been used to reproduce specific results of a number of experiments and thereby demonstrates its value as a predictive tool. A series of parametric sensitivity studies have been used to offer detailed explanations of the pore level controls on gas flow regime transitions and to make specific qualitative predictions about the impact of a wide range of system variables – fluid properties, pore network architecture, injection and depletion rates, system scale, and fracture spacing – on the behaviour of important petrophysical and reservoir engineering quantities relevant to CO_2 sequestration and solution gas drive processes e.g. critical gas saturation, CH_4-oil and CO_2-brine relative permeabilities (K_r), residual saturation, displacement efficiency, and sealing integrity. The main conclusions of the research, some of which have appeared as chapter summaries, are presented next. This is followed by a discussion of some specific practical significance of the research findings and then a list of recommendations for future work in this area.

9.2 Conclusions regarding gravity-driven regime transitions, including a comparison of the flow characteristics of CH_4 and CO_2 in brine at low capillary numbers with coupled non-equilibrium mass transfer effects.

- A classification of gravity-driven regimes carried out by a selective parametric sensitivity of key variables that define the local Bond number – i.e. mean pore radius, gas-liquid interfacial tension (IFT), gas-liquid density difference ($\Delta\rho$), and system height – shows that gravity-driven regimes can be grouped into two broad classes: (a) stable [Bo < 1], and (b) unstable (migratory) flow [Bo > = 1]. Changes in the critical gas saturation (S_{gc}) in response to the variation in any one of the parameters of the Bond number was found to depend strongly on the prevailing regime and the topological properties of the network.

- Simulation results predict that the change in the strength of the gravitational gradient from a core scale to a gridblock scale could lead to fundamental changes in flow regimes which have so far been neglected in current upscaling procedures. Particular attention has been drawn to the effects of these scale-dependent transitions on gas breakthrough saturation, the residual gas saturation distribution and the gas-liquid contact area available for diffusion. Success in accurately quantifying these effects will depend to a large extent on the precision with which IFTs, fluid densities and the pore size distributions are measured.

- The PSD variance and pore connectivity were found to have a very strong influence upon gas evolution pattern and on S_{gc} – even though both variables are unaccounted for in standard Bond number definitions.

- Simulation results of comparisons of CH_4 and CO_2 regimes injected into equivalent networks at five different combinations of temperatures and pressures showed that CH_4-H_2O systems exhibited higher Bond numbers and were therefore more gravity biased than CO_2-H_2O systems. Gas dissolution had a complicated effect on flow regime - dissolution shrinks gas structures but may also alter their topology, leading to

the exploration of new evolution pathways which might result in an increase or a decrease in breakthrough saturation. The impact of dissolution was most pronounced at low system pressures (≤100psia). The higher solubility of CO_2 in water compared to CH_4 tended to reduce differences between $S_{gc}^{CH_4}$ and $S_{gc}^{CO_2}$ (breakthrough saturations of CH_4 and CO_2, respectively) which might be caused by the greater gravity bias of CH_4 (except in the case where the superior net gravity forces on CH_4 flow led to a regime transition from stable to migratory).

- In four out of the five temperature and pressure combinations considered, differences between $S_{gc}^{CH_4}$ and $S_{gc}^{CO_2}$ were not significant. However, at a temperature of 25^{o}C and a pressure of 3500psia, $S_{gc}^{CO_2}$ was more than double $S_{gc}^{CH_4}$ – essentially because CO_2 flow was characterized by much lower Bond numbers than CH_4 flow under this particular condition. For temperatures and pressures above the CO_2 critical point, CO_2 and CH_4 flow regimes in brine displayed generally similar characteristics, suggesting that flow coefficients (E.g. relative permeability) of CH_4 and CO_2 in brine could be used interchangeably in continuum type simulators with effectively the same results.

- Gas solubility in brine was found to be a poor guide to predicting the volumetric fraction of the injected gas (CO_2 or CH_4) that can be dissolved as pressure changes. Solubility generally increases with pressure but we also found that the fraction of injected gas that can dissolve decreases with increase in pressure since gas density also increases. A dissolvability index is proposed to help better correlate the dissolution capacity of brine to CO_2 as system pressure changes.

- The CO_2 solubility trapping capacity of brine at conditions typical of candidate aquifers for CO_2 storage was predicted to be limited to about 0.06PV of aquifer equivalence of total injected CO_2 i.e. brine may not dissolve CO_2 greater than 1/20th PV of aquifer before complete saturation occurs. However, our simulations show that if 38% of total injected CO_2 can be dissolved then snap-off imbibition mechanisms during the dissolution can help to reduce the connectivity of the undissolved CO_2 and render it less mobile.

- The salient features of the gas saturation patterns resulting from two injection experiments by Dumoré (1970) and Geistlinger et al (2006) were successfully reproduced, giving additional confidence in the modeling approach.

9.3 Conclusions on the results obtained under the coupled effects of capillary, gravity, and viscous forces, including a comparison of the flow characteristics of CH_4 and CO_2 in brine at varying injection rates.

- Whilst a reduction of IFT is a key process objective during CO_2 injection for EOR that is often envisioned to enhance displacement efficiency by reducing the capillary pressure, simulations involving coupled gravity and viscous effects have, however, shown that the gains in displacement efficiency by lowering capillary pressure are only apparent when gravity is considered negligible. Incorporation of gravity forces in the flow equations caused CO_2 to easily override the liquid phase as IFT was decreased, leading to a sharp decline in displacement efficiency.

- A comparative study of viscous-driven regime transitions of the binary fluid systems of CO_2-H_2O and CH_4-H_2O, at two sets of pressure and temperature conditions (T=35^oC, P=1500psia; and T=25^oC and P=1500psia) shows that despite the fairly significant disparity between CO_2/H_2O and CH_4/H_2O properties at these conditions, the displacement behaviours of CO_2 and CH_4 in the range of flow velocity characteristic of flow in reservoirs were very similar. However, CO_2 displacement efficiency began to increase faster than that of CH_4 as injection rate was increased beyond a critical point.

- The conventional viscous-capillary scaling group has been shown to fall short of meeting the essential criteria of replicating force balances at different scales. Furthermore, a naïve interpretation of the more generalised viscous-capillary scaling group can easily lead to erroneous outcomes – the possible changes in model aspect ratio due to a change from one scale to the other is just as important a factor to consider as the changes in absolute model dimensions if a consistent force balance is to be maintained at different scales.

- A scoping investigation into the impact of dynamic changes in heavy oil viscosity due to CO_2 injection in a semi-miscible EOR process demonstrated how the unique features of the modelling approach adopted here (a realistic treatment of inter-phase mass transfer, efficient handling of the full spectrum of the interactions between capillary, gravity and viscous forces) can facilitate the examination of practical issues in a rigorous way.

- The efficacy of the modelling approach used in this thesis – especially the capillary-viscous coupling – has been demonstrated by the reproducing some immiscible displacement experiments of Lenormand et al (1988), under varying viscosity ratios and capillary numbers. The result displayed excellent agreement between experiment and simulation.

9.4 Conclusions regarding applications of the model to the analysis of important multiphase flow processes relevant to CO_2 storage.

9.4.1 Capillary Sealing Mechanism during CO_2 Storage in Saline Aquifers

Sensitivity studies were performed on networks incorporating reservoir-caprock assemblies to examine the impact of varying caprock capillary entry thresholds on sealing integrity under a range of flow regimes, at different gravity gradients or notional network length scales. The following highlight the main conclusions.

- Under capillary dominated flow, the maximum possible CO_2 saturation can be securely established below a sealing layer with an average pore entry threshold only twice as large as that in the underlying reservoir. This means that the sealing integrity of a capping rock could be maintained even in the presence of structural defects like fractures and fissures, as long as the reduced local entry thresholds within these 'weak points' are at least twice the average entry threshold in the reservoir rock with which it is in contact.

- As network model length scale increased (i.e. as the gravity gradient and the available buoyancy force increased), the level of CO_2 saturation that could be established within the reservoir before the failure of the capillary sealing

mechanism decreased for each reservoir-seal assembly, but not monotonically. For the network with a seal of average entry threshold twice as large as in the reservoir (*Cap_1/2*), reservoir CO_2 saturation before seal failure (S_{ginv}) dropped precipitously by more than fourfold as the flow regime changed from capillary dominated to a gravity biased regime, whilst for seals with entry thresholds 10 times and above the thresholds within the reservoir zone (*Cap_1/10* and *Cap_1/100*), CO_2 saturation before seal failure actually increased as flow transitions from a capillary to a gravity biased regime. On the other hand, as flow regimes transitions from gravity biased at 10g to migratory flow at 100g, S_{ginv} in *Cap_1/2* increased by 40% whilst the S_{ginv} in *Cap_1/10* decreased by more than 15%.

- One of the striking revelations from these studies of capillary sealing mechanisms is that sealing integrity does not degrade proportionally with increase in length scale or gravity gradient. Under migratory regime, the maximum height that a continuous CO_2 plume can attain is constrained by the fragmenting effect of brine re-imbibition mechanisms which invariably accompanies the migration process. Moreover, by the time the migrating CO_2 cluster touches the base of the seal most of its original buoyancy potential would have been dissipated through fragmentation. Still, as more CO_2 accumulates below the seal, the rate of increase in effective buoyancy force that can be imposed on the seal is slowed down by the lateral spreading of the accumulating CO_2.

- These results restate the importance of incorporating the full spectrum of gravity-driven regimes in the modelling of CO_2 migration. When CO_2 injected in a thick reservoir (thick enough to sustain a large gravity gradient) and with an average entry threshold only half that in its caprock is allowed to evolved under all possible gravity-driven flow regimes, a higher reservoir CO_2 saturation before seal failure is likely to be observed if migratory flow is properly captured, compared to a scenario where only the biasing effect of gravity on CO_2 evolution is accounted for. Therefore, in the calculation of the total buoyancy force that would likely be imposed on a top seal by injected CO_2, it should not be supposed that the

estimate of the maximum plume height for such a calculation must be equal to the total vertical thickness of the reservoir.

- Effective containment of dissolved CO_2 within the reservoir formation may require a greater number of constraints (tighter, thicker, and more structurally homogeneous caprocks) than are necessary to trap free CO_2.

9.4.2 Impact of Regime Transitions on Unsteady State CO_2-Brine Relative Permeability Functions

- Brine K_r was generally orders of magnitudes larger than CO_2 K_r regardless of flow regime. CO_2 K_r was found to exhibit wide variability in endpoint and shape that strongly depends on the prevailing flow regime. Under stable regime, a transition from capillary dominated flow (at Bo=0.043) to a gravity biased flow (at Bo=0.43) led to a more than fivefold decrease in CO_2 S_{gc} even though CO_2 K_r remained largely the same. This puts additional constraints on the upscaling procedures of CO_2 K_r functions and the schemes by which gridblocks should be populated with K_r functions during dynamic simulation runs.

- The estimation of CO_2 K_r under migratory flow conditions required the formulation and implementation of an unsteady-state K_r model. The resulting K_{rg} function generated by this model oscillated unevenly between finite values and zero due to the intermittency of production, but also exhibited a higher order structure which was exploited to develop a new trapping model for use in reservoir simulation of CO_2 storage. The proposed trapping model dispenses with the use of bounding curves whilst having the advantage of being directly anchored to dynamic pore level interactions between capillary and gravity forces.

- Accurate prediction of CO_2 migration patterns may depend on the allocation of appropriate CO_2 K_r functions according to gridblock size and the dominant local CO_2-brine displacement configuration (what is the dominant direction of CO_2 throughput?, is it through the bottom face or the sides i.e. gravity destabilized flow?, or is it through the top face, i.e. gravity stabilised flow?). The complexities introduced by the incorporation of gravity effects into CO_2-brine K_r functions

should be justified given that there will likely be fewer options available for validating simulation models of aquifers compared to that of conventional oil and gas reservoirs – limited scope for history matching because of fewer data points e.g. wells, etc. In other words, the building of better constrained forward modelling tools like K_r functions offers a practical means for raising the level of confidence in the simulation results of CO_2 storage in deep aquifers.

9.5 Conclusions on the Interpretation and extrapolation of Pilton (a pseudonym) depressurization experiment: A Case Study

This segment of the thesis provided an opportunity to apply the model developed in this research to the analysis of a carefully conducted experiment that yielded a wide range of measured laboratory data. The main goals of the work case study were to: (i) To anchor the pore-scale simulator to reservoir samples using rock-specific petrophysical data; (ii) To undertake a parametric study of the depressurisation process at the pore-scale, the pore network model being used as an investigative tool to offer an interpretation of the experimental trends; (iii) To build a predictive model of the reservoir sample by matching the experimental production profiles; (iv) To use this numerical surrogate to examine production and relative permeability issues using different depletion rates and different rock/fluid parameters; and (v) To use the simulation results to re-interpret a range of experimental data and help explain any apparent inconsistencies. The main conclusions are as follows.

9.5.1 Specific conclusions relating to early scoping studies are as follows:

The unique physical circumstances of the experiment were found to explain the observed results: the core size and permeability, the fluid and rock/fluid properties, the initial liquid saturation distributions, and, to a lesser extent, the depletion rate. Parametric sensitivities demonstrated that the underlying depressurization processes of bubble nucleation and bubble growth could be expected to lead to a substantial reduction in pre-depletion oil saturation.

- ✓ A combination of high initial water saturation (S_{wi}), high depletion rate and low gas/oil interfacial tension are predicted to lead to an intense and rapid build-up of embryonic bubbles.
- ✓ The short, tight core and the negligible viscous pressure gradient meant that simulated bubble growth was highly dendritic and largely unaffected by buoyancy. Analytical calculations suggest that gas structures would need to exceed approximately 4cm in height for gravity bias to become an issue (400cm for spontaneous bubble migration).
- ✓ The spreading films of oil between gas and water encouraged continuous expulsion of oil from the system throughout the depressurisation
- ✓ The impact of system wettability upon the depletion process was found to be complex and multifaceted. Depending on the wettability condition assumed, higher or lower bubble nucleation densities were required to match the base experiment. A mixed-wet model was assumed for the predictive simulation runs based on supplied data and related literature.

9.5.2 Specific conclusions relating to conditions away from the experimental conditions 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.

- Changes in the spreading coefficient through systematic variations of gas-oil, oil-water, and gas-water interfacial tensions (σ_{go}, σ_{wg}, σ_{ow}) by ±10% from their baseline values caused variations in S_{gc} in both 2D and 3D Pilton analogues. For 2D networks, S_{gc} decreased significantly (up to 50% from the base case) in proportion to the fraction of the pressure range characterised by negative spreading. The IFT combination (σ_{go}+10%, σ_{wg}+10%, σ_{ow}-10%) exhibited the lowest S_{gc} overall – less than half that observed in the base case. Depletion rates of 1, 10, and 100psi/day were considered and similar behaviours were observed at all rates. 3D simulations exhibited far less sensitivity to changes in interfacial tension – the greater pore connectivity in 3D networks allowing growing bubbles to readily find alternative evolution pathways to the production buffer. Results for depletion rates of 10psi/day and 100psi/day leads to the conclusion that neither 10% variations in interfacial tension nor changes in depletion rate would have any significant impact on the outcome of Pilton depletions.

- Rock fabric was found to be a major determinant of Pilton depletion behaviour. Compared to two alternative 2D rock architectures used in our latest simulations – one a 3mD network representative of a chalk sample and the other 300mD network more characteristic of clastic rocks – an un-fractured Pilton system yielded the largest S_{gc}. This was found to hold for all depletion rates considered (1, 10, and 100psi/day). Values calculated from depletions using the 3mD and 300mD networks were considerably lower than those observed for the Pilton network by 35% and 42%, respectively. In addition, oil recovery from the Pilton surrogate was found to exceed recoveries from both 3mD and 300mD systems. When gravity forces are included in the calculations, the S_{gc} values observed for the 3mD and

300mD networks were predicted to be much lower than that found in the Pilton network (by 35% and 42%, respectively).

- Further simulations on gravity effects predict gas saturation at any given pressure to broadly decrease with an increase in effective gravity – hence we see that S_{gc} is essentially scale-dependent, which raises some important issues when attempting to populate reservoir-scale models. Nevertheless, the impact of gravity on S_{gc} should remain negligible in waterflooded Pilton material up to a height of approximately 15m.

- Analysis of simulation results shows that the magnitude of S_{gc} cannot be dissociated from how it is defined. Throughout this segment of the thesis S_{gc} has been defined as the gas saturation at the start of bulk gas production from the top of the system. Note, however, that alternative definitions can be framed. One definition relates to the saturation at which a continuous interconnected gas phase first spans the porous medium. This definition is, however, not universally applicable since it is possible to have non-zero flux exiting the network without the formation of a network spanning cluster. For gas evolution under migratory regimes or gas evolution in the presence of fractures, where gas is highly mobile and flow generally discontinuous, S_{gc} may be better defined as the saturation at first production: this would give very low S_{gc} values (approaching zero in some cases).

- S_{gc} could be reduced by approximately 20 - 60% by introducing conductive fractures within the matrix blocks. Variation in the spacing between the fractures led to differences in the S_{gc} response – the farther apart the fractures were the smaller the decrease in S_{gc} induced. Two fracture orientations were investigated (lateral and diagonal) and both oil-filled and water-filled fractures were considered. Results suggest that the orientation of the fracture does not appear to be very important nor do the assumptions made about fracture phase occupancy and fracture volume. Variations in S_{gc} as a result of using volumeless fractures or disabling matrix-fracture diffusion is limited to a few percentage points. Sg profiles from simulations with and without fracture-matrix diffusion overlap during the

majority of the depletion and only begin to diverge at around 1800psia. 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.

- 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 general, S_{gc} for un-fractured Pilton depressurisation is predicted to be relatively high (averaging 0.20 for an S_{wi} of 0.616) on account of the matrix architecture, the effectively instantaneous nature of bubble nucleation, and the insensitivity of the solution gas drive process to changes in depletion rate in the range 1 – 100psi/day. Published results of depressurisation experiments suggest that these behaviours are not unique to Pilton depressurisation. The literature shows that high S_{gc} and a lack of S_{gc} response to variation in depletion rate is broadly correlated to lower permeability samples (the largest S_{gc} reported for a North Sea rock sample was 0.24, obtained with 27mD Miller field sample at 0.55 S_{wi} – compared with S_{gc} of 0.20 for 0.23mD Pilton core at 0.616 S_{wi}).

9.6 Practical Significance of the Research

The practical significance of this work is discussed below under two main headings.

9.6.1 Parameterization of Darcian models and laboratory practices for the determination of flow coefficients

In addition to providing general insights into the pore-level mechanisms that govern a range of observed gas flow phenomena, this research has made suggestions regarding ways for optimizing/upscaling petrophysical input

parameters for reservoir simulators. Because of the limited sizes of standard laboratory cores, proper upscaling of laboratory-derived gas K_r curves has been shown to be most critical for reservoir simulation of gravity-dominated processes such as CO_2 storage in brine. This work offers specific recommendations on how to incorporate the effect of regime transitions on gas K_r as we move from the centimetre-scale of laboratory cores to the tens-of-meters-scale of typical reservoir gridblocks, including a model to directly calculate unsteady-state K_r curves that accounts for hysteresis in residual gas saturation.

Results showing that the flow regimes of CO_2-H_2O and CH_4-H_2O binary fluid systems at temperature and pressure conditions relevant to CO_2 sequestration in saline aquifers are almost the same, expands the options available to reservoir engineers regarding the specific fluid combinations to use to generate K_r curves for use in CO_2 or CH_4 flow simulations. This could translate into significant savings in time and resources.

The impact of CO_2 dissolution on CO_2 flow behaviour in brine saturated networks at high pressures (>10.34MPa) was found to be very small even at very low capillary numbers, suggesting that CO_2 flow experiments can produce reliable results without the need to pre-equilibrate the brine (prior saturation of the brine with CO_2) before experiments. This should greatly simplify experimental procedures.

With regards to depressurization, the finding that recovery efficiency increases with an increase in the initial water-saturation pre-depletion should provide reservoir managers with a useful scheduling guideline for maximising the overall economic benefits of blowdown post-waterfloods.

9.6.2 Contribution towards modelling of fluid flow in porous media

This research has demonstrated that the coupled effects of capillary, gravity, and viscous forces on gas flow through porous media, and in the presence of non-equilibrium mass transfer, can be implemented in network models in a relatively straightforward and modular way. The advantages of this modelling technique are

demonstrated by the ease with which crucial interactions have been isolated for detailed examination during this study, e.g. the effect of gravity/capillary force on sealing integrity during CO_2 storage or the effect of time evolution of heavy oil viscosity on the behaviour of viscous fingering during CO_2 injection for EOR. This inspires the hope that future studies of fluid flow at the pore-scale would find the modelling technique developed here a useful platform on which to extend our understanding of multi-phase flow phenomena in porous media.

9.7 Recommendations for Future Work

Future work in this area of research may be divided into two main subject categories as discussed below.

9.7.1 Injection processes

The current research has been focused on understanding flow processes under the assumption of static geochemical and geomechanical equilibrium. Changes in the stress fields within the porous media (induced by the high pressure differentials necessary to achieve injection rate targets) could, however, lead to rock failure or fines movement in the vicinity of the well, altering the original pore space architecture. The incorporation of geomechanical effects in the model could help shade light on the impact of dynamic evolution of the pore space on gas migration patterns. The work presented here on fractured chalk could serve as a useful starting point.

The dissolution of CO_2 in brine is generally expected to trigger a chain of chemical reactions between the rock and the aqueous phase. Estimates of the rate and extent of these reactions vary considerably, whilst experimental data relevant to the *in situ* conditions in deep saline aquifers are hard to come by. The model developed here could be extended to include the impact of geochemical reactions on CO_2 flow and trapping. These geochemical reactions could either be hardwired or coupled to the simulator from proven geochemical reaction engines such as PHREEQC.

The density of a CO_2-saturated brine is estimated to increase by approximately 1% and this then sets up convective currents within the brine phase if there is an uneven distribution of dissolved CO_2 concentration. The convective mixing would therefore tend to speed up the process of brine equilibration, in conjunction with the diffusion process

already accounted for by the current model. Whilst a slight change in brine density alone may have only a negligible impact on multiphase buoyancy-driven regime transition, density-driven convective mixing could nevertheless have a significant effect on the overall CO_2 dissolution rate. The implications of these interactions are not well understood and need further investigation.

The large timescales required for the mineralization of sequestered CO_2 in saline aquifers necessarily increases the uncertainties associated with the storage security in the short (first few hundred years) and medium terms (first few thousand years). In the medium term after injection, current understanding predicts that the bulk of the CO_2 would most likely exist as a free phase or as a dissolved phase. Whilst there has been considerable attention to the study of the risks of the leakage of free CO_2, the risks associated with the leakage and the potential liberation of dissolved CO_2 from solution (due to depressurization of the aquifer following an unforeseen catastrophic tectonic event) has been largely unexamined. The model developed here can provide a robust platform for this examination.

9.7.2 Depressurization processes

Apart from depletion rate and initial water saturation, there are very few other primary parameters that a reservoir engineer can vary in order to optimize the performance of an oil recovery process via depressurization. One possible way to increase oil recovery during depressurization might be to increase the nucleation density via microseismicity, whereby artificially induced micro vibrations could potentially catalyse the bubble nucleation process. This proposal should involve an experimental component which will be used to derive the essential physical relations that will then go into building a network model.

9.7.2.1 Specific outstanding issues regarding the depressurization case study

- **Tighter anchoring:** 2-phase relative permeabilities and MixWet determination of S_{wi}.
    a. The non-uniqueness of the network anchoring parameters could be addressed by matching 2-phase relative permeabilities from laboratory measurements so that the underlying network structure is more consistent

with the Pilton reservoir core in terms of both volumetrics and transport properties.

b. Realistic drainage simulations using an existing in-house 2-phase simulator (*MixWet*) could be conducted to better characterize the initial water saturation prior to depletion for different wettability conditions.

- **Lower depletion rates**: Depletions rates below 0.5psi/day have not been considered mainly because of the prohibitive running time that will be required to make a run to the final pressure. Changing the depletion rate by two orders of magnitude has not impacted S_{gc} in any systematic or significant way. If necessary, <0.5psi/day runs using the existing code would have to be performed with smaller models, although there may be the possibility of using a new C++ version of the code, currently under development, for larger-scale simulations.

- **Fractures in 3D networks:** the impact of vertical and diagonal fractures on 3D systems at different S_{wi} could be investigated. 2D networks have been used throughout this study to carry out scoping runs after which more targeted (but CPU intensive) 3D simulations have been performed. The trends observed for 2D simulations are often reproduced by 3D simulations (e.g. impact of S_{wi} and depletion rate upon S_{gc}) but occasionally, as in the case of spreading coefficient sensitivities, qualitative differences in the trends of results obtained by 2D and 3D networks can emerge. Thus future 3D sensitivities should provide a more representative picture of the impact of fractures.