OPTIMISATION OF CO_2 INJECTION INTO UKCS OILFIELDS

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Abstract

CO_2 sequestration is a topic of some current interest as a potential means of mitigating the effects of climate change. The injection of CO_2 is an established and successful technique for Incremental Oil Recovery (IOR) from onshore North American oil fields. Although, not yet an established offshore technique, CO_2 injection may offer one means of mitigating a projected decline in North Sea oil production, as well as providing environmental benefits.

There may however be a trade-off between IOR and CO_2 sequestration efficiency. If CO_2 injection is efficient in terms of gas injected per incremental barrel of oil, less CO_2 will need to be injected for IOR. The issue of optimising CO_2 injection for both IOR and CO_2 sequestration therefore arises, a potentially key control being the optimal WAG ratio. At the 24th IEA EOR meeting in Regina a paper was presented which investigated IOR/CO_2 sequestration cooptimisation for both WAG and CO_2 injection without water. This was for a specific case of a relatively heavy (24 degrees API) Canadian oil reservoir, for which CO_2 is immiscible at reservoir pressure. This study concluded that, for the reservoir considered, the best optimisation of IOR and sequestration targets was downdip CO_2 injection without water, coupled with active well controls to limit gas production.

In this paper we consider optimisation of CO_2 injection for typical UKCS fields, which have rather different reservoir properties. In particular, we are primarily interested in light oil reservoirs and we would expect that CO_2 is usually miscible with oil at reservoir pressure. We have therefore conducted a complementary optimisation study, appropriate to typical UKCS fields. This has included 3D simulation of both simple generic and field models. Both these types of model include typical high connectivity pathways and realistic gas production constraints which limit oil recovery.

Our results support previous experience that for UKCS type fields with high connectivity pathways, through which gas may channel, WAG tends to give markedly higher IOR than CO_2 injection without water. Only for idealised homogeneous models do we find that injection without water gives higher IOR. Our initial generic model gave similar CO_2 sequestration for WAG and injection without water, but on optimising the completion policy, WAG proved

significantly better. In contrast, for our heterogeneous field model, injection without water was better for CO_2 sequestration, even though WAG was preferred for IOR. This suggests that, in practice, optimisation for IOR and CO_2 sequestration will be field specific and will involve selection of the most appropriate completion policy and WAG ratio.

INTRODUCTION

The injection of CO_2 is an established and successful technique for Incremental Oil Recovery (IOR) from onshore North American oil fields [1]. Although, not yet an established offshore technique, CO_2 injection may offer one means of mitigating a projected decline in North Sea oil production, as well as providing environmental benefits. A European CO_2 emissions trading scheme has recently started which provides a mechanism for realising value from CO_2 sequestration [2]. When considering CO_2 injection for IOR there may however be a trade-off between IOR and CO_2 sequestration. In a reservoir with a low gas utilisation factor for CO_2 injection, the IOR process will in general be more efficient, but the amount of gas sequestered will also be lower. We do not consider here post-flush CO_2 injection aimed at maximising the CO_2 volume sequestered.

At the 24th IEA EOR meeting in Regina in 2003, a paper [3] was presented which investigated the possibility of simultaneous optimisation of IOR and CO_2 sequestration. This paper considered both Water Alternating Gas (WAG) and Continuous CO_2 Gas Injection (CGI) without water for a specific case of a relatively heavy (24°API) Canadian oil reservoir, for which CO_2 is immiscible at reservoir pressure. It concluded that, for the particular reservoir considered, the best optimisation of IOR and sequestration targets was by a process of down-dip CO_2 injection without water, coupled with active well controls to limit gas production. This was because injection of water utilised pore space that could not subsequently be occupied by CO_2.

This paper describes the results of a complementary study to that reported in [3], to investigate the simultaneous optimisation of miscible CO_2 injection processes for incremental recovery efficiency and CO_2 sequestration, using models in which the reservoir properties and fluids are representative of light oil UKCS reservoirs. We have carried out a short literature search but did not find any other published papers directly relevant to this work. Reservoir heterogeneity is usually a critical factor for gas injection processes, so we have studied two different heterogeneous three-dimensional sector models.

This paper is organised as follows. In the next section the two types of models used in the studies are described. The results of optimising the well control and completion strategy are then presented, followed by optimisation of the WAG ratio. Some economic results are then given, followed by a summary of conclusions.

MODEL DESCRIPTION

Two models were studied to investigate the effects of different heterogeneities. The idealised generic model is uniform apart from two laterally extensive high permeability streaks connecting injector and producer [Figure 1]. This model has the virtue of simplicity, so its behaviour is easier to understand. However, its heterogeneity, though realistic in that there is good connectivity between injector and producer, is extreme. In contrast the field model incorporates realistic, but more complex, levels of heterogeneity on both large and small scales [Figure 1]. In this model there is a wide distribution of different permeabilities, vertical flow barriers and faulting. This model provides a number of more subtly connected pathways between injector and producer.

Generic Model

This model is defined by a block tilted at a uniform dip of 5°, with a width of 2000 feet and a length of 4000 feet in the dip direction. Its thickness is 200 feet. The heterogeneity is limited to two high permeability streaks, each having a thickness of 10 ft and covering the whole area of the model; the permeability is assigned a uniform value of 1000 md in each of these streaks, and is assigned a uniform value of 100 md throughout the remainder of the model.

The model contains two wells: a down-dip injector and an up-dip producer, which are placed along the centre-line of the grid. In the base case model, both wells are completed through all the simulation layers; a number of sensitivity cases were also considered, in which the completion locations were varied in both the producer and the injector.

PVT properties were typical of UKCS light oils and the model was initialised at a pressure significantly above the bubble point. Relative permeability curves for the generic model were defined using Corey functions. The Corey exponents and end point values used to generate these curves were chosen to generate water to intermediate wet curves typical of UKCS fields using Craig's wettability criteria [4].

The model was discretised using a uniform grid with 7 by 50 by 60 grid blocks. A number of sensitivity studies were carried out to assess the effect of grid refinements in the y-direction (NY = 18, 50 and 80) and the z-direction (NZ = 18, 60 and 100) in order to confirm that the grid was sufficiently refined to resolve the flow processes that are of importance in modelling gas injection. With the grid resolution that was used in the final model, each high permeability streak was represented by three model layers.

Making use of the symmetry of the model, the simulation studies were actually carried out with a grid representing approximately one half of the area of the tilted block, with a grid size of 4 by 50 by 60 grid blocks; the STOIIP in the resulting simulation model was 15.4 MMstb. Some further sensitivity studies were carried out to confirm that this reduction in the modelled area did not have a significant impact on the results.

Table 1 summarises the main reservoir parameters.

Parameter	Value	Units
k_x, k_y (overall)	100	mD
k_x, k_y (high k layers)	1000	mD
k_v/k_h	0.1	dimensionless
ϕ	0.15	fraction
ntg	1	fraction
dip (y direction)	5	degrees
S_{orw}	0.25	fraction
S_{wc}	0.20	fraction
S_{org}	0.05	fraction
STOIIP	15.45 (half model)	MMstb

Table 1: Key reservoir parameters – generic model

Initially, the reservoir was waterflooded for approximately 7 years. During the waterflooding period the production well was controlled on a maximum production of 10% HCPV/year, with a minimum BHP of 2000 psia. The injection well was controlled on a pressure maintenance basis with a maximum injected rate of 10% HCPV/year and a maximum BHP of 10000 psia. Once water breakthrough occurred, after around 4 years of water injection, the water cut increased quickly reaching a value of 90% after around 7 years of water injection, which was taken as the starting point for the gas injection processes.

Each of the cases was run for a further twenty years beyond this point, with either an extended waterflood, a WAG process with various ratios of water to gas, or a continuous gas injection. The oil saturation at the end of the extended waterflood is shown in Figure 2. During gas injection, the production well was controlled on maximum target rate of 10% HCPV, with a minimum BHP of 2000 psia and maximum gas production rate of 2 MMscf/day. The injection well used the same control parameters as during the waterflood, maintaining the average reservoir pressure. For the WAG cases the length of a full WAG cycle was one year, with the length of the water and gas injection periods adjusted to give the appropriate WAG ratio.

Field Model

The field model geology consists of channel sands with localised shale barriers [Figure 1]. The approximate overall dimensions of the sector model were 2300 feet wide by 6900 feet in the dip direction with an average thickness of some 250 feet. The mean dip was a little less than for the generic model. This model used a grid size of 7 by 18 by 110 giving a STOIIP of 76.4 MMstb. Horizontal and vertical grid dimensions were comparable to the generic model. In an initial sensitivity study, finer resolution was investigated by doubling the number of vertical layers to 220. Results obtained from this sensitivity analysis confirmed that the original model was sufficiently refined.

A different set of typical UKCS light oil PVT properties were used. Although the model was initialised at a lower pressure than the generic model it is worth noting that in both models the reservoirs were producing above their respective bubble points throughout the simulations. Similar relative permeability curves were used as for the generic model.

The following table summarises some of the main model parameters.

Parameter	Value	Units
ntg	1	fraction
dip	0 - 5°	degrees
S_{orw}	0.25	fraction
S_{wc}	0.175	fraction
S_{org}	0.05	fraction
STOIIP	76.4	MMstb

Table 2: Key reservoir parameters – field model

Although several wells were defined these were controlled in a similar overall way to the generic model.

OPTIMISATION

Producer Completion Shut-Off

In the base models both producers and injectors were completed throughout the whole interval. One possible means of optimisation is to close producer completions when they first start to produce CO_2. This was investigated for the generic model for the 1:1 WAG and CGI cases. The simulator automatically closed producer individual completions once CO_2 was produced. Once CO_2 had been produced in all completions, they were re-opened starting from the bottom to encourage gas to flow into the bottom part of the reservoir, which was the main unswept area after miscible flooding. The following table summarises these results.

Here the gross gas utilisation is the cumulative CO_2 injected divided by the IOR. The net gas utilisation is the cumulative injected less cumulative produced divided by the IOR. It can be seen that shutting off producer completions only has a very marginal effect in the generic sector model. Note however that CGI gives substantially less IOR than 1:1 WAG for much higher gas utilisation, ie backproduction and re-cycling. The additional CO_2 sequestered by CGI from the greater CO_2 injection is relatively small.

Case	Gas injection case	IOR % STOIIP	Net gas utilisation, Mscf/stb	Gross gas utilisation, Mscf/stb	CO_2 sequestered, %HCPV
Base	1:1 WAG	9.7	6.4	15.2	21.2
Producer completions shut-off	1:1 WAG	9.8	6.4	15.2	21.7
Base	Continuous	5.1	13.9	31.4	24.2
Producer completions shut-off	Continuous	5.0	14.1	31.9	24.0

Table 3: Effect of shutting–off producer completions in generic model

Injection Completion Optimisation

In both the base generic and field models, the bottom part of the reservoir is the main unswept region after CO_2 injection, see for example Figures 3,4,5 and 6. For the generic model optimisation therefore proceeded by only injecting CO_2 into the lower third of the model below the lowest high permeability streak. For the WAG cases water was injected into the upper two-thirds of the interval above the lowest high permeability streak. This strategy was aimed at compensating for the differential effects of viscous and gravity forces on CO_2 and water. It substantially improved the IOR, backproduction and CO_2 sequestration as can be seen from Table 4 and Figures 3 and 5. Figure 3 for 1:1 WAG shows a much more uniform sweep for the optimised case. Though Figure 5 for CGI shows an improved sweep in that more of the regions around the high permeability streaks are better swept, the flood is still dominated by CO_2 channelling through these streaks.

Gas injection case	IOR % STOIIP		Net gas utilisation Mscf/stb		Gross gas utilisation Mscf/stb		CO_2 sequestered, %HCPV	
	Base	Opt	Base	Opt	Base	Opt	Base	Opt
3:1 WAG	11.9	19.6	5.0	4.3	11.5	7.4	20.5	29.2
1:1 WAG	9.7	18.7	6.4	4.9	15.2	9.3	21.2	31.7
1:3 WAG	7.4	16.0	8.7	5.8	20.5	11.0	21.9	32.1
Continuous	5.1	7.4	13.9	10.4	31.4	22.0	24.2	27.0

Table 4: Generic model optimisation

Optimisation of the field model proceeded on a similar basis also giving substantial improvements as can be seen from the following table and Figures 4 and 6. These show an improved sweep in the lower half of the model for both 1:1 WAG and CGI and also lower final oil saturations for 1:1 WAG in the higher dip section.

Gas injection case	IOR % STOIIP		Net gas utilisation Mscf/stb		Gross gas utilisation Mscf/stb		CO_2 sequestered, %HCPV	
	Base	**Opt**	**Base**	**Opt**	**Base**	**Opt**	**Base**	**Opt**
3:1 WAG	12.1	14.2	2.0	2.2	6.7	4.3	11.8	15.1
1:1 WAG	14.3	19.5	2.1	2.2	13.2	10.9	16.0	21.1
1:3 WAG	14.7	20.3	2.5	2.4	23.8	17.5	17.8	23.9
Continuous	9.0	13.3	8.8	8.8	53.0	35.8	38.2	44.8

Table 5: Field model optimisation

WAG Ratio Optimisation

These two models both predict substantial IOR, and backproduction. However, they differ in the effect of choosing different WAG ratios. This is illustrated by Figure 7 on which have been included some additional cases in order to show the trend more clearly. This figure shows base (non-optimised) cases only, but the trends are similar for the optimised cases. For the generic model IOR is maximised at about 20% injected by reservoir volume, but for the field model at about 75%. For both models CO_2 sequestration is maximised by only injecting CO_2. However, for the generic model injecting at more than 25% gives relatively little benefit, but for the field model there is a doubling of CO_2 sequestration increasing injection proportion from 75% to 100%. The final percentage of initial hydrocarbon volume occupied by retained CO_2 is typical of North American experience and expectations from earlier studies [1]. Figure 8 shows the rather different distribution of sequestrated CO_2 predicted in the field model for CGI and WAG. For CGI most of the CO_2 is in the upper half of the model. For 1:1 WAG CO_2 saturations are lower with higher saturations in the higher dip region nearer the producer.

CO_2 Backproduction And Re-Cycling

Backproduction of injected CO_2 and consequent re-cycling is an inevitable issue in such scenarios which can substantially affect economics. The recycling ratio is the ratio of cumulative gross to net CO_2 injection which can be calculated from the net and gross utilisation factors in Tables 4 and 5. Figure 9 shows how this depends on optimisation, WAG ratio and heterogeneity. For the non-optimised generic model the recycling ratio is around two irrespective of the WAG ratio and this is reduced slightly on optimisation. For the non-optimised field model the recycling ratio is substantially higher, particularly for higher WAG ratios. However, for all cases optimisation is able to reduce the recycling ratio significantly.

ECONOMIC VALUE

For the field model, WAG gives more IOR, but CGI sequesters more CO_2. Here we crudely estimate the relative economic value taking account only of the undiscounted value of IOR and CO_2 sequestration and ignoring associated costs. The assessment is illustrated by some example calculations using dollar values. A CO_2 sequestration credit in the range of 20 to 50 $/tonne of CO_2 sequestrated has been quoted as being required to make CO_2 injection economic, a typical value being 35 $/tonne [5]. This is considerably higher than the initial EU ETS trading value of 8 to 10 Euros/tonne and corresponding non-compliance fine of 40 Euros/tonne [2]. (At the time of writing one Euro is worth about 1.27 US dollars.) However, the EU ETS trading value is likely to be more in line with the quoted economic range when the non-compliance fine is raised to 100 Euros/tonne in the next phase of the scheme in 2008.

Figure 10 compares the relative values of WAG schemes compared to CGI for 1:1 and 1:3 WAG. It is apparent that only in the extreme scenario when the oil price is low and sequestration credit value high is CGI likely to have greater value than WAG. This is explained by Figure 11 which shows the oil and CO_2 value split for three price scenarios for 1:3 WAG and CGI. For WAG schemes the oil value dominates, even in the low oil and high CO_2 credit regime. (Note that this plot is similar for the other WAG ratios considered.) Only in the low oil and high CO_2 credit regime for CGI does the CO_2 sequestration value become comparable to the oil value.

CONCLUSIONS

Heterogeneous 3D models of typical UKCS light oil reservoirs have been constructed and used to investigate optimisation of post-waterflood miscible CO_2 injection.

Substantial improvements in IOR, CO_2 sequestration and backproduction were obtained from optimisation. Three approaches were considered, producer and injector completion policy and WAG ratio.

- Injecting gas into the lower completions was effective for both CGI and WAG. This gave a better sweep as the injected gas tended to move upwards towards the producer.
- Injecting water into the upper completions was effective for WAG. This improved the sweep as injected water tended to slump downwards.
- Finding the best WAG ratio was effective for WAG. This improved sweep by balancing the tendency of injected gas to rise and of injected water to slump.
- Shutting off producer completions on gas breakthrough was ineffective for both CGI and WAG. Once a gas pathway to the producer was established,

all of the potential production interval was close enough to allow gas production to recur.

Optimised WAG gave higher IOR than optimised CGI. Optimised CGI gave higher CO_2 sequestration than WAG.

Under most price scenarios a WAG scheme is likely to have a greater value (ignoring asociated costs) than a CGI scheme, as most of the value lies in the oil. Only in a low oil price and high CO_2 sequestration value regime does a CGI scheme become more valuable.

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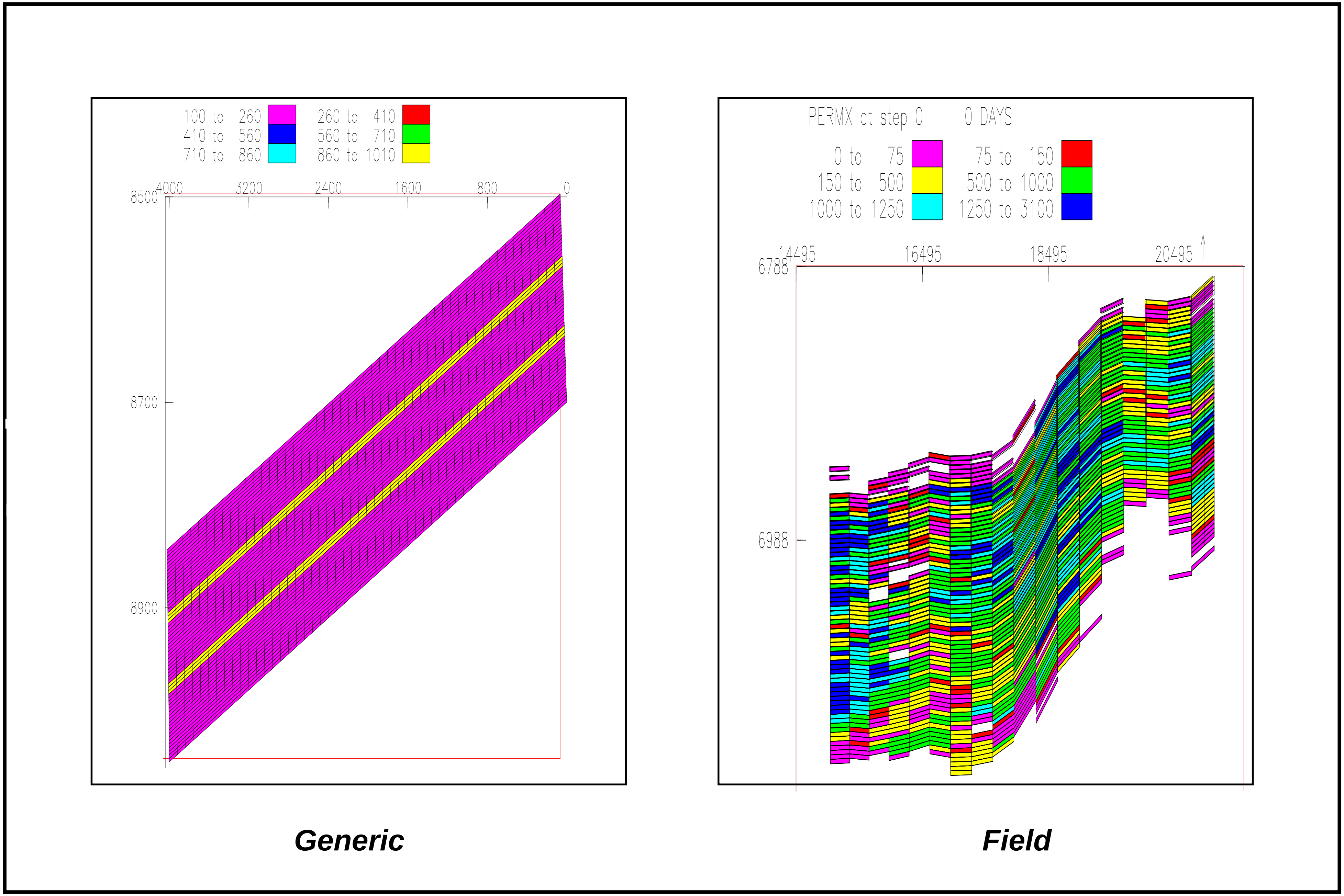


Figure 1: Model permeability variation

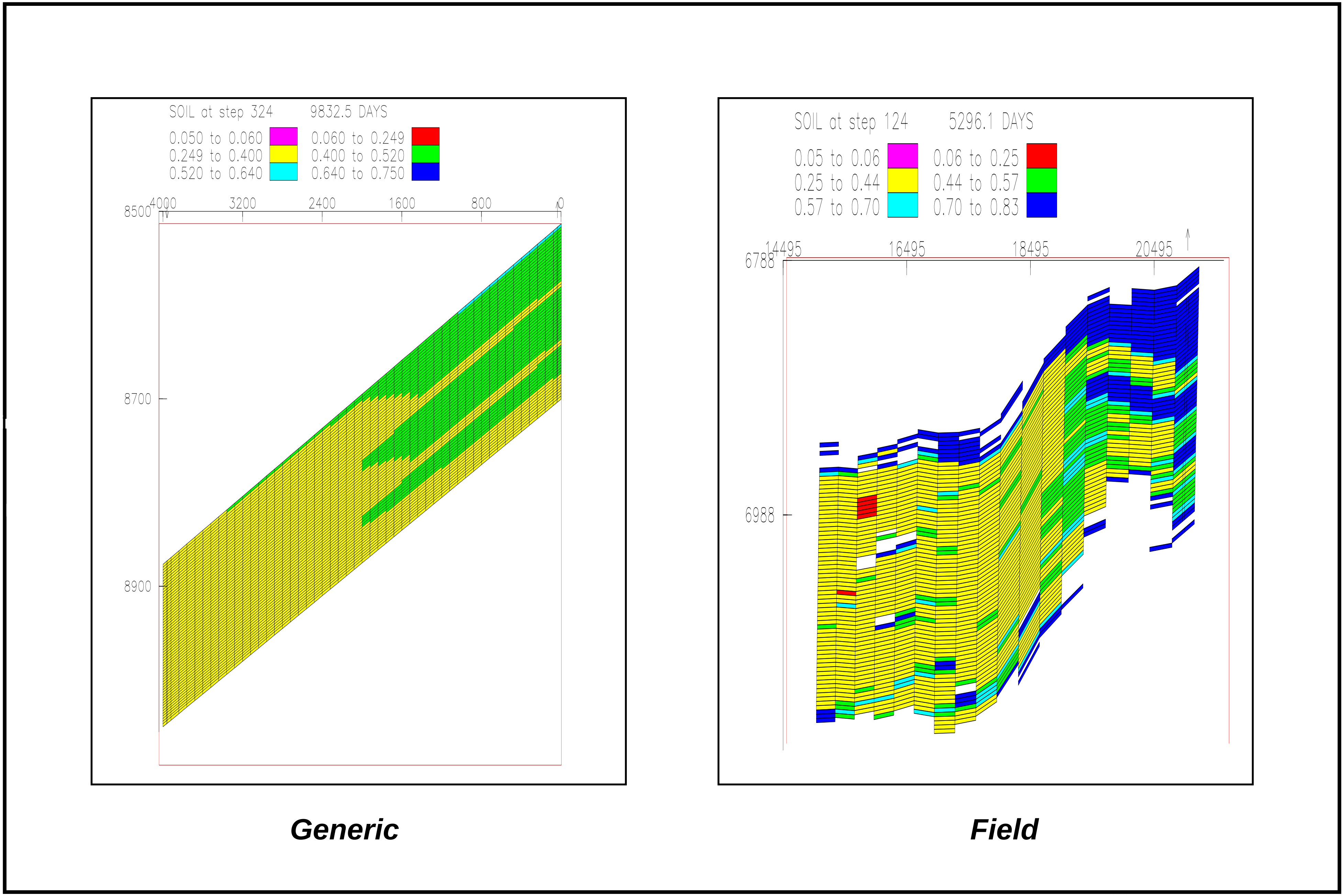


Figure 2: Post waterflood oil saturations

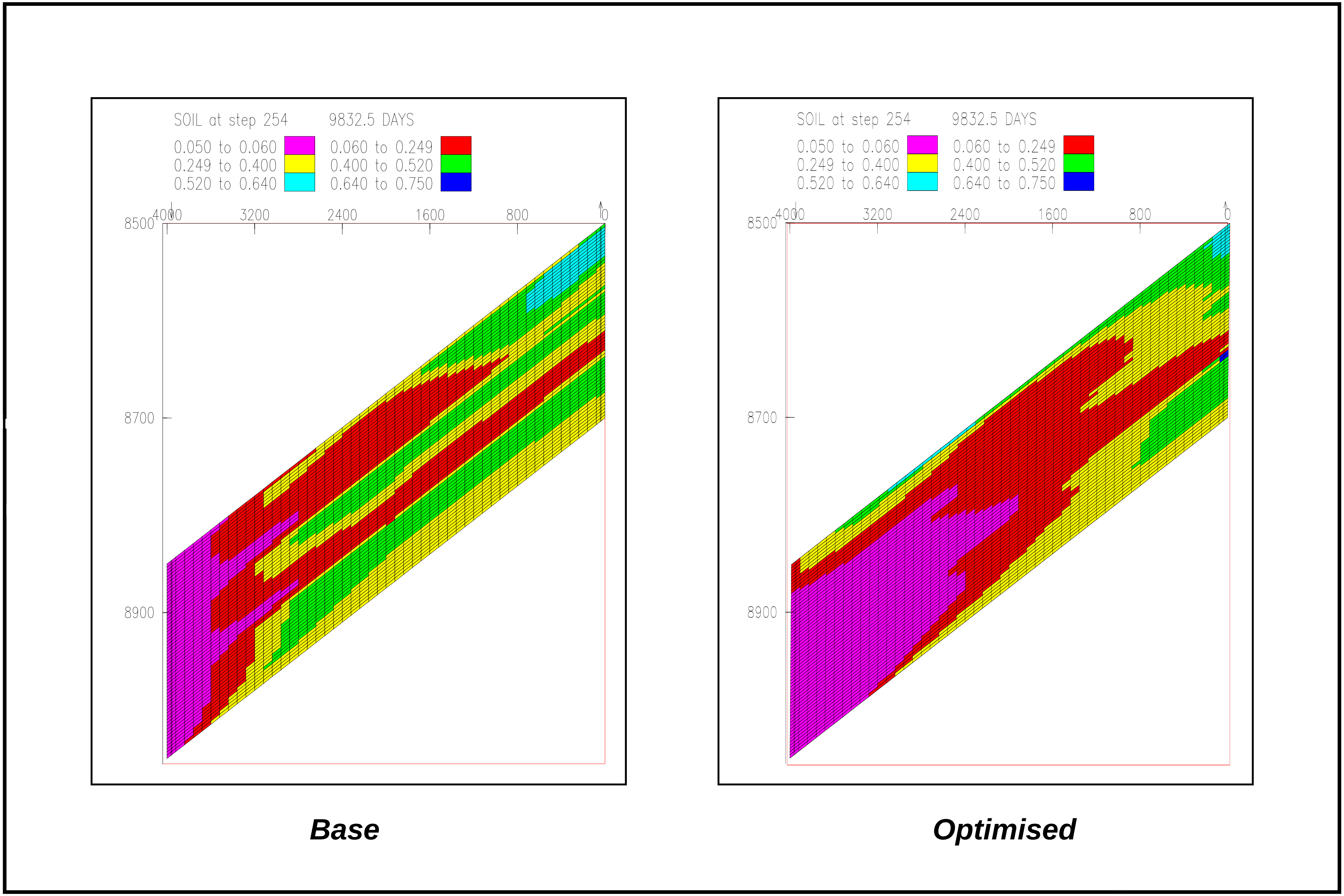
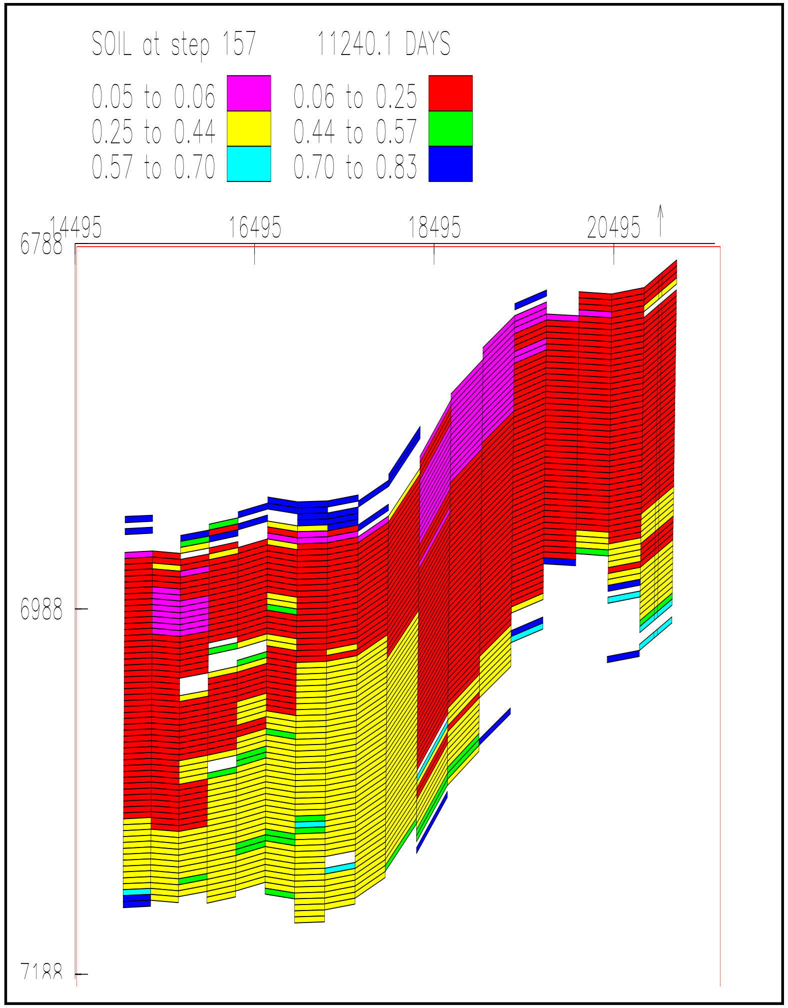
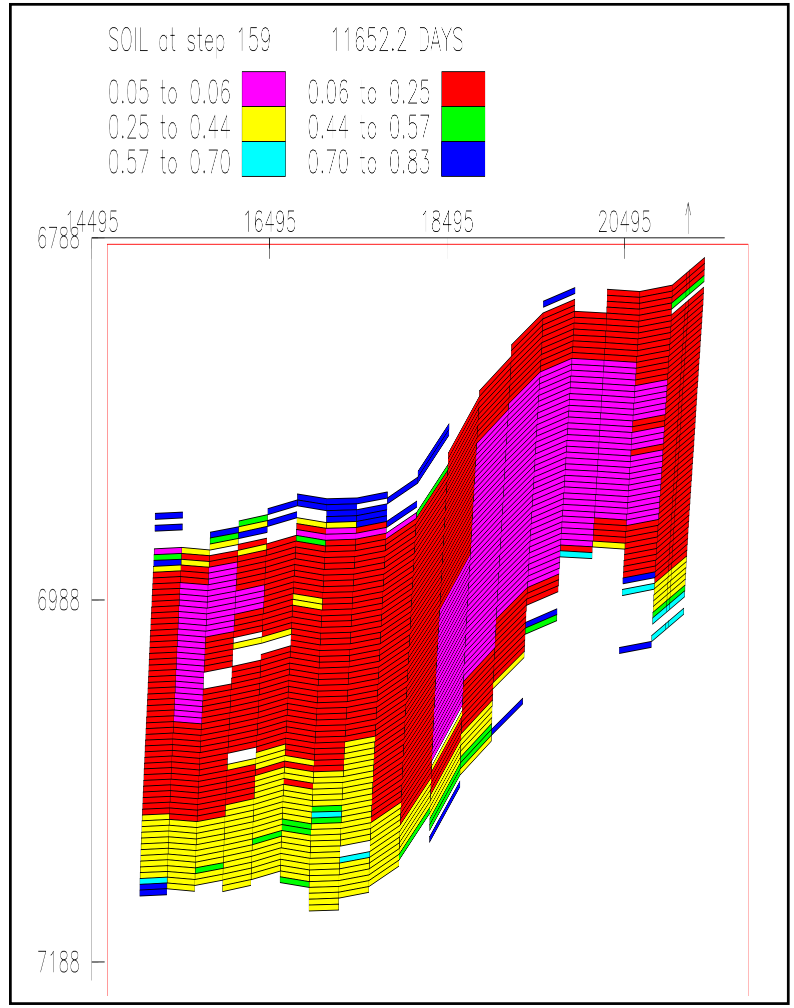


Figure 3: Generic model 1:1 WAG oil saturations

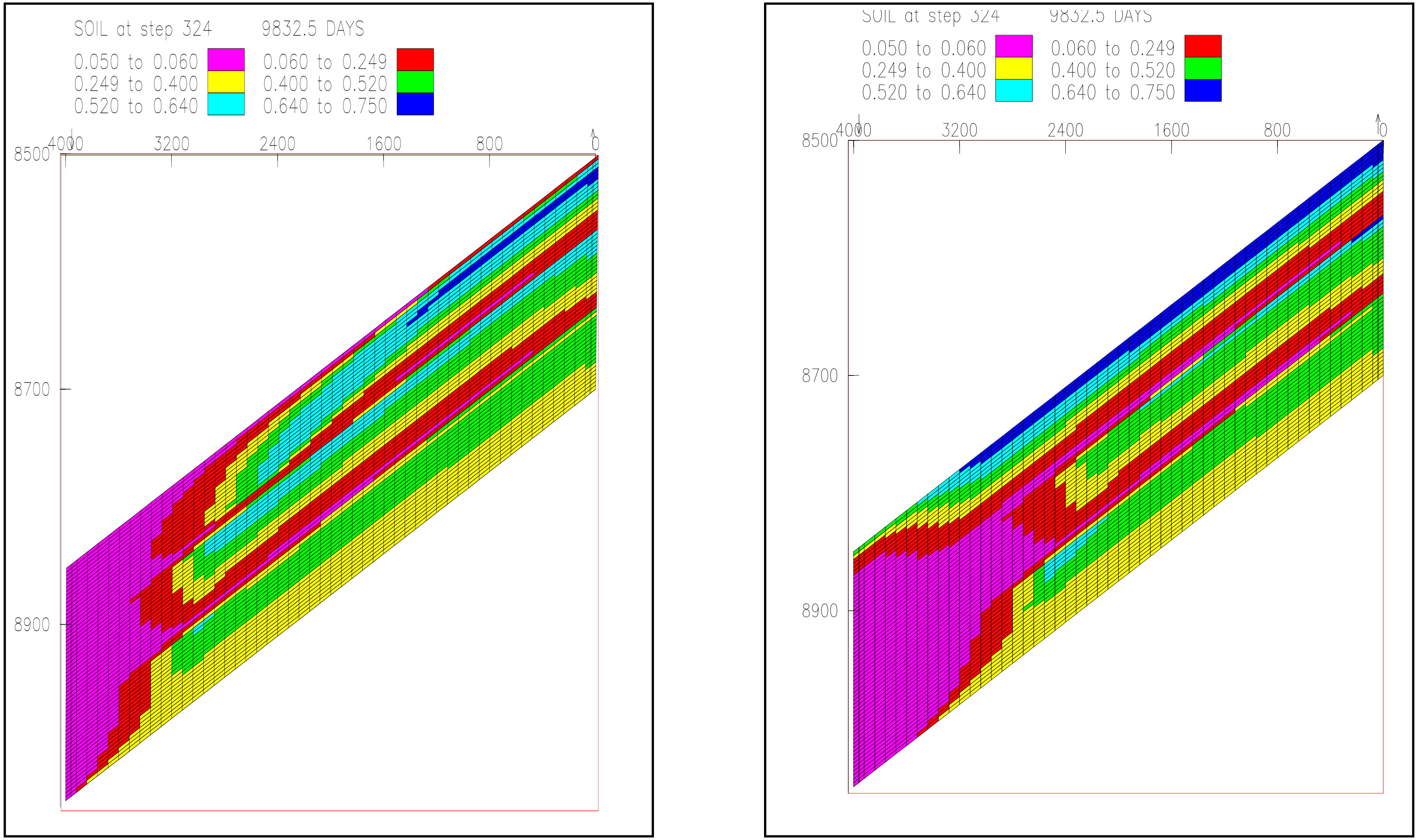


Base



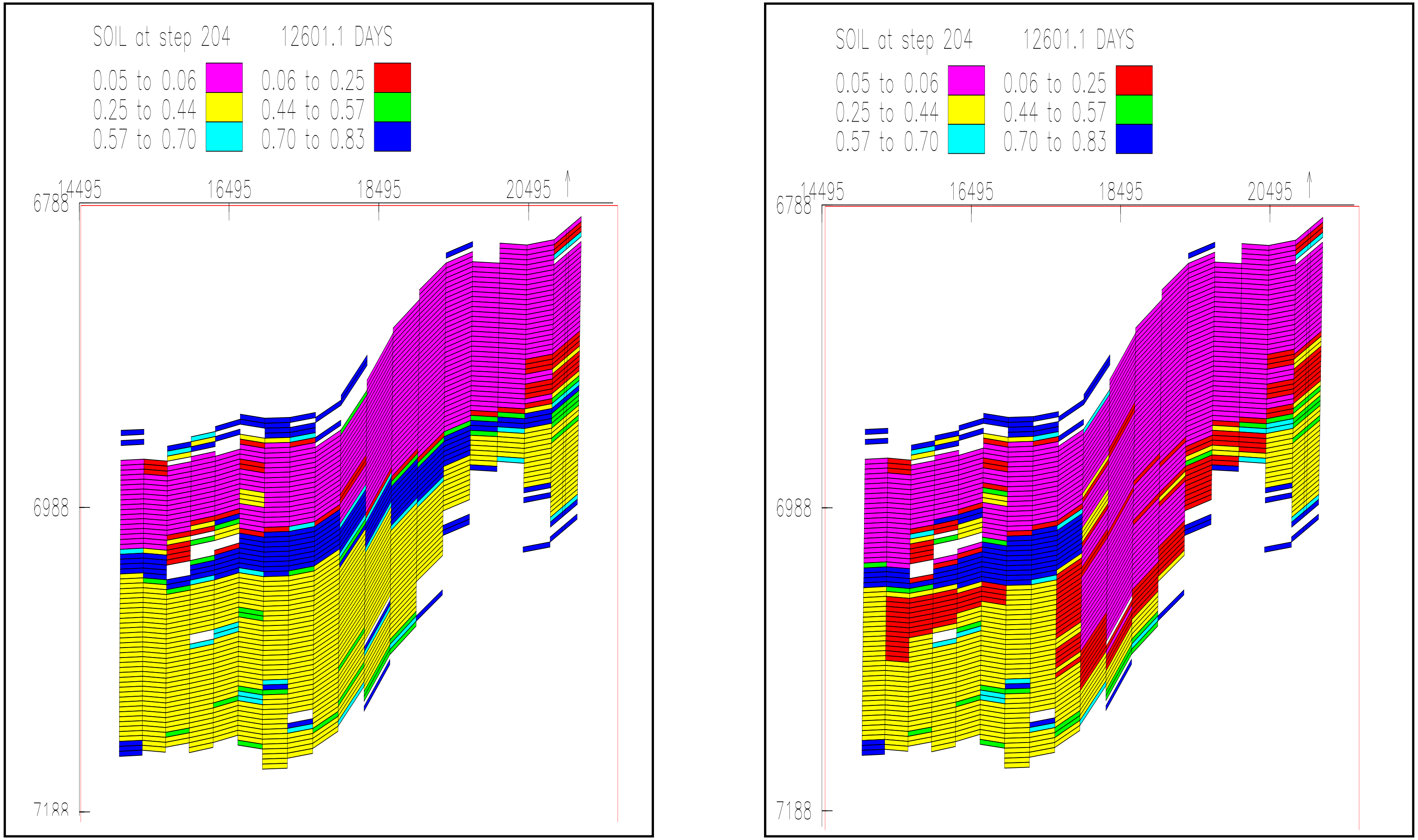
Optimised

Figure 4: Field model 1:1 WAG oil saturations



Base ***Optimised***

Figure 5: Generic model CGI oil saturations



Base ***Optimised***

Figure 6: Field model CGI oil saturations

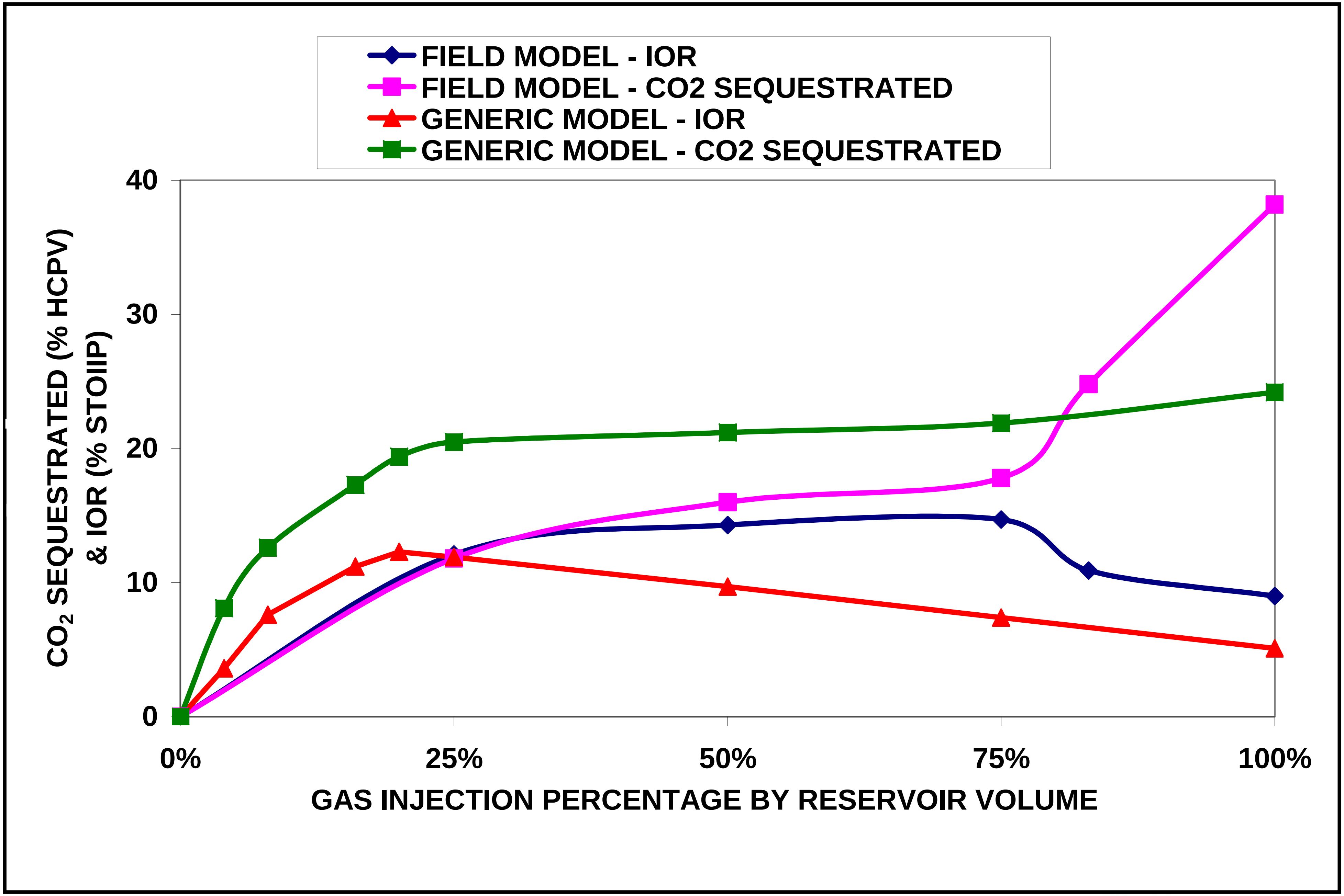


Figure 7: **Dependence on WAG Ratio (Base cases)**

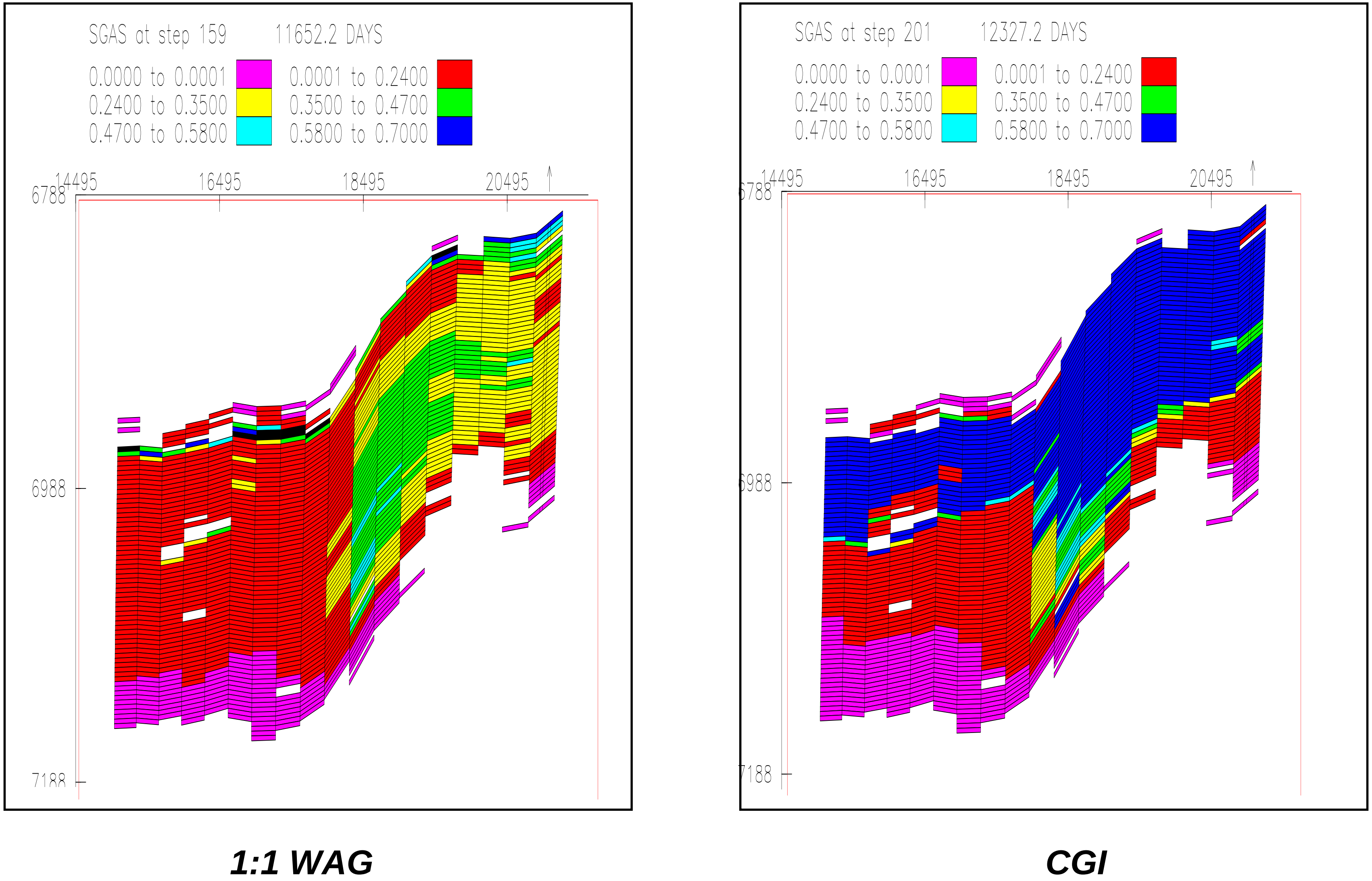


Figure 8: **Optimised field model gas saturations**

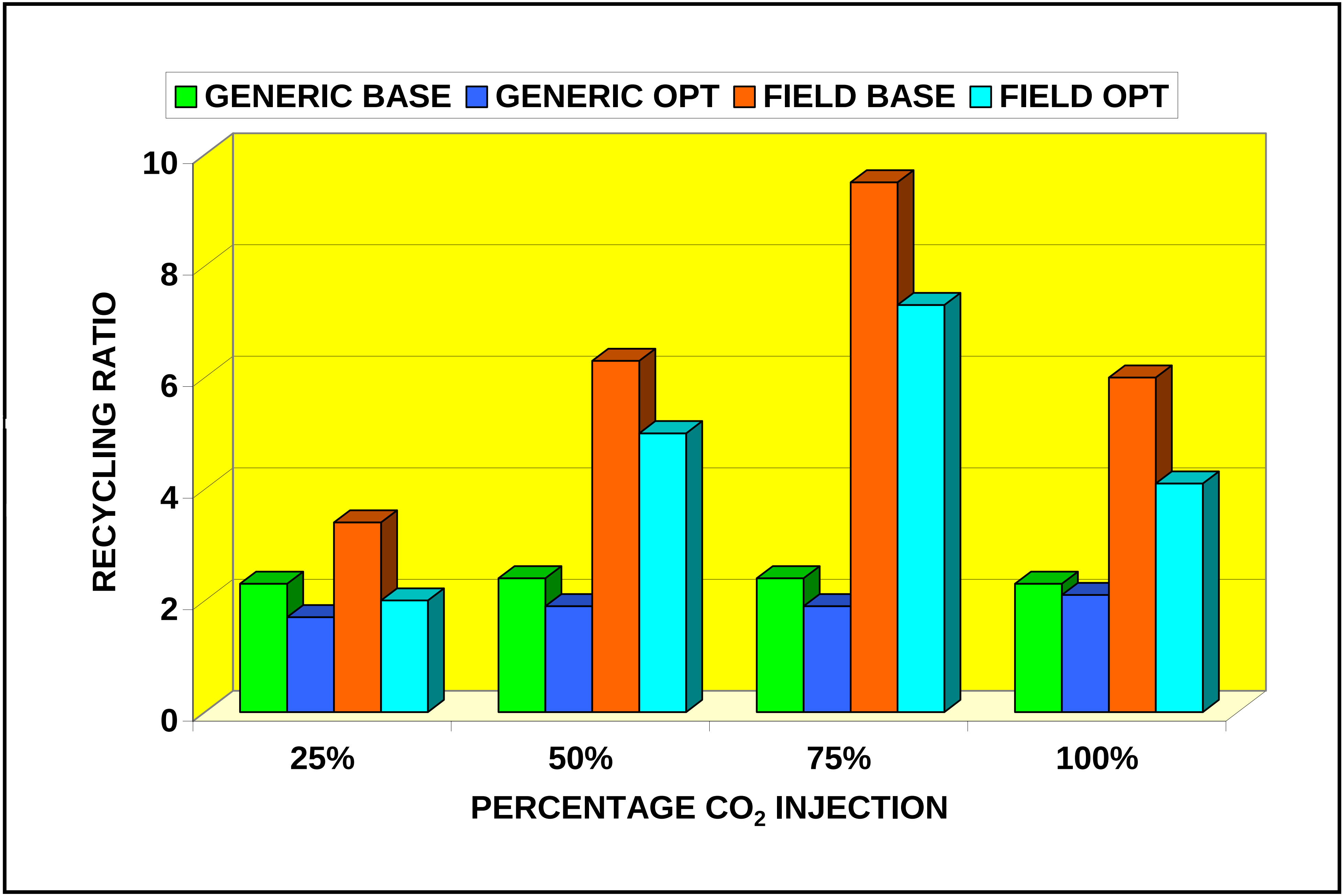


Figure 9: **Optimising injection completions reduces CO_2 backproduction**

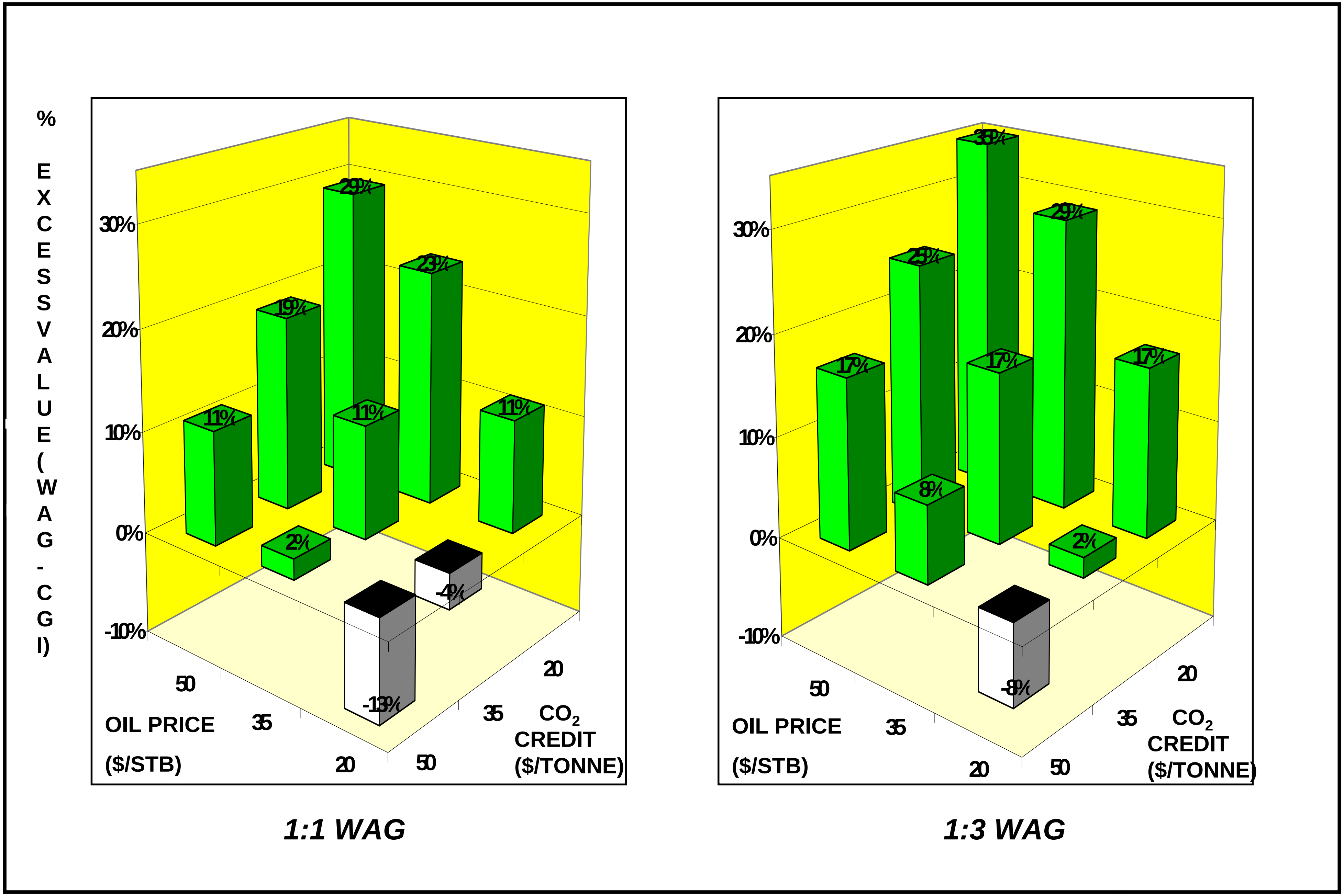
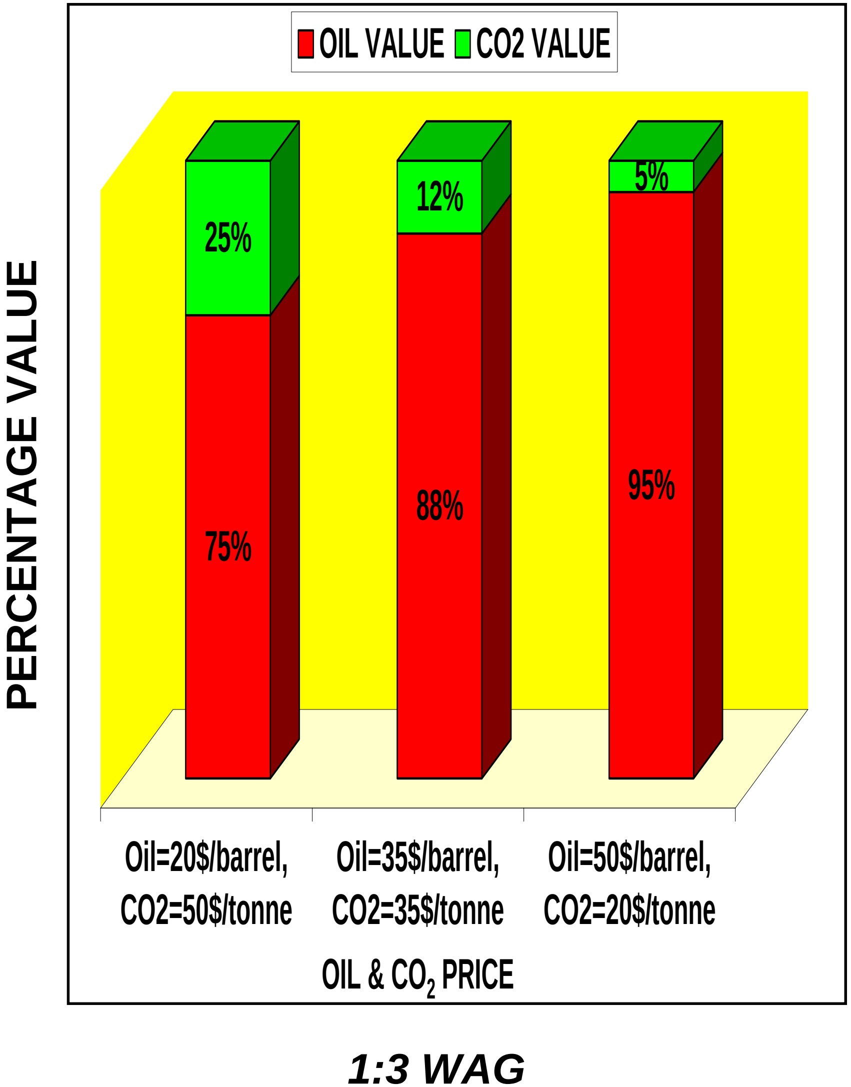


Figure 10: **Relative value of WAG compared to CGI**



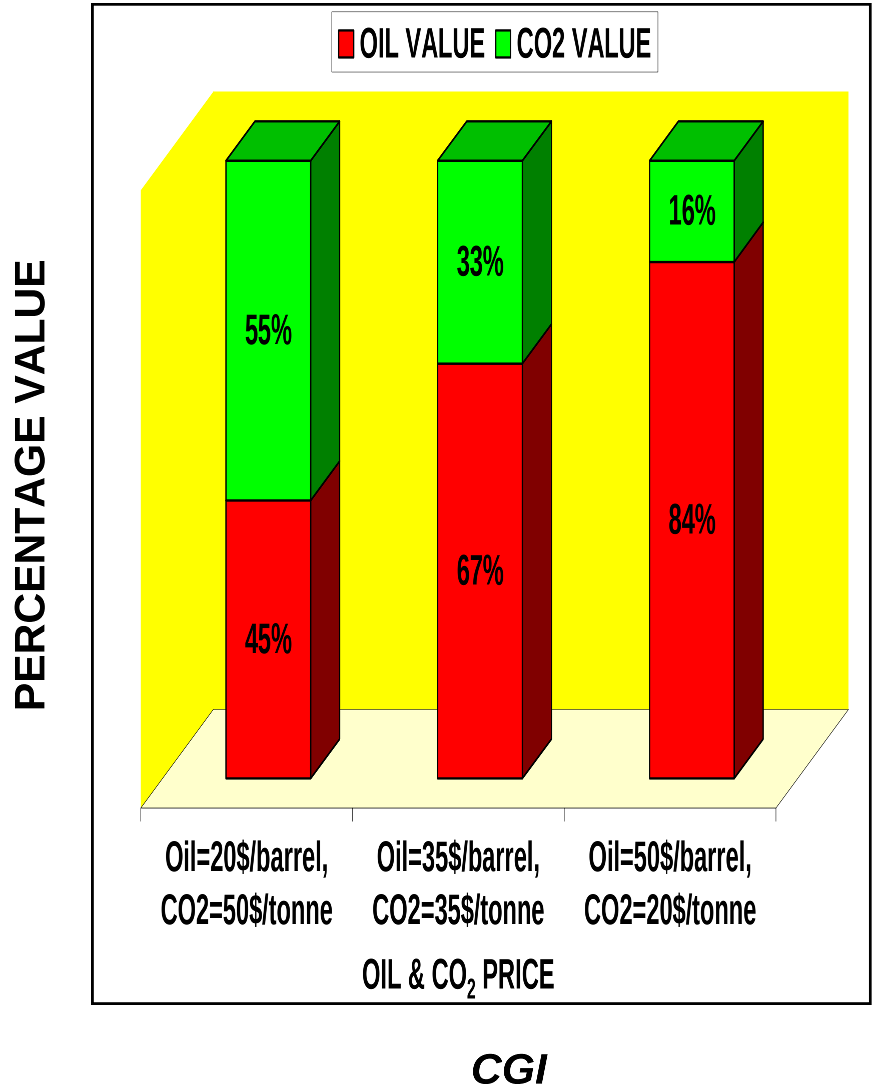


Figure 11: **Relative value of oil and CO_2 sequestration**