A SIMULATION STUDY TO VERIFY STONE'S SIMULTANEOUS WATER AND GAS INJECTION PERFORMANCE IN A 5-SPOT PATTERN

A Thesis

by

MAZEN TAHER BARNAWI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2008

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee,	Daulat D. Mamora
Committee Members,	Jerome J. Schubert
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ABSTRACT

A Simulation Study to Verify Stone's Simultaneous Water and Gas Injection

Performance in a 5-Spot Pattern. (May 2008)

Mazen Taher Barnawi, B.S., King Fahd University of Petroleum and Minerals

Chair of Advisory Committee: Dr. Daulat D. Mamora

Water alternating gas (WAG) injection is a proven technique to enhance oil recovery. It has been successfully implemented in the field since 1957 with recovery increase in the range of 5-10% of oil-initially-in-place (OIIP). In 2004, Herbert L. Stone presented a simultaneous water and gas injection technique. Gas is injected near the bottom of the reservoir and water is injected directly on top at high rates to prevent upward channeling of the gas. Stone's mathematical model indicated the new technique can increase vertical sweep efficiency by 3-4 folds over WAG. In this study, a commercial reservoir simulator was used to predict the performance of Stone's technique and compare it to WAG and other EOR injection strategies. Two sets of relative permeability data were considered. Multiple combinations of total injection rates (water plus gas) and water/gas ratios as well as injection schedules were investigated to find the optimum design parameters for an 80 acre 5-spot pattern unit.

Results show that injecting water above gas may result in better oil recovery than WAG injection though not as indicated by Stone. Increase in oil recovery with SSWAG injection is a function of the gas critical saturation. The more gas is trapped in the

formation, the higher oil recovery is obtained. This is probably due to the fact that areal sweep efficiency is a more dominant factor in a 5-spot pattern. Periodic shut-off of the water injector has little effect on oil recovery. Water/gas injection ratio optimization may result in a slight increase in oil recovery. SSWAG injection results in a steady injection pressure and less fluctuation in gas production rate compared to WAG injection.

DEDICATION

I wish to dedicate my thesis:

To

My wonderful mother & late father for bringing me up to who I am today, for your guidance, support and prayers.

To

My siblings for your love & prayers and for being there for me when I needed you.

To

My adorable daughter, Sadeem, and the soon expected one, you light up my life.

Last to

My lovely wife, Nourah, for your patience and continuous encouragement, would never have made it without you!

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Mamora, and my committee members, Dr. Schubert and Dr. Sun, for their guidance and support throughout the course of this research.

My thanks also go to my friends, my colleagues, the department faculty, and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to Dr. Herbert L. Stone, who was very helpful with discussion on the data used to build the reservoir model used in this study.

Thanks to Schlumberger Middle East S.A. for giving me the opportunity to continue my professional development and sponsoring me all the way.

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CHAPTER I

INTRODUCTION

It is an established fact that injecting water and gas in alternating cycles or simultaneously has the potential to increase oil recovery after water flooding. That is because gas has the ability to further displace some, if not all, of the waterflood residual oil, S_{orw}. Water on the other hand has better sweep efficiency than gas. Combing the two together results in lowering gas relative permeability in the formation and controls its mobility, thereby improving the overall displacement and sweep efficiencies (Christensen et al. 2001).

Since the first water alternating gas (WAG) injection was implemented in 1957, different combinations of water and gas injection have been studied and tested. Today, WAG is considered a proven enhanced oil recovery (EOR) technique while the experience with simultaneous water and gas (SWAG) injection is still very limited in the industry (Christensen et al. 2001). Initially in the case of WAG, injected water and gas flow as a uniform mixture in the reservoir. As the mixture flows further away from the injector, the two phases segregate with gravity. After complete segregation is reached, two distinct flow zones are formed. Only gas flows near the top of the formation and only water flows at the bottom.

This thesis follows the style of *SPE Reservoir Evaluation & Engineering.*

1.1 Stone's Simultaneous Water and Gas Injection Method

Recently, Stone (2004) have reintroduced Warner's approach of SWAG injection (Warner 1977) with some modifications. The aim of Stone's technique is to enable maximum contact of the injected gas with formation oil before the gas migrates upward and finds its way to the producer. In other words, extend the zone of mixed water and gas flow in the formation before gravity segregates them. The design calls for simultaneous but selective injection of water and gas (SSWAG). A dual completion injector is used to inject gas near the bottom of the formation and water at high rate is injected in the top remaining part of the reservoir. The rational for injecting water at relatively a high rate is to prevent or at least delay injected gas from migrating upward and instead force the gas to move further horizontally into the formation. In order to establish gas mobility in the upper portion of the formation, water injection is periodically shut-off allowing upward movement of injected gas. Another approach to establish such gas mobility is by injecting gas, at very low rate, together with the water into the upper portion of the formation. Eventually, complete gravity segregation will take place similar to the case with WAG but at a further distance from the injector.

Based on his modeling study, Stone indicated that SSWAG injection can result in gas vertical sweep efficiency 3-4 times greater than that of WAG injection. It was also indicated that SSWAG can be implemented in thin reservoirs if combined with the use of horizontal injection and production wells. Fig. 1 and Fig. 2 show the application of

Stone's method in vertical and horizontal wells respectively. Only the former is covered in this study.

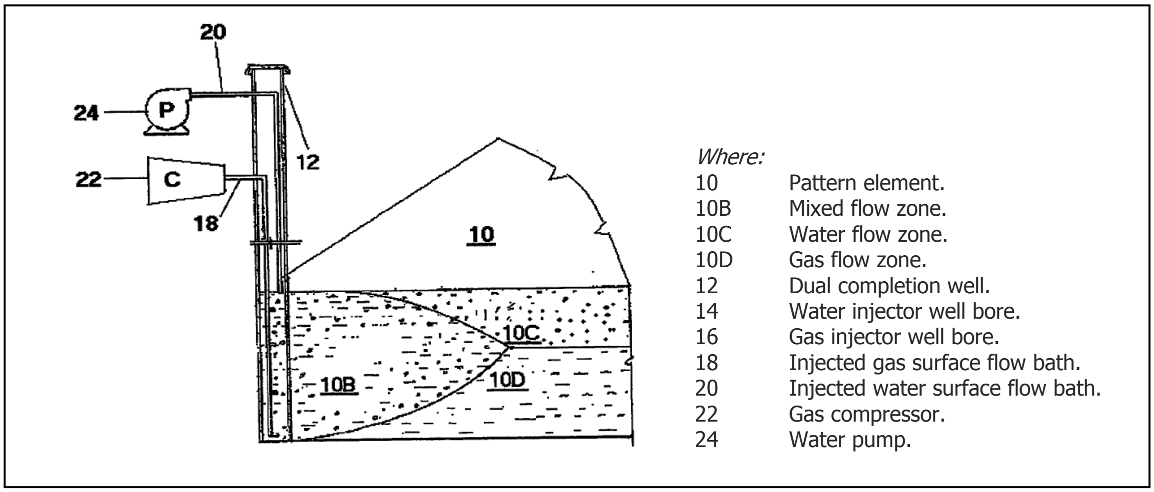

Fig. 1 – Stone's SSWAG injection application in vertical wells (Stone 2003).

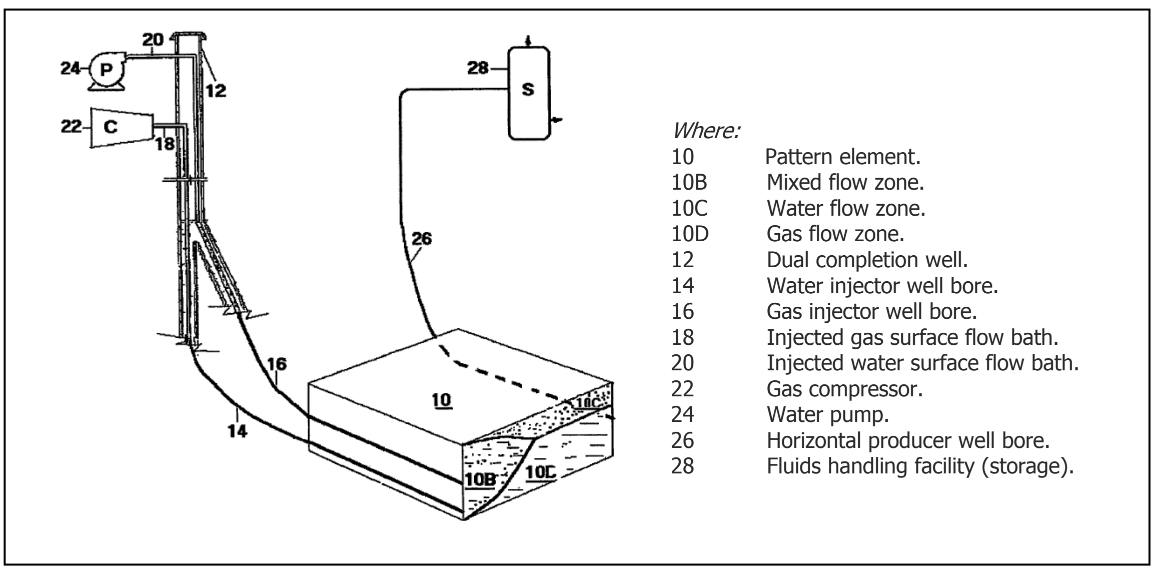

Fig. 2 – Stone's SSWAG injection application in horizontal wells (Stone 2003).

1.2 Research Objectives

The main objective of this study is to evaluate and compare the oil recovery performance of Stone's SSWAG injection to that of conventional WAG injection in a 5-spot injection pattern. SSWAG performance will also be compared to other injection strategies, including water flooding, gas injection, and SWAG injection.

The study will also investigate the effect of fluids relative permeability and some design parameters, such as water/gas ratio and periodic water injection shut-offs, on oil recovery. Evaluations are performed with the help of Schlumberger black-oil reservoir simulator (ECLIPSE-100). The used simulation model represents one-eighth of an 80-acre 5-spot injection pattern-unit.

CHAPTER II

BACKGROUND

This chapter describes the different techniques of combined water and gas injection. It also summarizes simultaneous water and gas injection studies and field pilot tests that were found in the literature.

2.1 Combined Water and Gas Injection Classification

The classification is usually done based on displacement miscibility. In miscible flooding, a minimum pressure is required for the injected gas to mix completely with contacted formation oil forming one single phase that can displace all the oil with no residual saturation. CO_2 is a common gas used for miscible flooding (Jarrell et al. 2002). For the purpose of this study, injection techniques are divided into two categories based on their injection schedules. These are alternating injection and simultaneous injection.

2.1.1 Alternating Injection

In WAG, the two phases are injected in alternating cycles through the same completion interval. Injection period and injected volume of either phase are referred to as the half-cycle and the half-cycle slug respectively. WAG injection may be further subdivided into three main types. When the water/gas ratio is kept constant until the total required volume of gas slug is injected, the process is called ***conventional WAG***. In ***tapered WAG***, on the other hand, this ratio is changing. Gas slugs are injected alternately with continuously increasing water slug volumes. In both processes, after the total required volume of gas is injected, the process may be followed by water or less expensive gas injection (Jarrell et al. 2002).

A third type of WAG injection is referred to as ***Hybrid WAG***. In this case, a large slug of gas is injected, followed by small alternating cycles of water and gas injection (Christensen et al. 2001).

2.1.2 Simultaneous Injection

In simultaneous injection, both water and gas are injected at the same time into a portion or the entire thickness of the formation. It is subdivided into two techniques. In one technique, water and gas are mixed at the surface and injected together through a single well bore. The process is referred to as simultaneous water and gas or ***SWAG*** injection (Christensen et al. 2001).

In the second technique, no mixing takes place at the surface. The two phases are pumped separately using a dual completion injector and are selectively injected into the formation. Usually gas is injected at the bottom of the formation and water injected into the upper portion. This study refers to the latter technique as selective simultaneous water and gas (***SSWAG***) injection.

2.2 Literature Review

The technique of simultaneous water and gas injection has been considered in a few EOR feasibility studies but has rarely been implemented. It was first tested in 1963 in the Seeligson field, Southwest Texas, USA (Walker and Turner 1968). Since then, only four other field tests or projects have been reported in the literature. In general there are two modes of simultaneous water and gas injection. They are injected either as a two-phase mixture from the surface or injected separately into two different formation zones.

2.2.1 Review of SWAG Injection

Caudle and Dyes (1958) are believed to be the first to study the SWAG injection technique in an attempt to improve sweep efficiency during miscible displacement. Laboratory model studies indicated that sweep efficiency can be greatly increased if the miscible front is followed by a low mobility fluid. A SWAG injection in the proper water/gas ratio can result in a low mobility zone within the reservoir, thereby, combining the benefits of miscible displacement of oil and better sweep efficiency. Assuming water and gas flow in a uniform mixture, Caudle and Dyes presented a method for calculating the optimum water/gas injection ratio from the gas-oil relative permeability curves. Blackwell et al. (1960) presented another method for calculating this injection ratio based on total segregation of the two-phases while flowing through the formation.

Walker and Turner (1968) reported the first SWAG field trial by Humble Oil & Refining Co. SWAG injection was initiated in the Seeligson Field (Zone 20B-07) March, 1963 to improve the sweep efficiency from a previous enriched gas injection project. At first, the three wells selected for SWAG injection did not take the required volumes of water and gas. Hence, a fourth injector was added. Initial injection rates were 1,070 BWPD and 2,230 MSCF/D of enriched gas. Later, injection difficulties were faced, low injection rate and high pressures, resulting in reservoir pressure decline. Then in an attempt to improve injectivity at relatively low pressures, SWAG injection was converted to WAG injection and eventually stopped in June, 1965. Sweep efficiency during the SWAG injection period could not be evaluated due to wellbore communication problem in one of the injectors. Overall, no substantial increase in oil recovery was observed.

Slack and Ehrlich (1981) examined simultaneous water and N_2 ($SWAN_2$) injection. They concluded that for reservoir rocks with favorable relative permeability characteristics, the displacement mechanism associated with $SWAN_2$ injection is capable of causing displacement of significant amount of waterflood residual oil at reasonable water/N_2 ratios and in reasonable times.

Harjadiwinangun (1984) presented a feasibility study using black oil simulation model to select the best pressure maintenance strategy for the Ardjuna field (E-22 Reservoir). The strategies considered for the study were: (a) natural depletion, (b) gas injection, (c) water injection, and (d) SWAG injection. Table 1 lists recovery estimates for the different injection scenarios. SWAG injection gave the highest oil recovery estimate but gas injection was found to be the most favorable economically.

TABLE 1 - HARJADIWINANGUN (1984) FEASIBILITY STUDY RESULTS

Case	Description	Oil Recovery (% OIIP)
1	Natural depletion.	40.9
2	Water injection with addition of 10 injectors and 8 producers.	45.1
3	Gas injection with the addition of 6 new producers.	56.6
4	SWAG with the addition of 10 injectors and 8 producers.	57.5

Stephenson et al. (1993) reported on the SWAG injection pilot tests performed in the Joffre Viking field, Canada (Fig. 3). The field was abandoned in 1960's after reaching its economic limits, 42% OIIP recovered with water flooding. In early 1980's, simulation studies and laboratory tests proved that more oil can be recovered with miscible CO_2 flooding. Pilot tests with miscible water alternating CO_2 ($WACO_2$) injection and CO_2-Foam injection showed that injected CO_2 contacted only the top 1/3 of the formation due to gravity segregation and unfavorable mobility. In an attempt to improve CO_2 conformance, simultaneous water and CO_2 ($SWACO_2$) injection pilot was started in June, 1988 in a truncated inverted 9-spot pattern-unit (approximately 158 acre/well spacing). Refer to pattern "D" in Fig. 3. This pilot was considered to be the ultimate test since two of the producers during the test had been used as water injectors earlier in the life of the reservoir. Cumulatively, more than 5.34 million barrels of water had been injected into those wells, insuring that region of the reservoir is at waterflood residual oil saturation. Results showed $SWACO_2$ injection at water/CO_2 ratio approaching 1:1 improved CO_2 sweep efficiency in comparison with the earlier approaches. Additional 7.5% OIIP was recovered from the pattern unit.

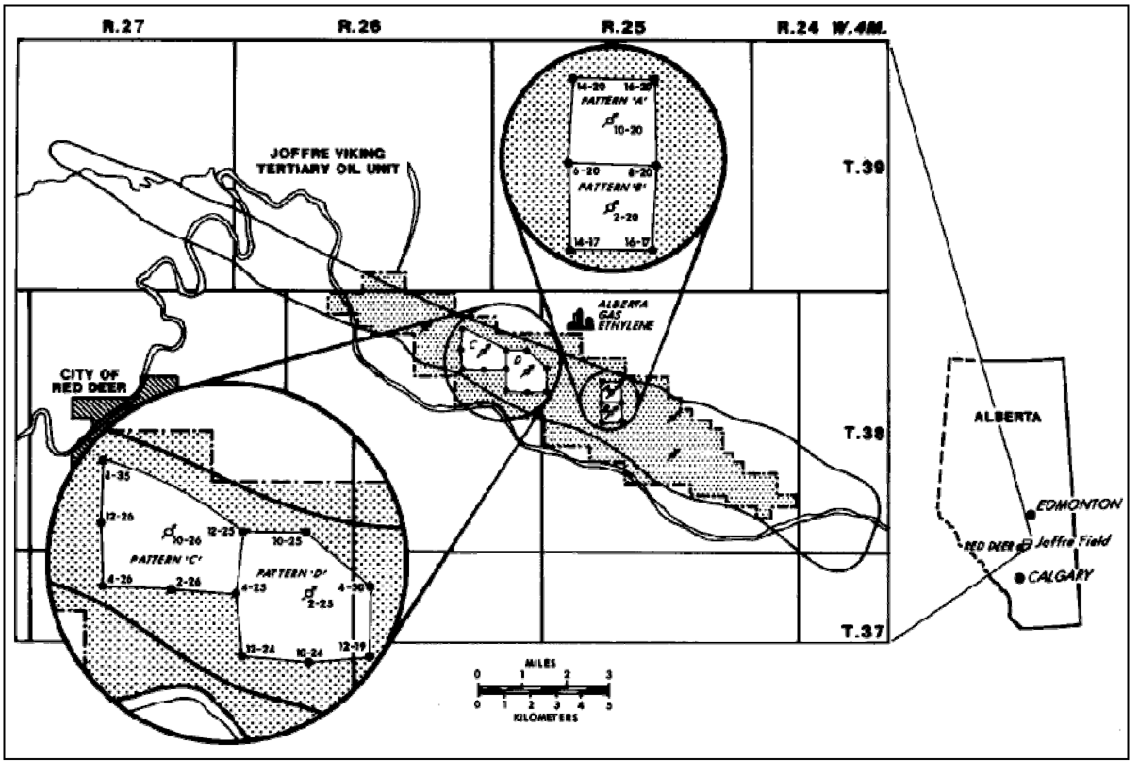

Fig. 3 – Map showing location of the Joffre Viking field (Stephenson et al. 1993). Also shows pattern "D" (truncated inverted 9-spot pattern) used for SWAG injection.

Attanucci et al. (1993) and Robie et al. (1995) both reported on the $SWACO_2$ injection trial performed in the Rangely field, Colorado, USA. Based on field operations and simulation studies, the expected advantages of $SWACO_2$ injection over $WACO_2$ injection were to: (1) improve oil recovery, (2) reduce operating cost either by reducing gas production or by eliminating some of the labor work associated with $WACO_2$ conversions. $SWACO_2$ injection was initiated in six wells that had been part of a line-drive pattern. Operationally, the trial was successful with the use of an automated surface control system that monitored and modified the flow rate of water and CO_2 mixture. The system was also able to prevent backflow of either injectant in to the distribution system of the other fluid. Improvement in oil recovery during $SWACO_2$ injection trial was not very obvious because of workover interference and metering problems at the collection station. Nevertheless, there were encouraging observations including an improvement in oil production decline rate in some of the producers and a steady gas production compared to the case of $WACO_2$ injection.

Several publications (Ma and Youngren 1994; Stoisits et al. 1995a; Ma et al. 1995) were presented on the SWAG injection pilot at the Kuparuk River field, Alaska, USA (Fig. 4). The field was mainly managed with WAG injection. SWAG injection was considered in an effort to reduce capital expenditure by: (1) eliminating separate water and gas injection lines to the drill sites required for WAG injection, (2) eliminating WAG conversion operations, and (3) reducing the handling cost by minimizing GOR fluctuation. A two-dimensional cross-sectional simulation study estimated that SWAG injection at 1:1 water/gas ratio would provide a better control on injected gas mobility and increase incremental oil recovered over an initial waterflood by 5.0% OIIP compared to 4.5% OIIP in the case of WAG injection. A patented surface injection setup was developed for this SWAG injection pilot (Stoisits et al. 1995b). Water and gas were mixed at a central processing facility. Multiphase flow is then injected into a single surface line to the injection sites. Inline static mixers were installed at the sites to condition the multiphase flow prior to being passed to nearby injection wells. SWAG injection began in June, 1994 and lasted for only 17 days. Separation between the two injected phases was observed at the surface during the test. Injection rate losses were also experienced and attributed to lower bottom hole pressure (BHP) at the injectors rather than to reduction in relative permeability because of the two-phase injection. The test demonstrated the feasibility of SWAG injection although it was not long enough to fully evaluate the effect of this injection technique on oil recovery.

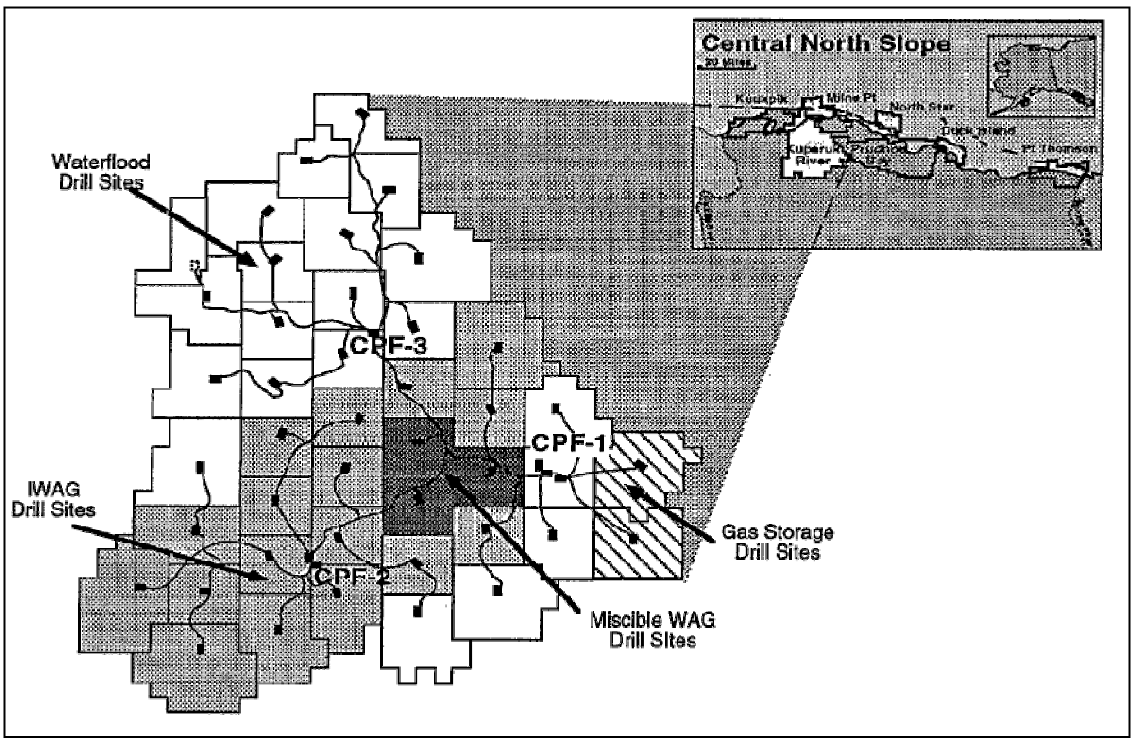

Fig. 4 – Map showing location of the Kuparuk River field (Ma and Youngren 1994).

Bagci and Tuzunoglu (1998) conducted laboratory experiments using a three-dimensional physical model to study the effect of well configuration on immiscible CO_2 displacement processes. The model (30 cm X 30 cm X 6 cm) represented a limestone reservoir with 38% porosity, 8 darcies absolute permeability and 18° API oil gravity. Fig. 5 shows the three combinations of vertical and horizontal well configurations that were considered for injection and production. In total, 20 runs were carried out investigating various injection processes, namely, continuous CO_2 injection, waterflood, $WACO_2$ injection, and $SWACO_2$ injection. Some of the study results are listed in Table 2. For $SWACO_2$ injection runs, the best oil recovery (20.6% OIIP) was obtained when vertical injector and horizontal producer (VI-HP) were used. Less that 8% OIIP recovery was obtained when matching injection and production wells were used during $SWACO_2$ injection. Water flooding using vertical injector and vertical producer (VI-VP) gave the overall highest oil recovery of 37.2% OIIP.

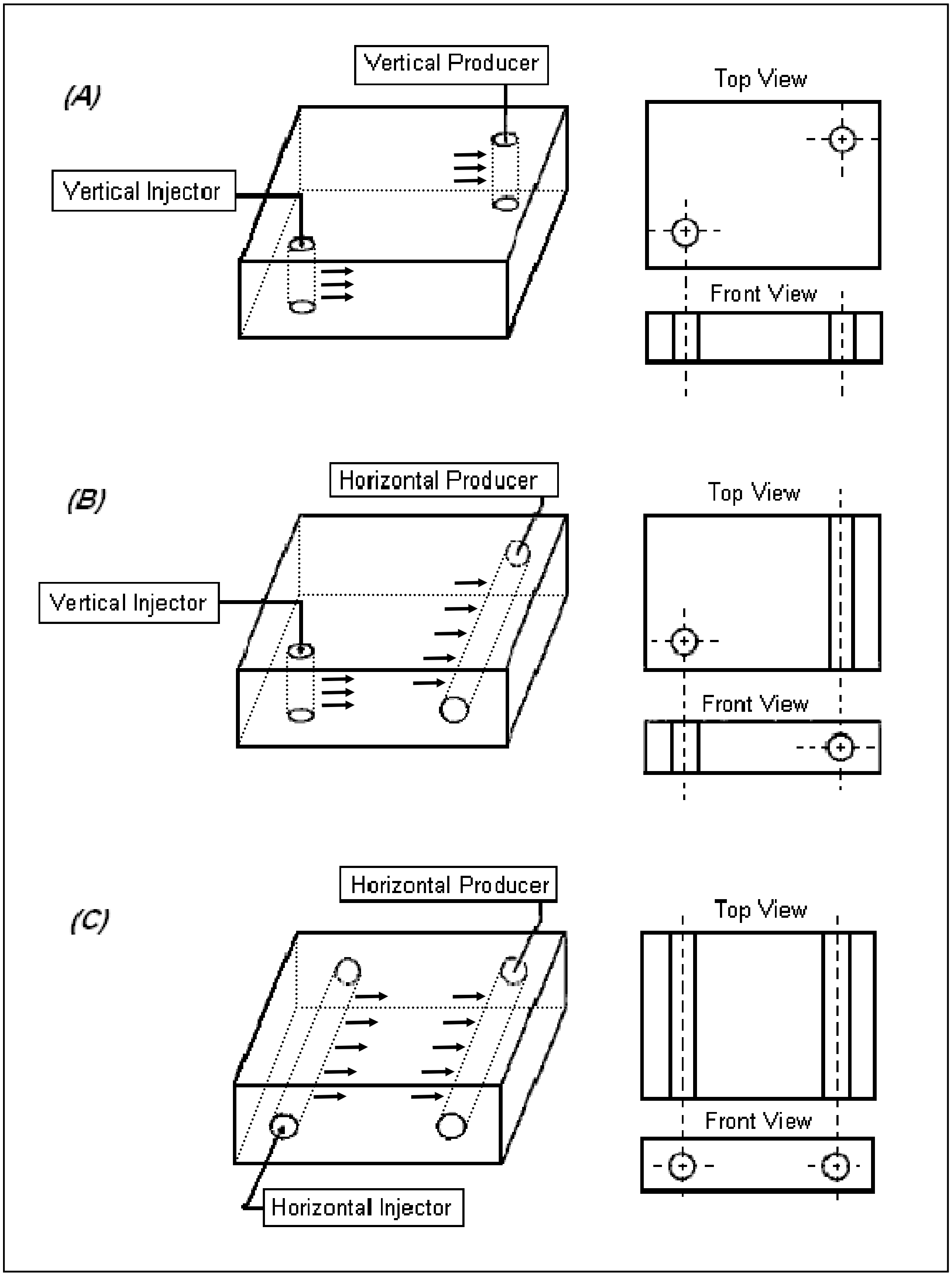

Fig. 5 – Bagci and Tuzunoglu (1998) 3D model well configurations. (A) Vertical injection and vertical production (VI-VP). (B) Vertical injection and horizontal production (VI-HP). (C) Horizontal injection and horizontal production (HI-HP).

TABLE 2 - BAGCI AND TUZUNOGLU (1998) EXPERIMENTAL RESULTS

Run No.	Well Configuration	Injection Method	Injection Rate CO_2 (cc/min)	Injection Rate Water (cc/hr)	WAG Ratio (W:G)	Total Injected PV	Oil Recovery (% OIIP)
1	VI-VP	Continuous CO_2	573	-	-	110.0	6.21
2	VI-VP	Waterflood	-	200	-	0.9	37.2
3	VI-VP	$SWACO_2$	1,000	200	-	100.0	7.56
9	VI-VP	$WACO_2$	200	200	1:7	4.8	21.04
10	VI-HP	Waterflood	-	200	-	0.8	24.33
13	VI-HP	$WACO_2$	200	200	1:7	4.8	18.29
15	VI-HP	$SWACO_2$	1,000	200	-	220.0	20.61
16	VI-HP	Continuous CO_2	1,000	-	-	230.0	15.06
17	HI-HP	$WACO_2$	200	200	1:7	4.9	14.94
18	HI-HP	Waterflood	-	200	-	0.8	17.5
19	HI-HP	Continuous CO_2	1,000	-	-	220.0	1.89
20	HI-HP	$SWACO_2$	1,000	200	-	245.0	7.87

Quale et al. (2000) reported on the first used of SWAG injection as the EOR strategy in the Siri field in the North Sea (Fig. 6). The reservoir is a closed 25m thick sandstone formation with good porosity and fairly good permeability. It was developed with five producers and two SWAG injectors (one highly deviated and the other fully horizontal). The project initially called for the use of conventional WAG injection as the EOR strategy. The lack of injected gas resources (not enough associated gas is produced); the need for reservoir pressure maintenance; and the need to archive minimum air and water discharges favored the implementation of SWAG injection instead. SWAG Injection has begun in June, 1999 with a surface facility design that prevents backflow. Specific well star-up and shut-in procedures are followed to prevent hydrate formation. Two-phase mixture of produced gas, produced water and sea water (if needed) are injected in the range of 25,000-50,000 BWPD and 7-14 MSCF/D of gas for each of the two injectors.

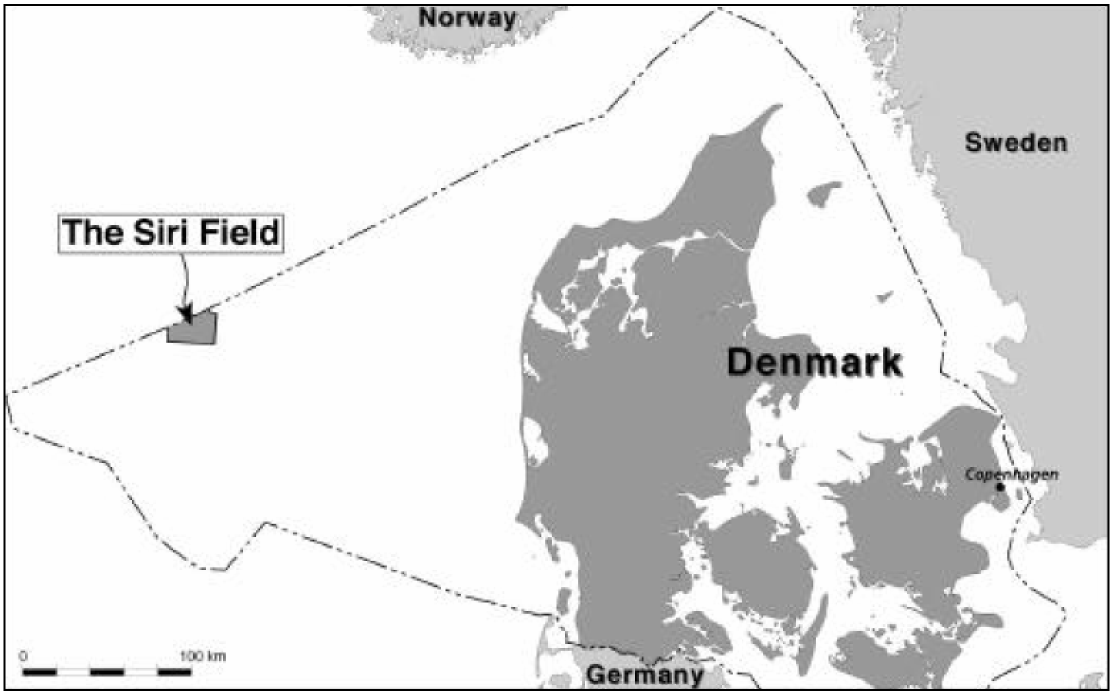

Fig. 6 – Map showing the location of the Siri field (Quale et al. 2000).

At first, SWAG injection concept was found to fulfill all the requirements of the Siri Field project and provided stable and full reinjection of produced fluids. Later, Berge et al. (2002) reported injectivity reduction during SWAG injection attributed to the effect of near-well two-phase relative permeability. No data was presented on oil recovery although it was mentioned that expected recoverable oil is in the excess of 35% OIIP.

Sohrabi et al. (2005) performed a pore-scale near-miscible SWAG injection in a laboratory experiment. Water and gas were injected simultaneously into a high pressure glass micro-model that was initially displaced to waterflood residual oil saturation. The experiment was first preformed at 1:1 water/gas injection ratio then repeated at 4:1 water/gas injection ratio. In both cases, the total injection rate was the same as that during the previous waterflood. Results showed that significant amount of waterflood residual oil was produced during the near-miscible SWAG injection. Captured images showed that nearly 100% of the oil contacted by the injected gas was produced but 100% residual oil recovery is not possible. That is because some of the oil was bypassed or trapped in pores due to water shielding and pore topology (dead-ends). The study also concluded that water/gas injection ratio during SWAG injection had no significant effect on improving oil recovery, which disagrees with some earlier findings (Warner 1977).

Al-Quraini et al. (2007) simulated different EOR strategies (water flooding; CO_2 injection and some combinations of the two) for the development of the West Sak reservoir located in Alaska's North Slope. Oil in this reservoir is characterized as heavy (12-22° API) with varying viscosity (50-3000 cp). Three-dimensional black oil simulation results showed superior oil recoveries with $WACO_2$ injection and $SWACO_2$ injection over water flooding or gas injection alone. About 30% OIIP increase in oil recovery was estimated when water and CO_2 injections were combined.

2.2.2 Review of SSWAG Injection

Warner (1977) is believed to be the first to consider the concept of SSWAG injection in a simulation study, where gas in injected near the bottom of the formation and water injected into the upper portion of the formation. Typical sandstone reservoirs, which are near their economical oil production limits, were the subject of this study. The objective was to find the best miscible CO_2 injection technique as a tertiary recovery mechanism after primary depletion and water flooding. The study also investigated the effect of variations in several reservoir parameters on tertiary oil recovery. A two-dimensional cross-sectional compositional model (25x1x5 with variable ΔY), shown in Fig. 7, was used to simulate a quarter of a five-spot pattern. Four different CO_2 injection techniques were studied: (1) continuous CO_2 injection; (2) slug CO_2 injection; (3) $WACO_2$ injection, and (4) $SSWACO_2$ with water injected into the top three of five layers and CO_2 into the bottom two.

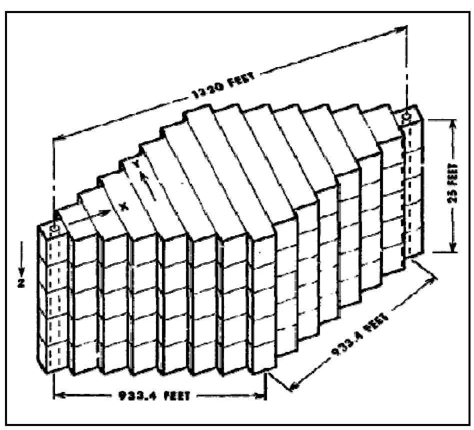

Fig. 7 – Warner (1977) Grid configuration used for $SSWACO_2$ injection.

In general, simulation results showed that the success of CO_2 injection is a function of the rate at which CO_2 segregates. The faster the segregation occurs the lower the incremental oil recovery. In all scenarios studied, complete gravity segregation between injected water and CO_2 was reached before half of the reservoir rock had been swept by the mixture of the two phases. The results, shown in Table 3, indicated that $SSWACO_2$ injection was the best injection technique, recovering nearly 50% of the waterflood residual oil.

Warner indicated that the ratio of $\boldsymbol{k_v/k_h}$ had the most effect on CO_2 segregation rate for the scenarios considered in the study. The smaller the ratio was the slower the segregation, therefore, better incremental oil recovery. Results also showed that water/CO_2 ratio during $SSWACO_2$ injection influenced both oil recovery and the recovery speed. Three water/CO_2 ratios were simulated in the study (1:1, 2:1 and 3:1). In general the 2:1 ratio resulted in more oil recovery than the 1:1 ratio at a given time and faster recovery than the 3:1 ratio for a given recovery percentage. Warner also indicated that well-spacing had a more significant effect on $SSWACO_2$ injection performance than the other injection techniques. Reducing well spacing, from 40 to 10 acre, increased tertiary oil recovery, from 12.7 to 17.2% OIIP respectively.

TABLE 3 - WARNER (1977) STUDY RESULTS

Injection Method	Oil Recovery (% OIIP)
Continuous CO_2 Injection	5.6
Slug CO_2 Injection	6.3
$WACO_2$	10.3
$SSWACO_2$	12.7

Surguchev et al. (1996) in a three-dimensional simulation study, compared the tertiary oil recovery performance of WAG, foam assisted WAG (FAWAG), and SSWAG injection strategies. The used reservoir model was characterized with extreme absolute permeability contrast ($\boldsymbol{k_h}$ bottom layer 2-20 md, $\boldsymbol{k_h}$ top layer = 2200 md). A combination of vertical and horizontal injection and production wells was considered in the study (see Fig. 8). Simulation results on secondary recovery with waterflood estimated only about 15% OIIP was recovered at economical limit with most of the production coming from the smaller upper layer. In the case of SSWAG injection, gas was injected into the lower (100 ft thick) layer and water into the upper (40 ft think) layer. The study found both WAG and SSWAG injections to be effective in tertiary oil recovery. When a permeability barrier is placed between the two layers, SWAG injection outperformed WAG injection (33.1% to 26.6% OIIP respectively).

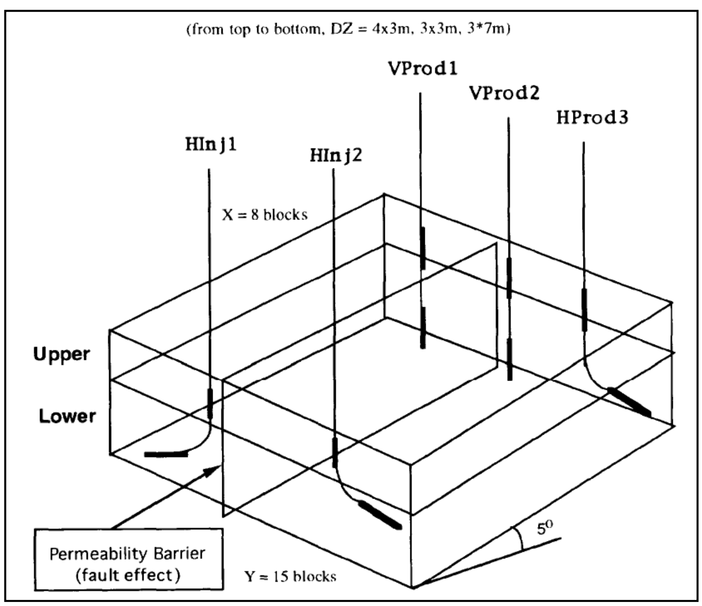

Fig. 8 – Surguchev et al. (1996) simulation model schematic with a combination of vertical & horizontal injectors & producers.

In a simulation study to optimize oil recovery from carbonate reservoirs, Gharbi (2003) investigated the performance of SSWAG, WAG, and SWAG injections. The three-dimensional simulation model used for the study represented a typical Middle Eastern carbonate reservoir (360 ft thick, 22 % porosity, 115 md. permeability, 29° API oil with 3.12 cp viscosity). In the case of SSWAG injection, horizontal water and gas injection wells were considered. The water injector was placed 50 ft from the top of the reservoir and the gas injector was placed 50 ft from the bottom. The producer, on the other hand, was kept vertical. Estimated results showed that SSWAG injection was the most profitable injection strategy for that reservoir. The study concluded that SSWAG injection using combination of injectors and producers improved oil recovery significantly at a shorter project life than WAG or SWAG injections. Algharabi et al. (2007a, 2007b) utilized a similar injection and production wells combination to that of Gharbi (2003) for their sensitivity analyses on several SSWAG injection design parameters.

Stone (2004) reintroduced Warner's approach of SSWAG with gas injected near the bottom of the formation and water on top (Warner 1977). The difference is that Stone called for injecting water at high rates directly on top of where the gas is injected. The high water injection rate is to obstruct injected gas from flowing vertically (control gas mobility). It is also to force the injected gas to penetrate deeper horizontally into the reservoir compared to the case during WAG injection before complete segregation occurs. Stone estimated that this injection method can result in 3-4 times better vertical gas sweep efficiency compared to conventional WAG injection. The study also indicated that combining the selective injection approach together with horizontal injectors and producers makes it effective even in thin formations (Stone 2003). A two-dimensional quasi–steady state reservoir simulator was used to eliminate numerical dispersion normally associated with commercial reservoir simulators.

Rossen et al. (2006) investigated the effect of combined water and gas injection techniques on how far the two-phase mixed flow can penetrate into the formation before reaching the point of complete segregation. Results from analytical methods, verified by numerical reservoir simulation, were used to estimate the distance from the injector to the point of complete segregation. Uniform co-injections or SWAG and SSWAG (water above the gas) injections where two of the methods considered in this study. The simulation model was a two-dimensional cross-sectional model.

Results showed that for a fixed total injection rate, SSWAG injection resulted in deeper point of compete segregation than SWAG injection, twice as deep for the case examined. Hence, a better vertical sweep is obtained with the former. Then at fixed (or limited) injection pressure, better injectivity was obtained during SSWAG injection compared to the injectivity during SWAG injection. That is because of the high mobility regions for each of the injected phases next to the injector. In other words, higher injection rate can be achieved with SSWAG at a given injection pressure, therefore, injected gas would travel deeper into the formation before complete segregation. The study also showed that SSWAG injection in the entire height of the formation or in a portion of it has little to no effect on how deep the mixed flow zone penetrates into it. However, the latter would affect injectivity negatively.

CHAPTER III

SIMULATION MODEL

3.1 Simulation Requirements

Stone's SSWAG injection method was suggested for vertical and horizontal wells. Only vertical injection and production wells in a 5-spot pattern are simulated in this study (Fig. 9). Selected model represents one-eight of an 80-acre five-spot injection pattern. Since both water and gas are to be injected to displace oil, the use of a three-phase model is needed. Stone's second relative permeability model was used for estimating the three phase relative permeability (Stone 1973).

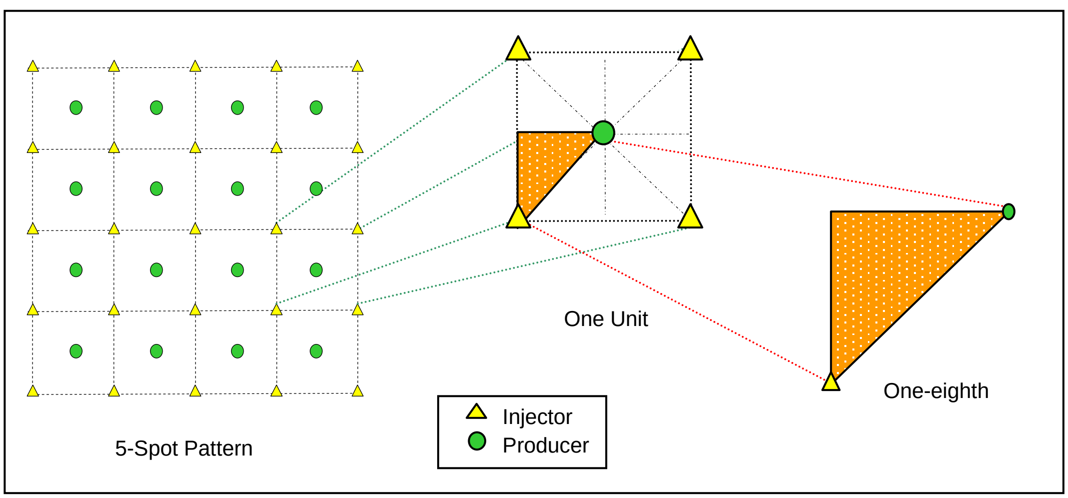

Fig. 9 – Schematic diagram of a 5-spot pattern. Also showing one unit and one-eighth.

In this study, three-dimensional simulation is necessary to fully evaluate the production performance of SSWAG injection. 100% sweep could not be assumed neither in the areal nor in the cross-sectional direction. Three-dimensional simulation is also important to capture the effect of the pattern geometry on fluid flow.

The following measures were taken to reduce numerical dispersion. First, assuming immiscible displacement of formation oil by injected gas, a black oil simulator (Schlumberger ECLIPSE-100) was selected for the study instead of a compositional simulator. Second, the model represents only one-eighth of the 80-acre 5-spot pattern-unit (Fig. 9). Therefore, finer grid blocks, especially near the wells, can be used. Lastly, the grid blocks used were oriented to be parallel to the flow direction between the injector and the producer wells (Fig. 10). This last measure is important when the displacing phase is much more mobile than the displaced phase (Mattax and Dalton 1990).

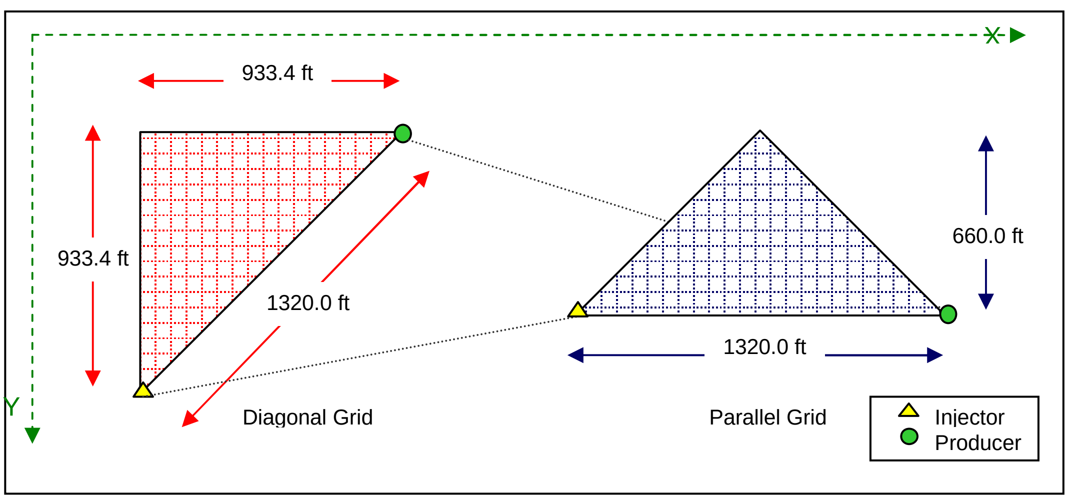

Fig. 10 – Schematic diagrams of diagonal and parallel grid orientations. Diagonal grid (left) and parallel grid (right).

3.2 Reservoir Description

The simulation model rock and fluid properties are similar to those used by in Stone's study (Stone 2004). Additional data have been adopted where necessary for the simulator to function properly. The reservoir consists of two homogenous layers with equal porosities. The thicker upper layer has relatively low absolute permeability. Table 4 describes the reservoir in more detail.

TABLE 4 - RESERVOIR DESCRIPTION AND ROCK PROPERTIES

Layer	Property	Value
	Total Thickness, ft.	290.0
	Well Spacing (5-Spot), acre	80.0
	Formation Depth, ft.	8,000.0
	Gas-Oil Contact, ft.	None
	Water-Oil Contact, ft.	15,000.0
	Rock Compressibility, psi^{-1}	1.0E-09
Upper	Thickness, ft.	190.0
	Porosity. %	21.0
	Vertical Permeability, md.	56.5
	Horizontal Permeability, md.	225.0
Lower	Thickness, ft.	100.0
	Porosity. %	21.0
	Vertical Permeability, md.	240.0
	Horizontal Permeability, md.	600.0

3.3 Fluid Properties

For ECLIPSE-100 to run three-phase simulation, it needs fluid PVT and relative permeability data for both water-oil and gas-liquid systems. Stone (2004) presented one set of relative permeability data that can be used for both fluid systems but no PVT date was presented. Table 5 contains the fluid initial and surface properties used in the simulation model.

TABLE 5 - FLUID SURFACE AND INITIAL PROPERTIES

Property	Value
Initial Pressure, psia	3,000.0
Initial Oil Saturation, %	80.0
Initial Water Saturation, %	20.0
Water Compressibility, psi^{-1}	1.0E-09
Water Surface Gravity	1.07
Water Viscosity, cp.	0.31
Water Formation Volume Factor, RB/STB	1.0
Oil Surface Gravity, °API	35
Oil Viscosity, cp.	0.75
Gas Surface Gravity	0.7
Gas Viscosity, cp.	0.0425

3.3.1 Oil and Gas PVT Data

Tables 6 and 7 show the typical oil and gas PVT data that are were adopted for the study respectively. The data was adjusted in order to match the initial oil and gas properties provided in Table 5. Curves of the individual properties are plotted in Fig. 11 through Fig. 13.

TABLE 6 - OIL PVT DATA

R_s (fraction)	p (psia)	B_o (RB/STB)	μ_o (cp.)
0.047	178.0	1.1190	1.435118
0.090	288.0	1.1530	1.211123
0.154	525.0	1.1990	1.106076
0.223	750.0	1.2390	1.028836
0.290	1,025.0	1.2770	0.967044
0.356	1,250.0	1.3130	0.919156
0.424	1,500.0	1.3530	0.874356
0.493	1,750.0	1.3910	0.834964
0.568	2,000.0	1.4320	0.799434
0.648	2,250.0	1.4770	0.770082
0.735	2,500.0	1.5260	0.737642
0.768	2,600.0	1.5450	0.727600
0.768	2,700.0	1.5400	0.733355
0.768	2,800.0	1.5350	0.738298
0.768	2,900.0	1.5320	0.743242
0.768	**3,000.0**	**1.5260**	**0.750000**
0.768	3,100.0	1.5240	0.753128
0.768	3,500.0	1.5110	0.772400
0.768	4,000.0	1.4960	0.797116
0.768	4,500.0	1.4830	0.822606
0.768	5,000.0	1.4770	0.847322
0.768	5,500.0	1.4721	0.872103
0.768	6,000.0	1.4710	0.896964

TABLE 7 - GAS PVT DATA

p (psia)	B_g (RB/MSCF)	μ_g (cp.)
178.0	18.6999110	0.02281
288.0	11.7275156	0.02300
525.0	6.7479964	0.02648
750.0	4.4648264	0.02802
1,025.0	3.3178985	0.02957
1,250.0	2.6322351	0.03054
1,500.0	2.1816563	0.03247
1,750.0	1.8575245	0.03402
2,000.0	1.6206589	0.03556
2,250.0	1.4425646	0.03730
2,500.0	1.2965272	0.03923
2,600.0	1.2624290	0.03979
2,700.0	1.2150365	0.04047
2,800.0	1.1710518	0.04115
2,900.0	1.1301208	0.04182
3,000.0	**1.0919369**	**0.04250**
3,200.0	1.0227753	0.04387
3,400.0	0.9618034	0.04523
4,000.0	0.8156931	0.04930
4,500.0	0.7238777	0.05271
5,000.0	0.6505391	0.05611
5,500.0	0.5906183	0.05951
6,000.0	0.5407474	0.06291

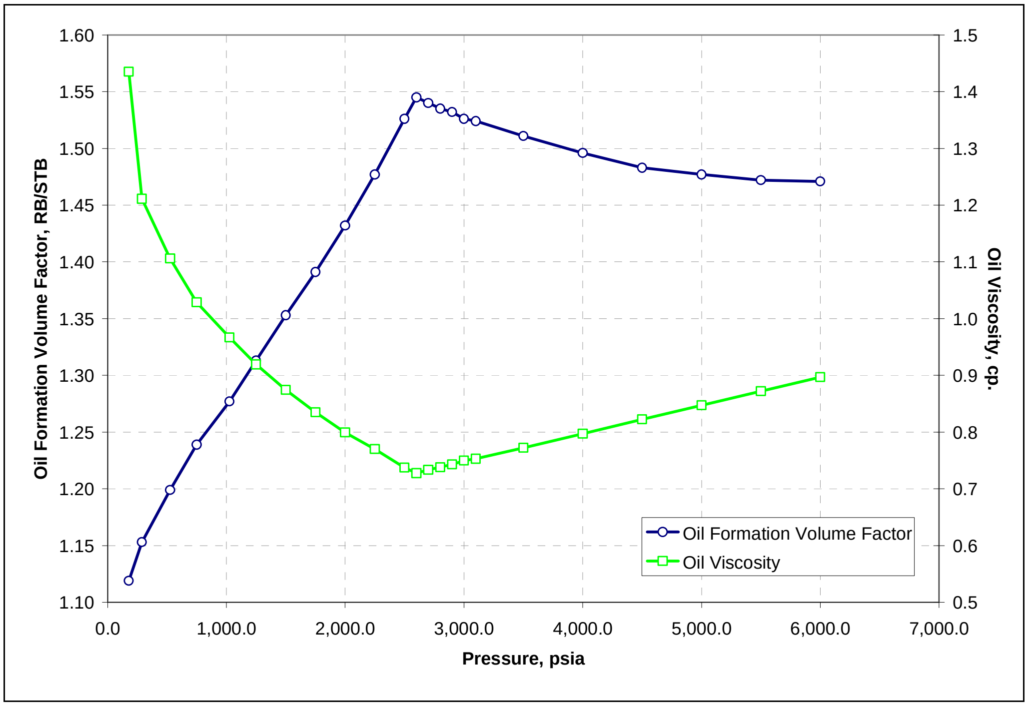

Fig. 11 – Plot of oil formation volume factor & oil viscosity versus pressure.

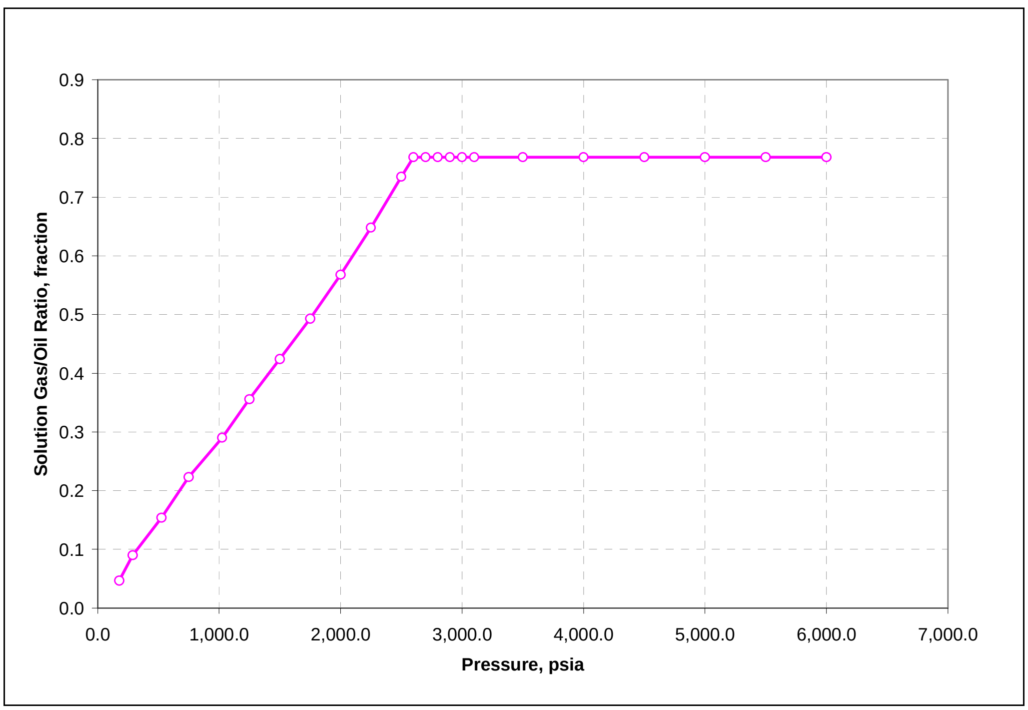

Fig. 12 – Plot of solution gas/oil ratio versus pressure.

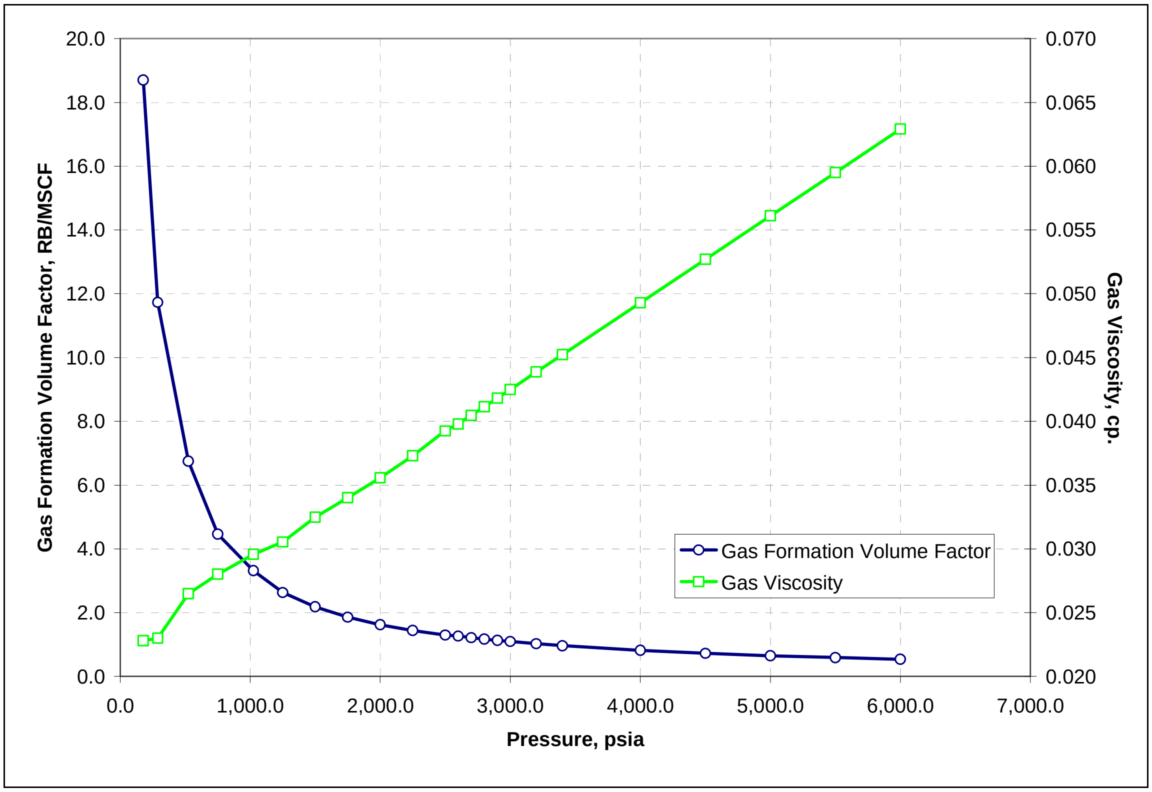

Fig. 13 – Plot of gas formation volume factor & gas viscosity versus pressure.

3.3.2 Relative Permeability Data

Two groups of relative permeability data were considered in this study. The first is similar to that of Stone where a single relative permeability set, Table 8, is used for both water-oil and gas-liquid systems. Stone (2004) presented that relative permeability data as gas-liquid data. If water saturation is considered, instead of the gas, the reversed curves serve as water-oil relative permeability. For the purpose of this study, this set of relative permeability data is referred to as the “S” set.

TABLE 8 - "S" SET OF RELATIVE PERMEABILITY DATA		
S_g (fraction)	k_{rg} (fraction)	k_{rog} (fraction)
0.00	0.0000	1.0000
0.02	0.0000	0.9115
0.04	0.0000	0.8288
0.06	0.0000	0.7517
0.08	0.0000	0.6800
0.10	0.0000	0.6133
0.12	0.0000	0.5516
0.14	0.0000	0.4945
0.16	0.0000	0.4418
0.18	0.0000	0.3933
0.20	0.0000	0.3488
0.22	0.0000	0.3081
0.24	0.0001	0.2710
0.26	0.0003	0.2372
0.28	0.0006	0.2066
0.30	0.0012	0.1789
0.32	0.0021	0.1541
0.34	0.0036	0.1319
0.36	0.0057	0.1121
0.38	0.0088	0.0945
0.40	0.0129	0.0791
0.42	0.0184	0.0655
0.44	0.0255	0.0538
0.46	0.0346	0.0436
0.48	0.0461	0.0349
0.50	0.0603	0.0276
0.52	0.0777	0.0214
0.54	0.0988	0.0163
0.56	0.1241	0.0122
0.58	0.1541	0.0089
0.60	0.1894	0.0062
0.62	0.2307	0.0042
0.64	0.2787	0.0028
0.66	0.3341	0.0017
0.68	0.3976	0.0010
0.70	0.4702	0.0005
0.72	0.5526	0.0002
0.74	0.6458	0.0001
0.76	0.7508	0.0000
0.78	0.8685	0.0000
0.80	1.0000	0.0000

The other set of relative permeability data, “M” set, is a typical one. The gas-liquid and water-oil data are listed in Tables 9 and 10 respectively. The main difference between the “S’ and the “M” sets is in the gas relative permeability as shown in Fig. 14 and Fig. 15. In the “M” set, gas is very mobile from the beginning, 5% critical saturation, while in the “S” set gas is relatively less mobile with a critical saturation of 20%. Another difference is in the waterflood residual oil saturation, S_{orw} 25% and 18% in the “M” and “S” sets respectively. It is important to mention that no capillary pressure data was included with either set, i.e. capillary pressure is zero psia.

TABLE 9 - "M" SET OF GAS-LIQUID RELATIVE PERMEABILITY DATA

S_g (fraction)	k_{rg} (fraction)	k_{rog} (fraction)
0.00	0.000000	0.900000
0.05	0.004389	0.724054
0.10	0.016608	0.570544
0.15	0.036175	0.438425
0.20	0.062847	0.326599
0.25	0.096462	0.233902
0.30	0.136893	0.159099
0.35	0.184043	0.100859
0.40	0.237829	0.057735
0.45	0.298179	0.028125
0.50	0.365033	0.010206
0.55	0.438335	0.001804
0.60	0.518036	0.000000
0.65	0.604092	0.000000
0.70	0.696463	0.000000
0.75	0.795110	0.000000
0.80	0.900000	0.000000

TABLE 10 - "M" SET OF WATER-OIL RELATIVE PERMEABILITY DATA		
S_w (fraction)	k_{rw} (fraction)	k_{row} (fraction)
0.20	0.000000	0.900000
0.25	0.000364	0.709187
0.30	0.002536	0.544963
0.35	0.007892	0.405962
0.40	0.017660	0.290741
0.45	0.032987	0.197760
0.50	0.054960	0.125368
0.55	0.084625	0.071765
0.60	0.122991	0.034959
0.65	0.171041	0.012686
0.70	0.229732	0.002243
0.75	0.300000	0.000000

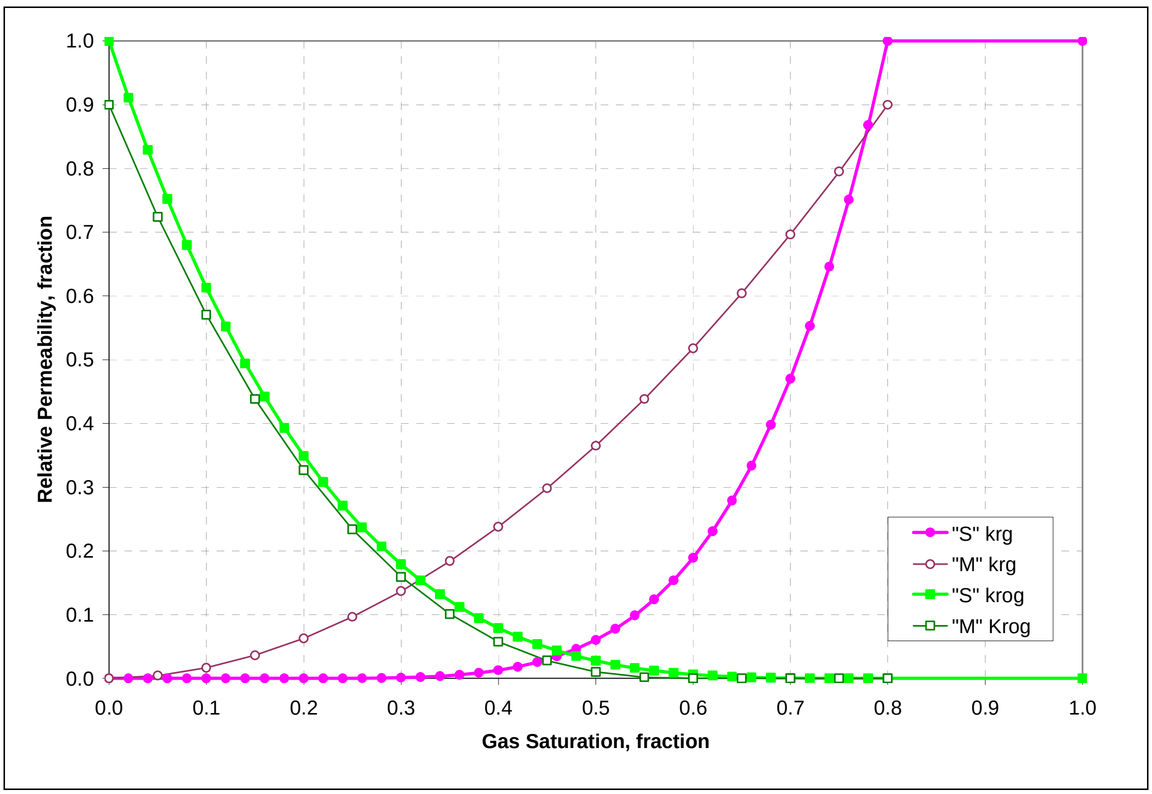

Fig. 14 – Plot of "M" and "S" sets of gas-liquid relative permeability versus gas saturation.

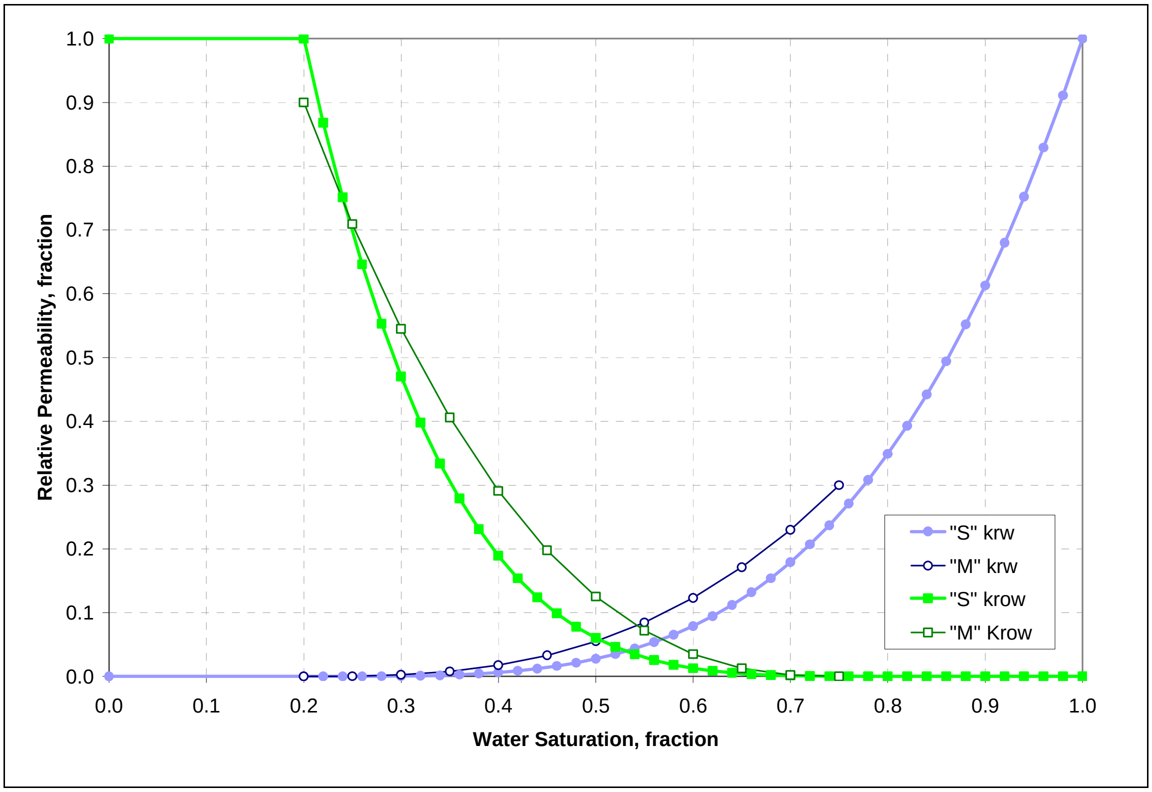

Fig. 15 – Plot of "M" and "S" sets of water-oil relative permeability versus water saturation.

3.4 Grid Configuration Selection

It was important to utilize a grid that has an adequate number of cells and can run within acceptable amount of computation time. Table 11 lists the simulation runs that were carried out to check the sensitivity of oil recovery calculations to grid size and configuration. All cases were simulated with the same input and control parameters but with different grid configurations.

TABLE 11 - GRID SELECTION SENSITIVITY RUNS								
	No. of Cells				(X,Y) Size Range		Areal	Run
	X	Y	Z	Total	min	Max	Increment	Time
Case	(ea)	(ea)	(ea)	(ea)	(ft.)	(ft.)	(factor)	(min.)
1A	11	6	15	990	4.0	618.19	2.7404	5.7
2A	21	11	15	3,465	4.0	280.33	1.5295	14.2
3A1	41	21	15	12,915	4.0	114.41	1.1825	48.1
4A	81	41	15	49,815	4.0	43.28	1.06134	236.1
5A	41	21	6	5,166	4.0	114.41	1.1825	3.6
6A	41	21	20	17,220	4.0	114.41	1.1825	111.8

3.4.1 Areal Grid Configuration

Four different grid configurations were investigated in the areal direction. In all cases, ΔX and ΔY sizes are incrementally changed by a constant factor, always keeping the smallest cells, 4.0 ft., at the wells and the coarsest cells in the center of the reservoir (see Fig. 16 through Fig. 19). Simulation oil recovery (presented in Fig. 20) showed that cases 2A, 3A1 and 4A are very comparable. Case 3A1 with a grid of (41x21x15) was found to be the best considering fine gridding and reasonable run time of about 50 minutes.

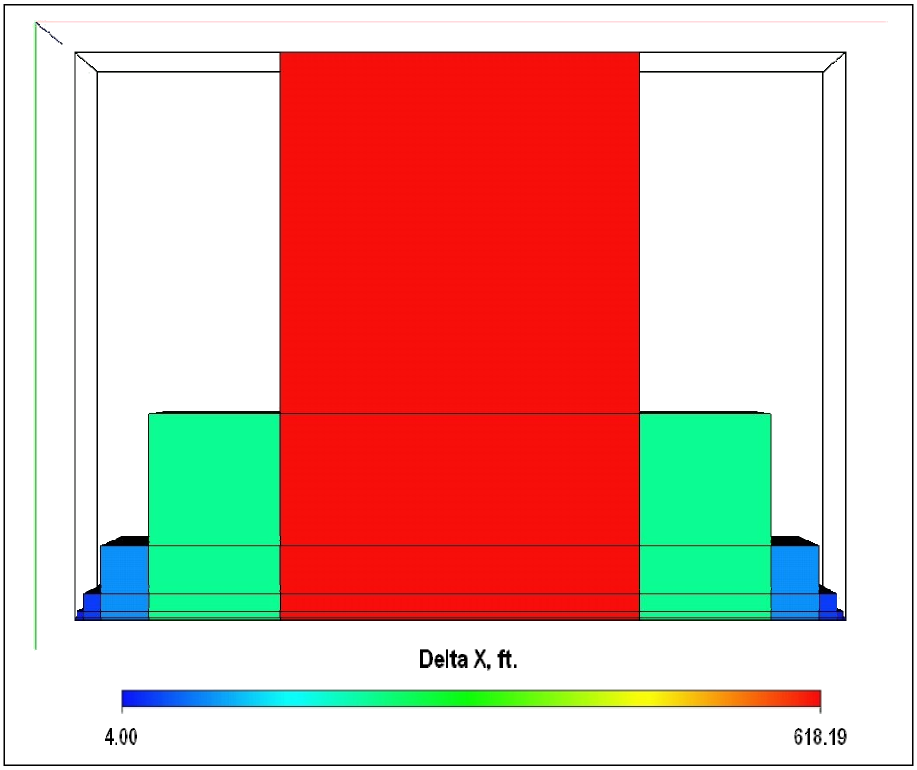

Fig. 16 – Areal grid (11x06x15), case 1A.

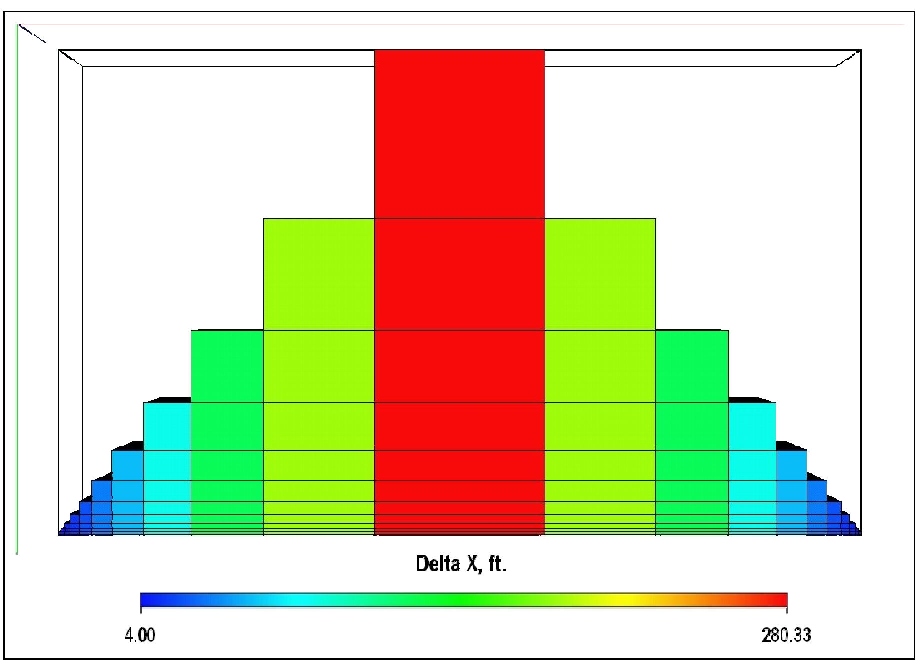

Fig. 17 – Areal grid (21x11x15), case 2A.

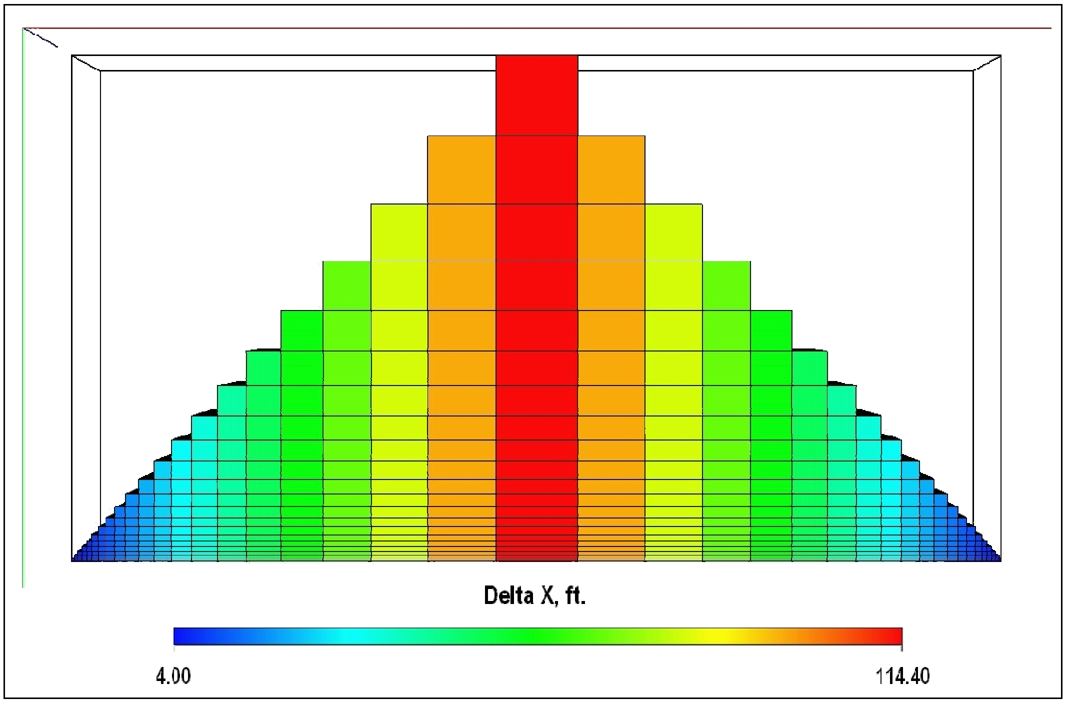

Fig. 18 – Areal grid (41x21x15), case 3A1.

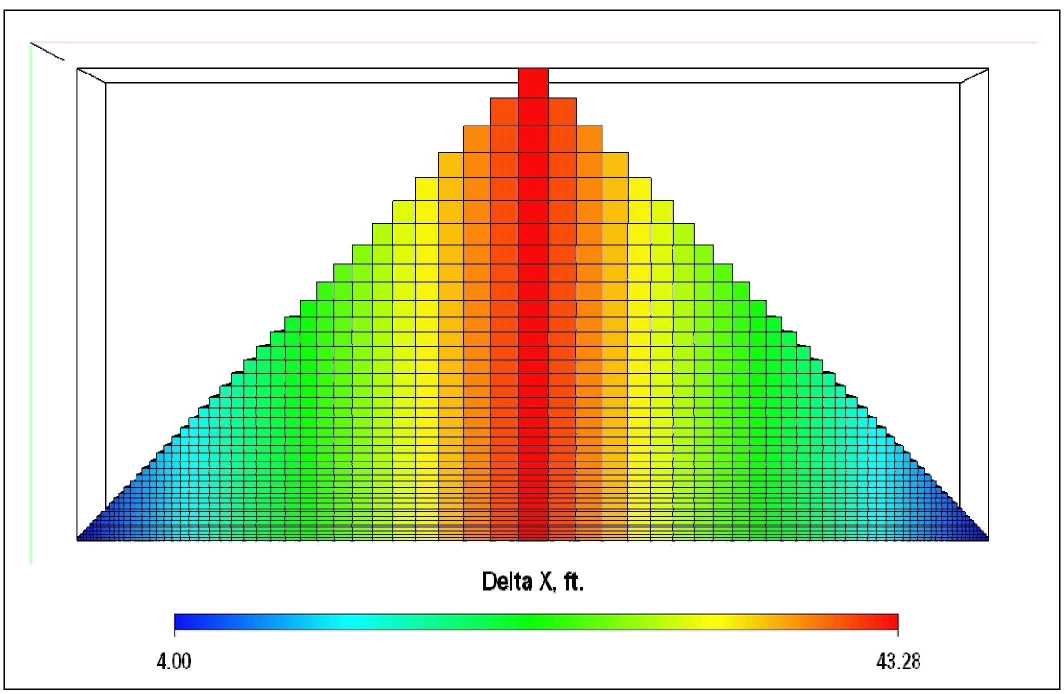

Fig. 19 – Areal grid (81x41x15), case 4A.

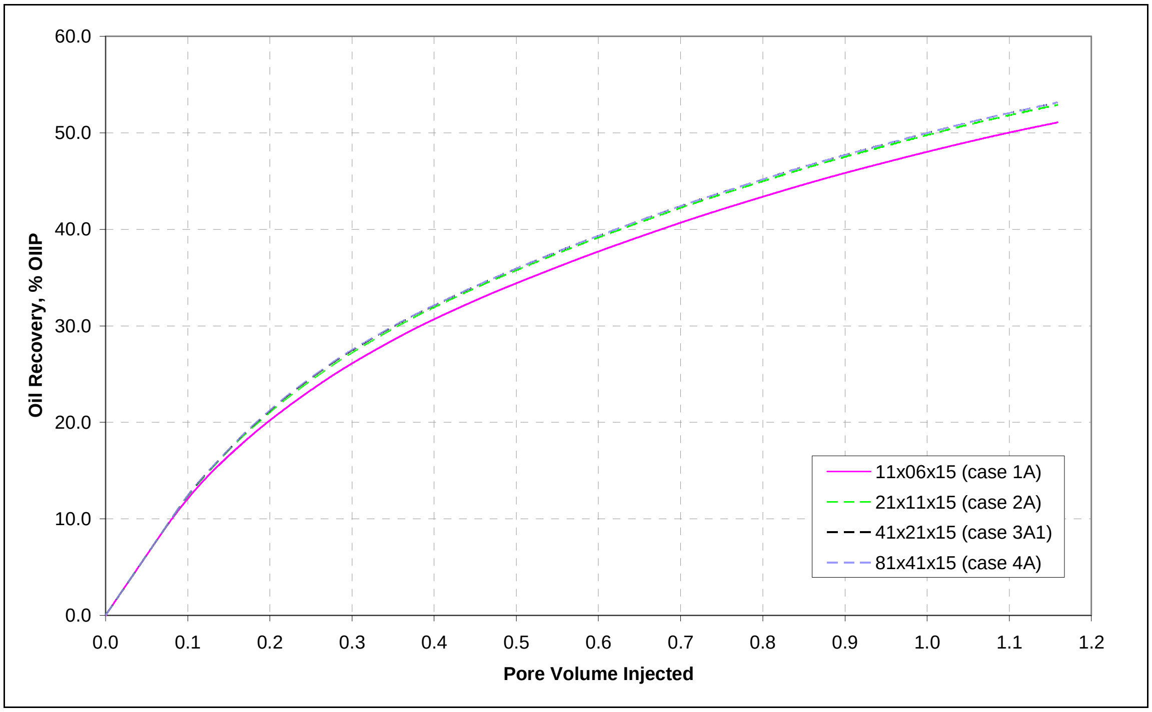

Fig. 20 – Oil recovery versus PV injected for investigated areal grid configurations.

3.4.2 Cross-Sectional Grid Configuration

Two additional cases (case 5A of 6 layers and case 6A of 20 layers) were compared to case 3A1 of 15 layers. Fig. 21 through Fig. 23 show the three cross-sectional configurations. Case 6A was limited to 20 layers because that is the maximum number of layers that can be connected to a well in the ECLIPSE-100 simulator. Simulation results for the different cress-sectional configurations (compared in Fig. 24), showed no difference in oil recovery calculation when 15 layers or more are used. Considering the finest grid at reasonable simulation time, the (41x21x15) grid configuration was selected for the study (see Fig. 25).

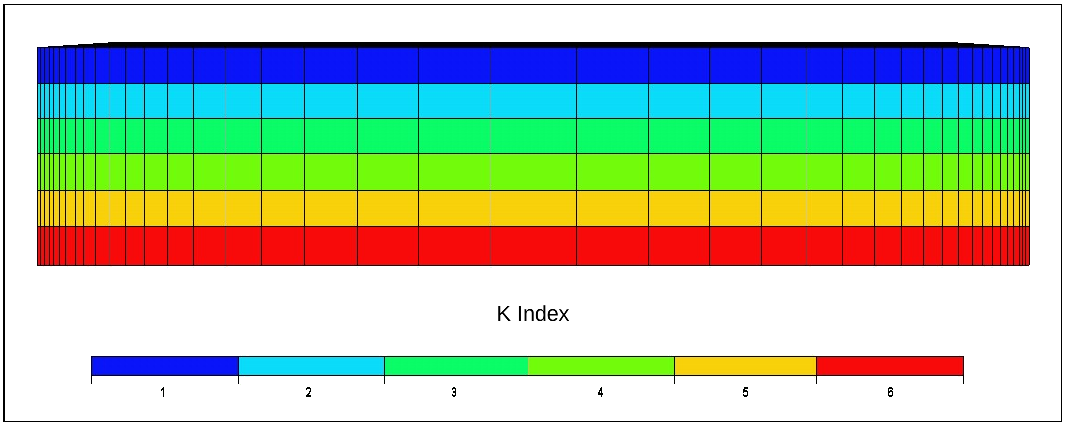

Fig. 21 – Cross-sectional grid (41x21x06), case 5A.

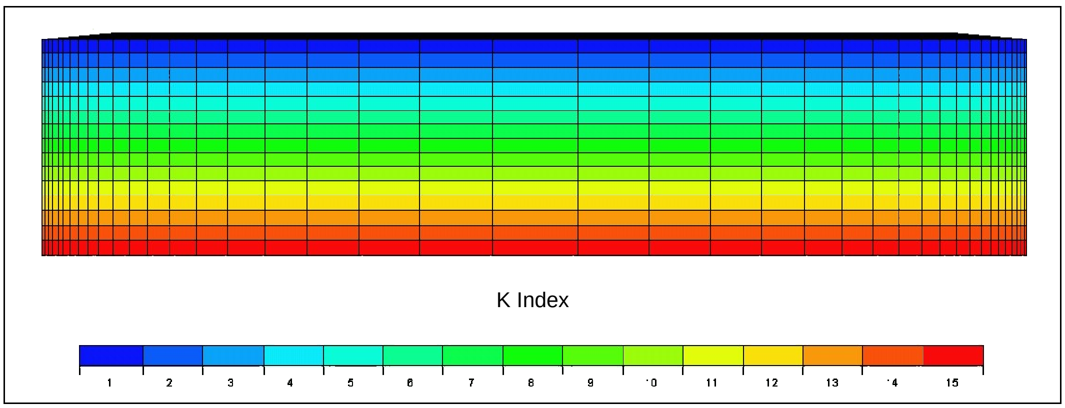

Fig. 22 – Cross-sectional grid (41x21x15), case 3A1.

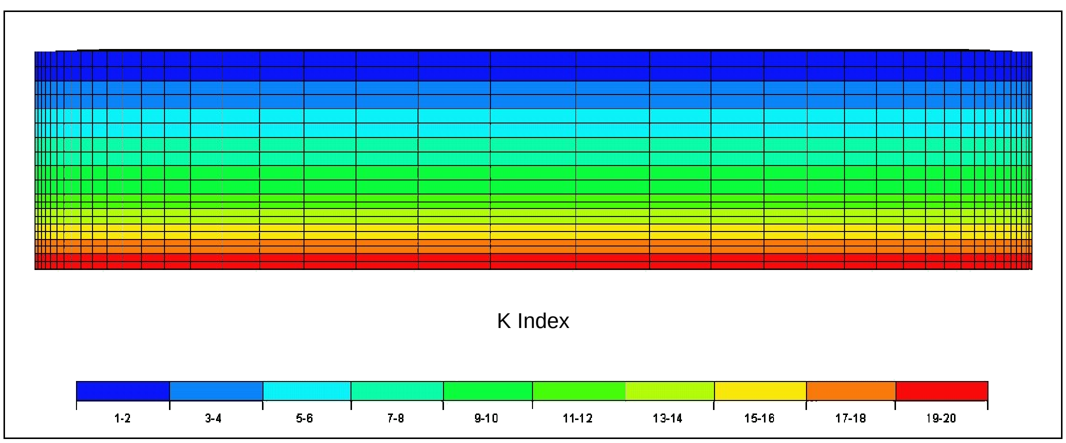

Fig. 23 – Cross-sectional grid (41x21x20), case 7A.

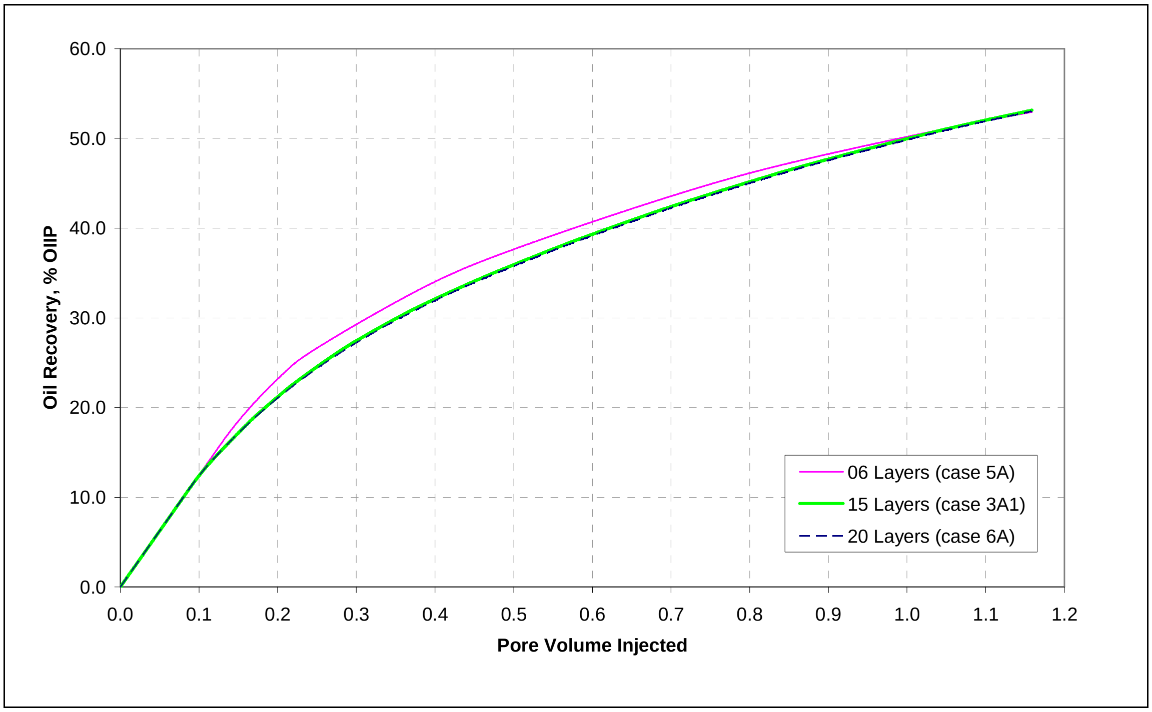

Fig. 24 – Oil recovery versus PV injected for investigated cross-sectional grid configurations.

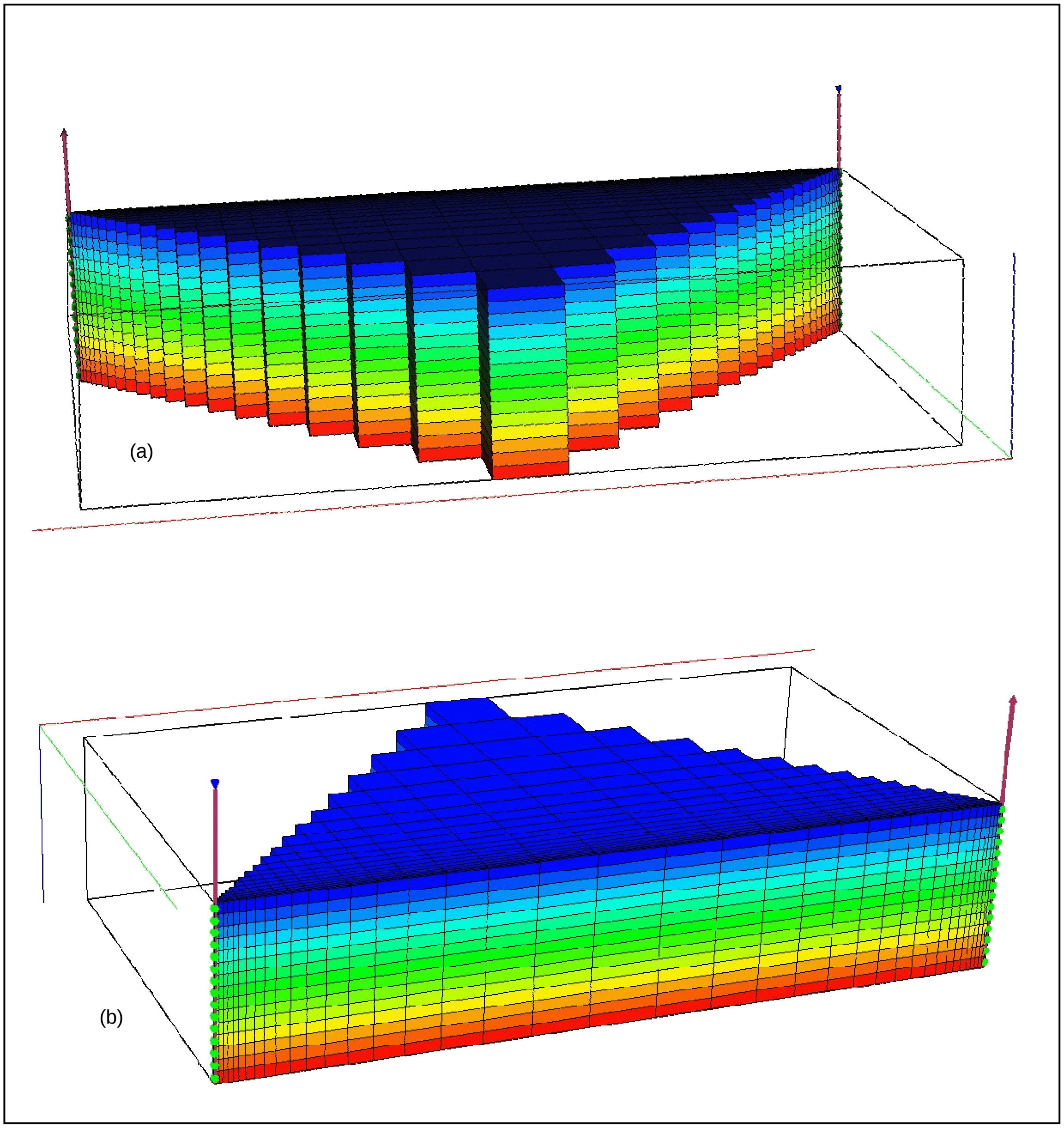

Fig. 25 – Schematic diagram of selected grid configuration. (a) Rare view, (b) Front view.

CHAPTER IV

SIMULATION RUNS ORGANIZATION

Results from over 100 simulation runs are presented in the study. They are subdivided into two main groups based on the relative permeability data used in the simulation.

4.1 Runs Using the "M" Set of Relative Permeability Data

In the first group simulation were carried out using the "M" set of relative permeability to evaluate the production performance of SSWAG injection versus mainly conventional WAG injection. Other drives or EOR methods were also considered in the evaluation, namely SWAG injection, natural depletion, gas injection and water flooding. Each of these oil recovery methods was simulated at 500 and 1,000 RB/D/Well injection rate. WAG injection was simulated at two different half-cycles. First at 3 months then at 6 months at each of the injection rates above. Water/gas injection ratio was maintained at 1:1 during WAG and SWAG injections runs.

SSWAG injection production performance was also investigated at the same injection rates above but in more detail. Each rate was first simulated at water/gas ratios of 1:1, 7:3 and 9:1 while maintaining continuous injection of both phases. The next step was to investigate the effect of periodic shut-offs of water injection into the upper portion of the reservoir. Stone (2004) suggested this practice to permit the gas injected into the lower portion of the reservoir to segregate and rise up, at a controlled rate, into the upper layers. No set guidelines were presented on how often these shut-offs should take place nor how long they should they last. Arbitrarily, four water injection shut-off schedules were selected for the purpose of the study. Each water injection/shut-off schedule was simulated 6 times at the combination of the three water/gas ratios and the two injection rates mentioned above. It was important that the injected gas rate was increased every time water injection was stopped to match the constant rate of production and maintain reservoir pressure. Therefore, the water/gas ratios indicated for those SSWAG injection runs represent only the period of simultaneous water and gas injection. Details on all runs using the "M" set of relative permeability are listed in Table 12.

TABLE 12 - SIMULATION RUNS USING THE "M" SET

Case	EOR Method	Injector Completion W (Layers)	Injector Completion G (Layers)	Injection Rate W (RB/D)	Injection Rate G (RB/D)	Total Prod. Rate (RB/D)	Injection Ratio (W : G)	WAG Cycle Water On/Off (months)
7A	ND	NA	NA	0	0	500	NA	NA
7B	ND	NA	NA	0	0	1,000	NA	NA
8A	GI	NA	1 - 15	0	500	500	0 : 1	NA
8B	GI	NA	1 - 15	0	1,000	1,000	0 : 1	NA
9A	WF	1 - 15	NA	500	0	500	1 : 0	NA
9B	WF	1 - 15	NA	1,000	0	1,000	1 : 0	NA
10A	SWAG	1 - 15	1 - 15	250	250	500	1 : 1	NA
10B	SWAG	1 - 15	1 - 15	500	500	1,000	1 : 1	NA
11A	WAG	1 - 15	1 - 15	500	500	500	1 : 1	WAG 3 / 3
11B	WAG	1 - 15	1 - 15	1,000	1,000	1,000	1 : 1	WAG 3 / 3
12A	WAG	1 - 15	1 - 15	500	500	500	1 : 1	WAG 6 / 6
12B	WAG	1 - 15	1 - 15	1,000	1,000	1,000	1 : 1	WAG 6 / 6

Table 12 continued.

Case	EOR Method	Injector Completion W (Layers)	Injector Completion G (Layers)	Injection Rate W (RB/D)	Injection Rate G (RB/D)	Total Prod. Rate (RB/D)	Injection Ratio (W : G)	WAG Cycle Water On/Off (months)
3A1	SSWAG	1 - 14	15	250	250	500	1 : 1	NA
3A2	SSWAG	1 - 14	15	350	150	500	7 : 3	NA
3A3	SSWAG	1 - 14	15	450	50	500	9 : 1	NA
3B1	SSWAG	1 - 14	15	500	500	1,000	1 : 1	NA
3B2	SSWAG	1 - 14	15	700	300	1,000	7 : 3	NA
3B3	SSWAG	1 - 14	15	900	100	1,000	9 : 1	NA
13A1	SSWAG	1 - 14	15	250	250	500	1 : 1	5 / 1
13A2	SSWAG	1 - 14	15	350	150	500	7 : 3	5 / 1
13A3	SSWAG	1 - 14	15	450	50	500	9 : 1	5 / 1
13B1	SSWAG	1 - 14	15	500	500	1,000	1 : 1	5 / 1
13B2	SSWAG	1 - 14	15	700	300	1,000	7 : 3	5 / 1
13B3	SSWAG	1 - 14	15	900	100	1,000	9 : 1	5 / 1
14A1	SSWAG	1 - 14	15	250	250	500	1 : 1	5.5 / 0.5
14A2	SSWAG	1 - 14	15	350	150	500	7 : 3	5.5 / 0.5
14A3	SSWAG	1 - 14	15	450	50	500	9 : 1	5.5 / 0.5
14B1	SSWAG	1 - 14	15	500	500	1,000	1 : 1	5.5 / 0.5
14B2	SSWAG	1 - 14	15	700	300	1,000	7 : 3	5.5 / 0.5
14B3	SSWAG	1 - 14	15	900	100	1,000	9 : 1	5.5 / 0.5
15A1	SSWAG	1 - 14	15	250	250	500	1 : 1	2 / 1
15A2	SSWAG	1 - 14	15	350	150	500	7 : 3	2 / 1
15A3	SSWAG	1 - 14	15	450	50	500	9 : 1	2 / 1
15B1	SSWAG	1 - 14	15	500	500	1,000	1 : 1	2 / 1
15B2	SSWAG	1 - 14	15	700	300	1,000	7 : 3	2 / 1
15B3	SSWAG	1 - 14	15	900	100	1,000	9 : 1	2 / 1
16A1	SSWAG	1 - 14	15	250	250	500	1 : 1	2.5 / 0.5
16A2	SSWAG	1 - 14	15	350	150	500	7 : 3	2.5 / 0.5
16A3	SSWAG	1 - 14	15	450	50	500	9 : 1	2.5 / 0.5
16B1	SSWAG	1 - 14	15	500	500	1,000	1 : 1	2.5 / 0.5
16B2	SSWAG	1 - 14	15	700	300	1,000	7 : 3	2.5 / 0.5
16B3	SSWAG	1 - 14	15	900	100	1,000	9 : 1	2.5 / 0.5

4.2 Runs Using the “S” Set of Relative Permeability Data

In this second group of simulation runs, the exact same procedure as used earlier was repeated using the “S” set of relative permeability data. Additional scenarios were simulated to investigate other SSWAG injection design parameters. Cases 23C, 23D and 24D represent higher injection rates. In case 28B, a fifth water injection shut-off schedule was simulated with equal times of water shut-off (gas injection only) and simultaneous water and gas injection. Then cases 29B and 30B investigated the effect of SSWAG injectors’ completion intervals on oil recovery.

In all simulation cases described so far, no combinations of oil recovery methods were considered. In other words, each oil recovery method was simulated separately from day one of production until abandonment (30 years). At this point, additional cases were considered in which waterflood is the initial EOR method. Once water cut at the producer reaches 80%, waterflood is replaced by SWAG injection, WAG injection, or by SSWAG injection. Each of these combinations was simulated at 500 and 1,000 RB/D/Well injection rates. In case of waterflood-SSWAG injection, it was also evaluated at on of the arbitrarily selected water injection shut-off schedules. Details of all the performed runs using the “S” set of relative permeability data are listed in Table 13.

TABLE 13 - SIMULATION RUNS USING THE "S" SET

		Injector Completion		Injection Rate		Total Prod.	Injection	WAG Cycle
	EOR	W	G	W	G	Rate	Ratio	Water On/Off
Case	Method	(Layers)	(Layers)	(RB/D)	(RB/D)	(RB/D)	(W : G)	(months)
17A	ND	NA	NA	0	0	500	NA	NA
17B	ND	NA	NA	0	0	1,000	NA	NA
18A	GI	NA	1 - 15	0	500	500	0 : 1	NA
18B	GI	NA	1 - 15	0	1,000	1,000	0 : 1	NA
19A	WF	1 - 15	NA	500	0	500	1 : 0	NA
19B	WF	1 - 15	NA	1,000	0	1,000	1 : 0	NA
20A	SWAG	1 - 15	1 - 15	250	250	500	1 : 1	NA
20B	SWAG	1 - 15	1 - 15	500	500	1,000	1 : 1	NA
21A	WAG	1 - 15	1 - 15	500	500	500	1 : 1	WAG 3 / 3
21B	WAG	1 - 15	1 - 15	1,000	1,000	1,000	1 : 1	WAG 3 / 3
22A	WAG	1 - 15	1 - 15	500	500	500	1 : 1	WAG 6 / 6
22B	WAG	1 - 15	1 - 15	1,000	1,000	1,000	1 : 1	WAG 6 / 6
23A1	SSWAG	1 - 14	15	250	250	500	1 : 1	NA
23A2	SSWAG	1 - 14	15	350	150	500	7 : 3	NA
23A3	SSWAG	1 - 14	15	450	50	500	9 : 1	NA
23B1	SSWAG	1 - 14	15	500	500	1,000	1 : 1	NA
23B2	SSWAG	1 - 14	15	700	300	1,000	7 : 3	NA
23B3	SSWAG	1 - 14	15	900	100	1,000	9 : 1	NA
23C	SSWAG	1 - 14	15	1,000	1,000	2,000	1 : 1	NA
23D	SSWAG	1 - 14	15	2,000	2,000	4,000	1 : 1	NA
24A1	SSWAG	1 - 14	15	250	250	500	1 : 1	5 / 1
24A2	SSWAG	1 - 14	15	350	150	500	7 : 3	5 / 1
24A3	SSWAG	1 - 14	15	450	50	500	9 : 1	5 / 1
24B1	SSWAG	1 - 14	15	500	500	1,000	1 : 1	5 / 1
24B2	SSWAG	1 - 14	15	700	300	1,000	7 : 3	5 / 1
24B3	SSWAG	1 - 14	15	900	100	1,000	9 : 1	5 / 1
24D	SSWAG	1 - 14	15	2,000	2,000	4,000	1 : 1	5 / 1
25A1	SSWAG	1 - 14	15	250	250	500	1 : 1	5.5 / 0.5
25A2	SSWAG	1 - 14	15	350	150	500	7 : 3	5.5 / 0.5
25A3	SSWAG	1 - 14	15	450	50	500	9 : 1	5.5 / 0.5
25B1	SSWAG	1 - 14	15	500	500	1,000	1 : 1	5.5 / 0.5
25B2	SSWAG	1 - 14	15	700	300	1,000	7 : 3	5.5 / 0.5
25B3	SSWAG	1 - 14	15	900	100	1,000	9 : 1	5.5 / 0.5
26A1	SSWAG	1 - 14	15	250	250	500	1 : 1	2 / 1
26A2	SSWAG	1 - 14	15	350	150	500	7 : 3	2 / 1
26A3	SSWAG	1 - 14	15	450	50	500	9 : 1	2 / 1
26B1	SSWAG	1 - 14	15	500	500	1,000	1 : 1	2 / 1
26B2	SSWAG	1 - 14	15	700	300	1,000	7 : 3	2 / 1
26B3	SSWAG	1 - 14	15	900	100	1,000	9 : 1	2 / 1

Table 13 continued.

Case	EOR Method	Injector Completion W (Layers)	Injector Completion G (Layers)	Injection Rate W (RB/D)	Injection Rate G (RB/D)	Total Prod. Rate (RB/D)	Injection Ratio (W : G)	WAG Cycle Water On/Off (months)
27A1	SSWAG	1 - 14	15	250	250	500	1 : 1	2.5 / 0.5
27A2	SSWAG	1 - 14	15	350	150	500	7 : 3	2.5 / 0.5
27A3	SSWAG	1 - 14	15	450	50	500	9 : 1	2.5 / 0.5
27B1	SSWAG	1 - 14	15	500	500	1,000	1 : 1	2.5 / 0.5
27B2	SSWAG	1 - 14	15	700	300	1,000	7 : 3	2.5 / 0.5
27B3	SSWAG	1 - 14	15	900	100	1,000	9 : 1	2.5 / 0.5
28B	SSWAG	1 - 14	15	500	500	1,000	1 : 1	3 / 3
29B	SSWAG	1 - 12	13 - 15	500	500	1,000	1 : 1	NA
30B	SSWAG	1 - 5	6 - 15	500	500	1,000	1 : 1	NA
31A	WF/SWAG	1 - 15	1 - 15	250	250	500	1 : 1	NA
31B	WF/SWAG	1 - 15	1 - 15	500	500	1,000	1 : 1	NA
32A	WF/WAG	1 - 15	1 - 15	500	500	500	1 : 1	WAG 3 / 3
32B	WF/WAG	1 - 15	1 - 15	1,000	1,000	1,000	1 : 1	WAG 3 / 3
33A	WF/SSWAG	1 - 14	15	250	250	500	1 : 1	NA
33B	WF/SSWAG	1 - 14	15	500	500	1,000	1 : 1	NA
34A	WF/SSWAG	1 - 14	15	250	250	500	1 : 1	5 / 1
34B	WF/SSWAG	1 - 14	15	500	500	1,000	1 : 1	5 / 1

Samples of ECLIPSE simulation data files are presented in the appendixes. Appendixes A through D present data files for the SSWAG, SWAG and WAG injections. Appendixes E through I contain supplement files for grid construction, porosity, permeability, and fluid PVT data.

CHAPTER V

"M" DATA SET SIMULATION RESULTS DISCUSSION

Oil recovery efficiency is used as the main comparison basis to evaluate and compare the different EOR methods considered in this study, mainly WAG versus SSWAG injections. This chapter presents results considering only the "M" set of relative permeability data.

5.1 Results Overview at 500 RB/D/Well Injection Rate

Fig. 26 presents results for all the scenarios examined considering the "M" set of relative permeability data at 500 RB/D/Well injection rate. On the figure, oil recovery calculation is presented at 0.25, 0.5 and 1.0 pore volume (PV) injected. Comparison of the different EOR methods considered at this injection rate showed that gas injection (case 8A) is the worst recovery method, resulting in only 33% OIIP recovery at 1.0 PV injected. Surprisingly, water flooding (case 9A) gave the overall best oil recovery, 57% OIIP, at the same injected PV. The two unique cycles of WAG injection and SWAG injection (cases 11A & 12A, and 10A respectively) produced similar oil recoveries, 50% OIIP. Then out of all the SSWAG injection scenarios examined at this rate (cases 3A1, 3A2, 3A3, 13A1, 13A2, 13A3, 14A1, 14A2, 14A3, 15A1, 15A2, 15A3, 16A1, 16A2 and 16A3), the best performance was obtained when continuous SSWAG injection was used at 9:1 water/gas injection ratio (i.e. case 3A3). In that case, 56% OIIP was produced by the time 1.0 PV was injected, which is slightly less than oil recovery with waterflood along although the opposite is true if these particular scenarios (9A and 3A3) were compared at 0.25 and 0.5 PV injected.

Two things were observed from the different SSWAG injection cases presented in Fig. 26. First, for the same SSWAG injection schedule, decreasing the amount of injected gas positively affects oil recovery. For an example, in cases 13A1, 13A2 and 13A3 water/gas ratio was increased from 1:1 to 7:3 then to 9:1 which resulted in 47%, 51% and 54% OIIP recovery respectively at 1.0 PV injected. The same trend was observed at 0.25 and 0.5 PV injected. Second, for the same SSWAG water/gas injection ratio and at the same PV injected, periodic water injection shut-offs had no significant effect on oil recovery. In average, 1-2% OIIP reduction in oil recovery was observed when water injection was shut-off periodically compared to continuous SSWAG injection.

Fig. 27 shows oil recovery versus time for the three continuous SSWAG injection cases and all other recovery methods including natural depletion of the reservoir (case 7A). There, it is clear that SSWAG injection at water/gas injection ratio higher than 1:1 performed better than considered WAG injection. At 9:1 water/gas injection ratio, SSWAG injection also outperformed water flooding in the first 5,000 days (13.7 yeas).

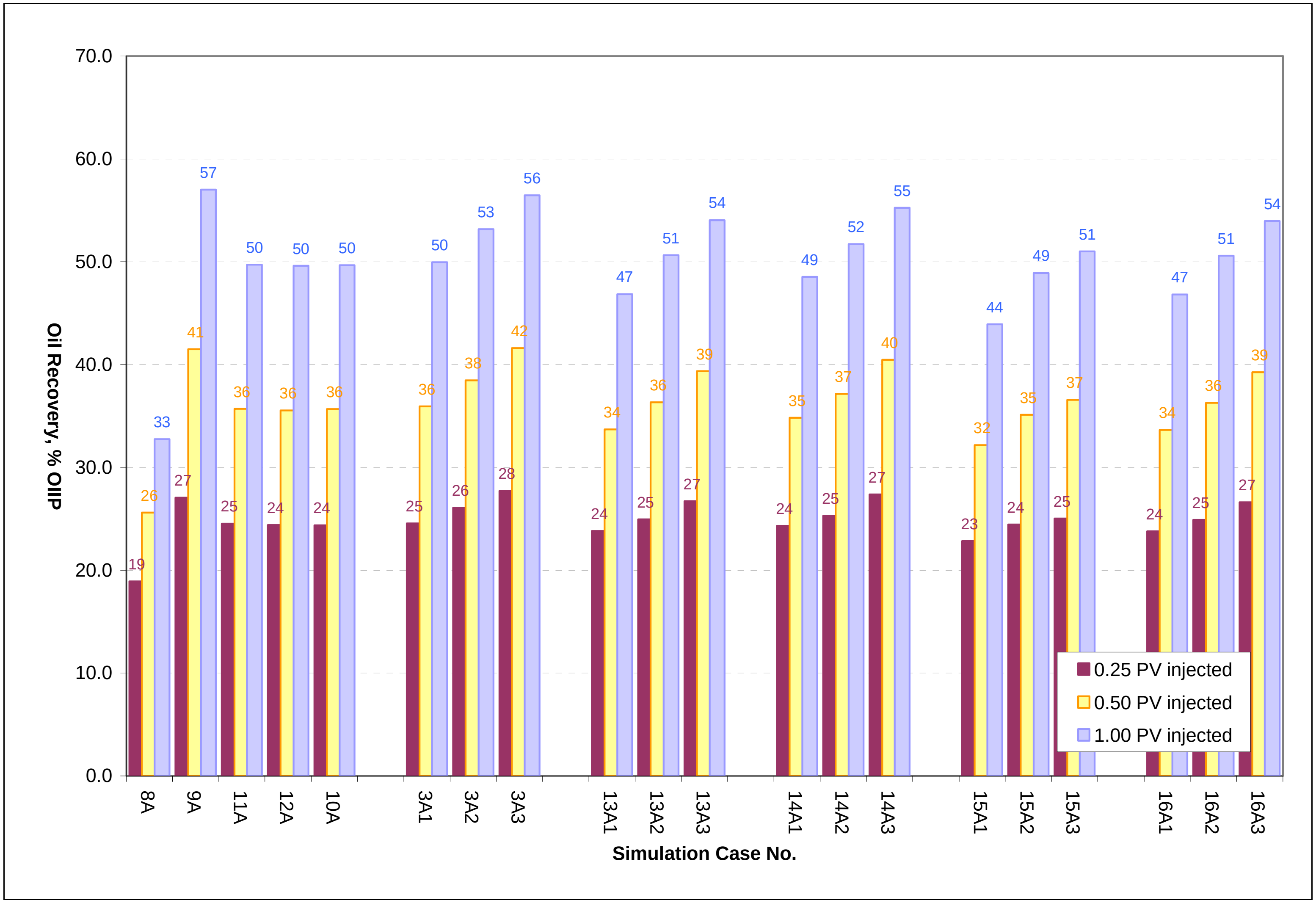

Fig. 26 – Oil recovery for selected injection scenarios using the "M" set at 500 RB/D/Well injection rate. Estimates are presented at 0.25, 0.5 and 1.0 PV injected.

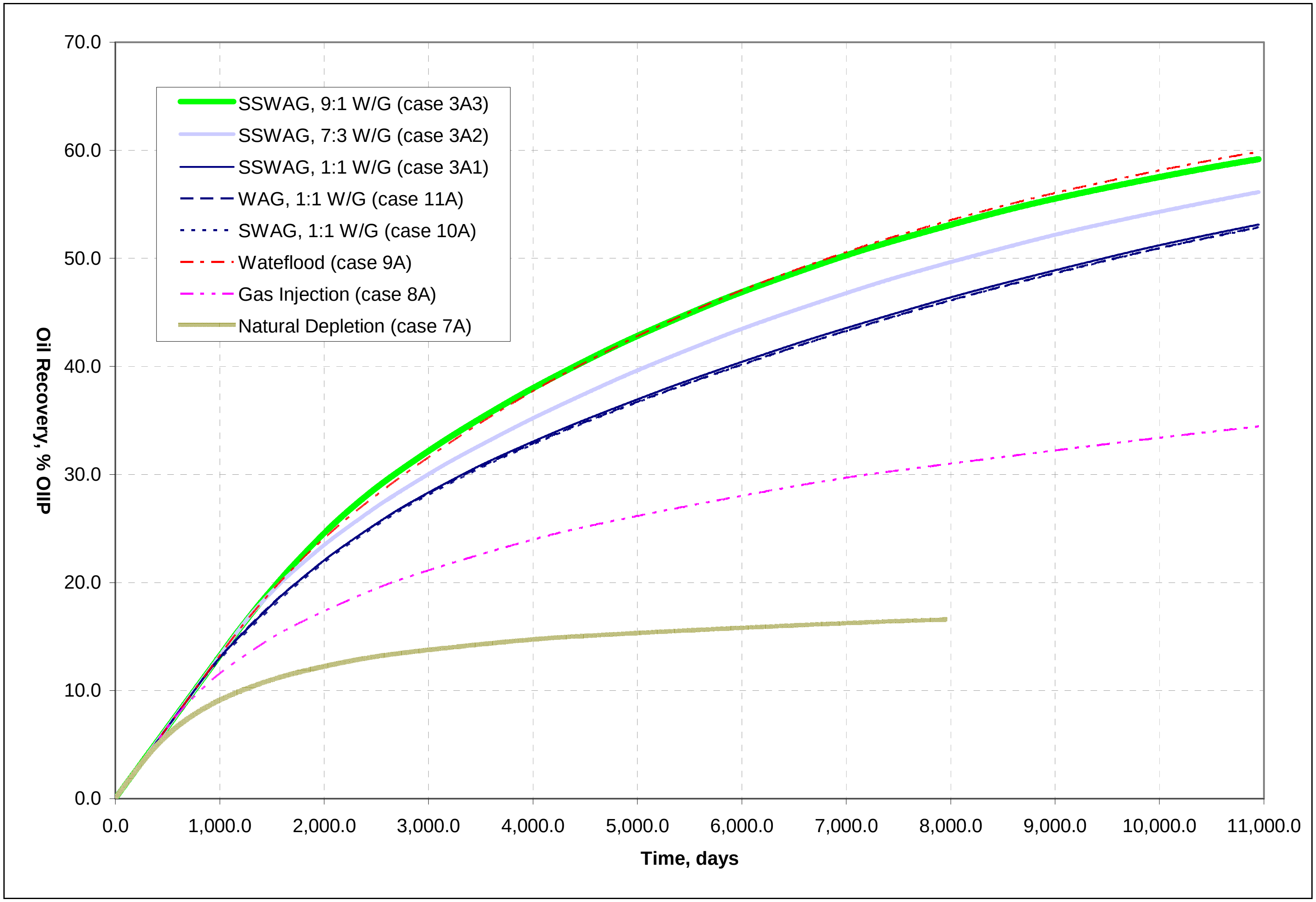

Fig. 27 – Oil recovery versus time for selected injection scenarios using the "M" set at 500 RB/D/Well injection rate.

5.2 Results Overview at 1,000 RB/D/Well Injection Rate

Simulation results for injection scenarios considering the “M” set of relative permeability data at 1,000 RB/D/Well injection rate are shown in Fig. 28. The figure is similar to Fig. 26 expert that results are shown at 0.5, 1.0 and 2.0 PV injected instead of at 0.25, 0.5 and 1.0 PV injected. In comparison at 1.0 PV injected, the higher injection rate resulted in 1-3% OIIP recovery increase in most cases, 5% higher in the case of gas injection (case 8A vs. case 8B).

Overall, there is no change in the trends observed earlier at 500 RB/D/Well injection rate. At 2.0 PV injected, gas injection produced the lowest oil recover of 49% OIIP (case 8B) while water flooding was the best recovery method producing 66% OIIP (case 9B). At the same PV injected and 1:1 water/gas injection ratio, WAG, SWAG, and continuous SSWAG injections (cases 11B, 12B, 10B and 3B1 respectively) all resulted in similar oil recovery figures in the range of 62-63% OIIP. In the case of SSWAG injection, a slightly higher oil recovery, 64-65% OIIP, was obtained when water/gas injection ratio was increased to 7:3 and later to 9:1 (cases 3B2 and 3B3 respectively). Fig. 28 also shows that SSWAG injection with various water injection shut-off schedules (cases 13B1, 13B2, 13B3, 14B1, 14B2, 14B3, 15B1, 15B2, 15B3, 16B1, 16B2 and 16B3) did not result in oil recovery increase compare to the continuous SSWAG injections (cases 3B1, 3B2, and 3B3) at the same water/gas injection ratio.

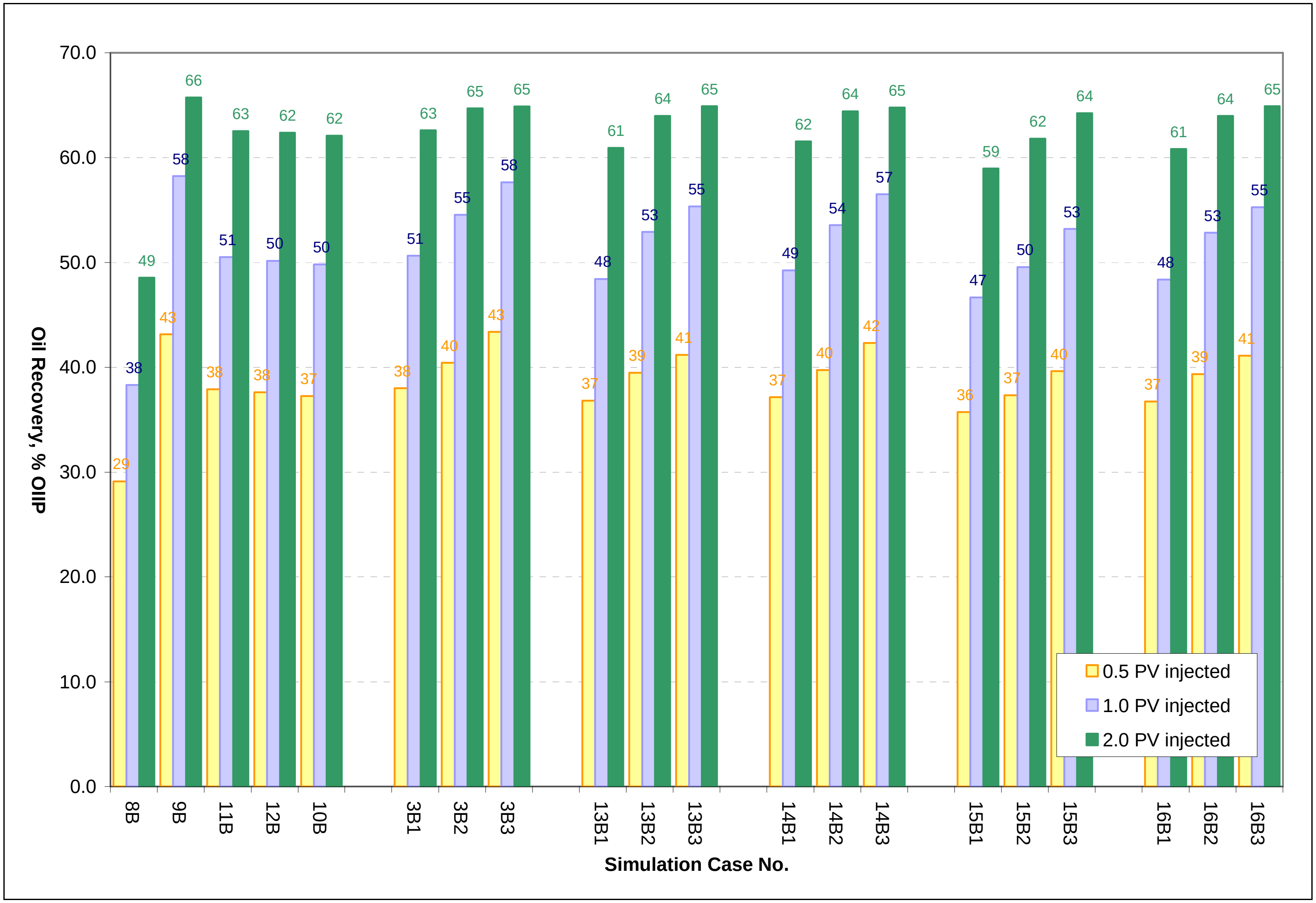

Fig. 28 – Oil recovery for selected injection scenarios using the "M" set at 1,000 RB/D/Well injection rate. Estimates are presented at 0.5, 1.0 and 2.0 PV injected.

In Fig. 29, oil recovery estimates for selected scenarios are related to that of natural depletion (case 7B) as a function of time for the same reservoir volume produced. It also shows that increasing water/gas injection ratio speeds up oil recovery. For an example, at the ratio of 9:1 (case 3B3), it took 5,500 days to obtain 60% OIIP recovery while at the ratio of 7:3, the same amount of oil was recovered in 6,450 days.

5.3 Fluid Saturations Distribution

Fig. 30 through Fig. 34 represent snap shots of fluid saturations distribution during some of the simulated scenarios at 1,000 RB/D/Well injection rate. The span shots are presented from two directions (cross-sectional and areal) at four steps (0.1, 0.5, 1.0 and 2.0 PV injected). In the case of gas injection (Fig. 30), gas segregation happened immediately at the injector. Gas then flowed through the top layers overrunning formation oil and quickly found its way to the producer. By the time 0.1 PV of gas is injected, injected gas had already broken through at the producer. At 2.0 PV injected, just over half of the formation had gas saturation present. In the case of water flooding (Fig. 31), gravity segregation occurred at a considerable distance away from the injector providing better vertical sweep around the injector than gas injection. Initially, water front advanced evenly through the top layers. In the relatively high permeability bottom layers, the water front was distorted as injected water under-ran formation oil. Injected water eventually reaches the producer but at a longer time period than the gas in case 8B. At 2.0 PV, injected water had already contacted most of the formation.

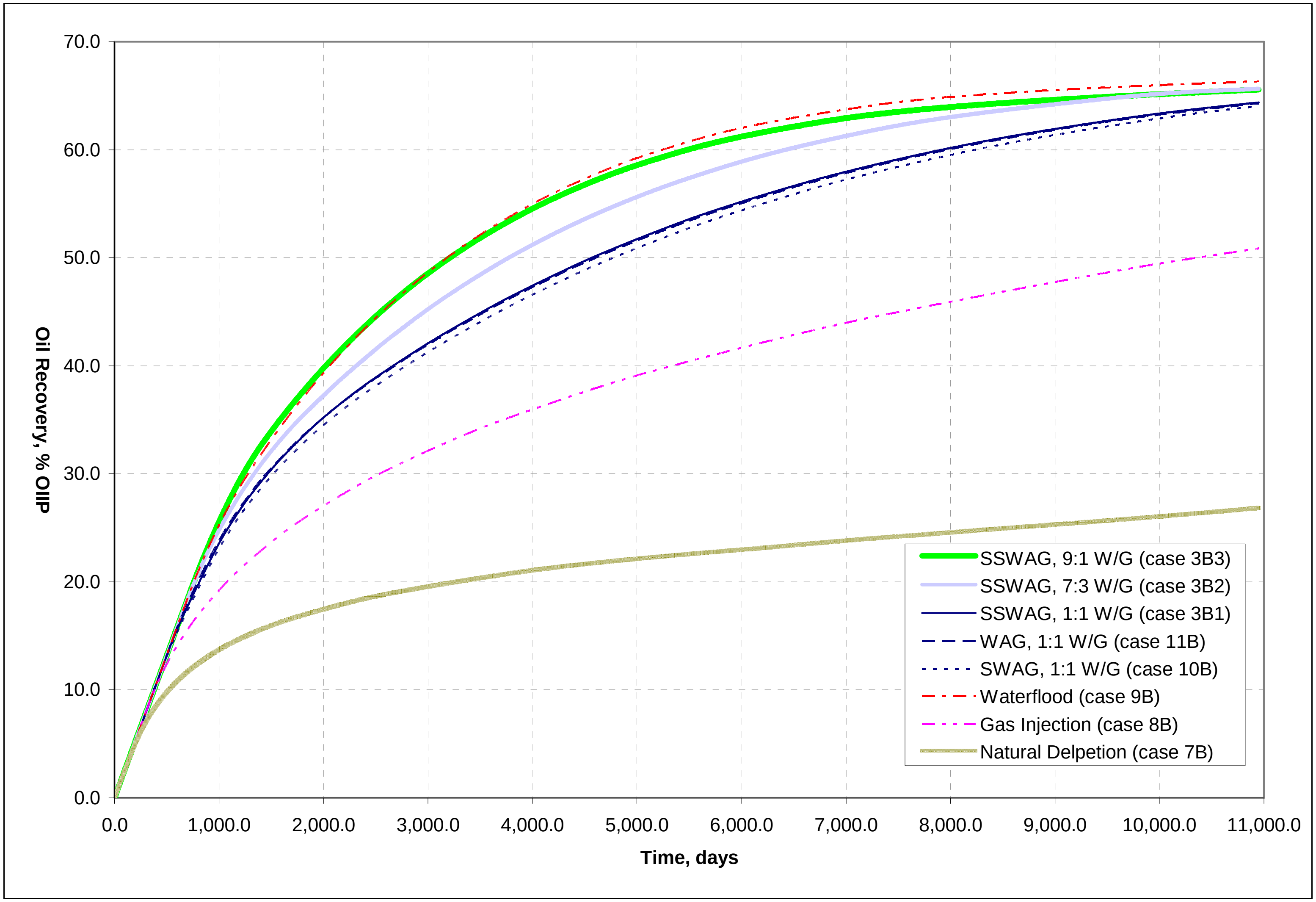

Fig. 29 – Oil recovery versus time for selected injection scenarios using the "M" set at 1,000 RB/D/Well injection rate.

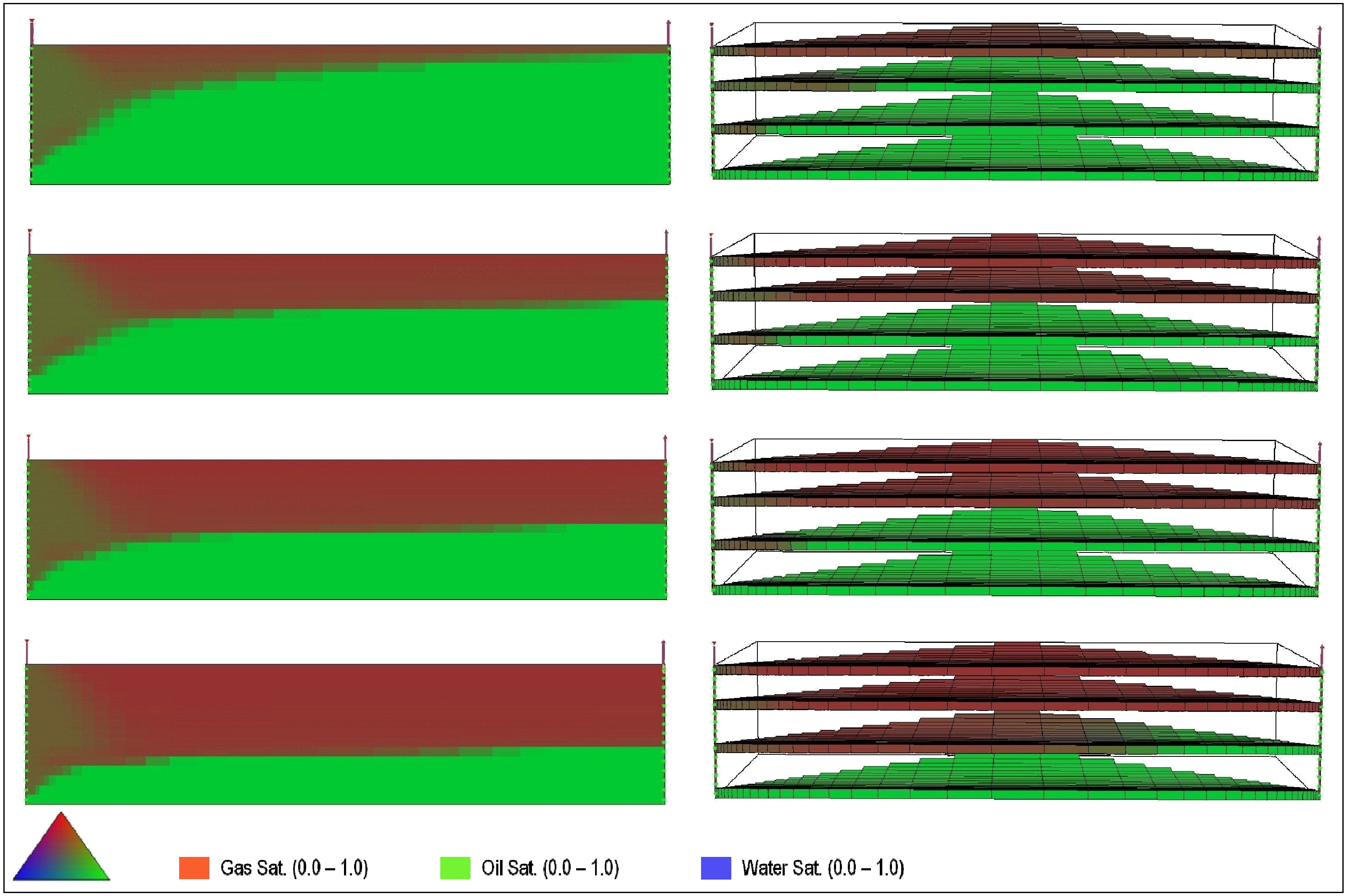

Fig. 30 – Fluid saturations distribution during gas injection (case 8B). On the left from top to bottom, cross-sectional views at 0.1, 0.5, 1.0 and 2.0 PV injected. Corresponding areal views shown on the right (layers no. 1, 5, 10, and 15).

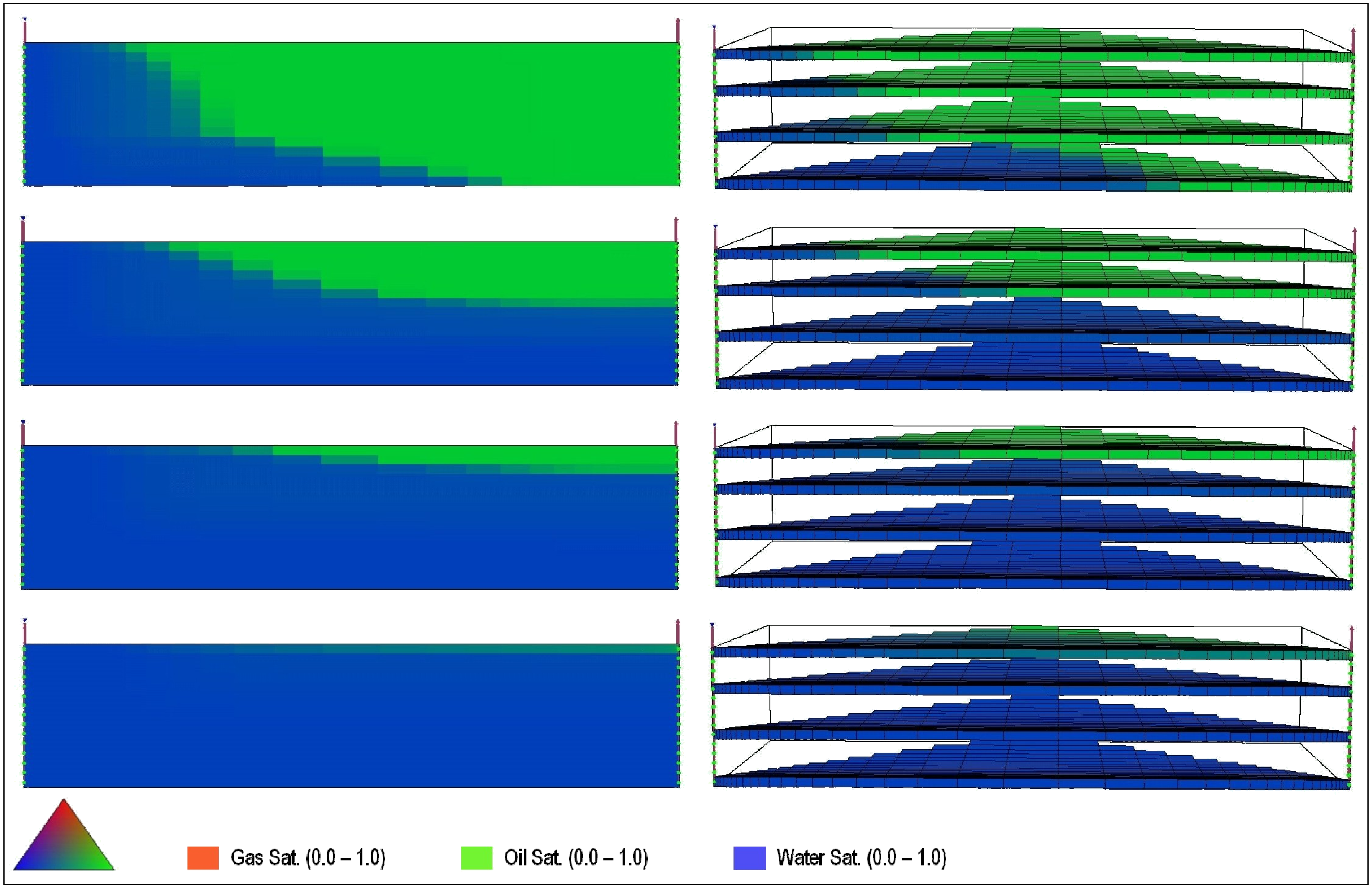

Fig. 31 – Fluid saturations distribution during water flooding (case 9B). On the left from top to bottom, cross-sectional views at 0.1, 0.5, 1.0 and 2.0 PV injected. Corresponding areal views shown on the right (layers no. 1, 5, 10, and 15).

Fig. 32, Fig. 33 and Fig. 34 represent SWAG, WAG and continuous SSWAG injections respectively all at 1:1 water/was injection ratio. The three cases produced similar saturations distribution for injected gas, injected water and formation oil. Water under-ran oil and flowed to the producer via the bottom high permeability layers. Gas segregated immediately in the case of WAG injection. Injected gas traveled a little deeper into the formation in the other two injection scenarios. In all three cases, complete segregating of the injected water and injected gas occurred at about 360 ft away from the injector (27% the distance between the injector and the producer). After segregation, gas flowed only in the top 38 ft of the formation, i.e. only 13% of formation thickness was swept by injected gas.

A close look at the oil saturation in the swept areas is shown in Fig. 35 for the cases of WAG and continuous SSWAG injections (cases 11B and 3B1 respectively). The areas swept by gas only (top layers) had the lowest oil saturation, around 20%. Surprisingly, the areas of mixed water and gas flow showed higher oil saturations than the areas swept by water only (see Fig. 35 at 1.0 and 2.0 PV injected). The only physical explanation to this observation is that oil was trapped by flowing water.

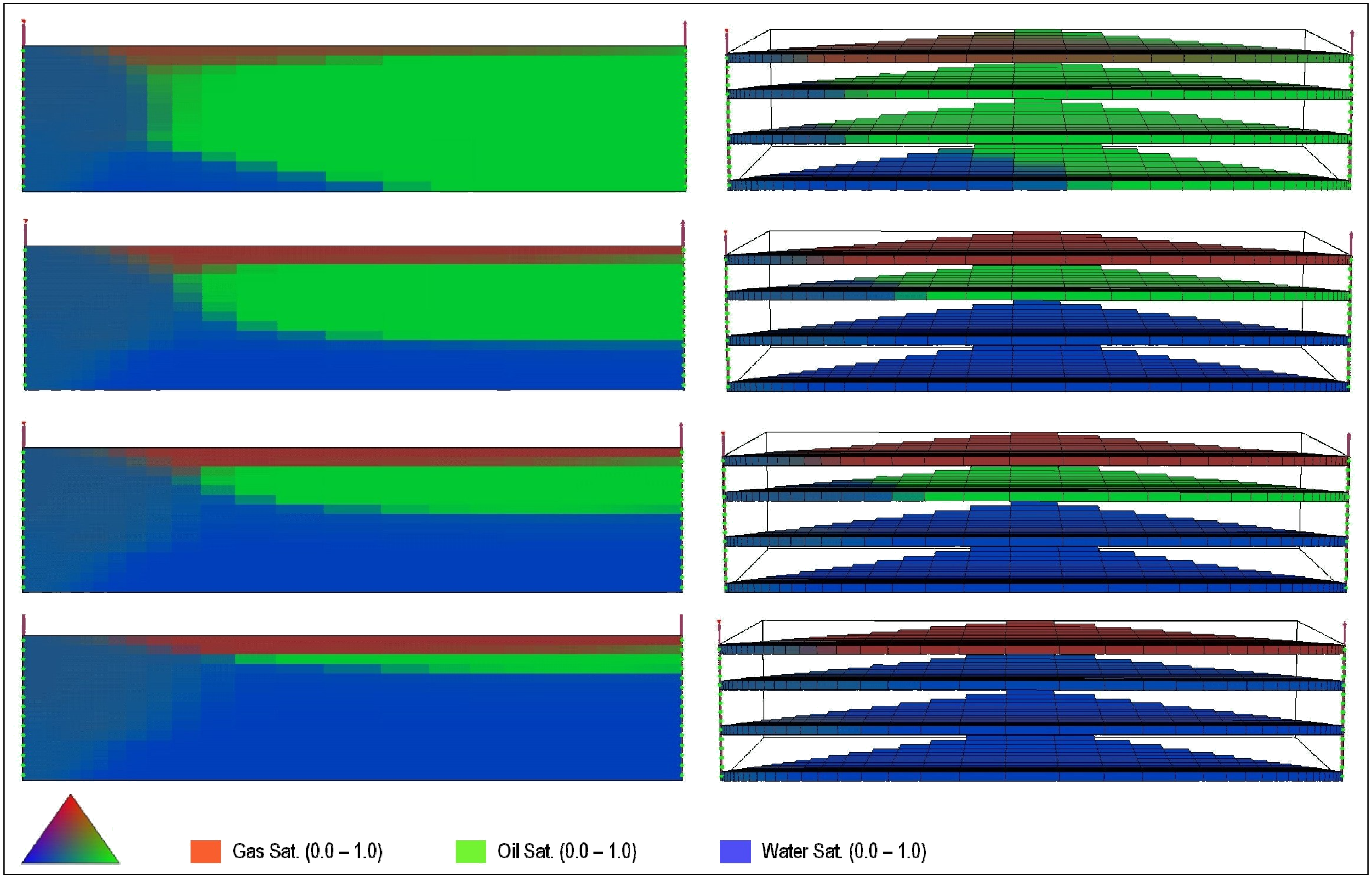

Fig. 32 – Fluid saturations distribution during SWAG injection (case 10B). On the left from top to bottom, cross-sectional views at 0.1, 0.5, 1.0 and 2.0 PV injected. Corresponding areal views shown on the right (layers no. 1, 5, 10, and 15).

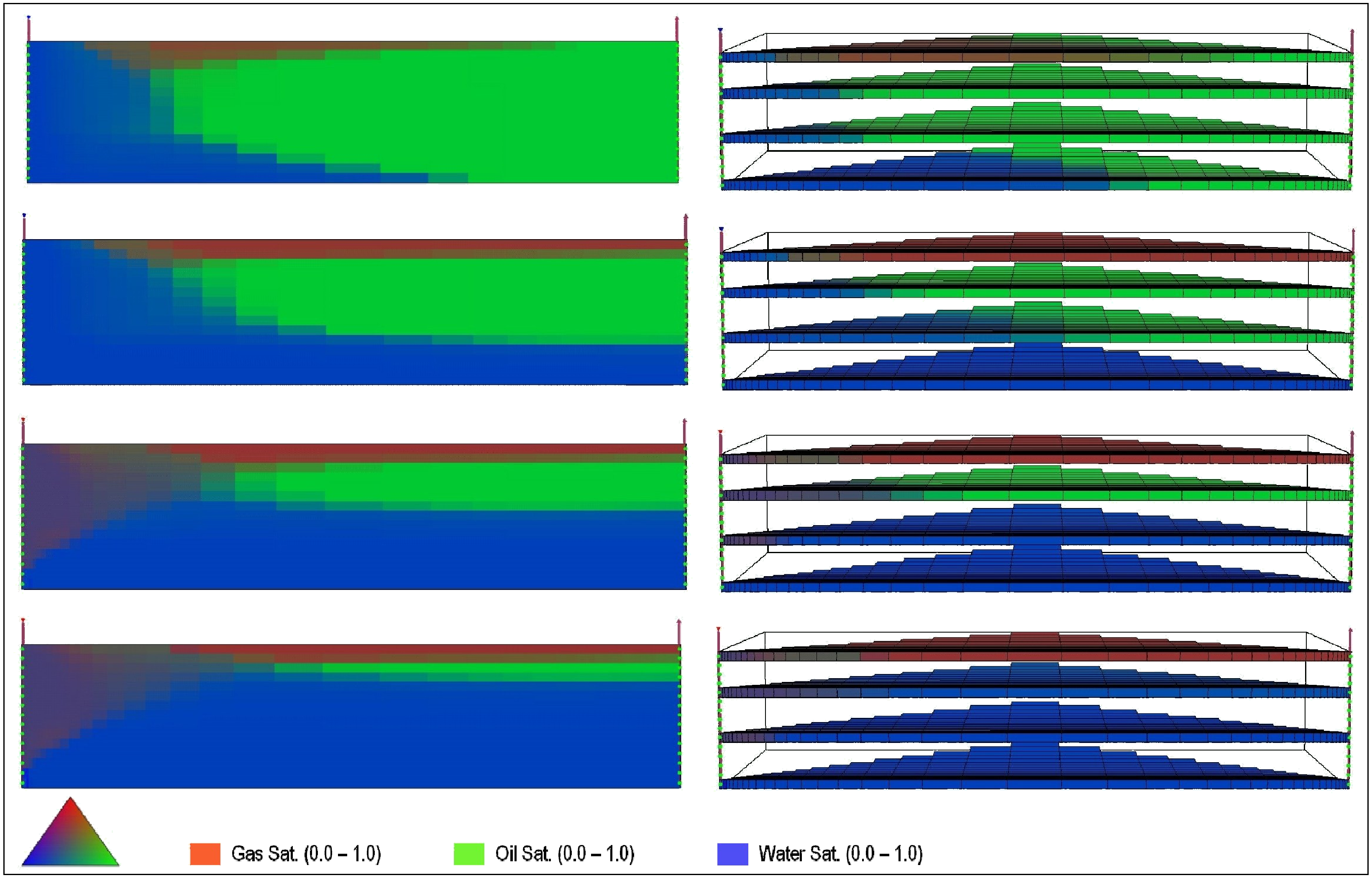

Fig. 33 – Fluid saturations distribution during WAG injection (case 11B). On the left from top to bottom, cross-sectional views at 0.1, 0.5, 1.0 and 2.0 PV injected. Corresponding areal views shown on the right (layers no. 1, 5, 10, and 15).

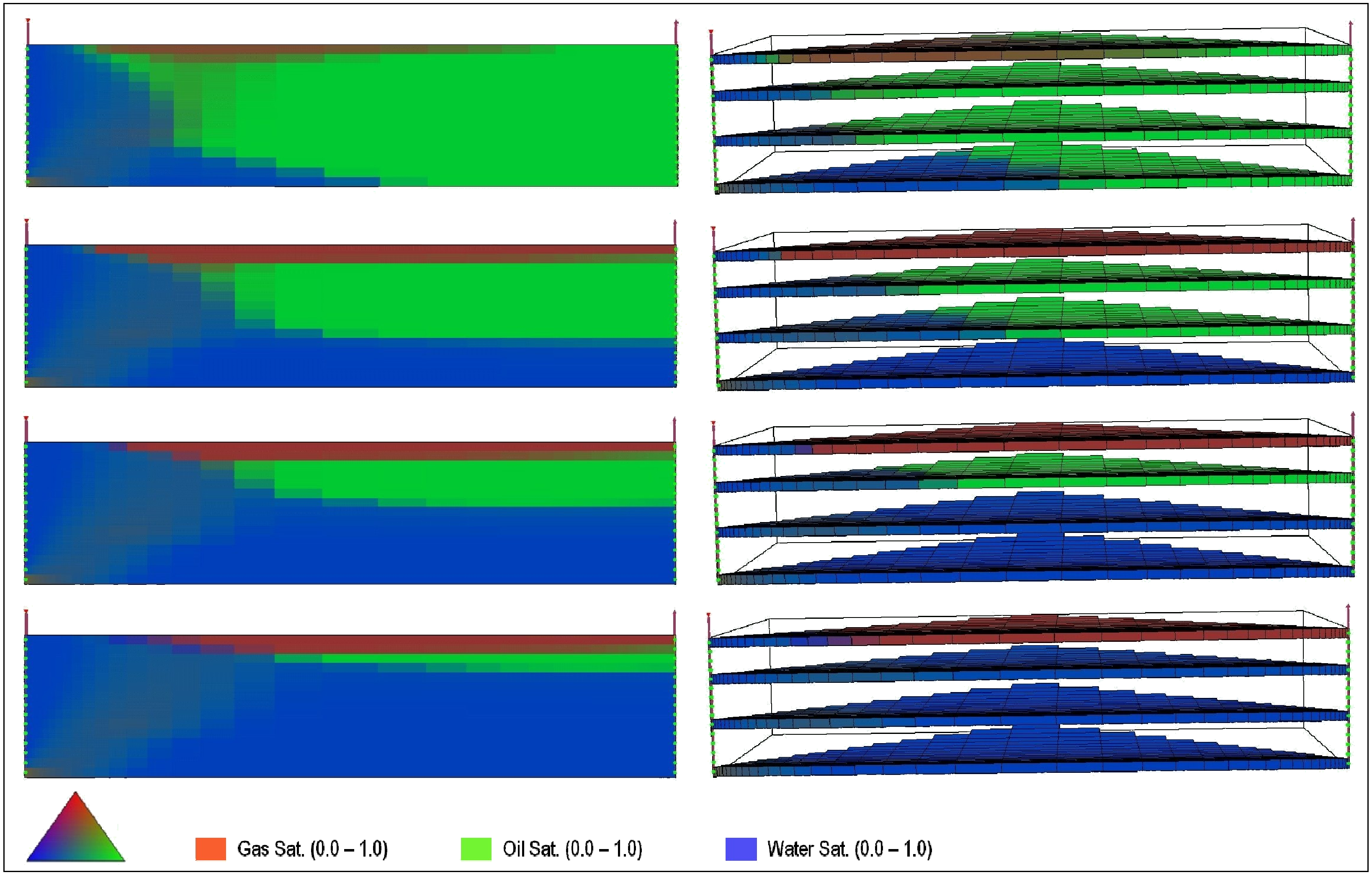

Fig. 34 – Fluid saturations distribution during SSWAG injection (case 3B1). On the left from top to bottom, cross-sectional views at 0.1, 0.5, 1.0 and 2.0 PV injected. Corresponding areal views shown on the right (layers no. 1, 5, 10, and 15).

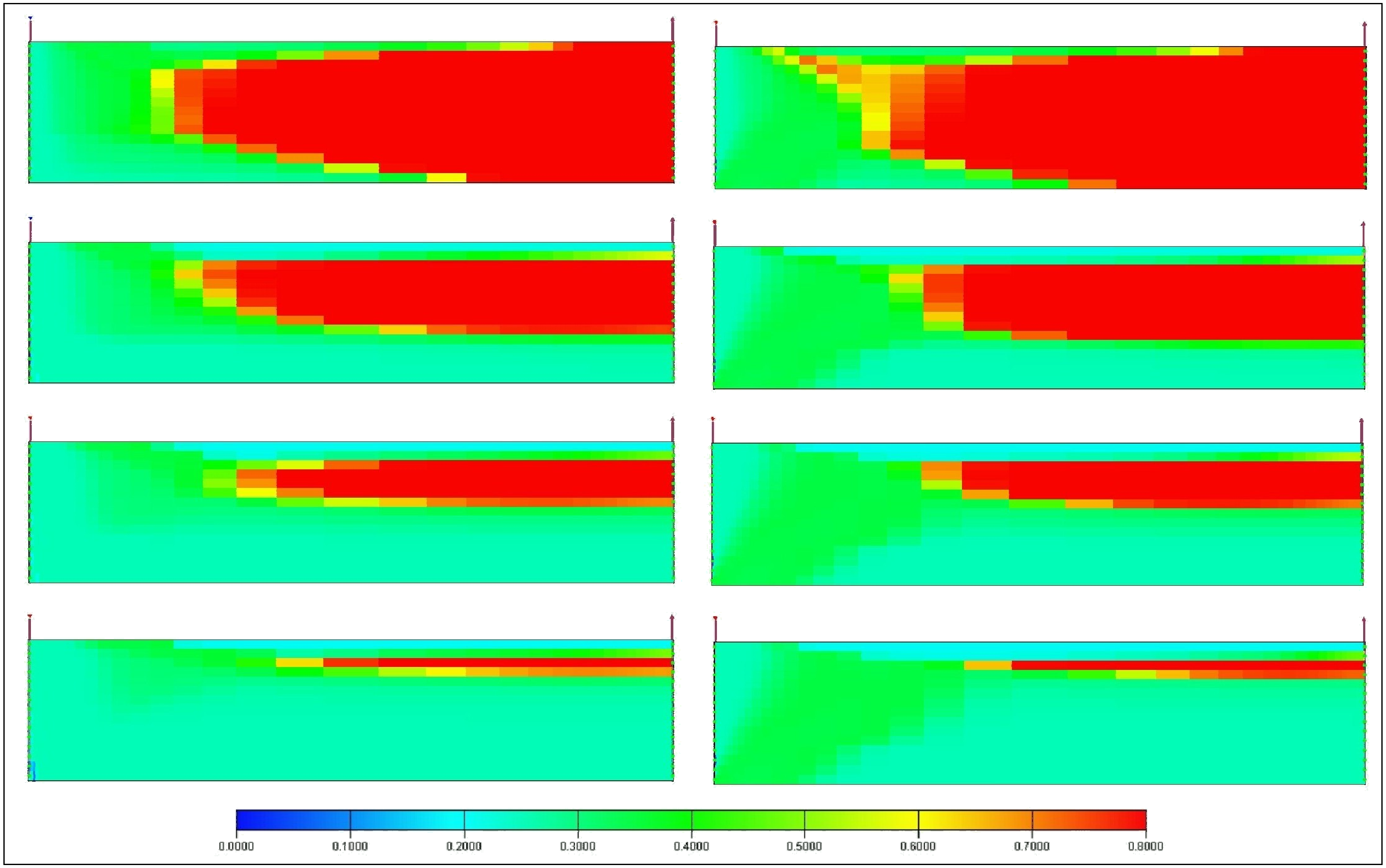

Fig. 35 – Cross-sectional views showing oil saturation during WAG (case 11B) and SSWAG (case 3B1) injections. In both cases (WAG snaps on the left and SSWAG snaps on the right), snap shots are presented at 0.1, 0.5, 1.0 and 2.0 PV injected from top to bottom respectively.

CHAPTER VI

"S" DATA SET SIMULATION RESULTS DISCUSSION

In this chapter, only results from simulation runs performed with the "S" set of relative permeability data are discussed. This includes results for the same injection rates considered earlier and additional scenarios at higher injection rates. It also includes results of combined EOR methods, i.e. initial oil recovery by waterflood followed by one of the combined water and gas injection methods for secondary recovery. Finally, investigation results on SSWAG injector completion are presented. The results are mainly presented in similar manner to that followed in the previous chapter.

6.1 Results Overview at 500 RB/D/Well Injection Rate

Fig. 36 shows the results of examined scenarios at 500 RB/D/Well injection rate. Oil recovery estimates are presented at 0.25, 0.5 and at 1.0 PV injected. Overall, better oil recoveries were obtained compared to using the "M" set of relative permeability data at the same injection rate. At 1.0 PV injected, gas injection (case 18A) resulted in the lowest oil recovery of 41% OIIP. The next lowest was SWAG injection (case 20A) giving 57% OIIP recovery. The two unique WAG injection cycles (case 11A & 12A) and waterflood (case 19A) resulted in equal oil recoveries, 59% OIIP. SSWAG injection was by far the best injection method in this formation yielding 65-66% recovery at 1.0 PV injected (cases 23A1, 23A2).

SSWAG injection scenarios with water injection shut-off schedules (cases 24A1, 24A2, 24A3, 25A1, 25A2, 25A3, 26A1, 26A2, 26A3, 27A1, 27A2 and 27A3) had no significant effect on oil recovery compare to continuous SSWAG injection (cases 23A1, 23A2 and 23A3. In these cases, the trend of increasing recovery by reducing injected gas does not apply.

Fig. 37 presents oil recovery versus time for the continuous SSWAG injection cases and all other injection methods as well as natural deletion. It shows that SSWAG injection was always better than WAG injection and any other injection method for the examined water/gas injection ratios. On this figure, oil recovery estimates for natural depletion (case 17A) were at fist questionable. Examining the results showed that when formation pressure dropped below the bubble point pressure, 2,600 psia, gas came out of solution and remained in the formation until it reached critical saturation. At the mean time oil rate increased to substitute for the drop in gas production since the producer is controlled by constant reservoir volume produced. Eventually gas became mobile in the formation and was produced with the oil.

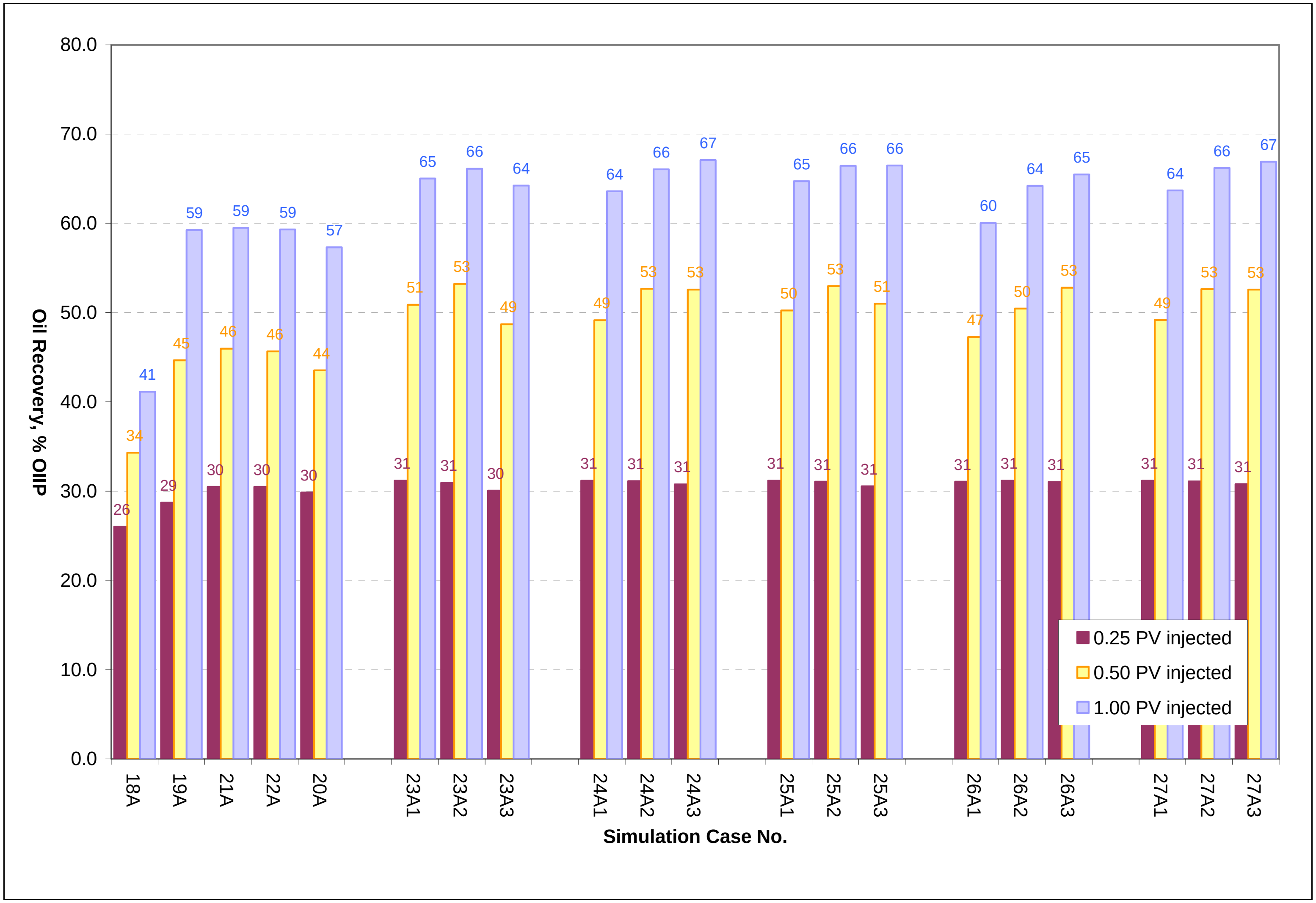

Fig. 36 – Oil recovery for selected injection scenarios using the "S" set at 500 RB/D/Well injection rate. Estimates are presented at 0.25, 0.5 and 1.0 PV injected.

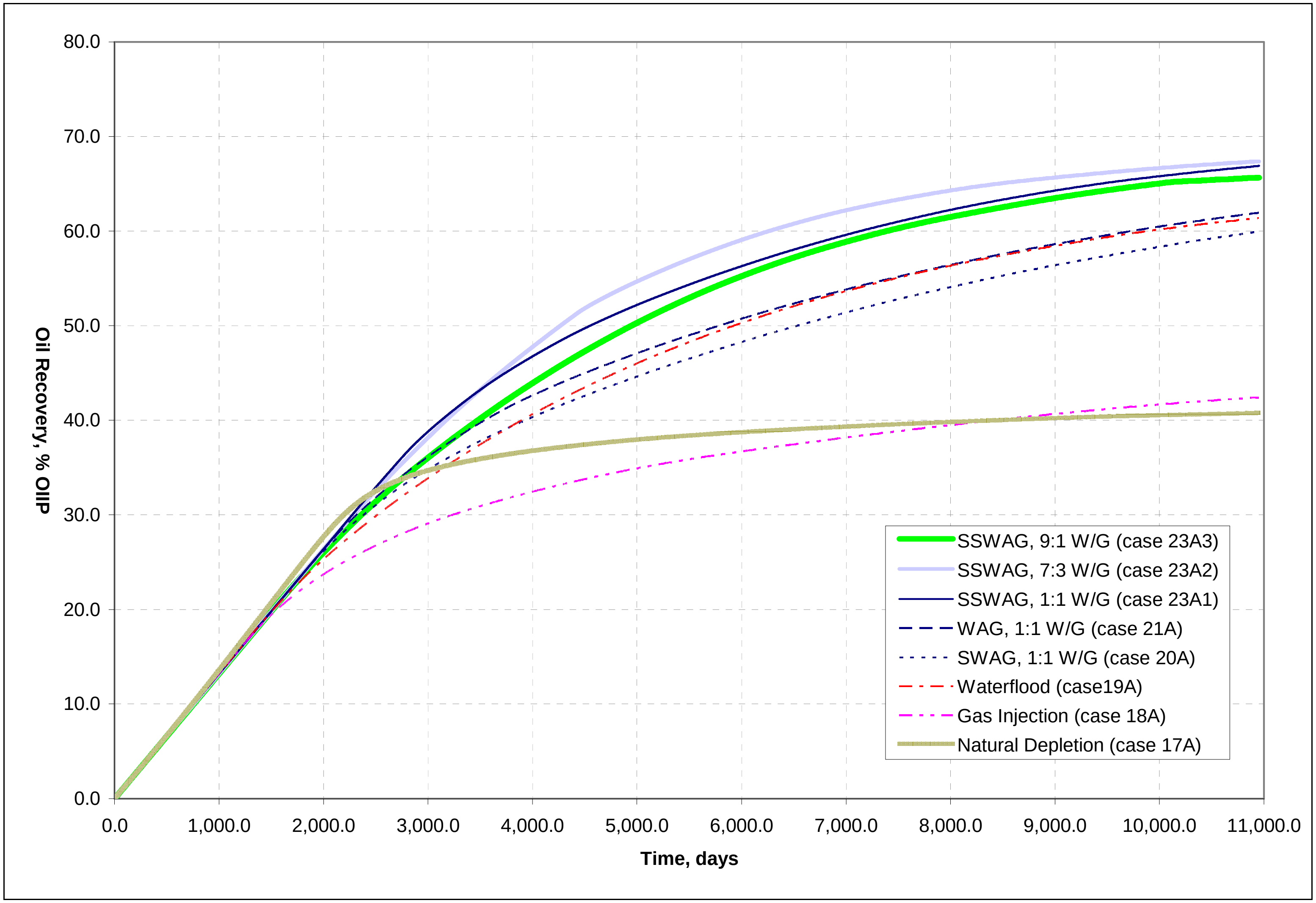

Fig. 37 – Oil recovery versus time for selected injection scenarios using the "S" set at 500 RB/D/Well injection rate.

6.2 Results Overview at 1,000 RB/D/Well Injection Rate

In Fig. 38, the results of scenarios similar to those considered in Fig. 36 are presented but 1000 RB/D/Well injection rate. At 1.0 PV injected, higher oil recoveries were estimated at this injection rate than at 500 RB/D/Well, therefore, this is a more efficient injection. Ranking of the different injection methods in terms of oil recovery remained unchanged at 1.0 PV injected with the exception of WAG injection (cases 21B and 22B) outperforming water flooding (case 19B). Gas injection (case 18B) recovery estimates were the lowest while SSWAG injection gave the highest oil recovery (cases 23B1 and 23B2).

At 2.0 PV injected, equal oil recoveries were estimated by water flooding and gas injection, 63% OIIP. Similarly, estimates for WAG and SSWAG injections were very close, 71%-72% OIIP. SWAG injection (case 20B) was estimated in between the two, 67% OIIP.

With regard to examined SSWAG injection scenarios, the relationship between water/gas injection ratio and oil recovery was found to be inconsistent at 0.5 and 1.0 PV injected. Then at 2.0 PV injected, a reversed trend is observed, i.e. for the same SSWAG injection schedule, oil recovery decreases slightly as the water/gas injection ratio is increased. The ratio of 1:1 seemed to be always the best choice. It remained true for examined injection scenarios that at the same water/gas injection ratio, the different schedules of water injection shut-off had no significant effect on oil recovery.

Oil recovery estimates for natural depletion, continuous SSWAG injection, and other EOR methods are plotted versus time on Fig. 39. The comparison between WAG and SSWAG injections showed that the latter outperforms the former when water/gas injection ratio is 1:1. At 7:3 water/gas injection ratio, SSWAG injection (case 23B2) recovered oil faster that WAG injection (case 21B). Eventually, when injection is continued for long times at this rate and water/gas ratio, more oil was by WAG injection. For an example, 65% OIIP oil recovery was estimated after about 3,600 days (10 years) of SSWAG injection (case 23B2) while it takes 4,500 days (12.3 years) to recover the same amount of oil by WAG injection. At a relatively long time, 10,000 days (27.4 years) oil recoveries for SSWAG and WAG are estimated at 70% and 71% respectively. The 1% OIIP difference can be negligible considering the extra volumes of gas that need to be injected in the case of WAG injection (1:1 water/gas ratio) and the additional years of injection.

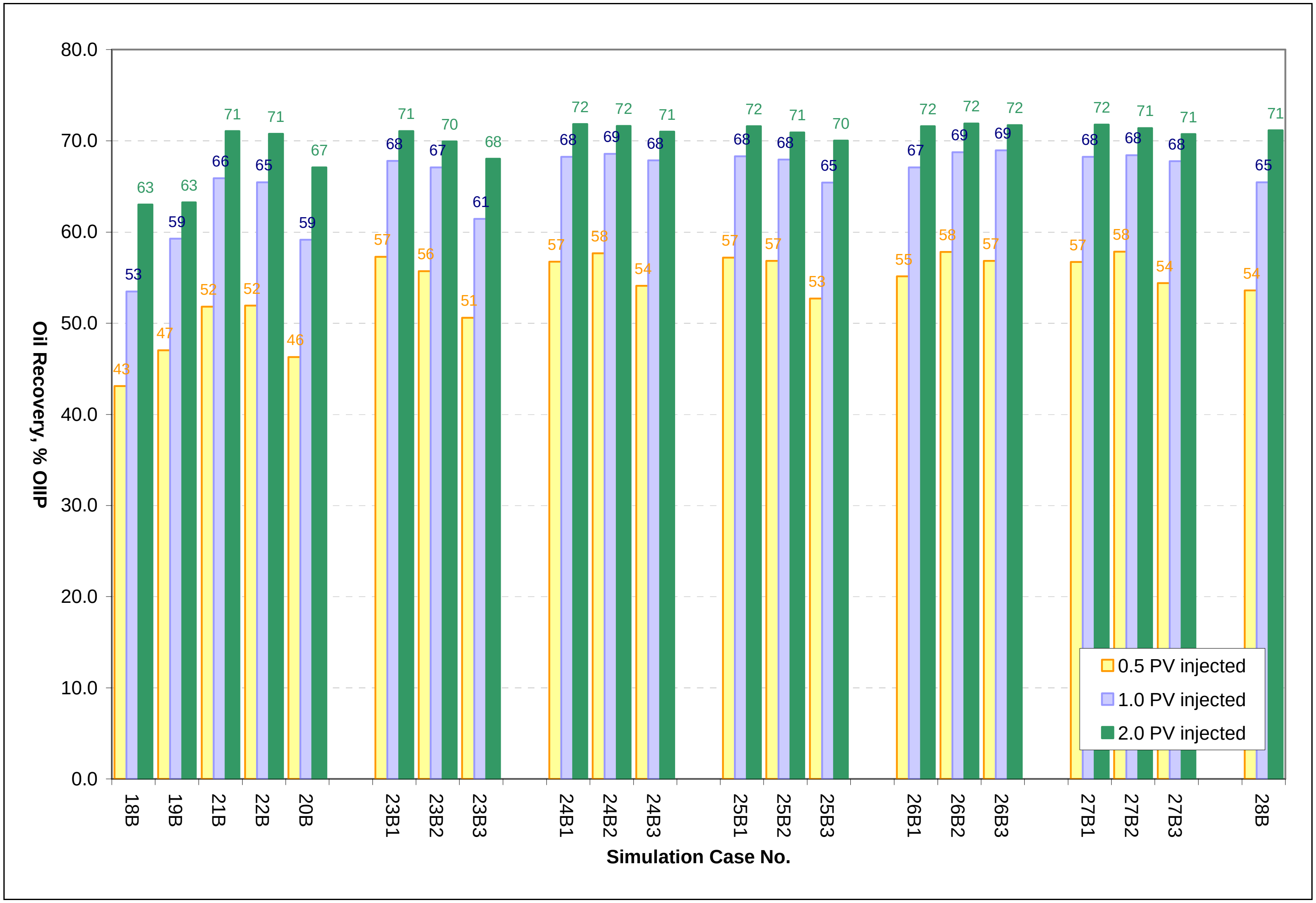

Fig. 38 – Oil recovery for selected injection scenarios using the "S" set at 1,000 RB/D/Well injection rate. Estimates are presented at 0.5, 1.0 and 2.0 PV injected.

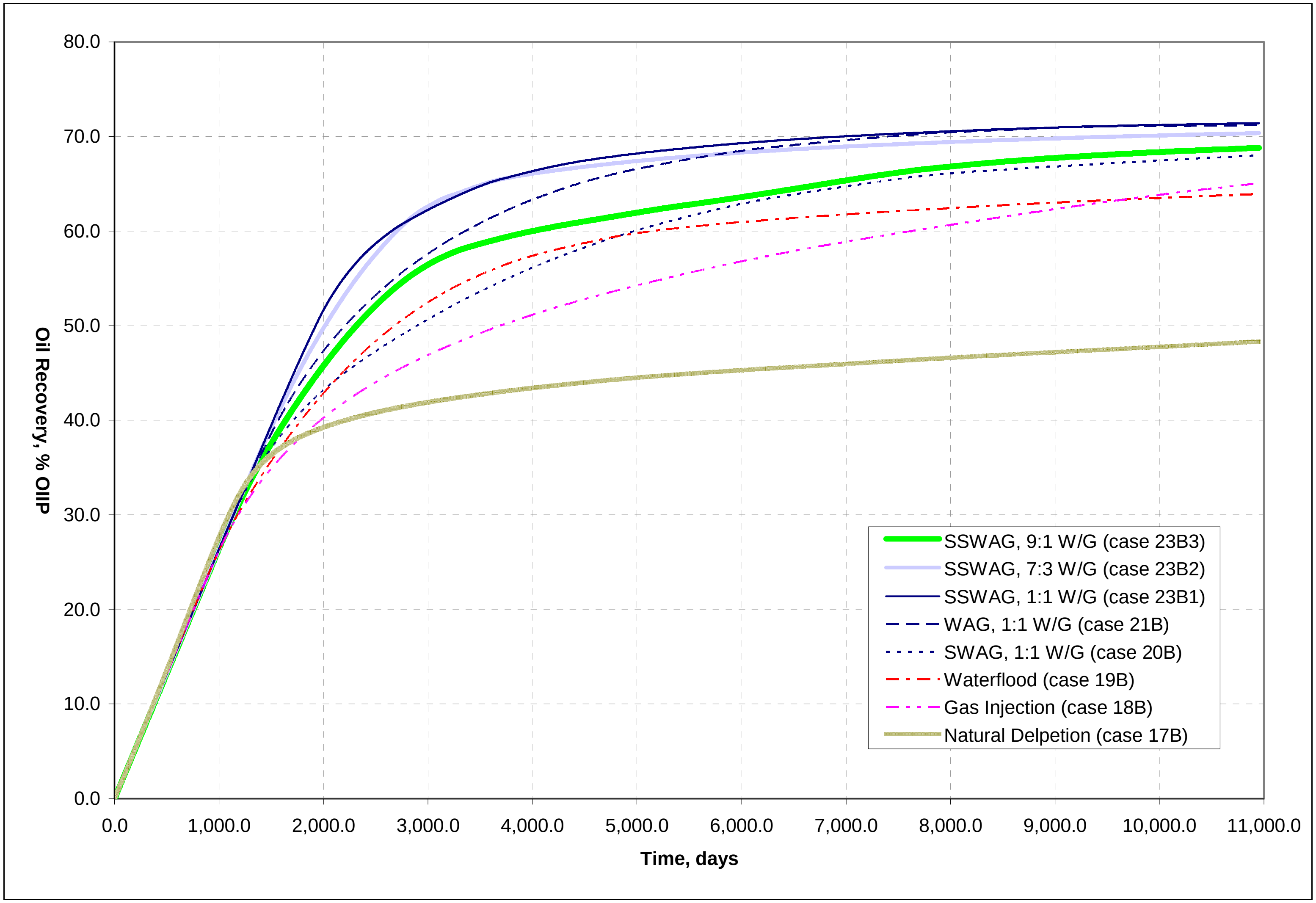

Fig. 39 – Oil recovery versus time for selected injection scenarios using the "S" set at 1,000 RB/D/Well injection rate.

6.3 Fluid Saturations Distribution

Fig. 40 through Fig. 44 are cross-sectional and areal snap shots of fluid saturations during selected simulation cases at 1,000 RB/D/Well injection rate. Each figure shows saturations disruption at 0.1, 0.5, 1.0 and 2.0 PV injected. In the case of gas injection (case 18B, Fig. 40), gas did not segregate immediately near the injector especially in the top part of the formation where permeability is relatively low. More gas was trapped in the formation compared to case 8b and it took loner for the injected gas to break through at the producer. This provided better vertical sweep of formation oil in the areas contacted by injected gas. At 0.1 PV injected, no gas had reached the producer yet. Eventually, injected gas migrated to the top layers and overran formation oil to reach the producer at the other end of the reservoir model. After breakthrough, gas injection loses efficiency. At 2.0 PV injected, just over half of the reservoir has been contacted by injected gas.

In the case of water flooding (case 19B, Fig. 41), similar behavior to that of case 9B is observer. Water under-ran formation oil to reach the producer through the high permeability bottom layers. It was noticed that for this set of relative permeability data, water breakthrough during water flooding (case 19B) occurred before gas breakthrough in the case of gas injecting flooding (case 18B). The opposite happened using the earlier "M' set of relative permeability data. After breakthrough, the method of water flooding was more effective in oil recovery compared to gas injection. In the former, most of the reservoir was contacted by injected water by the time 1.0 PV injected was injected.

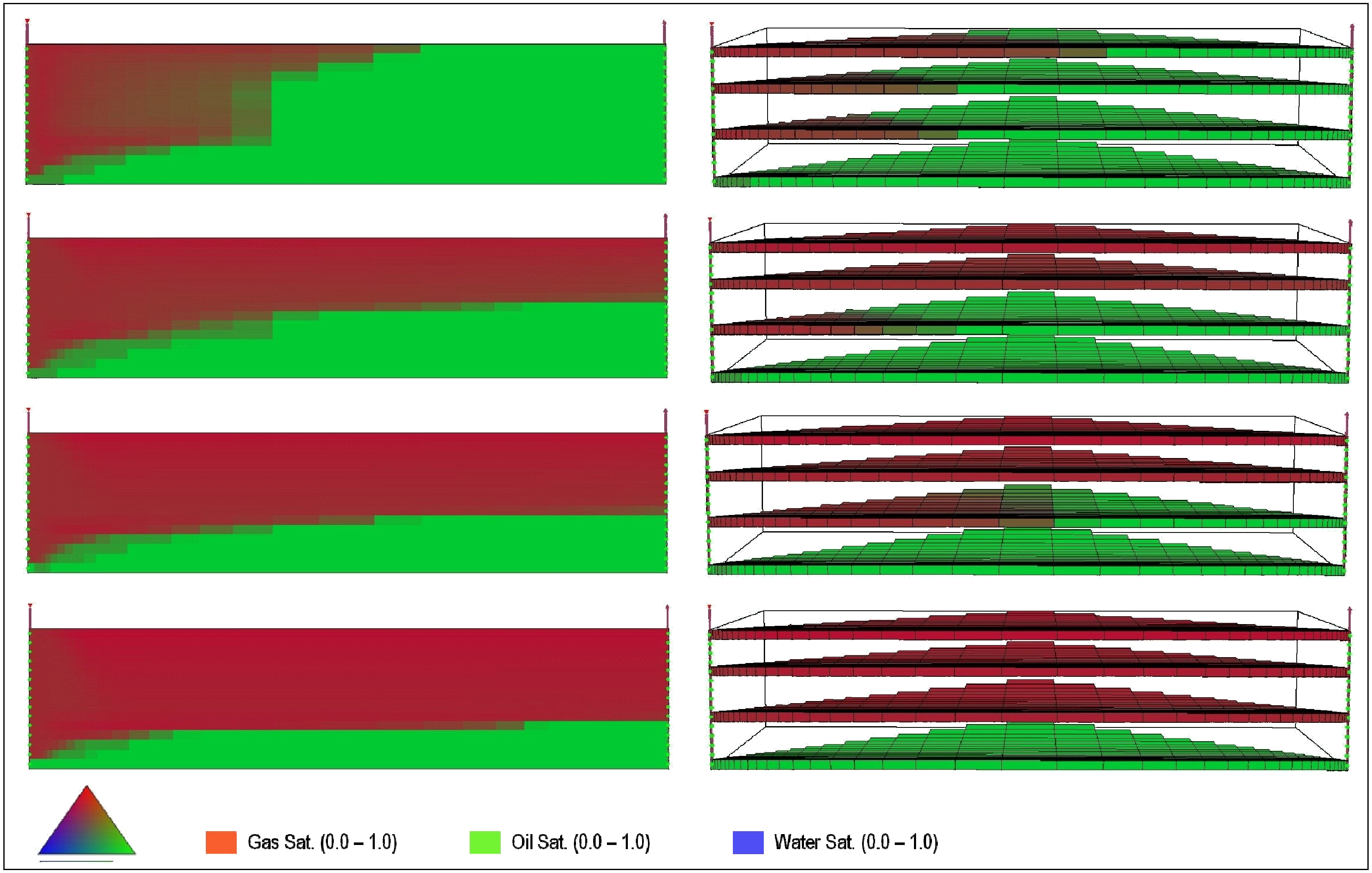

Fig. 40 – Fluid saturations distribution during gas injection (case 18B). On the left from top to bottom, cross-sectional views at 0.1, 0.5, 1.0 and 2.0 PV injected. Corresponding areal views shown on the right (layers no. 1, 5, 10, and 15).

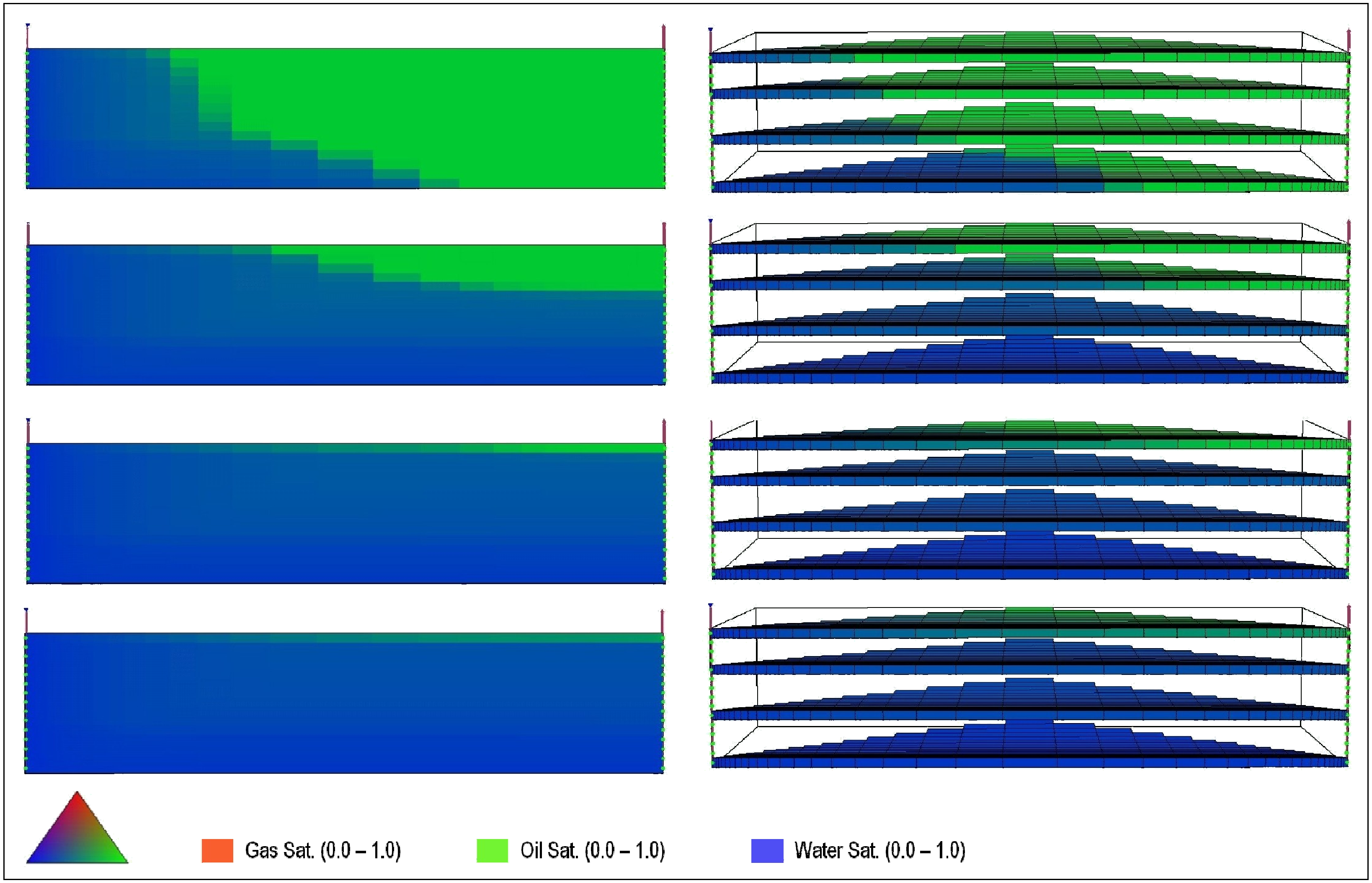

Fig. 41 - Fluid saturations distribution during water flooding (case 19B). On the left from top to bottom, cross-sectional views at 0.1, 0.5, 1.0 and 2.0 PV injected. Corresponding areal views shown on the right (layers no. 1, 5, 10, and 15).

Fig. 42, Fig. 43 and Fig. 44 show fluid saturations distribution during SWAG, WAG and SSWAG injections respectively. All three cases (20B, 21B and 23B1) represent 1:1 water/gas injection ratio for the purpose of comparison. The figures show that in all three cases, the mixed flow of injected water and gas traveled deeper into the formation compared to cases 10B, 11B and 3B1 (using the “M” set data) before the two phases segregate completely. In case of SWAG injection, the point of complete segregation was at about half the reservoir distance between the injector and the producer when 2.0 PV was injected. For the same PV injected during WAG injection, the point of complete segregation was at about three-quarters of the reservoir distance away from the injector. In both cases, after the point of complete segregation, injected gas contacted only the top 2 layers while the reset of the formation was effectively water flooded (no gas).

A look at the fluid saturations distribution during comparable SSWAG injection (Fig. 44), shows similar behavior to that observe with SWAG and WAG. At 0.5 PV injected, the two phases appeared to have completely segregated at about three-quarters the reservoir length. Unlike during SWAG and WAG injections, that point kept advancing deeper into the formation, hence, more areas contacted by the injected gas during SSWAG injection. By the time 1.0 PV was injected, there was no distinct phase segregation in the formation. Fig. 45 shows a side view of how injected water and gas propagate through the formation during WAG (case 21B) versus during SSWAG (case 23B1). It also confirms that 100% areal sweep can not be assumed in this study.

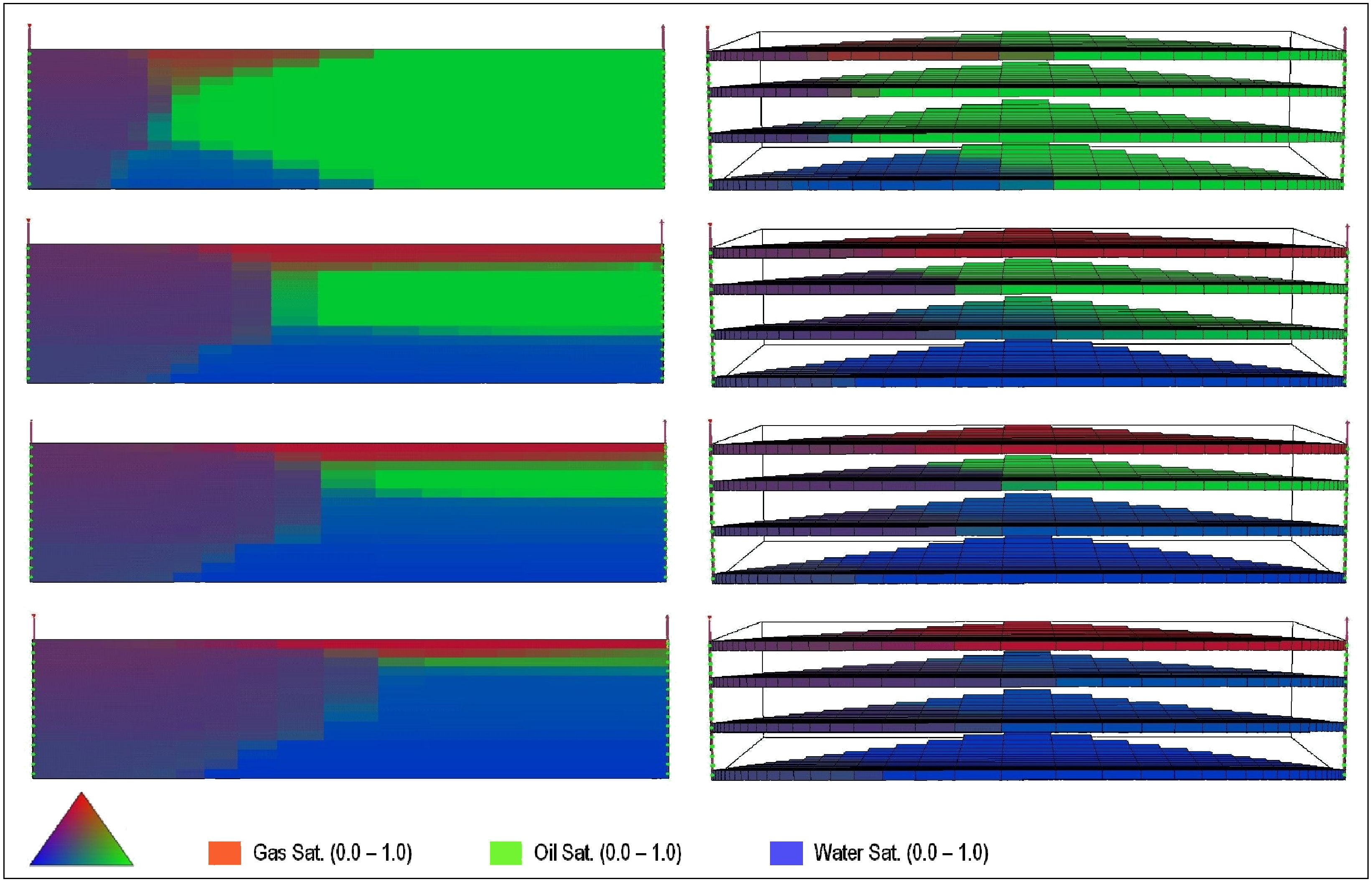

Fig. 42 – Fluid saturations distribution during SWAG injection (case 20B). On the left from top to bottom, cross-sectional views at 0.1, 0.5, 1.0 and 2.0 PV injected. Corresponding areal views shown on the right (layers no. 1, 5, 10, and 15).

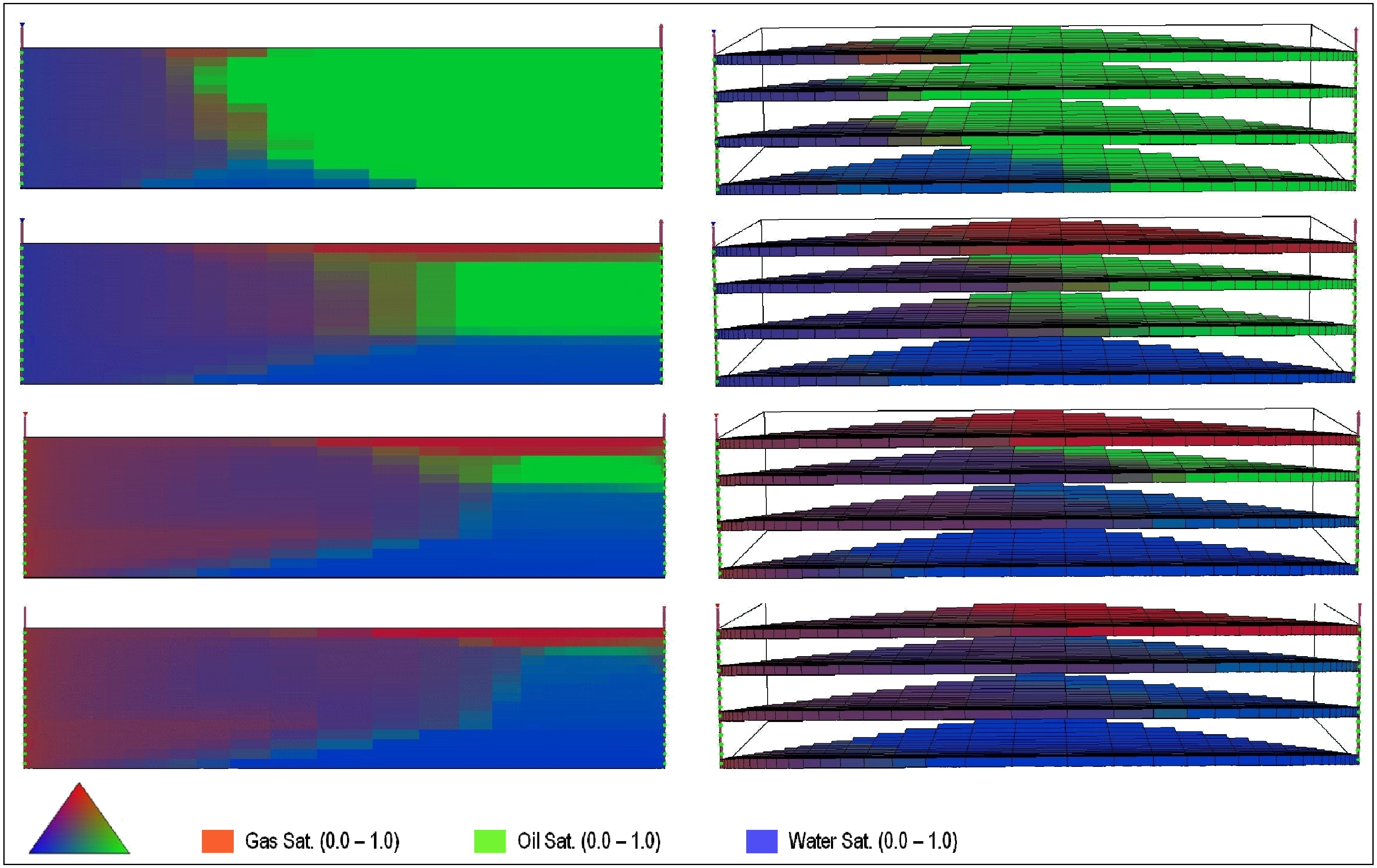

Fig. 43 – Fluid saturations distribution during WAG injection (case 21B). On the left from top to bottom, cross-sectional views at 0.1, 0.5, 1.0 and 2.0 PV injected. Corresponding areal views shown on the right (layers no. 1, 5, 10, and 15).

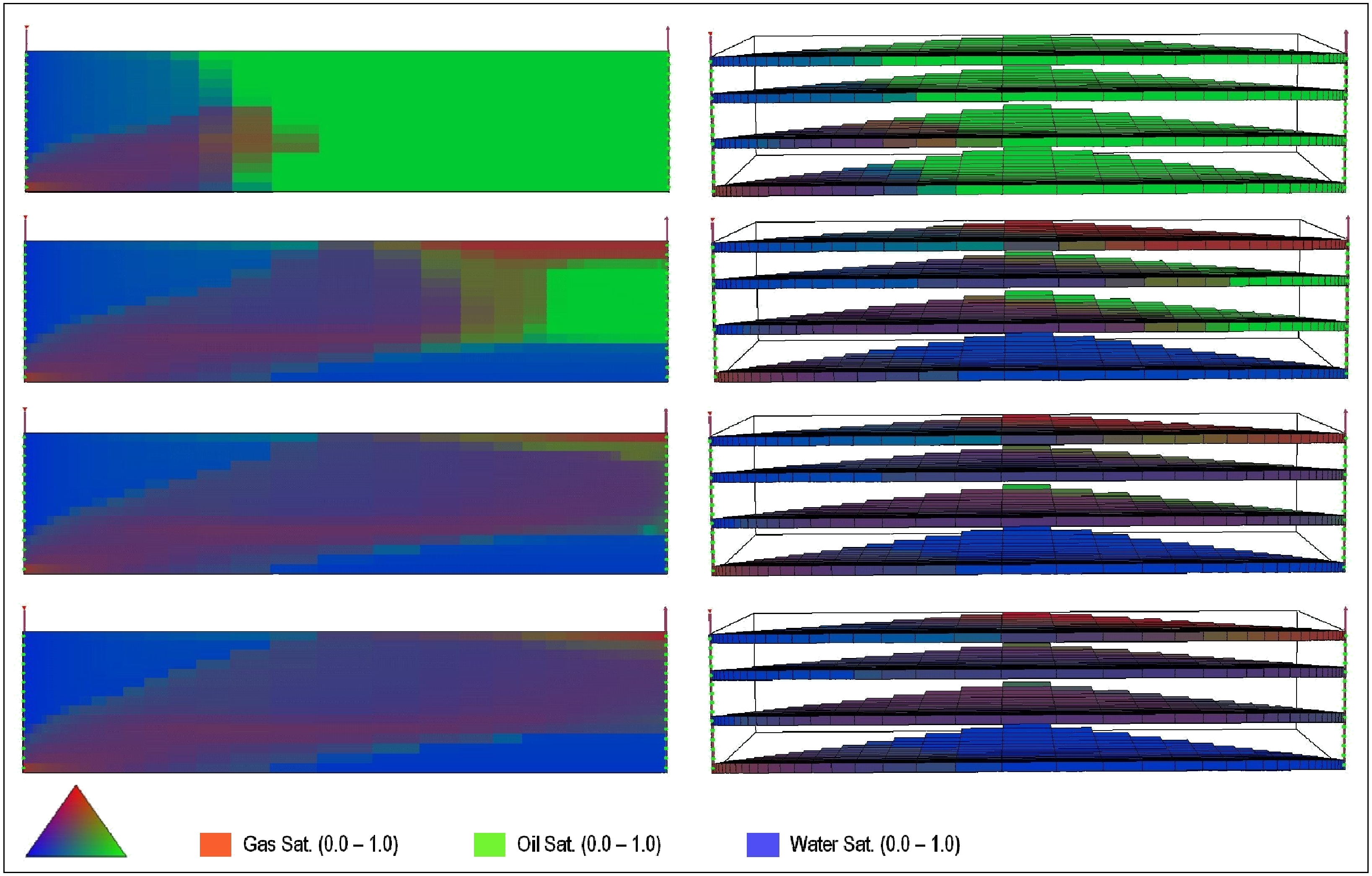

Fig. 44 – Fluid saturations distribution during SSWAG injection (case 23B1). On the left from top to bottom, cross-sectional views at 0.1, 0.5, 1.0 and 2.0 PV injected. Corresponding areal views shown on the right (layers no. 1, 5, 10, and 15).

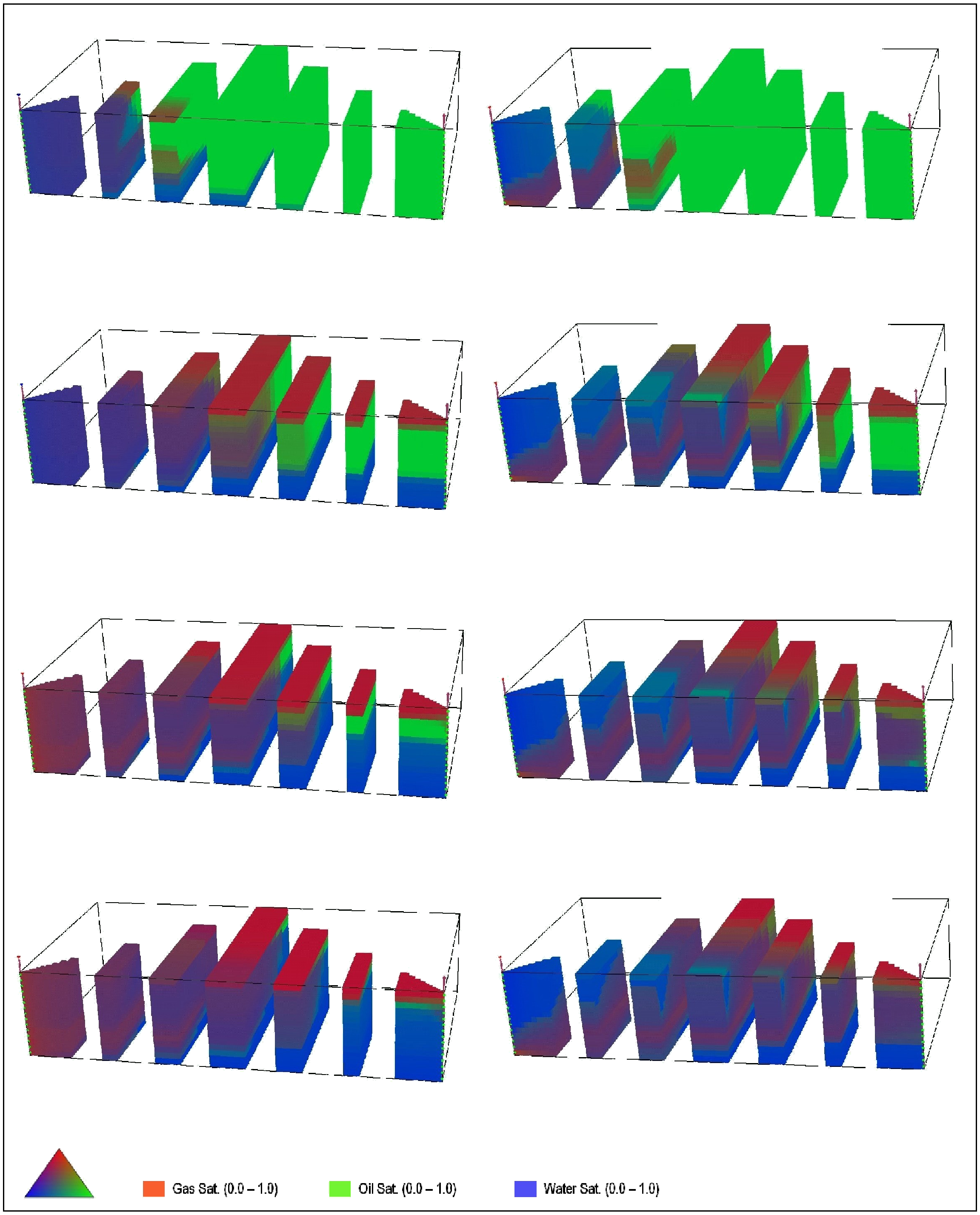

Fig. 45 – Side views showing fluid saturations distribution during WAG (case 21B) and SSWAG (case 23B1) injections. In both cases (WAG snaps on the left and SSWAG spans on the right), snap shots are presented at 0.1, 0.5, 1.0 and 2.0 PV injected from top to bottom respectively.

6.4 Investigating Higher SSWAG Injection Rates

Continuous SSWAG injection at 1:1 water/gas injection ratio was simulated at two additional injection rates, 2,000 and 4000 RB/D/Well (cases 23C and 23D respectively), in order to investigate the effect of injection rate effect on oil recovery amount and recovery speed. Fig. 46 shows oil recovery estimates as a function of time for each of the four simulated injection rates. It is clear that the higher the injection rate, the faster oil is recovered. For an example, 65% OIIP is recovered in 3,600 days when the injection rate is 1,000 RB/D/Well while it takes only 1,340 days to recover the same amount of oil when the injection rate is increased to 4,000 RB/D/Well. Of course, there must be a consideration for the practicality of the injection rate. Injecting at 4,000 RB/D/Well in a one-eighth of a unit means 32,000 RB/D in a single injector in the field.

On the other hand, it seems that there is an optimum injection rate in order to maximize the ultimate oil recovery, which is not necessarily the higher rate possible. At 2.0 PV injected, injecting at 1,000 RB/D was found to yield the maximum oil recovery among all four cases studied. Fig. 47 shows oil recovery estimates for the diffident SSWAG injection rates versus PV injected for 30 years. All rates have the same oil recovery until one of the injected phases breakthrough at the producer.

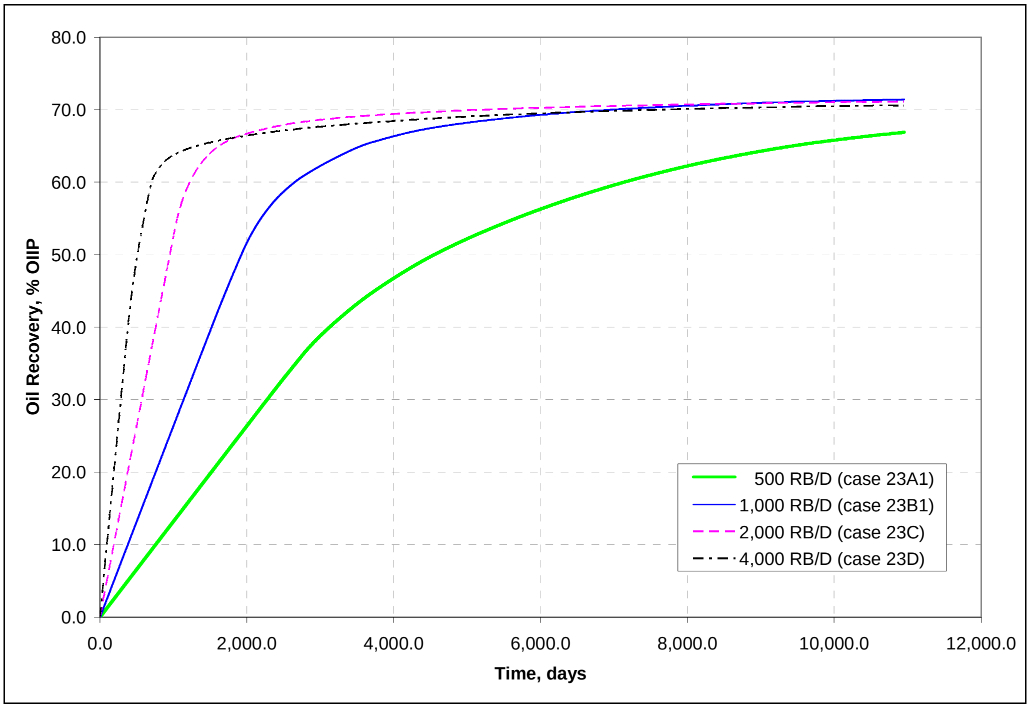

Fig. 46 – Plot oil recovery versus time at different SSWAG injection rates (30 Yrs).

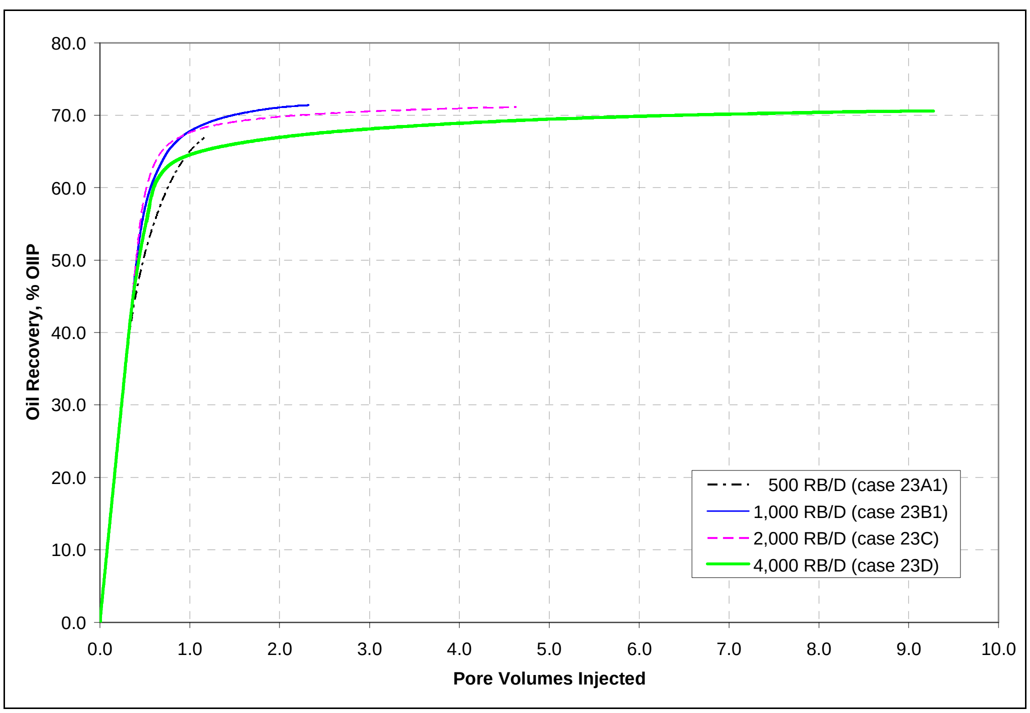

Fig. 47 – Plot oil recovery versus PV injected at different SSWAG injection rates (30 Yrs).

6.5 Periodic Water Injection Shut-Off Effect on Oil Recovery

As indicated earlier, no significant effect on oil recovery was observed for periodic water injection shut-off during SSWAG injection. That was found to be true at the same water/gas injection ratio for either of the studied injection rates, 500 or 1,000 RB/D/Well. Case 24D was simulated to investigate if the same is true at higher injection rates. In this case, the injection rate was kept at 4000 RB/D/Well at 1:1 water/gas ratio. Water injection was shut-off for 1 month after every 5 months of SSWAG injection.

In Fig. 48 presents oil recovery estimate versus time for comparable SSWAG injection cases with and without water injection shut-offs. Comparing oil recovery difference between cases 23B1 and 24B1 (at 1,000 RB/D/Well injection rate) versus the difference between cases 23D and 24D (at 4,000 RB/D/Well injection rate) shows that at the relatively high injection rate, periodic shutting of water injection has more significant impact on oil recovery than at the lower injection rate. Of course, it’s important to mention that more gas is injected in the case of the higher rate when water injecting is shut.

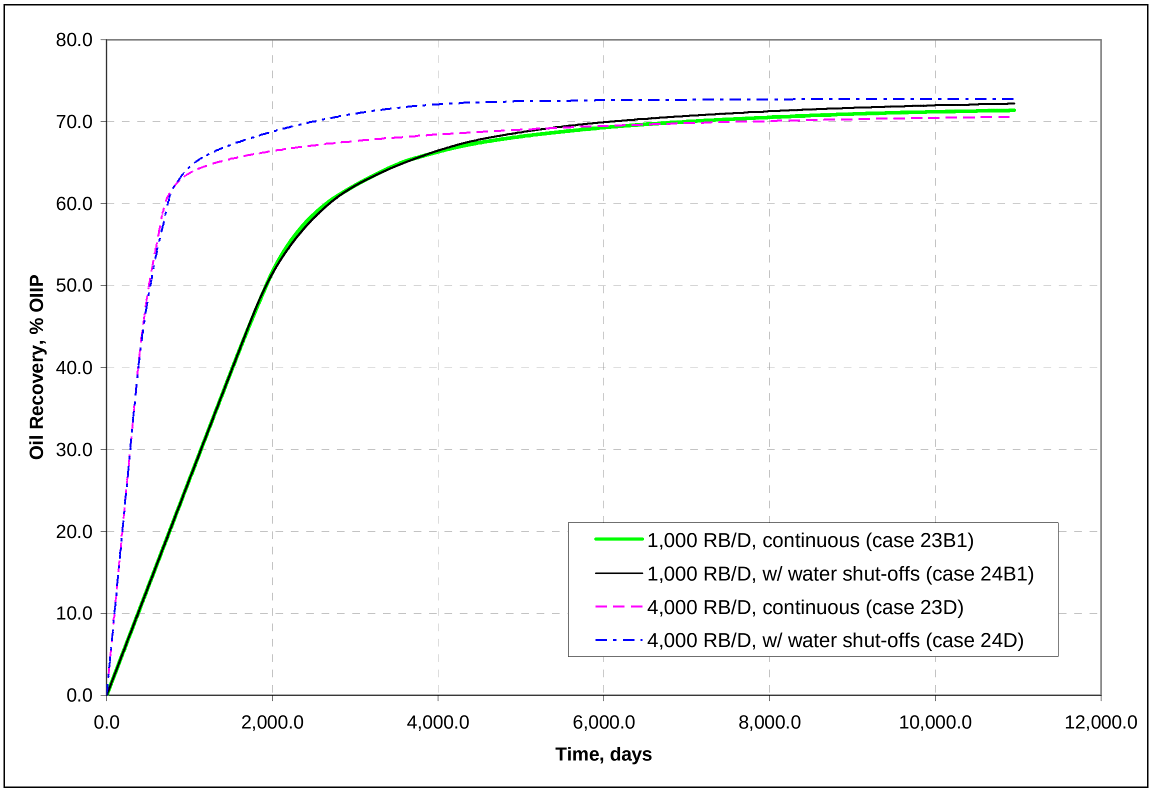

Fig. 48 – Plot oil recovery versus time for SSWAG injection scenarios with and without periodic water injection shut-offs.

6.6 Effect of SSWAG Injector Completion on Oil Recovery

In the all SSWAG injection scenarios discussed so far, gas was always injected in the bottom 20 ft of the formation and water injected in the reaming top part (270 ft). In case 29B, the injector well completion was changed to 60 ft at the bottom for gas injection and 230 ft on top for water injection. The in case 30B, gas was injected in the bottom 195 ft and only 95 ft for water injection.

Oil recovery estimates from case 23B1 was compared to the last two cases (see Fig. 49). The injection rate and water/gas ratio were kept constant in all three cases

(1000 RB/D/Well and 1:1 respectively). Result showed there is no significant difference in oil recovery between the three considered completions.

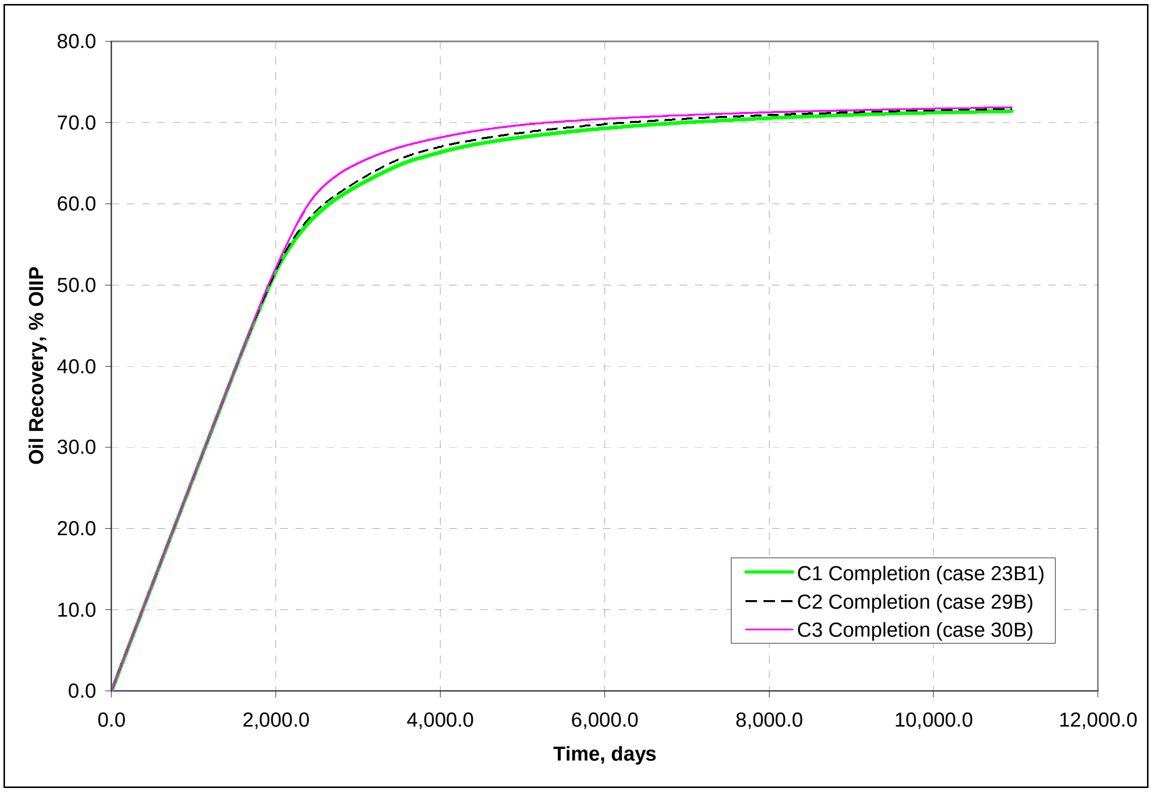

Fig. 49 – Plot oil recovery versus time for SSWAG injection scenarios with different gas and water injector completions.

6.7 Combined Injection Methods

Additional scenarios were simulated in which water flooding was first implemented until water-cut at the producer reaches an economical limit (80% of produced liquids). Then water flooding was replaced by SWAG, WAG or SSWAG injections. In every case, previous water flood injection rate was maintained during the following method of injection. Refer to cases 31A, 31B, 32A, 32B, 33A, 33B, 34A, and 34B in Table 13 for details.

Fig. 50 shows oil recovery estimates versus PV injected for the cases at 500 RB/D/Well injection rate as well as water flooding base case (case 19A). A similar plot is resented in Fig. 51 at 1,000 RB/D/Well injection rate where the base case was 19B. Incremental oil recovery estimates over water flooding are listed in Table 14. The combination with SSWAG injection performed better than the other combinations with SWAG and WAG injections.

TABLE 14 - COMBINED INJECTIONS OIL RECOVERY AFTER WATER FLOODING

Case	Description	Total Injection (RB/D)	Incremental Recovery at 1.1 PV (% OIIP)	Incremental Recovery at 2.3 PV (% OIIP)
31A	SWAG after water flooding	500	0.4	NA
32A	WAG after water flooding	500	1.1	NA
33A	Continuous SWAG after water flooding	500	3.2	NA
34A	SWAG w/ shut/offs after water flooding	500	2.5	NA
31B	SWAG after water flooding	1,000	0.4	4.0
32B	WAG after water flooding	1,000	1.2	4.0
33B	Continuous SWAG after water flooding	1,000	5.3	7.5
34B	SWAG w/ shut/offs after water flooding	1,000	6.3	7.8

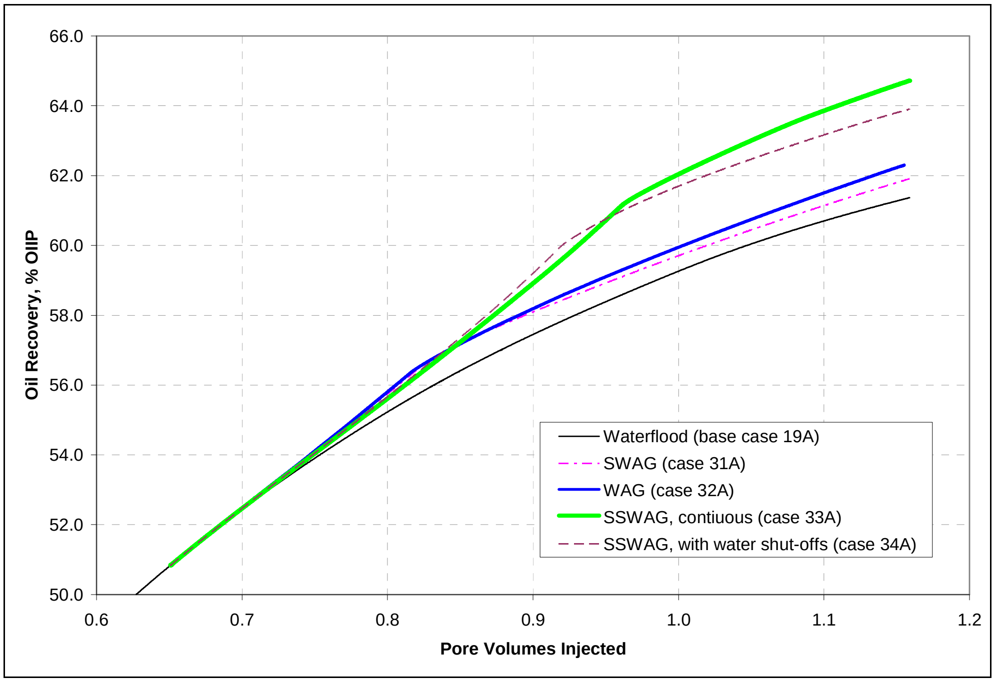

Fig. 50 – Plot of oil recovery versus PV injected for the combined injection methods scenarios at 500 RB/D/Well injection rate.

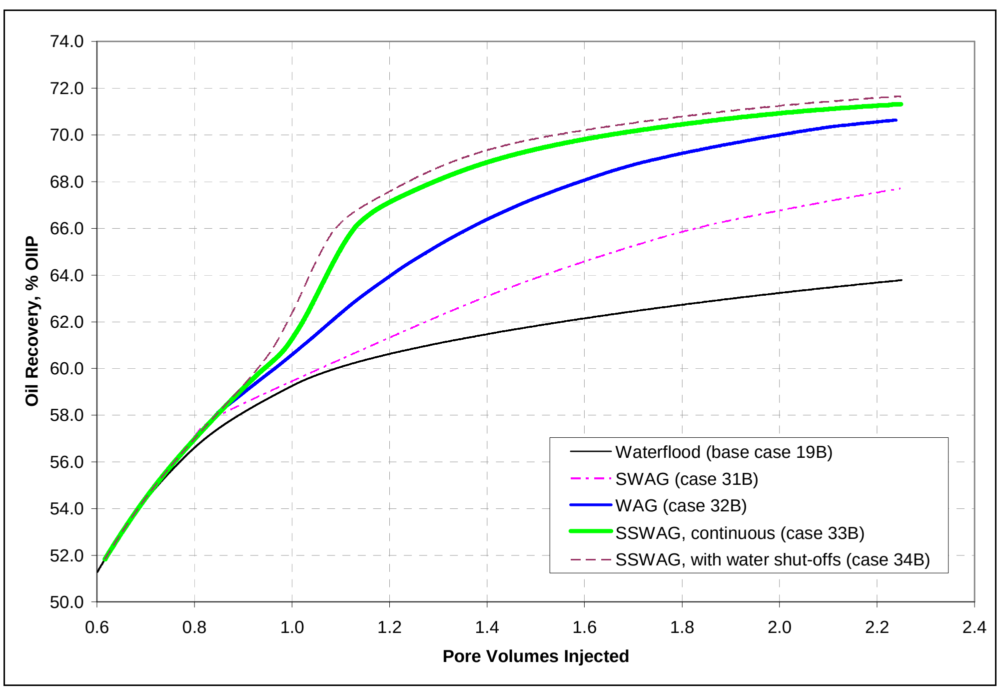

Fig. 51 – Plot of oil recovery versus PV injected for the combined injection methods scenarios at 1,000 RB/D/Well injection rate.

6.8 General Comparisons

Fig. 52 shows the average gas saturation in the formation as a function of injection time for SSWAG injection cases 3A1, 3B1, 23A1 and 23B1. It is clear that in the first two cases, using the “M” set at 500 and 1,000 RB/D/Well, injected gas was trapped in the formation to a max of about 7% saturation. Whereas in the cases using the “S” set, average gas saturation kept increasing in the formation to higher levels (17% and 25% saturation in cases 23A1 and 23B1 respectively). In all four cases, the steady increase in gas saturation is stopped at or even before reaching the corresponding critical gas saturation (5% and 20% for the “M’ and “S” sets respectively). This indicates there is very little gas trapped in the formations after reaching critical saturation or after establishing a flow channel to the producer, breakthrough.

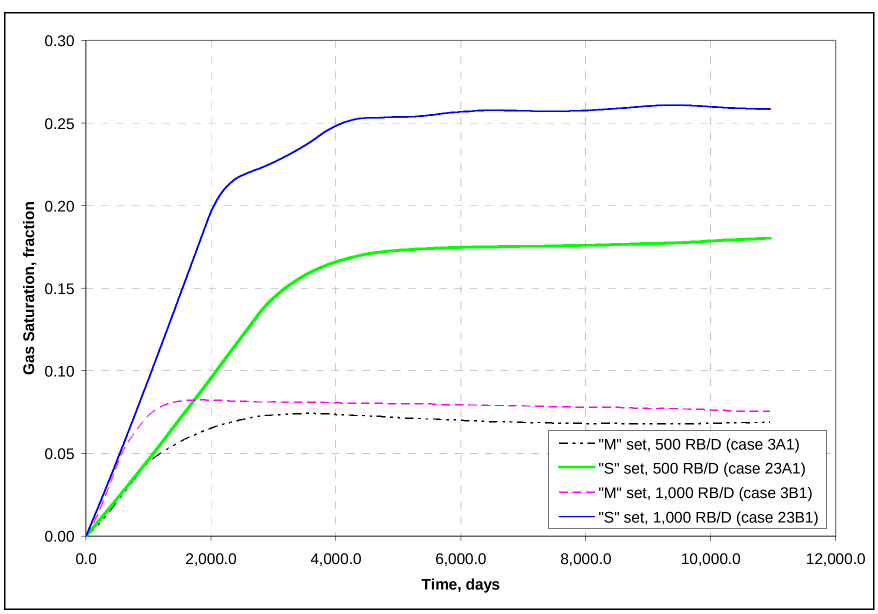

Fig. 52 – Plot of formation gas saturation estimate versus time during SSWAG injection scenarios using both sets of relative permeability.

Fig. 53 and Fig. 54 show water and gas breakthrough times for continuous SSWAG injection for both sets of relative permeability at 1:1 water/gas ratio and at injection rates of 500 and 1,000 RB/D/Well respectively. In Fig. 53 at 500 RB/D/Well, both gas breakthrough and water breakthrough occurred earlier in the case using the "M" set, although the gas reached the producer before the water. In the case using the "S" set, there was a delay in breakthrough times but water was the first to reach the producer. Similar behaviors are seen on Fig. 54 at the higher injection rates. Table 14 provides more detail on breakthrough times for these and some other selected cases.

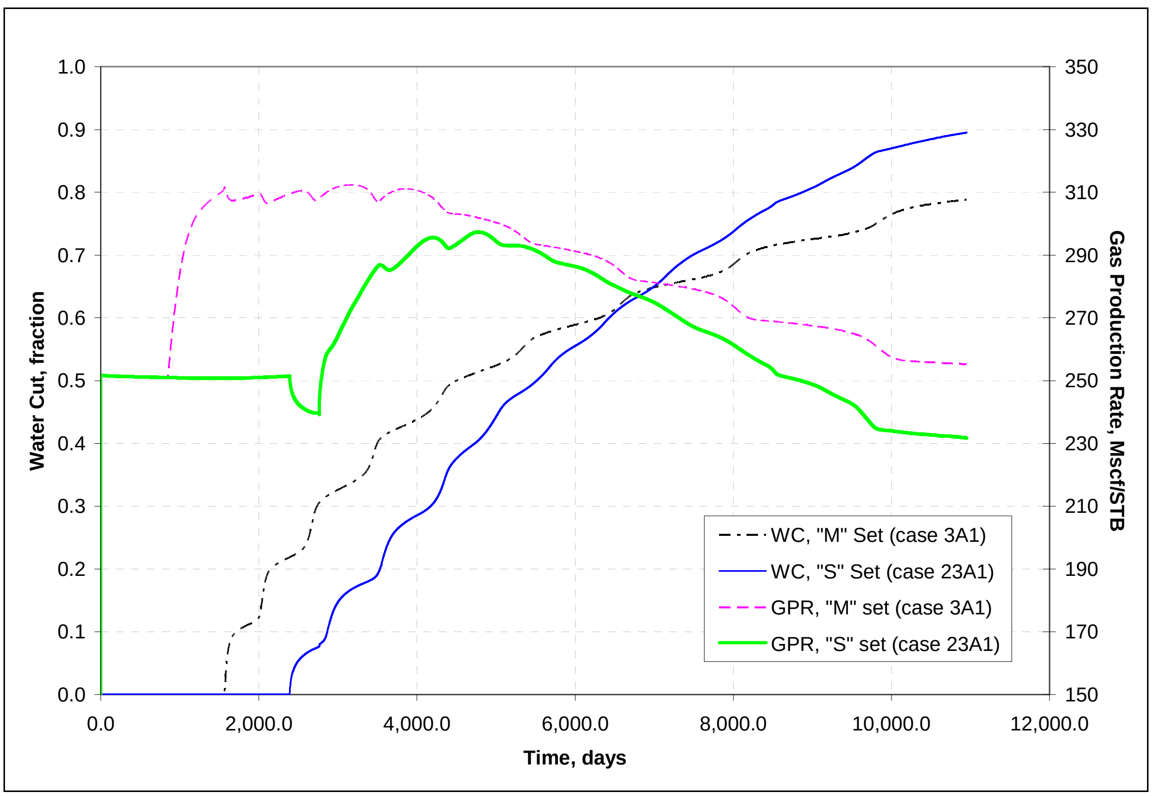

Fig. 53 – Plot of water-cut and gas production rate versus time during SSWAG injection at 500 RB/D/Well injection rate using both sets of relative permeability.

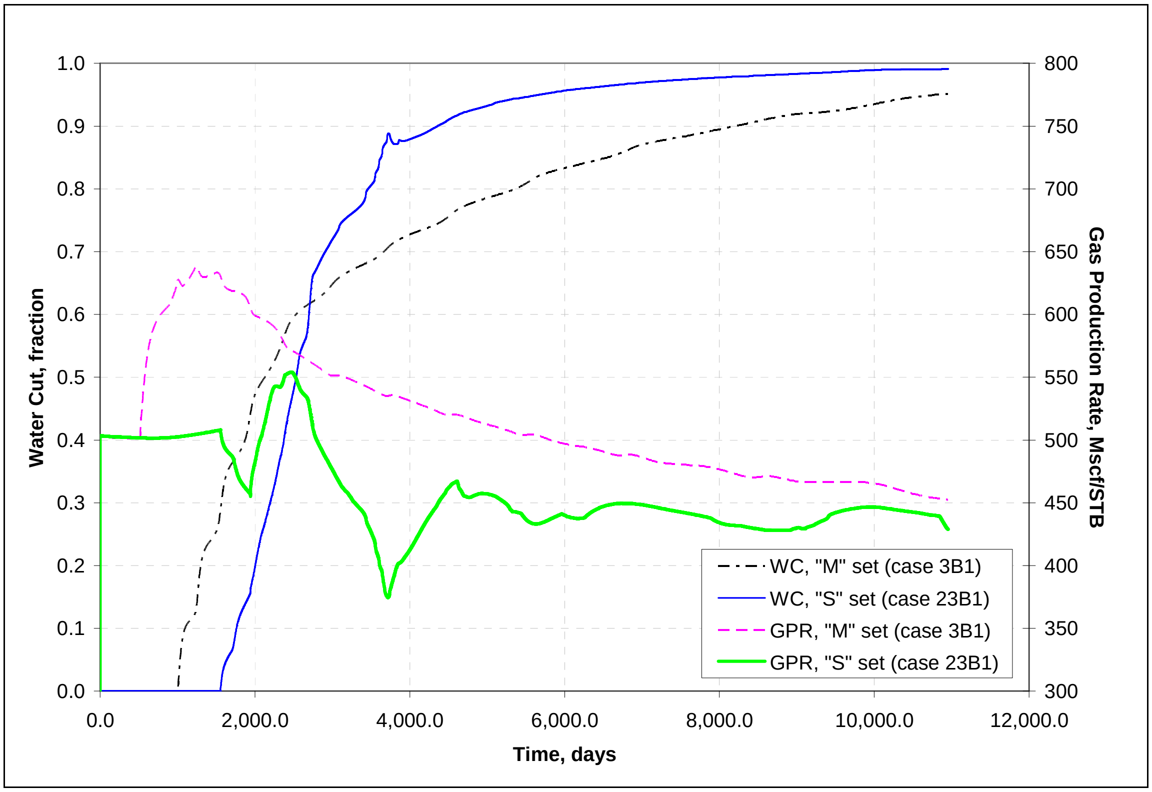

Fig. 54 – Plot of water-cut and gas production rate versus time during SSWAG injection at 1,000 RB/D/Well injection rate using both sets of relative permeability.

Fig. 55 and Fig. 56 show breakthrough times for SSWAG injection versus WAG injection for cases using the “S” set relative permeability data at 500 and 1,000 RB/D/Well respectively. Both figures show earlier water then gas breakthrough in the cases of WAG injection. Details on exact breakthrough times are listed in Table 15. It’s also point out the short term gas production rate fluctuation in both cases of WAG injection compared to relatively steady gas production rate in the cases of SSWAG injection.

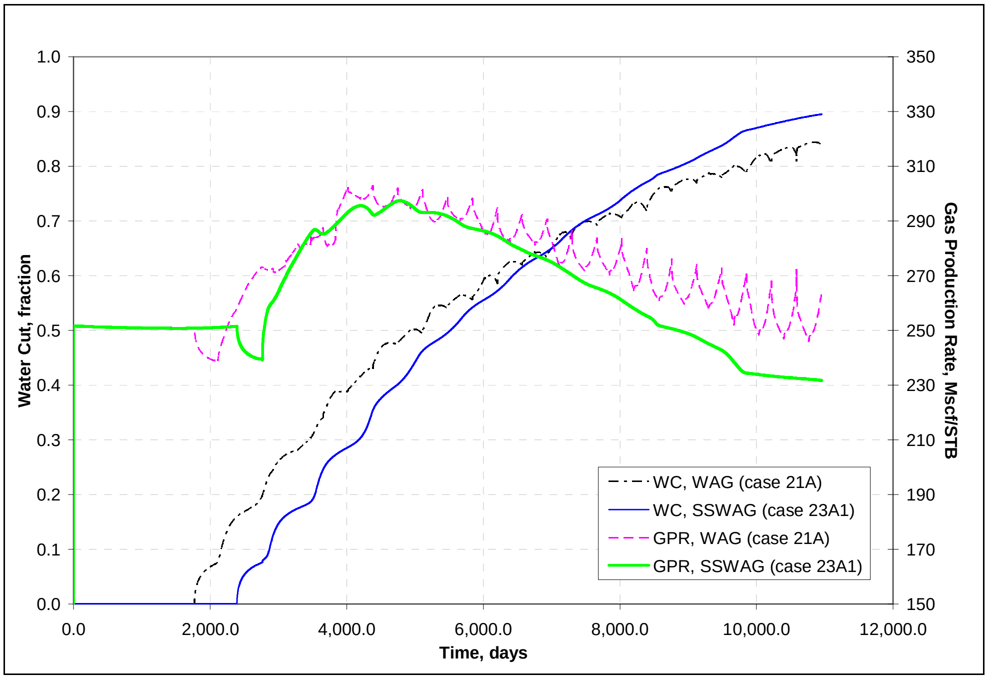

Fig. 55 – Plot of water-cut and gas production rate versus time during WAG and SSWAG injections at 500 RB/D/Well injection rate using the "S' set of relative permeability.

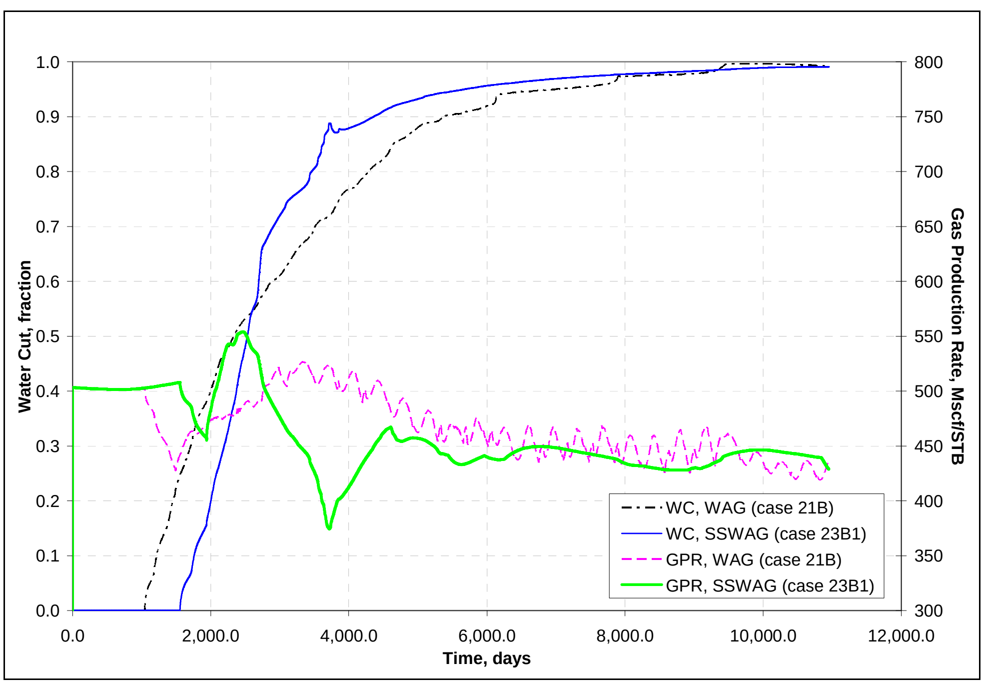

Fig. 56 – Plot of water-cut and gas production rate versus time during WAG and SSWAG injections at 1,000 RB/D/Well injection rate using the "S' set of relative permeability.

TABLE 15 - SUMMARY OF WATER AND GAS BREAKTHROUGH TIMES

	Relative		Total	W. Breakthrough		G. Breakthrough	
	Permeability	EOR	Injection	Time	PV	Time	PV
Case	Set	Method	(RB/D)	(days)	Injected	(days)	Injected
10A	M	SWAG	500	1,616	0.171	776	0.082
11A	M	WAG	500	1,498	0.159	858	0.091
3A1	M	SSWAG	500	1,566	0.166	849	0.090
10B	M	SWAG	1,000	990	0.210	441	0.093
11B	M	WAG	1,000	896	0.190	545	0.115
3B1	M	SSWAG	1,000	1,002	0.212	513	0.109
20A	S	SWAG	500	1,846	0.195	1,794	0.190
21A	S	WAG	500	1,769	0.187	2,106	0.223
23A1	S	SSWAG	500	2,388	0.253	2,764	0.292
20B	S	SWAG	1,000	1,115	0.236	1,075	0.228
21B	S	WAG	1,000	1,044	0.221	1,488	0.315
23B1	S	SSWAG	1,000	1,553	0.329	1,942	0.411
23C	S	SSWAG	2,000	981	0.208	1,026	0.217
23D	S	SSWAG	4,000	594	0.126	365	0.077
30B	S	SSWAG	1,000	1,797	0.380	1,815	0.384

Bottom hole injection pressures are shown in Fig. 57 and Fig. 58 for the same cases of WAG and SSWAG injections presented in Fig. 55 and Fig. 56 respectively. Both figures show continuous fluctuation in WAG injection pressures, more so at the higher injection rate. In comparison, pressures at the SSWAG injectors (water and gas) are relatively stable. The reason for the fluctuation in the cases of WAG injection is the reduced relative permeability for each of the two phases as they are injected through the same set of perforations. In the cases of SSWAG injection, higher mobility zones are formed around each of the two injectors as there is only one phase flow initially. This might be considered one of the advantages of SSWAG over WAG as fluctuation in operation pressure may reduce the injection system life.

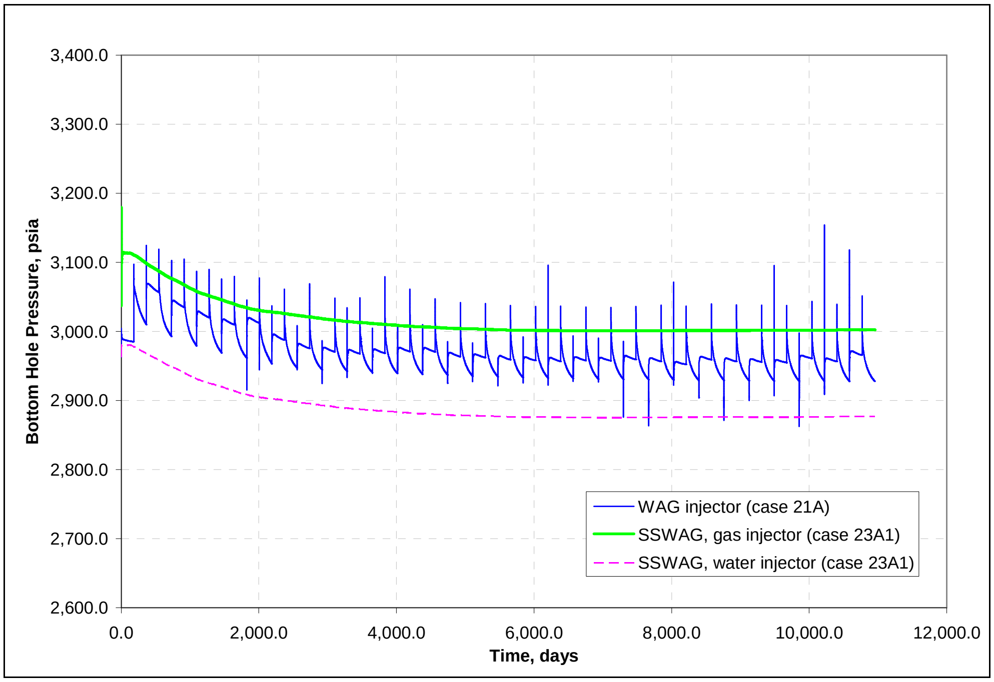

Fig. 57 – Plot of BHP versus time during WAG and SSWAG injections at 500 RB/D/Well injection rate using the "S' set of relative permeability.

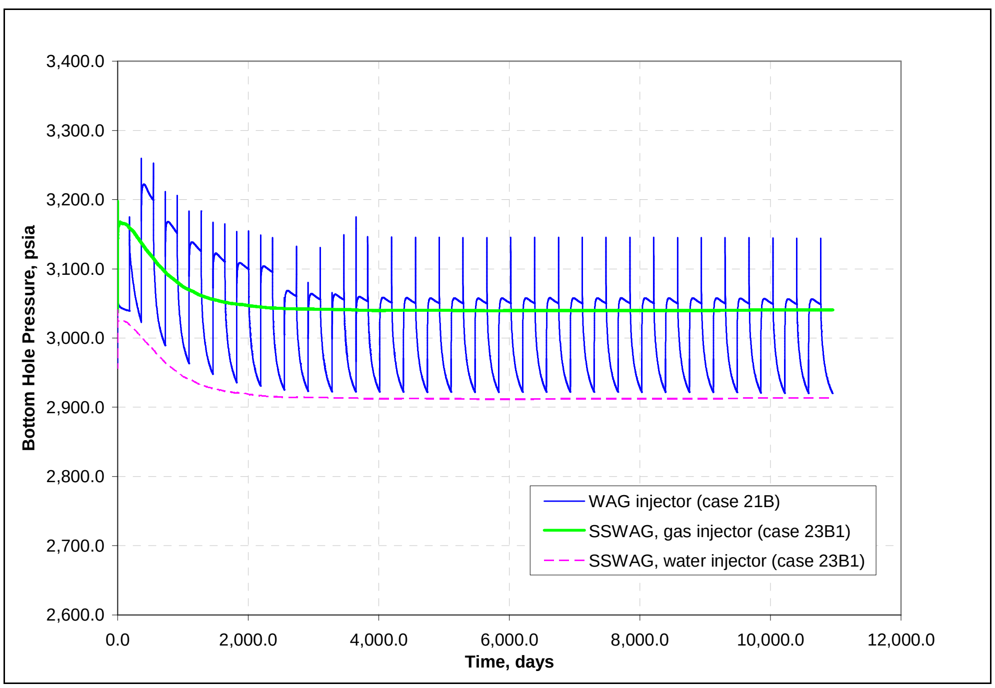

Fig. 58 – Plot of BHP versus time during WAG and SSWAG injections at 1,000 RB/D/Well injection rate using the "S' set of relative permeability.

CHAPTER VII

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

This was a simulation study utilizing Schlumberger's black oil simulator, ECLIPSE-100, to verify Stone's selective simultaneous water and gas injection design. The model used was a three-phase and three-dimensional representation of one-eight of an 80-acre 5-spot pattern-unit. The Cartesian grid was oriented such that one axis is parallel to the injector-producer direction. All simulation runs were carried out considering vertical injector well and production well completions. Reservoir rock and fluid properties similar to those used in Stone's study were used in this study. Additional hypothetical data was adopted where necessary for the stimulation model to run properly. Two unique sets of relative permeability data were investigated: the "S" set is similar to Stone's while the "M" set is a typical relative permeability data with a smaller critical gas saturation.

SSWAG oil recovery performance was compared to that from conventional WAG as well as to other EOR methods (gas flood, water flood, SWAG) and natural depletion. Sensitivity analyses were performed on several SSWAG design parameters to evaluate their effect on oil recovery. Parameters such as water/gas injection ratio, total injection rate, injection schedule and completion intervals for water and gas injections were investigated in this study.

7.2 Conclusions

The main conclusions from this study may be summarized as follows:

1. Injecting water directly on top of gas in the injector may delay the immediate migration of gas to the top of the reservoir. Eventually however, injected gas will segregate and flow straight to the producer, after which the displacement efficiency decreases significantly.
2. Critical gas saturation is essential for trapping gas in the reservoir, thereby, important for the success of SSWAG and WAG injections. The amount of oil contacted by the injected gas is proportional to the amount of free gas trapped in the formation. At low critical gas saturation, there is not much difference in oil recovery with SSWAG or WAG for the same water/gas injection ratio.
3. Water/gas injection ratio effect on recovery is dependent on how mobile the injected gas is once it enters the formation. In the case of the modified set of relative permeability data, injected gas is mobile once it reaches 5% saturation within a grid cell compared to 20% gas saturation in the case of Stone's relative permeability data set. In the first case, increasing water/gas ratio for a given total injection rate improved oil recovery. The opposite was mainly noticed when

Stone's set of relative permeability data was used (recovery increases when the ratio is lowered).

4. There is an optimum SSWAG injection rate for maximizing oil recovery and it is not necessarily the highest injection rate possible.
5. Periodic water injection shut-off during SSWAG injection has no significant effect on oil recovery at the relatively low injection rates (500 and 1,000 RB/D/Well). A more significant impact was observed at 4,000 R/D injection rate. The latter could be a result of the additional gas injected into the formation when there is no water being injected (lower effective water/gas ratio).
6. As long as gas is injected at the bottom part and water at the top of the formation, there seems to be no effect on oil recovery of the extent of the reservoir thickness that receives the injected gas.
7. For a lesser amount of injected gas, SSWAG injection resulted in higher oil recovery than WAG injection at the relatively low injection rates.
8. At the injector, SSWAG injection pressures were stable compared to the fluctuation in WAG injection pressure. This is due to the higher injected phase mobility around SSWAG water and gas injectors compared to that of WAG. Continuous fluctuation in operating pressures is detrimental to the injection facilities.
9. At the producer, SSWAG injection reduced the fluctuation normally associated with WAG injection. Thus, SSWAG injection could reduce gas handling cost.

10. SSWAG injection will also eliminate the extra operation required to alternate water and gas injection in the case of WAG. Of course, that is true only if SSWAG injection is continuous without periodic water injection shut-offs.

7.3 Recommendations

For future research, it is proposed to investigate the followings:

1. Evaluate SSWAG injection at higher injection rates than those considered in this study. It may be necessary to consider horizontal well completions as suggested by Stone.
2. Besides relative permeability, there are many other reservoir properties that may influence the performance of SSWAG injection. Capillary pressure, k_v/k_h ratio and reservoir heterogeneity are some that can be considered for investigation.
3. There are also several design parameters, not investigated in this study, which could affect the oil recovery by SSWAG injection. Well spacing within the same 5-spot pattern or even considering different patterns (7-spot or 9-spot) may greatly affect the areal sweep efficiency and, therefore, oil recovery.

NOMENCLATURE

B_g	Gas formation volume factor
B_o	Oil formation volume factor
BWPD	Barrels of water per day
D	Day
EOR	Enhanced oil recovery
FAWAG	Foam assisted WAG
HI-HP	Horizontal injector – horizontal producer
k_{h}	Horizontal permeability
k_{r}	Relative permeability
k_{rg}	Gas relative permeability
k_{rog}	Oil relative permeability in gas-liquid system
k_{row}	Oil relative permeability in oil-water system
k_{rw}	Water relative permeability
k_{v}	Vertical permeability
md	Millidarcy
μ_g	Gas viscosity
Mscf/d	Thousand standard cubic feet per day
μ_o	Oil viscosity
OIIP	Oil initially in place
p	Pressure

PV	Pore volume injected
R_s	Solution gas oil ratio
RB	Reservoir barrels per day
S_{g}	Gas Saturation
S_{orw}	Waterflood residual oil saturation
STB	Stock-tank barrel
S_{w}	Water saturation
$SWACO_2$	Simultaneous water and CO_2
SWAG	Simultaneous water and Gas
$SSWACO_2$	Selective simultaneous water and CO_2
SSWAG	Selective simultaneous water and Gas
VI-HP	Vertical injector – horizontal producer
VI-VP	Vertical injector – vertical producer
$WACO_2$	Water-Alternating-CO_2
WAG	Water-Alternating-Gas

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APPENDIX A

SAMPLE SIMULATION DATA FILE: CONTINUOUS SSWAG INJECTION

```
-- RUNSPEC section ============================================
-- The RUNSPEC section is the first section of an ECLIPSE data input file.
-- It contains the run title, start date, units, various problem dimensions
-- (numbers of blocks, wells, tables etc.), flags for phases or components
-- present and option switches.
RUNSPEC
-- Checking Data file - No simulation:
--NOSIM
-- Suppress Eclipse warning messages
NOWARN
-- Run title:
TITLE
 5 Spot Pattern Waterflood
-- Phase present:
OIL
WATER
GAS
DISGAS
-- Use FIELD unit:
FIELD
-- Simulation Start date:
START
 01 Jan 2000 /
-- Dimensions of the well data to be used:
WELLDIMS
10 20 2 10 /
-- Cartesian geometry:
CART
--Specify Grid dimensions:
DIMENS
41 21 15 /
-- Default PVT Tables Dimensions
TABDIMS
 1 1 50 50 /
-- Linear solver stack size:
NSTACK
25 /
SAVE
/

-- Grid section ================================================
-- The GRID section determines the basic geometry of the simulation
-- grid and various rock properties (porosity, absolute permeability,
-- net-to-gross ratios) in each grid cell. From this information,
-- the program calculates the grid block pore volumes, mid-point
-- depths and inter-block transmissibilities.
GRID
-- Default Block Centered Geometry.
-- The origin in Cartesian geometry is the top left back corner.
Include
'c-GRID.dat'
/
-- Porosity Data:
Include
```

```
'C-PORO.dat'
/
-- Absolute permeability Data in the X, Y & Z directions:
Include
'C-PERM.dat'
/
-- Grid output controls:
--RPTGRID
-- 1 1 1 1 1 7*0 1 /
-- Output initial file:
INIT

-- Properties Section =========================================
-- The PROPS section of the input data contains pressure and
-- saturation dependent properties of the reservoir fluids and rocks.
PROPS
--Relative Permeability & PVT Data:
Include
'B-SPVT.dat'
/
-- Fluids Surface densities / Gravities (API, W sepc.g, G spec.g):
GRAVITY
35 1.07 0.7 /
--Rock compressibility at Pref:
ROCK
 3000.0 1.0E-09 /
-- Water PVT Properties at Pref (Pref Bwref Cw Vw viscosibility=dVw/dP):
PVTW
 3000.0 1.00 1.0E-09 0.31 0.0 /
-- Properties output controls:
--RPTPROPS
-- SWFN SGFN PVTO PVTW PVDG SOF3 /

-- Regions Section =============================================
-- The REGIONS section divides the computational grid into regions.
REGIONS
-- No. of Saturation Regions:
SATNUM
 12915*1 /
-- Regions output controls:
--RPTREGS
-- 1 1 1 5*0 1 /

-- Solution Section ============================================
-- The SOLUTION section contains sufficient data to define the
-- initial state (pressure, saturations, compositions) of every
-- grid block in the reservoir.
SOLUTION
-- Initial equilibration conditions at Datum depth & Pref.:
EQUIL
-- Datum Pref    WOC    Pcow GOC Pcog
 8145.0  3000.0  15000  0    0   0    1  0  0 /
-- Rs versus depth Tables at initial conditions:
RSVD
-- Depth Rsi
 8000.0  0.768
 8300.0  0.768 /
-- Solution output controls:
--RPTSOL
-- PRESSURE SWAT SGAS SOIL FIP /
-- Output basic restart files every time step:
RPTRST
 BASIC=2 /

-- Summary Section ============================================
-- The SUMMARY section specifies a number of variables that are
```

```
-- to be written to Summary files after each time step of the
-- simulation. The graphics post-processor may be used to display
-- the variation of variables in the Summary files with time and
-- with each other.
SUMMARY
-- Requests a neat tabulated output of the RSM summary file:
RUNSUM
-- Requests RUNSUM output to go to a separate RSM file:
SEPARATE
-- Requests that the summary data is only produced at report times:
--RPTONLY
-- Specify Field/Group/Wellparameters to be written in the RSM.
-- Requests a basic set of field/group/well keywords for all:
-- ALL
--  Production Rates
FOPR
FWPR
FGPR
FVPR
--FLPR
--  Production Totals
FOPT
FWPT
FGPT
FVPT
--FLPT
--  Injection Rates
--FOIR
FWIR
FGIR
FVIR
--  Injection Totals
--FOIT
FWIT
FGIT
FVIT
--  Saturations
FOSAT
FWSAT
FGSAT
--  Ratios
FGOR
FWGR
--FGLR
FRS
--  Avg Pressure & Water Cut
FPR
FWCT
FOE
--  BHP for each Well
WBHP
/
--WWCT
--/
--WOPR
--/
--WWPR
--/
--WGPR
--/
--WOIR
--/
--WWIR
--/
--WGIR
--/
```

```
-- Schedule Section ============================================
-- The SCHEDULE section specifies the operations to be simulated
-- (production and injection controls and constraints) and the
-- times at which output reports are required. Vertical flow
-- performance curves and simulator tuning parameters may also
-- be specified in the SCHEDULE section.
SCHEDULE
-- Schedule output control switches:
RPTSCHED
 0 0 0 0 0 0 2 0 0 0 0 1 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 /
DRSDT
0.005 /
-- Well general specifications:
-- Name, Group, I, J, Dref, Phase, Rdrain, Flag, Auto Shut,..
WELSPECS
'PR' 'A' 41 21 1* 'OIL'  /
 'W' 'A' 01 21 1* 'WAT'  /
 'G' 'A' 01 21 1* 'GAS' 3* /
 /
-- Well completion specification data:
-- Name,I,J,K1,K2,Status,1,0,diam,3*default, penetration direc.:
COMPDAT
'PR' 41 21 01 15 'OPEN' 1 0 0.5 3* Z /
 'W' 01 21 01 14 'OPEN' 1 0 0.5 3* Z /
 'G' 01 21 15 15 'OPEN' 1 0 0.5 3* z /
 /
-- Control data for production wells:
-- Name,status,control mode,Oq,Wq,Gq,Lq,ResV,BHP,THP,..:
WCONPROD
'PR' 'OPEN' 'RESV' 4* 1000 14.7 /
 /
-- Economic limit data for production wells:
-- Name, Oq, Gq, WC, GOR, WGR, ...:
WECON
'PR' 0.5 1* 0.95 /
 /
WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
 /
WCONINJP
'G' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TUNING
 1* 1.0 0.01 /
 /
 2* 100 1* 24 5* /
-- Specifies the number and length of the timesteps required
TSTEP
 1*30.0 182*60.0
 /
END
```

APPENDIX B

SAMPLE SIMULATION DATA FILE: SSWAG INJECTION WITH PERIODIC WATER INJECTION SHUT-OFFS

```
-- RUNSPEC section ============================================
-- The RUNSPEC section is the first section of an ECLIPSE data input file.
-- It contains the run title, start date, units, various problem dimensions
-- (numbers of blocks, wells, tables etc.), flags for phases or components
-- present and option switches.
RUNSPEC
-- Checking Data file - No simulation:
--NOSIM
-- Suppress Eclipse warning messages
NOWARN
-- Run title:
TITLE
 5 Spot Pattern Waterflood
-- Phase present:
OIL
WATER
GAS
DISGAS
-- Use FIELD unit:
FIELD
-- Simulation Start date:
START
 01 Jan 2000 /
-- Dimensions of the well data to be used:
WELLDIMS
10 20 2 10 /
-- Cartesian geometry:
CART
--Specify Grid dimensions:
DIMENS
41 21 15 /
-- Default PVT Tables Dimensions
TABDIMS
 1 1 50 50 /
-- Linear solver stack size:
NSTACK
25 /
SAVE
/
-- Grid section ================================================
-- The GRID section determines the basic geometry of the simulation
-- grid and various rock properties (porosity, absolute permeability,
-- net-to-gross ratios) in each grid cell. From this information,
-- the program calculates the grid block pore volumes, mid-point
-- depths and inter-block transmissibilities.
GRID
-- Default Block Centered Geometry.
-- The origin in Cartesian geometry is the top left back corner.
Include
'c-GRID.dat'
/
```

```
-- Porosity Data:
Include
'C-PORO.dat'
/
-- Absolute permeability Data in the X, Y & Z directions:
Include
'C-PERM.dat'
/
-- Grid output controls:
--RPTGRID
-- 1 1 1 1 1 7*0 1 /
-- Output initial file:
INIT
-- Properties Section ==========================================
-- The PROPS section of the input data contains pressure and
-- saturation dependent properties of the reservoir fluids and rocks.
PROPS
--Relative Permeability & PVT Data:
Include
'B-SPVT.dat'
/
-- Fluids Surface densities / Gravities (API, W sepc.g, G spec.g):
GRAVITY
35 1.07 0.7 /
--Rock compressibility at Pref:
ROCK
 3000.0 1.0E-09 /
-- Water PVT Properties at Pref (Pref Bwref Cw Vw viscosibility=dVw/dP):
PVTW
 3000.0 1.00 1.0E-09 0.31 0.0 /
-- Properties output controls:
--RPTPROPS
-- SWFN SGFN PVTO PVTW PVDG SOF3 /
-- Regions Section ============================================
-- The REGIONS section divides the computational grid into regions.
REGIONS
-- No. of Saturation Regions:
SATNUM
 12915*1 /
-- Regions output controls:
--RPTREGS
-- 1 1 1 5*0 1 /
-- Solution Section ===========================================
-- The SOLUTION section contains sufficient data to define the
-- initial state (pressure, saturations, compositions) of every
-- grid block in the reservoir.
SOLUTION
-- Initial equilibration conditions at Datum depth & Pref.:
EQUIL
-- Datum Pref    WOC    Pcow GOC Pcog
 8145.0  3000.0  15000  0    0   0    1  0  0 /
-- Rs versus depth Tables at initial conditions:
RSVD
-- Depth Rsi
 8000.0  0.768
 8300.0  0.768 /
-- Solution output controls:
--RPTSOL
-- PRESSURE SWAT SGAS SOIL FIP /
-- Output basic restart files every time step:
RPTRST
 BASIC=2 /
-- Summary Section ============================================
-- The SUMMARY section specifies a number of variables that are
-- to be written to Summary files after each time step of the
-- simulation. The graphics post-processor may be used to display
```

```
-- the variation of variables in the Summary files with time and
-- with each other.
SUMMARY
-- Requests a neat tabulated output of the RSM summary file:
RUNSUM
-- Requests RUNSUM output to go to a separate RSM file:
SEPARATE
-- Requests that the summary data is only produced at report times:
--RPTONLY
-- Specify Field/Group/Wellparameters to be written in the RSM.
-- Requests a basic set of field/group/well keywords for all:
-- ALL
--  Production Rates
FOPR
FWPR
FGPR
FVPR
--FLPR
--  Production Totals
FOPT
FWPT
FGPT
FVPT
--FLPT
--  Injection Rates
--FOIR
FWIR
FGIR
FVIR
--  Injection Totals
--FOIT
FWIT
FGIT
FVIT
--  Saturations
FOSAT
FWSAT
FGSAT
--  Ratios
FGOR
FWGR
--FGLR
FRS
--  Avg Pressure & Water Cut
FPR
FWCT
--Recovery Efficiency
FOE
--  BHP for each Well
WBHP
/
--WWCT
--/
--WOPR
--/
--WWPR
--/
--WGPR
--/
--WOIR
--/
--WWIR
--/
--WGIR
--/
-- Schedule Section ==========================================
```

```
-- The SCHEDULE section specifies the operations to be simulated
-- (production and injection controls and constraints) and the
-- times at which output reports are required. Vertical flow
-- performance curves and simulator tuning parameters may also
-- be specified in the SCHEDULE section.
SCHEDULE
-- Schedule output control switches:
RPTSCHED
 0 0 0 0 0 0 2 0 0 0 0 1 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 /
DRSDT
 0.005 /
-- Well general specifications:
-- Name, Group, I, J, Dref, Phase, Rdrain, Flag, Auto Shut,..
WELSPECS
'PR' 'A' 41 21 1* 'OIL'  /
 'W' 'A' 01 21 1* 'WAT'  /
 'G' 'A' 01 21 1* 'GAS' 3* /
 /
-- Well completion specification data:
-- Name,I,J,K1,K2,Status,1,0,diam,3*default, penetration direc.:
COMPDAT
'PR' 41 21 01 15 'OPEN' 1 0 0.5 3* Z /
 'W' 01 21 01 14 'OPEN' 1 0 0.5 3* Z /
 'G' 01 21 15 15 'OPEN' 1 0 0.5 3* z /
 /
-- Control data for production wells:
-- Name,status,control mode,Oq,Wq,Gq,Lq,ResV,BHP,THP,..:
WCONPROD
'PR' 'OPEN' 'RESV' 4* 1000 14.7 /
 /
-- Economic limit data for production wells:
-- Name, Oq, Gq, WC, GOR, WGR, ...:
--WECON
--'PR' 0.5 1* 0.95 /
-- /
TUNING
 0.001 01.0 0.001 6* 0.01 /
 /
 2* 100 1* 50 5* /
-- Include Injection Schedule
-- Water Injection Periodic shut-off
-- 5 Months on
-- 1 Month off
-- Total Period = 30 Years
-- Gas Injection:
WCONINJP
'G' 'GAS' 'OPEN' 5600 /
'PR' /
 /
-- Water Injection:
WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
3*50.0
 /
WCONINJP
'W' 'WAT' 'SHUT' 5600 /
'PR' /
 /
TSTEP
2.5 30.0
 /
```

```
WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
3*50.0
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WCONINJP
'W' 'WAT' 'SHUT' 5600 /
'PR' /
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TSTEP
2.5 30.0
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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WCONINJP
'W' 'WAT' 'SHUT' 5600 /
'PR' /
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TSTEP
2.5 30.0
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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TSTEP
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'W' 'WAT' 'SHUT' 5600 /
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TSTEP
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'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'SHUT' 5600 /
'PR' /
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TSTEP
2.5 30.0
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
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WCONINJP
'W' 'WAT' 'SHUT' 5600 /
'PR' /
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TSTEP
2.5 30.0
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
3*50.0
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TSTEP
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2.5 30.0
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'SHUT' 5600 /
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TSTEP
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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WCONINJP
'W' 'WAT' 'SHUT' 5600 /
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TSTEP
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
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WCONINJP
'W' 'WAT' 'SHUT' 5600 /
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TSTEP
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'W' 'WAT' 'OPEN' 5600 /
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TSTEP
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'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'SHUT' 5600 /
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TSTEP
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'OPEN' 5600 /
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3*50.0
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WCONINJP
'W' 'WAT' 'SHUT' 5600 /
'PR' /
 /
TSTEP
2.5 30.0
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
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'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'SHUT' 5600 /
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'SHUT' 5600 /
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TSTEP
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'SHUT' 5600 /
'PR' /
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TSTEP
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'SHUT' 5600 /
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'W' 'WAT' 'OPEN' 5600 /
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TSTEP
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'W' 'WAT' 'SHUT' 5600 /
'PR' /
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TSTEP
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
3*50.0
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'W' 'WAT' 'SHUT' 5600 /
'PR' /
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TSTEP
2.5 30.0
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WCONINJP
```

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'W' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
3*50.0
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WCONINJP
'W' 'WAT' 'SHUT' 5600 /
'PR' /
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TSTEP
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'SHUT' 5600 /
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
3*50.0
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WCONINJP
'W' 'WAT' 'SHUT' 5600 /
'PR' /
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TSTEP
2.5 30.0
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
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3*50.0
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WCONINJP
'W' 'WAT' 'SHUT' 5600 /
'PR' /
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TSTEP
2.5 30.0
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
3*50.0
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WCONINJP
'W' 'WAT' 'SHUT' 5600 /
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'PR' /
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TSTEP
2.5 30.0
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'SHUT' 5600 /
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TSTEP
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'SHUT' 5600 /
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
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'W' 'WAT' 'SHUT' 5600 /
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TSTEP
2.5 30.0
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WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
3*50.0
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WCONINJP
'W' 'WAT' 'SHUT' 5600 /
'PR' /
 /
TSTEP
2.5 30.0
 /
--==========
END
```

APPENDIX C

SAMPLE SIMULATION DATA FILE: SWAG INJECTION

```
-- RUNSPEC section =============================================
-- The RUNSPEC section is the first section of an ECLIPSE data input file.
-- It contains the run title, start date, units, various problem dimensions
-- (numbers of blocks, wells, tables etc.), flags for phases or components
-- present and option switches.
RUNSPEC
-- Checking Data file - No simulation:
--NOSIM
-- Suppress Eclipse warning messages
NOWARN
-- Run title:
TITLE
 5 Spot Pattern Waterflood
-- Phase present:
OIL
WATER
GAS
DISGAS
 -- Use FIELD unit:
FIELD
-- Simulation Start date:
START
 01 Jan 2000 /
-- Dimensions of the well data to be used:
WELLDIMS
10 20 2 10 /
-- Cartesian geometry:
CART
--Specify Grid dimensions:
DIMENS
41 21 15 /
-- Default PVT Tables Dimensions
TABDIMS
 1 1 50 50 /
-- Linear solver stack size:
NSTACK
25 /
SAVE
/
-- Grid section ================================================
-- The GRID section determines the basic geometry of the simulation
-- grid and various rock properties (porosity, absolute permeability,
-- net-to-gross ratios) in each grid cell. From this information,
-- the program calculates the grid block pore volumes, mid-point
-- depths and inter-block transmissibilities.
GRID
-- Default Block Centered Geometry.
-- The origin in Cartesian geometry is the top left back corner.
Include
'c-GRID.dat'
/
-- Porosity Data:
Include
'C-PORO.dat'
```

```
/
-- Absolute permeability Data in the X, Y & Z directions:
Include
'C-PERM.dat'
/
-- Grid output controls:
--RPTGRID
-- 1 1 1 1 1 7*0 1 /
 -- Output initial file:
INIT
-- Properties Section ==========================================
-- The PROPS section of the input data contains pressure and
-- saturation dependent properties of the reservoir fluids and rocks.
PROPS
--Relative Permeability & PVT Data:
Include
'B-SPVT.dat'
/
-- Fluids Surface densities / Gravities (API, W sepc.g, G spec.g):
GRAVITY
35 1.07 0.7 /
--Rock compressibility at Pref:
ROCK
 3000.0 1.0E-09 /
-- Water PVT Properties at Pref (Pref Bwref Cw Vw viscosibility=dVw/dP):
PVTW
 3000.0 1.00 1.0E-09 0.31 0.0 /
-- Properties output controls:
--RPTPROPS
-- SWFN SGFN PVTO PVTW PVDG SOF3 /
-- Regions Section ==============================================
-- The REGIONS section divides the computational grid into regions.
REGIONS
-- No. of Saturation Regions:
SATNUM
 12915*1 /
-- Regions output controls:
--RPTREGS
-- 1 1 1 5*0 1 /
-- Solution Section ============================================
-- The SOLUTION section contains sufficient data to define the
-- initial state (pressure, saturations, compositions) of every
-- grid block in the reservoir.
SOLUTION
-- Initial equilibration conditions at Datum depth & Pref.:
EQUIL
-- Datum Pref    WOC    Pcow GOC Pcog
 8145.0  3000.0  15000  0    0   0    1  0  0 /
-- Rs versus depth Tables at initial conditions:
RSVD
-- Depth Rsi
 8000.0  0.768
 8300.0  0.768 /
-- Solution output controls:
--RPTSOL
-- PRESSURE SWAT SGAS SOIL FIP /
-- Output basic restart files every time step:
RPTRST
 BASIC=2 /
-- Summary Section ==============================================
-- The SUMMARY section specifies a number of variables that are
-- to be written to Summary files after each time step of the
-- simulation. The graphics post-processor may be used to display
-- the variation of variables in the Summary files with time and
-- with each other.
SUMMARY
```

```
-- Requests a neat tabulated output of the RSM summary file:
RUNSUM

-- Requests RUNSUM output to go to a separate RSM file:
SEPARATE

-- Requests that the summary data is only produced at report times:
--RPTONLY
-- Specify Field/Group/Wellparameters to be written in the RSM.

-- Requests a basic set of field/group/well keywords for all:
-- ALL

--  Production Rates
FOPR
FWPR
FGPR
FVPR
--FLPR
--  Production Totals
FOPT
FWPT
FGPT
FVPT
--FLPT
--  Injection Rates
--FOIR
FWIR
FGIR
FVIR
--  Injection Totals
--FOIT
FWIT
FGIT
FVIT
--  Saturations
FOSAT
FWSAT
FGSAT
--  Ratios
FGOR
FWGR
--FGLR
FRS
--  Avg Pressure & Water Cut
FPR
FWCT
FOE
--  BHP for each Well
WBHP
/
--WWCT
--/
--WOPR
--/
--WWPR
--/
--WGPR
--/
--WOIR
--/
--WWIR
--/
--WGIR
--/
```

```
-- Schedule Section ============================================
-- The SCHEDULE section specifies the operations to be simulated
-- (production and injection controls and constraints) and the
-- times at which output reports are required. Vertical flow
-- performance curves and simulator tuning parameters may also
-- be specified in the SCHEDULE section.

SCHEDULE


-- Schedule output control switches:
RPTSCHED
 0 0 0 0 0 0 2 0 0 0 0 1 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 /

DRSDT
0.005 /

-- Well general specifications:
-- Name, Group, I, J, Dref, Phase, Rdrain, Flag, Auto Shut,..
WELSPECS
'PR' 'A' 41 21 1* 'OIL'  /
 'W' 'A' 01 21 1* 'WAT'  /
 'G' 'A' 01 21 1* 'GAS' 3* /
 /

-- Well completion specification data:
-- Name,I,J,K1,K2,Status,1,0,diam,3*default, penetration direc.:
COMPDAT
'PR' 41 21 01 15 'OPEN' 1 0 0.5 3* Z /
 'W' 01 21 01 15 'OPEN' 1 0 0.5 3* Z /
 'G' 01 21 01 15 'OPEN' 1 0 0.5 3* z /
 /

-- Control data for production wells:
-- Name,status,control mode,Oq,Wq,Gq,Lq,ResV,BHP,THP,..:
WCONPROD
'PR' 'OPEN' 'RESV' 4* 1000 14.7 /
 /
-- Economic limit data for production wells:
-- Name, Oq, Gq, WC, GOR, WGR, ...:
WECON
'PR' 0.5 1* 0.95 /
 /
WCONINJP
'W' 'WAT' 'OPEN' 5600 /
'PR' /
 /
WCONINJP
'G' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TUNING
 0.001 1.0 0.001 /
 /
 2* 50 1* 24 5* /
-- Specifies the number and length of the timesteps required
TSTEP
 1*30.0 182*60.0
/
END
```

APPENDIX D

SAMPLE SIMULATION DATA FILE: WAG INJECTION

```
-- RUNSPEC section ==============================================
-- The RUNSPEC section is the first section of an ECLIPSE data input file.
-- It contains the run title, start date, units, various problem dimensions
-- (numbers of blocks, wells, tables etc.), flags for phases or components
-- present and option switches.
RUNSPEC
-- Checking Data file - No simulation:
--NOSIM
-- Suppress Eclipse warning messages
NOWARN
-- Run title:
TITLE
 5 Spot Pattern Waterflood
-- Phase present:
OIL
WATER
GAS
DISGAS
-- Use FIELD unit:
FIELD
-- Simulation Start date:
START
 01 Jan 2000 /
-- Dimensions of the well data to be used:
WELLDIMS
10 20 2 10 /
-- Cartesian geometry:
CART
--Specify Grid dimensions:
DIMENS
41 21 15 /
-- Default PVT Tables Dimensions
TABDIMS
 1 1 50 50 /
-- Linear solver stack size:
NSTACK
25 /
SAVE
 /

-- Grid section ================================================
-- The GRID section determines the basic geometry of the simulation
-- grid and various rock properties (porosity, absolute permeability,
-- net-to-gross ratios) in each grid cell. From this information,
-- the program calculates the grid block pore volumes, mid-point
-- depths and inter-block transmissibilities.
GRID
-- Default Block Centered Geometry.
-- The origin in Cartesian geometry is the top left back corner.
Include
'c-GRID.dat'
/
-- Porosity Data:
Include
```

```
'C-PORO.dat'
/
-- Absolute permeability Data in the X, Y & Z directions:
Include
'C-PERM.dat'
/
-- Grid output controls:
--RPTGRID
-- 1 1 1 1 1 7*0 1 /
-- Output initial file:
INIT

-- Properties Section ==========================================
-- The PROPS section of the input data contains pressure and
-- saturation dependent properties of the reservoir fluids and rocks.
PROPS
--Relative Permeability & PVT Data:
Include
'B-SPVT.dat'
/
-- Fluids Surface densities / Gravities (API, W sepc.g, G spec.g):
GRAVITY
35 1.07 0.7 /
--Rock compressibility at Pref:
ROCK
 3000.0 1.0E-09 /
-- Water PVT Properties at Pref (Pref Bwref Cw Vw viscosibility=dVw/dP):
PVTW
 3000.0 1.00 1.0E-09 0.31 0.0 /
-- Properties output controls:
--RPTPROPS
-- SWFN SGFN PVTO PVTW PVDG SOF3 /

-- Regions Section ==============================================
-- The REGIONS section divides the computational grid into regions.
REGIONS
-- No. of Saturation Regions:
SATNUM
 12915*1 /
-- Regions output controls:
--RPTREGS
-- 1 1 1 5*0 1 /

-- Solution Section =============================================
-- The SOLUTION section contains sufficient data to define the
-- initial state (pressure, saturations, compositions) of every
-- grid block in the reservoir.
SOLUTION
-- Initial equilibration conditions at Datum depth & Pref.:
EQUIL
-- Datum Pref    WOC    Pcow GOC Pcog
 8145.0  3000.0  15000  0    0   0    1  0  0 /
-- Rs versus depth Tables at initial conditions:
RSVD
-- Depth Rsi
 8000.0  0.768
 8300.0  0.768 /
-- Solution output controls:
--RPTSOL
-- PRESSURE SWAT SGAS SOIL FIP /
-- Output basic restart files every time step:
RPTRST
 BASIC=2 /

-- Summary Section ==============================================
-- The SUMMARY section specifies a number of variables that are
```

```
-- to be written to Summary files after each time step of the
-- simulation. The graphics post-processor may be used to display
-- the variation of variables in the Summary files with time and
-- with each other.
SUMMARY
-- Requests a neat tabulated output of the RSM summary file:
RUNSUM
-- Requests RUNSUM output to go to a separate RSM file:
SEPARATE
-- Requests that the summary data is only produced at report times:
--RPTONLY
-- Specify Field/Group/Wellparameters to be written in the RSM.
-- Requests a basic set of field/group/well keywords for all:
-- ALL
--  Production Rates
FOPR
FWPR
FGPR
FVPR
--FLPR
--  Production Totals
FOPT
FWPT
FGPT
FVPT
--FLPT
--  Injection Rates
--FOIR
FWIR
FGIR
FVIR
--  Injection Totals
--FOIT
FWIT
FGIT
FVIT
--  Saturations
FOSAT
FWSAT
FGSAT
--  Ratios
FGOR
FWGR
--FGLR
FRS
--  Avg Pressure & Water Cut
FPR
FWCT
FOE
--  BHP for each Well
WBHP
/
--WWCT
--/
--WOPR
--/
--WWPR
--/
--WGPR
--/
--WOIR
--/
--WWIR
--/
--WGIR
--/
```

```
-- Schedule Section =============================================
-- The SCHEDULE section specifies the operations to be simulated
-- (production and injection controls and constraints) and the
-- times at which output reports are required. Vertical flow
-- performance curves and simulator tuning parameters may also
-- be specified in the SCHEDULE section.
SCHEDULE
-- Schedule output control switches:
RPTSCHED
 0 0 0 0 0 0 2 0 0 0 0 1 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 /
DRSDT
0.005 /
-- Well general specifications:
-- Name, Group, I, J, Dref, Phase, Rdrain, Flag, Auto Shut,..
WELSPECS
'PR' 'A' 41 21 1* 'OIL'  /
'WAG' 'A' 01 21 1* 'WAT'  /
-- 'G' 'A' 01 21 1* 'GAS' 3* /
 /
-- Well completion specification data:
-- Name,I,J,K1,K2,Status,1,0,diam,3*default, penetration direc.:
COMPDAT
'PR' 41 21 01 15 'OPEN' 1 0 0.5 3* Z /
'WAG' 01 21 01 15 'OPEN' 1 0 0.5 3* Z /
-- 'G' 01 21 01 15 'OPEN' 1 0 0.5 3* z /
 /
-- Control data for production wells:
-- Name,status,control mode,Oq,Wq,Gq,Lq,ResV,BHP,THP,..:
WCONPROD
'PR' 'OPEN' 'RESV' 4* 1000 14.7 /
 /
-- Economic limit data for production wells:
-- Name, Oq, Gq, WC, GOR, WGR, ...:
--WECON
--'PR' 1.0 1* 0.95 /
-- /
TUNING
 0.001 01.0 0.001 /
 /
 2* 100 1* 50 5* /
-- Include WAG Cycles
-- WAG Cycles
-- 6 Month Gas
-- 6 Month Water
-- At WAG Ratio = 1.0
-- Total Period = 30 Years
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
```

```
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
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'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
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WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
62.5 2*60.0
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WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
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TSTEP
62.5 2*60.0
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WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
62.5 2*60.0
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WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
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TSTEP
62.5 2*60.0
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WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
62.5 2*60.0
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WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
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TSTEP
62.5 2*60.0
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WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
62.5 2*60.0
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WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
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TSTEP
62.5 2*60.0
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WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
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'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
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WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
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TSTEP
62.5 2*60.0
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WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
```

```
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
```

```
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
```

```
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
```

```
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
WCONINJP
'WAG' 'WAT' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
WCONINJP
'WAG' 'GAS' 'OPEN' 5600 /
'PR' /
 /
TSTEP
62.5 2*60.0
 /
--==========
END
```

APPENDIX E

MODEL INCLUDE FILE: C-GRID.DAT

```
-- Grid block sizes & Tops

-- DX --------------
BOX
01 01 01 21 01 15 /
DX
315*4.000
/
BOX
02 02 01 21 01 15 /
DX
315*4.730
/
BOX
03 03 01 21 01 15 /
DX
315*5.594
/
BOX
04 04 01 21 01 15 /
DX
315*6.615
/
BOX
05 05 01 21 01 15 /
DX
315*7.822
/
BOX
06 06 01 21 01 15 /
DX
315*9.250
/
BOX
07 07 01 21 01 15 /
DX
315*10.939
/
BOX
08 08 01 21 01 15 /
DX
315*12.936
/
BOX
09 09 01 21 01 15 /
DX
315*15.297
/
BOX
10 10 01 21 01 15 /
DX
315*18.090
/
BOX
```

11 11 01 21 01 15 /
DX
315*21.392
/
BOX
12 12 01 21 01 15 /
DX
315*25.297
/
BOX
13 13 01 21 01 15 /
DX
315*29.915
/
BOX
14 14 01 21 01 15 /
DX
315*35.376
/
BOX
15 15 01 21 01 15 /
DX
315*41.834
/
BOX
16 16 01 21 01 15 /
DX
315*49.471
/
BOX
17 17 01 21 01 15 /
DX
315*58.502
/
BOX
18 18 01 21 01 15 /
DX
315*69.181
/
BOX
19 19 01 21 01 15 /
DX
315*81.810
/
BOX
20 20 01 21 01 15 /
DX
315*96.745
/
BOX
21 21 01 21 01 15 /
DX
315*114.405
/
BOX
22 22 01 21 01 15 /
DX
315*96.745
/
BOX
23 23 01 21 01 15 /
DX
315*81.810
/
BOX
24 24 01 21 01 15 /

DX
315*69.181
/
BOX
25 25 01 21 01 15 /
DX
315*58.502
/
BOX
26 26 01 21 01 15 /
DX
315*49.471
/
BOX
27 27 01 21 01 15 /
DX
315*41.834
/
BOX
28 28 01 21 01 15 /
DX
315*35.376
/
BOX
29 29 01 21 01 15 /
DX
315*29.915
/
BOX
30 30 01 21 01 15 /
DX
315*25.297
/
BOX
31 31 01 21 01 15 /
DX
315*21.392
/
BOX
32 32 01 21 01 15 /
DX
315*18.090
/
BOX
33 33 01 21 01 15 /
DX
315*15.297
/
BOX
34 34 01 21 01 15 /
DX
315*12.936
/
BOX
35 35 01 21 01 15 /
DX
315*10.939
/
BOX
36 36 01 21 01 15 /
DX
315*9.250
/
BOX
37 37 01 21 01 15 /
DX

```
315*7.822
/
BOX
38 38 01 21 01 15 /
DX
315*6.615
/
BOX
39 39 01 21 01 15 /
DX
315*5.594
/
BOX
40 40 01 21 01 15 /
DX
315*4.730
/
BOX
41 41 01 21 01 15 /
DX
315*4.000
/
ENDBOX

-- DY ========================
BOX
01 41 01 01 01 15 /
DY
615*114.405
/
BOX
01 41 02 02 01 15 /
DY
615*96.745
/
BOX
01 41 03 03 01 15 /
DY
615*81.810
/
BOX
01 41 04 04 01 15 /
DY
615*69.181
/
BOX
01 41 05 05 01 15 /
DY
615*58.502
/
BOX
01 41 06 06 01 15 /
DY
615*49.471
/
BOX
01 41 07 07 01 15 /
DY
615*41.834
/
BOX
01 41 08 08 01 15 /
DY
615*35.376
/
BOX
```

```
01 41 09 09 01 15 /
DY
615*29.915
/
BOX
01 41 10 10 01 15 /
DY
615*25.297
/
BOX
01 41 11 11 01 15 /
DY
615*21.392
/
BOX
01 41 12 12 01 15 /
DY
615*18.090
/
BOX
01 41 13 13 01 15 /
DY
615*15.297
/
BOX
01 41 14 14 01 15 /
DY
615*12.936
/
BOX
01 41 15 15 01 15 /
DY
615*10.939
/
BOX
01 41 16 16 01 15 /
DY
615*9.250
/
BOX
01 41 17 17 01 15 /
DY
615*7.822
/
BOX
01 41 18 18 01 15 /
DY
615*6.615
/
BOX
01 41 19 19 01 15 /
DY
615*5.594
/
BOX
01 41 20 20 01 15 /
DY
615*4.730
/
BOX
01 41 21 21 01 15 /
DY
615*4.000
/
ENDBOX
```

```
-- DZ ========================
DZ
861*19
861*19
861*19
861*19
861*19
861*19
861*19
861*19
861*19
861*19
861*20
861*20
861*20
861*20
861*20 /

-- Cell top depths
TOPS
861*8000.0
861*8019.0
861*8038.0
861*8057.0
861*8076.0
861*8095.0
861*8114.0
861*8133.0
861*8152.0
861*8171.0
861*8190.0
861*8210.0
861*8230.0
861*8250.0
861*8270.0 /
```

APPENDIX F

MODEL INCLUDE FILE: C-PORO.DAT

```
-- Porosity Data:

PORO
-- Layer-01 ----------------------------------
20*0           01*0.05250           20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
     01*0.02625 39*0.10500 01*0.02625
-- Layer-02 ----------------------------------
20*0           01*0.05250           20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
     01*0.02625 39*0.10500 01*0.02625
-- Layer-03 ----------------------------------
20*0           01*0.05250           20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
```

```
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
     01*0.02625 39*0.10500 01*0.02625
-- Layer-04 ----------------------------------
20*0            01*0.05250            20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
     01*0.02625 39*0.10500 01*0.02625
-- Layer-05 ----------------------------------
20*0            01*0.05250            20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
     01*0.02625 39*0.10500 01*0.02625
-- Layer-06 ----------------------------------
20*0            01*0.05250            20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
```

```
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
   01*0.02625 39*0.10500 01*0.02625
-- Layer-07 ---------------------------------
20*0          01*0.05250          20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
   01*0.02625 39*0.10500 01*0.02625
-- Layer-08 ---------------------------------
20*0          01*0.05250          20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
   01*0.02625 39*0.10500 01*0.02625
-- Layer-09 ---------------------------------
20*0          01*0.05250          20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
```

```
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
    01*0.02625 39*0.10500 01*0.02625
-- Layer-10 ---------------------------------
20*0          01*0.05250          20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
    01*0.02625 39*0.10500 01*0.02625
-- Layer-11 ---------------------------------
20*0          01*0.05250          20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
    01*0.02625 39*0.10500 01*0.02625
-- Layer-12 ---------------------------------
20*0          01*0.05250          20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
```

```
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
     01*0.02625 39*0.10500 01*0.02625
-- Layer-13 ---------------------------------
20*0           01*0.05250           20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
     01*0.02625 39*0.10500 01*0.02625
-- Layer-14 ---------------------------------
20*0           01*0.05250           20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
     01*0.02625 39*0.10500 01*0.02625
-- Layer-15 ---------------------------------
20*0           01*0.05250           20*0
19*0 01*0.10500 01*0.21000 01*0.10500 19*0
18*0 01*0.10500 03*0.21000 01*0.10500 18*0
17*0 01*0.10500 05*0.21000 01*0.10500 17*0
16*0 01*0.10500 07*0.21000 01*0.10500 16*0
15*0 01*0.10500 09*0.21000 01*0.10500 15*0
```

```
14*0 01*0.10500 11*0.21000 01*0.10500 14*0
13*0 01*0.10500 13*0.21000 01*0.10500 13*0
12*0 01*0.10500 15*0.21000 01*0.10500 12*0
11*0 01*0.10500 17*0.21000 01*0.10500 11*0
10*0 01*0.10500 19*0.21000 01*0.10500 10*0
09*0 01*0.10500 21*0.21000 01*0.10500 09*0
08*0 01*0.10500 23*0.21000 01*0.10500 08*0
07*0 01*0.10500 25*0.21000 01*0.10500 07*0
06*0 01*0.10500 27*0.21000 01*0.10500 06*0
05*0 01*0.10500 29*0.21000 01*0.10500 05*0
04*0 01*0.10500 31*0.21000 01*0.10500 04*0
03*0 01*0.10500 33*0.21000 01*0.10500 03*0
02*0 01*0.10500 35*0.21000 01*0.10500 02*0
01*0 01*0.10500 37*0.21000 01*0.10500 01*0
 01*0.02625 39*0.10500 01*0.02625
 /
```

APPENDIX G

MODEL INCLUDE FILE: C-PERM.DAT

```
-- Permeability Data:

-- PERMX ==============
BOX
01 41 01 01 01 10 /
PERMX
410*112.5
/
BOX
01 41 02 20 01 10 /
PERMX
7790*225.0
/
BOX
01 41 21 21 01 10 /
PERMX
410*112.5
/

BOX
01 41 01 01 11 15 /
PERMX
205*300.0
/
BOX
01 41 02 20 11 15 /
PERMX
3895*600.0
/
BOX
01 41 21 21 11 15 /
PERMX
205*300.0
/
ENDBOX

-- PERMY ===============
BOX
01 01 01 21 01 10 /
PERMY
210*112.5
/
BOX
02 40 01 21 01 10 /
PERMY
8190*225.0
/
BOX
41 41 01 21 01 10 /
PERMY
210*112.5
/

BOX
```

```
01 01 01 21 11 15 /
PERMY
105*300.0
/
BOX
02 40 01 21 11 15 /
PERMY
4095*600.0
/
BOX
41 41 01 21 11 15 /
PERMY
105*600.0
/
ENDBOX

-- PERMZ ==============
PERMZ

-- Layer-01 -----------------------------------
20*0           01*14.1250           20*0
19*0 01*28.2500 01*56.5000 01*28.2500 19*0
18*0 01*28.2500 03*56.5000 01*28.2500 18*0
17*0 01*28.2500 05*56.5000 01*28.2500 17*0
16*0 01*28.2500 07*56.5000 01*28.2500 16*0
15*0 01*28.2500 09*56.5000 01*28.2500 15*0
14*0 01*28.2500 11*56.5000 01*28.2500 14*0
13*0 01*28.2500 13*56.5000 01*28.2500 13*0
12*0 01*28.2500 15*56.5000 01*28.2500 12*0
11*0 01*28.2500 17*56.5000 01*28.2500 11*0
10*0 01*28.2500 19*56.5000 01*28.2500 10*0
09*0 01*28.2500 21*56.5000 01*28.2500 09*0
08*0 01*28.2500 23*56.5000 01*28.2500 08*0
07*0 01*28.2500 25*56.5000 01*28.2500 07*0
06*0 01*28.2500 27*56.5000 01*28.2500 06*0
05*0 01*28.2500 29*56.5000 01*28.2500 05*0
04*0 01*28.2500 31*56.5000 01*28.2500 04*0
03*0 01*28.2500 33*56.5000 01*28.2500 03*0
02*0 01*28.2500 35*56.5000 01*28.2500 02*0
01*0 01*28.2500 37*56.5000 01*28.2500 01*0
    01*07.0625 39*28.2500 01*07.0625


-- Layer-02 -----------------------------------
20*0           01*14.1250           20*0
19*0 01*28.2500 01*56.5000 01*28.2500 19*0
18*0 01*28.2500 03*56.5000 01*28.2500 18*0
17*0 01*28.2500 05*56.5000 01*28.2500 17*0
16*0 01*28.2500 07*56.5000 01*28.2500 16*0
15*0 01*28.2500 09*56.5000 01*28.2500 15*0
14*0 01*28.2500 11*56.5000 01*28.2500 14*0
13*0 01*28.2500 13*56.5000 01*28.2500 13*0
12*0 01*28.2500 15*56.5000 01*28.2500 12*0
11*0 01*28.2500 17*56.5000 01*28.2500 11*0
10*0 01*28.2500 19*56.5000 01*28.2500 10*0
09*0 01*28.2500 21*56.5000 01*28.2500 09*0
08*0 01*28.2500 23*56.5000 01*28.2500 08*0
07*0 01*28.2500 25*56.5000 01*28.2500 07*0
06*0 01*28.2500 27*56.5000 01*28.2500 06*0
05*0 01*28.2500 29*56.5000 01*28.2500 05*0
04*0 01*28.2500 31*56.5000 01*28.2500 04*0
03*0 01*28.2500 33*56.5000 01*28.2500 03*0
02*0 01*28.2500 35*56.5000 01*28.2500 02*0
01*0 01*28.2500 37*56.5000 01*28.2500 01*0
    01*07.0625 39*28.2500 01*07.0625
```

```
-- Layer-03 ------------------------------------
20*0           01*14.1250           20*0
19*0 01*28.2500 01*56.5000 01*28.2500 19*0
18*0 01*28.2500 03*56.5000 01*28.2500 18*0
17*0 01*28.2500 05*56.5000 01*28.2500 17*0
16*0 01*28.2500 07*56.5000 01*28.2500 16*0
15*0 01*28.2500 09*56.5000 01*28.2500 15*0
14*0 01*28.2500 11*56.5000 01*28.2500 14*0
13*0 01*28.2500 13*56.5000 01*28.2500 13*0
12*0 01*28.2500 15*56.5000 01*28.2500 12*0
11*0 01*28.2500 17*56.5000 01*28.2500 11*0
10*0 01*28.2500 19*56.5000 01*28.2500 10*0
09*0 01*28.2500 21*56.5000 01*28.2500 09*0
08*0 01*28.2500 23*56.5000 01*28.2500 08*0
07*0 01*28.2500 25*56.5000 01*28.2500 07*0
06*0 01*28.2500 27*56.5000 01*28.2500 06*0
05*0 01*28.2500 29*56.5000 01*28.2500 05*0
04*0 01*28.2500 31*56.5000 01*28.2500 04*0
03*0 01*28.2500 33*56.5000 01*28.2500 03*0
02*0 01*28.2500 35*56.5000 01*28.2500 02*0
01*0 01*28.2500 37*56.5000 01*28.2500 01*0
     01*07.0625 39*28.2500 01*07.0625


-- Layer-04 ------------------------------------
20*0           01*14.1250           20*0
19*0 01*28.2500 01*56.5000 01*28.2500 19*0
18*0 01*28.2500 03*56.5000 01*28.2500 18*0
17*0 01*28.2500 05*56.5000 01*28.2500 17*0
16*0 01*28.2500 07*56.5000 01*28.2500 16*0
15*0 01*28.2500 09*56.5000 01*28.2500 15*0
14*0 01*28.2500 11*56.5000 01*28.2500 14*0
13*0 01*28.2500 13*56.5000 01*28.2500 13*0
12*0 01*28.2500 15*56.5000 01*28.2500 12*0
11*0 01*28.2500 17*56.5000 01*28.2500 11*0
10*0 01*28.2500 19*56.5000 01*28.2500 10*0
09*0 01*28.2500 21*56.5000 01*28.2500 09*0
08*0 01*28.2500 23*56.5000 01*28.2500 08*0
07*0 01*28.2500 25*56.5000 01*28.2500 07*0
06*0 01*28.2500 27*56.5000 01*28.2500 06*0
05*0 01*28.2500 29*56.5000 01*28.2500 05*0
04*0 01*28.2500 31*56.5000 01*28.2500 04*0
03*0 01*28.2500 33*56.5000 01*28.2500 03*0
02*0 01*28.2500 35*56.5000 01*28.2500 02*0
01*0 01*28.2500 37*56.5000 01*28.2500 01*0
     01*07.0625 39*28.2500 01*07.0625


-- Layer-05 ------------------------------------
20*0           01*14.1250           20*0
19*0 01*28.2500 01*56.5000 01*28.2500 19*0
18*0 01*28.2500 03*56.5000 01*28.2500 18*0
17*0 01*28.2500 05*56.5000 01*28.2500 17*0
16*0 01*28.2500 07*56.5000 01*28.2500 16*0
15*0 01*28.2500 09*56.5000 01*28.2500 15*0
14*0 01*28.2500 11*56.5000 01*28.2500 14*0
13*0 01*28.2500 13*56.5000 01*28.2500 13*0
12*0 01*28.2500 15*56.5000 01*28.2500 12*0
11*0 01*28.2500 17*56.5000 01*28.2500 11*0
10*0 01*28.2500 19*56.5000 01*28.2500 10*0
09*0 01*28.2500 21*56.5000 01*28.2500 09*0
08*0 01*28.2500 23*56.5000 01*28.2500 08*0
07*0 01*28.2500 25*56.5000 01*28.2500 07*0
06*0 01*28.2500 27*56.5000 01*28.2500 06*0
05*0 01*28.2500 29*56.5000 01*28.2500 05*0
```

```
04*0 01*28.2500 31*56.5000 01*28.2500 04*0
03*0 01*28.2500 33*56.5000 01*28.2500 03*0
02*0 01*28.2500 35*56.5000 01*28.2500 02*0
01*0 01*28.2500 37*56.5000 01*28.2500 01*0
     01*07.0625 39*28.2500 01*07.0625


-- Layer-06 ------------------------------------
20*0            01*14.1250            20*0
19*0 01*28.2500 01*56.5000 01*28.2500 19*0
18*0 01*28.2500 03*56.5000 01*28.2500 18*0
17*0 01*28.2500 05*56.5000 01*28.2500 17*0
16*0 01*28.2500 07*56.5000 01*28.2500 16*0
15*0 01*28.2500 09*56.5000 01*28.2500 15*0
14*0 01*28.2500 11*56.5000 01*28.2500 14*0
13*0 01*28.2500 13*56.5000 01*28.2500 13*0
12*0 01*28.2500 15*56.5000 01*28.2500 12*0
11*0 01*28.2500 17*56.5000 01*28.2500 11*0
10*0 01*28.2500 19*56.5000 01*28.2500 10*0
09*0 01*28.2500 21*56.5000 01*28.2500 09*0
08*0 01*28.2500 23*56.5000 01*28.2500 08*0
07*0 01*28.2500 25*56.5000 01*28.2500 07*0
06*0 01*28.2500 27*56.5000 01*28.2500 06*0
05*0 01*28.2500 29*56.5000 01*28.2500 05*0
04*0 01*28.2500 31*56.5000 01*28.2500 04*0
03*0 01*28.2500 33*56.5000 01*28.2500 03*0
02*0 01*28.2500 35*56.5000 01*28.2500 02*0
01*0 01*28.2500 37*56.5000 01*28.2500 01*0
     01*07.0625 39*28.2500 01*07.0625


-- Layer-07 ------------------------------------
20*0            01*14.1250            20*0
19*0 01*28.2500 01*56.5000 01*28.2500 19*0
18*0 01*28.2500 03*56.5000 01*28.2500 18*0
17*0 01*28.2500 05*56.5000 01*28.2500 17*0
16*0 01*28.2500 07*56.5000 01*28.2500 16*0
15*0 01*28.2500 09*56.5000 01*28.2500 15*0
14*0 01*28.2500 11*56.5000 01*28.2500 14*0
13*0 01*28.2500 13*56.5000 01*28.2500 13*0
12*0 01*28.2500 15*56.5000 01*28.2500 12*0
11*0 01*28.2500 17*56.5000 01*28.2500 11*0
10*0 01*28.2500 19*56.5000 01*28.2500 10*0
09*0 01*28.2500 21*56.5000 01*28.2500 09*0
08*0 01*28.2500 23*56.5000 01*28.2500 08*0
07*0 01*28.2500 25*56.5000 01*28.2500 07*0
06*0 01*28.2500 27*56.5000 01*28.2500 06*0
05*0 01*28.2500 29*56.5000 01*28.2500 05*0
04*0 01*28.2500 31*56.5000 01*28.2500 04*0
03*0 01*28.2500 33*56.5000 01*28.2500 03*0
02*0 01*28.2500 35*56.5000 01*28.2500 02*0
01*0 01*28.2500 37*56.5000 01*28.2500 01*0
     01*07.0625 39*28.2500 01*07.0625


-- Layer-08 ------------------------------------
20*0            01*14.1250            20*0
19*0 01*28.2500 01*56.5000 01*28.2500 19*0
18*0 01*28.2500 03*56.5000 01*28.2500 18*0
17*0 01*28.2500 05*56.5000 01*28.2500 17*0
16*0 01*28.2500 07*56.5000 01*28.2500 16*0
15*0 01*28.2500 09*56.5000 01*28.2500 15*0
14*0 01*28.2500 11*56.5000 01*28.2500 14*0
13*0 01*28.2500 13*56.5000 01*28.2500 13*0
12*0 01*28.2500 15*56.5000 01*28.2500 12*0
11*0 01*28.2500 17*56.5000 01*28.2500 11*0
```

```
10*0 01*28.2500 19*56.5000 01*28.2500 10*0
09*0 01*28.2500 21*56.5000 01*28.2500 09*0
08*0 01*28.2500 23*56.5000 01*28.2500 08*0
07*0 01*28.2500 25*56.5000 01*28.2500 07*0
06*0 01*28.2500 27*56.5000 01*28.2500 06*0
05*0 01*28.2500 29*56.5000 01*28.2500 05*0
04*0 01*28.2500 31*56.5000 01*28.2500 04*0
03*0 01*28.2500 33*56.5000 01*28.2500 03*0
02*0 01*28.2500 35*56.5000 01*28.2500 02*0
01*0 01*28.2500 37*56.5000 01*28.2500 01*0
    01*07.0625 39*28.2500 01*07.0625


-- Layer-09 ------------------------------------
20*0           01*14.1250           20*0
19*0 01*28.2500 01*56.5000 01*28.2500 19*0
18*0 01*28.2500 03*56.5000 01*28.2500 18*0
17*0 01*28.2500 05*56.5000 01*28.2500 17*0
16*0 01*28.2500 07*56.5000 01*28.2500 16*0
15*0 01*28.2500 09*56.5000 01*28.2500 15*0
14*0 01*28.2500 11*56.5000 01*28.2500 14*0
13*0 01*28.2500 13*56.5000 01*28.2500 13*0
12*0 01*28.2500 15*56.5000 01*28.2500 12*0
11*0 01*28.2500 17*56.5000 01*28.2500 11*0
10*0 01*28.2500 19*56.5000 01*28.2500 10*0
09*0 01*28.2500 21*56.5000 01*28.2500 09*0
08*0 01*28.2500 23*56.5000 01*28.2500 08*0
07*0 01*28.2500 25*56.5000 01*28.2500 07*0
06*0 01*28.2500 27*56.5000 01*28.2500 06*0
05*0 01*28.2500 29*56.5000 01*28.2500 05*0
04*0 01*28.2500 31*56.5000 01*28.2500 04*0
03*0 01*28.2500 33*56.5000 01*28.2500 03*0
02*0 01*28.2500 35*56.5000 01*28.2500 02*0
01*0 01*28.2500 37*56.5000 01*28.2500 01*0
    01*07.0625 39*28.2500 01*07.0625


-- Layer-10 ------------------------------------
20*0           01*14.1250           20*0
19*0 01*28.2500 01*56.5000 01*28.2500 19*0
18*0 01*28.2500 03*56.5000 01*28.2500 18*0
17*0 01*28.2500 05*56.5000 01*28.2500 17*0
16*0 01*28.2500 07*56.5000 01*28.2500 16*0
15*0 01*28.2500 09*56.5000 01*28.2500 15*0
14*0 01*28.2500 11*56.5000 01*28.2500 14*0
13*0 01*28.2500 13*56.5000 01*28.2500 13*0
12*0 01*28.2500 15*56.5000 01*28.2500 12*0
11*0 01*28.2500 17*56.5000 01*28.2500 11*0
10*0 01*28.2500 19*56.5000 01*28.2500 10*0
09*0 01*28.2500 21*56.5000 01*28.2500 09*0
08*0 01*28.2500 23*56.5000 01*28.2500 08*0
07*0 01*28.2500 25*56.5000 01*28.2500 07*0
06*0 01*28.2500 27*56.5000 01*28.2500 06*0
05*0 01*28.2500 29*56.5000 01*28.2500 05*0
04*0 01*28.2500 31*56.5000 01*28.2500 04*0
03*0 01*28.2500 33*56.5000 01*28.2500 03*0
02*0 01*28.2500 35*56.5000 01*28.2500 02*0
01*0 01*28.2500 37*56.5000 01*28.2500 01*0
    01*07.0625 39*28.2500 01*07.0625


-- Layer-11 ------------------------------------
20*0         01*060.0         20*0
19*0 01*120.0 01*240.0 01*120.0 19*0
18*0 01*120.0 03*240.0 01*120.0 18*0
17*0 01*120.0 05*240.0 01*120.0 17*0
```

```
16*0 01*120.0 07*240.0 01*120.0 16*0
15*0 01*120.0 09*240.0 01*120.0 15*0
14*0 01*120.0 11*240.0 01*120.0 14*0
13*0 01*120.0 13*240.0 01*120.0 13*0
12*0 01*120.0 15*240.0 01*120.0 12*0
11*0 01*120.0 17*240.0 01*120.0 11*0
10*0 01*120.0 19*240.0 01*120.0 10*0
09*0 01*120.0 21*240.0 01*120.0 09*0
08*0 01*120.0 23*240.0 01*120.0 08*0
07*0 01*120.0 25*240.0 01*120.0 07*0
06*0 01*120.0 27*240.0 01*120.0 06*0
05*0 01*120.0 29*240.0 01*120.0 05*0
04*0 01*120.0 31*240.0 01*120.0 04*0
03*0 01*120.0 33*240.0 01*120.0 03*0
02*0 01*120.0 35*240.0 01*120.0 02*0
01*0 01*120.0 37*240.0 01*120.0 01*0
     01*030.0 39*120.0 01*030.0


-- Layer-12 ------------------------------------
20*0          01*060.0          20*0
19*0 01*120.0 01*240.0 01*120.0 19*0
18*0 01*120.0 03*240.0 01*120.0 18*0
17*0 01*120.0 05*240.0 01*120.0 17*0
16*0 01*120.0 07*240.0 01*120.0 16*0
15*0 01*120.0 09*240.0 01*120.0 15*0
14*0 01*120.0 11*240.0 01*120.0 14*0
13*0 01*120.0 13*240.0 01*120.0 13*0
12*0 01*120.0 15*240.0 01*120.0 12*0
11*0 01*120.0 17*240.0 01*120.0 11*0
10*0 01*120.0 19*240.0 01*120.0 10*0
09*0 01*120.0 21*240.0 01*120.0 09*0
08*0 01*120.0 23*240.0 01*120.0 08*0
07*0 01*120.0 25*240.0 01*120.0 07*0
06*0 01*120.0 27*240.0 01*120.0 06*0
05*0 01*120.0 29*240.0 01*120.0 05*0
04*0 01*120.0 31*240.0 01*120.0 04*0
03*0 01*120.0 33*240.0 01*120.0 03*0
02*0 01*120.0 35*240.0 01*120.0 02*0
01*0 01*120.0 37*240.0 01*120.0 01*0
     01*030.0 39*120.0 01*030.0


-- Layer-13 ------------------------------------
20*0          01*060.0          20*0
19*0 01*120.0 01*240.0 01*120.0 19*0
18*0 01*120.0 03*240.0 01*120.0 18*0
17*0 01*120.0 05*240.0 01*120.0 17*0
16*0 01*120.0 07*240.0 01*120.0 16*0
15*0 01*120.0 09*240.0 01*120.0 15*0
14*0 01*120.0 11*240.0 01*120.0 14*0
13*0 01*120.0 13*240.0 01*120.0 13*0
12*0 01*120.0 15*240.0 01*120.0 12*0
11*0 01*120.0 17*240.0 01*120.0 11*0
10*0 01*120.0 19*240.0 01*120.0 10*0
09*0 01*120.0 21*240.0 01*120.0 09*0
08*0 01*120.0 23*240.0 01*120.0 08*0
07*0 01*120.0 25*240.0 01*120.0 07*0
06*0 01*120.0 27*240.0 01*120.0 06*0
05*0 01*120.0 29*240.0 01*120.0 05*0
04*0 01*120.0 31*240.0 01*120.0 04*0
03*0 01*120.0 33*240.0 01*120.0 03*0
02*0 01*120.0 35*240.0 01*120.0 02*0
01*0 01*120.0 37*240.0 01*120.0 01*0
     01*030.0 39*120.0 01*030.0
```

```
-- Layer-14 ------------------------------------
20*0          01*060.0          20*0
19*0 01*120.0 01*240.0 01*120.0 19*0
18*0 01*120.0 03*240.0 01*120.0 18*0
17*0 01*120.0 05*240.0 01*120.0 17*0
16*0 01*120.0 07*240.0 01*120.0 16*0
15*0 01*120.0 09*240.0 01*120.0 15*0
14*0 01*120.0 11*240.0 01*120.0 14*0
13*0 01*120.0 13*240.0 01*120.0 13*0
12*0 01*120.0 15*240.0 01*120.0 12*0
11*0 01*120.0 17*240.0 01*120.0 11*0
10*0 01*120.0 19*240.0 01*120.0 10*0
09*0 01*120.0 21*240.0 01*120.0 09*0
08*0 01*120.0 23*240.0 01*120.0 08*0
07*0 01*120.0 25*240.0 01*120.0 07*0
06*0 01*120.0 27*240.0 01*120.0 06*0
05*0 01*120.0 29*240.0 01*120.0 05*0
04*0 01*120.0 31*240.0 01*120.0 04*0
03*0 01*120.0 33*240.0 01*120.0 03*0
02*0 01*120.0 35*240.0 01*120.0 02*0
01*0 01*120.0 37*240.0 01*120.0 01*0
     01*030.0 39*120.0 01*030.0


-- Layer-15 ------------------------------------
20*0          01*060.0          20*0
19*0 01*120.0 01*240.0 01*120.0 19*0
18*0 01*120.0 03*240.0 01*120.0 18*0
17*0 01*120.0 05*240.0 01*120.0 17*0
16*0 01*120.0 07*240.0 01*120.0 16*0
15*0 01*120.0 09*240.0 01*120.0 15*0
14*0 01*120.0 11*240.0 01*120.0 14*0
13*0 01*120.0 13*240.0 01*120.0 13*0
12*0 01*120.0 15*240.0 01*120.0 12*0
11*0 01*120.0 17*240.0 01*120.0 11*0
10*0 01*120.0 19*240.0 01*120.0 10*0
09*0 01*120.0 21*240.0 01*120.0 09*0
08*0 01*120.0 23*240.0 01*120.0 08*0
07*0 01*120.0 25*240.0 01*120.0 07*0
06*0 01*120.0 27*240.0 01*120.0 06*0
05*0 01*120.0 29*240.0 01*120.0 05*0
04*0 01*120.0 31*240.0 01*120.0 04*0
03*0 01*120.0 33*240.0 01*120.0 03*0
02*0 01*120.0 35*240.0 01*120.0 02*0
01*0 01*120.0 37*240.0 01*120.0 01*0
     01*030.0 39*120.0 01*030.0

 /
```

APPENDIX H

MODEL INCLUDE FILE: B-MPVT.DAT ("M" RELATIVE PERMEABILITY SET AND PVT DATA INCLUDE FILE)

```
-- Relative Permeability Data ==========
--Water saturation functions (Sw, Krw, Krow, Pc):
SWOF
-- Sw    krw         krow        Pcow
0.20     0.000000    0.900000    0.0
0.25     0.000364    0.709187    0.0
0.30     0.002536    0.544963    0.0
0.35     0.007892    0.405962    0.0
0.40     0.017660    0.290741    0.0
0.45     0.032987    0.197760    0.0
0.50     0.054960    0.125368    0.0
0.55     0.084625    0.071765    0.0
0.60     0.122991    0.034959    0.0
0.65     0.171041    0.012686    0.0
0.70     0.229732    0.002243    0.0
0.75     0.300000    0.000000    0.0 /
--Gas saturation functions (Sg, Krg, Krog, Pc):
SGOF
-- Sg    krg         krog        Pcog
0.00     0.000000    0.900000    0.0
0.05     0.004389    0.724054    0.0
0.10     0.016608    0.570544    0.0
0.15     0.036175    0.438425    0.0
0.20     0.062847    0.326599    0.0
0.25     0.096462    0.233902    0.0
0.30     0.136893    0.159099    0.0
0.35     0.184043    0.100859    0.0
0.40     0.237829    0.057735    0.0
0.45     0.298179    0.028125    0.0
0.50     0.365033    0.010206    0.0
0.55     0.438335    0.001804    0.0
0.60     0.518036    0.000000    0.0
0.65     0.604092    0.000000    0.0
0.70     0.696463    0.000000    0.0
0.75     0.795110    0.000000    0.0
0.80     0.900000    0.000000    0.0 /
--3-phase Oil saturation functions models or (table: So, Krow, krog):
STONE2

-- --PVT data =================
-- Oil PVT Properties (Rs, Pbub, Bo, Vo):
PVTO
-- Rs    Pr     Bo          Vo
0.0467   178    1.119000    1.435118 /
0.09     288    1.153000    1.211123 /
0.154    525    1.199000    1.106076 /
0.223    750    1.239000    1.028836 /
0.29     1025   1.277000    0.967044 /
0.356    1250   1.313000    0.919156 /
0.424    1500   1.353000    0.874356 /
0.493    1750   1.391000    0.834964 /
```

```
0.568   2000    1.432000            0.799434 /
0.648   2250    1.477000            0.770082 /
0.735   2500    1.526000            0.737642 /
0.768   2600    1.545000            0.727600
        2700    1.540000            0.733355
        2800    1.535000            0.738298
        2900    1.532000            0.743242
        3000    1.526000            0.750000
        3100    1.524000            0.753128
        3500    1.511000            0.772400
        4000    1.496000            0.797116
        4500    1.483000            0.822606
        5000    1.477000            0.847322
        5500    1.472093            0.872103
        6000    1.471006            0.896964 /
/
-- Dry Gas PVT Properties (Pr, Bg, Vg):
PVDG
-- Pr   Bg (RB/MSCF)    Vg (cP)
178     18.69991095     0.022806
288     11.72751558     0.022999
525     6.747996438     0.026478
750     4.464826358     0.028024
1025    3.317898486     0.029570
1250    2.632235085     0.030537
1500    2.181656278     0.032469
1750    1.857524488     0.034015
2000    1.620658949     0.035562
2250    1.442564559     0.037301
2500    1.296527159     0.039234
2600    1.262429007     0.039794
2700    1.215036528     0.040471
2800    1.171051831     0.041147
2900    1.130120844     0.041824
3000    1.091936857     0.042500
3200    1.022775345     0.043872
3400    0.961803435     0.045225
4000    0.815693142     0.049303
4500    0.723877672     0.052705
5000    0.650539051     0.056106
5500    0.590618268     0.059508
6000    0.540747433     0.062909 /
```

APPENDIX I

MODEL INCLUDE FILE: B-SPVT.DAT ("S" RELATIVE PERMEABILITY SET AND PVT DATA INCLUDE FILE)

```
-- Relative Permeability Data ==========
--Water saturation functions (Sw, Krw, Krow, Pc):
SWOF
-- Sw    krw          krow         Pcow
0.00     0.0000000    1.0000000    0.0
0.2000   0.0000000    1.0000000    0.0
0.22     0.0000014    0.8680000    0.0
0.24     0.0000173    0.7510000    0.0
0.26     0.0000761    0.6460000    0.0
0.28     0.0002180    0.5530000    0.0
0.30     0.0004940    0.4700000    0.0
0.32     0.0009630    0.3980000    0.0
0.34     0.0016900    0.3340000    0.0
0.36     0.0027600    0.2790000    0.0
0.38     0.0042500    0.2310000    0.0
0.40     0.0062500    0.1890000    0.0
0.42     0.0088600    0.1540000    0.0
0.44     0.0122000    0.1240000    0.0
0.46     0.0163000    0.0988000    0.0
0.48     0.0214000    0.0777000    0.0
0.50     0.0276000    0.0603000    0.0
0.52     0.0349000    0.0461000    0.0
0.54     0.0436000    0.0346000    0.0
0.56     0.0538000    0.0255000    0.0
0.58     0.0655000    0.0184000    0.0
0.60     0.0791000    0.0129000    0.0
0.62     0.0945000    0.0087600    0.0
0.64     0.1120000    0.0057400    0.0
0.66     0.1320000    0.0036000    0.0
0.68     0.1540000    0.0021400    0.0
0.70     0.1790000    0.0011900    0.0
0.72     0.2070000    0.0006010    0.0
0.74     0.2370000    0.0002690    0.0
0.76     0.2710000    0.0001010    0.0
0.78     0.3080000    0.0000285    0.0
0.80     0.3490000    0.0000049    0.0
0.8200   0.3930000    0.0000000    0.0
0.84     0.4420000    0.0000000    0.0
0.86     0.4940000    0.0000000    0.0
0.88     0.5520000    0.0000000    0.0
0.90     0.6130000    0.0000000    0.0
0.92     0.6800000    0.0000000    0.0
0.94     0.7520000    0.0000000    0.0
0.96     0.8290000    0.0000000    0.0
0.98     0.9110000    0.0000000    0.0
1.00     1.0000000    0.0000000    0.0 /
--Gas saturation functions (Sg, Krg, Krog, Pc):
SGOF
-- Sg    krg          krog         Pcog
0.00     0.0000000    1.0000000    0.0
0.02     0.0000000    0.9110000    0.0
```

```
0.04    0.0000000    0.8290000    0.0
0.06    0.0000000    0.7520000    0.0
0.08    0.0000000    0.6800000    0.0
0.10    0.0000000    0.6130000    0.0
0.12    0.0000000    0.5520000    0.0
0.14    0.0000000    0.4940000    0.0
0.16    0.0000000    0.4420000    0.0
0.18    0.0000000    0.3930000    0.0
0.20    0.0000049    0.3490000    0.0
0.22    0.0000285    0.3080000    0.0
0.24    0.0001010    0.2710000    0.0
0.26    0.0002690    0.2370000    0.0
0.28    0.0006010    0.2070000    0.0
0.30    0.0011900    0.1790000    0.0
0.32    0.0021400    0.1540000    0.0
0.34    0.0036000    0.1320000    0.0
0.36    0.0057400    0.1120000    0.0
0.38    0.0087600    0.0945000    0.0
0.40    0.0129000    0.0791000    0.0
0.42    0.0184000    0.0655000    0.0
0.44    0.0255000    0.0538000    0.0
0.46    0.0346000    0.0436000    0.0
0.48    0.0461000    0.0349000    0.0
0.50    0.0603000    0.0276000    0.0
0.52    0.0777000    0.0214000    0.0
0.54    0.0988000    0.0163000    0.0
0.56    0.1240000    0.0122000    0.0
0.58    0.1540000    0.0088600    0.0
0.60    0.1890000    0.0062500    0.0
0.62    0.2310000    0.0042500    0.0
0.64    0.2790000    0.0027600    0.0
0.66    0.3340000    0.0016900    0.0
0.68    0.3980000    0.0009630    0.0
0.70    0.4700000    0.0004940    0.0
0.72    0.5530000    0.0002180    0.0
0.74    0.6460000    0.0000761    0.0
0.76    0.7510000    0.0000173    0.0
0.78    0.8680000    0.0000014    0.0
0.80    1.0000000    0.0000000    0.0 /
--3-phase Oil saturation functions models or (table: So, Krow, krog):
STONE2
-- --PVT data ================
-- Oil PVT Properties (Rs, Pbub, Bo, Vo):
PVTO
-- Rs   Pr      Bo          Vo
0.0467  178     1.119000    1.435118 /
0.09    288     1.153000    1.211123 /
0.154   525     1.199000    1.106076 /
0.223   750     1.239000    1.028836 /
0.29    1025    1.277000    0.967044 /
0.356   1250    1.313000    0.919156 /
0.424   1500    1.353000    0.874356 /
0.493   1750    1.391000    0.834964 /
0.568   2000    1.432000    0.799434 /
0.648   2250    1.477000    0.770082 /
0.735   2500    1.526000    0.737642 /
0.768   2600    1.545000    0.727600
        2700    1.540000    0.733355
        2800    1.535000    0.738298
        2900    1.532000    0.743242
        3000    1.526000    0.750000
        3100    1.524000    0.753128
        3500    1.511000    0.772400
        4000    1.496000    0.797116
        4500    1.483000    0.822606
        5000    1.477000    0.847322
```

```
        5500    1.472093 0.872103
        6000    1.471006 0.896964 /
/
-- Dry Gas PVT Properties (Pr, Bg, Vg):
PVDG
-- Pr   Bg (RB/MSCF)    Vg (cP)
178     18.69991095     0.022806
288     11.72751558     0.022999
525     6.747996438     0.026478
750     4.464826358     0.028024
1025    3.317898486     0.029570
1250    2.632235085     0.030537
1500    2.181656278     0.032469
1750    1.857524488     0.034015
2000    1.620658949     0.035562
2250    1.442564559     0.037301
2500    1.296527159     0.039234
2600    1.262429007     0.039794
2700    1.215036528     0.040471
2800    1.171051831     0.041147
2900    1.130120844     0.041824
3000    1.091936857     0.042500
3200    1.022775345     0.043872
3400    0.961803435     0.045225
4000    0.815693142     0.049303
4500    0.723877672     0.052705
5000    0.650539051     0.056106
5500    0.590618268     0.059508
6000    0.540747433     0.062909 /
```

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