



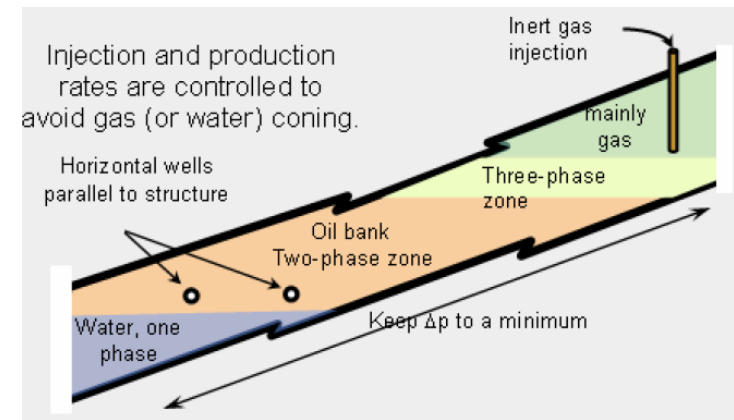
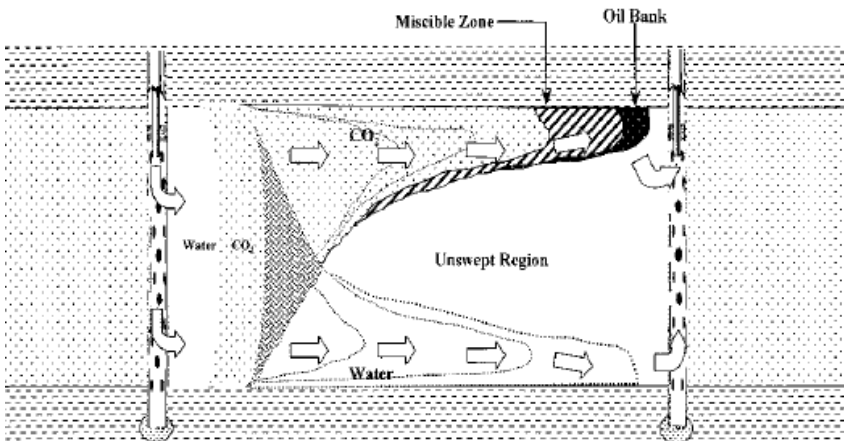
# EVALUATION AND OPTIMIZATION OF GAS ASSISTED GRAVITY DRAINAGE PROCESS

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# Introduction

- **Gravity overriding**, **viscous instability** of injection front and early breakthrough are common problem of gas injection, due to the unfavorable mobility ratio
- **Gas assisted gravity drainage (GAGD)** in dipping reservoir is one of the most efficient methods in both secondary and tertiary modes
- Gravity segregation helps to maintain pressure and the stability of gas flood front and also improves volumetric displacement efficiency



# Objectives

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1. To investigate the effects of design parameters and determine appropriate production strategy for dipping reservoir

- Oil production rate
  - Gas injection rate
  - Well pattern
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2. To determine the sensitivity of reservoir parameters

- Relative permeability correlation
  - Vertical to horizontal permeability ratio
  - Relative permeability to oil and gas.
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# Fractional Flow Equation

Gravity term

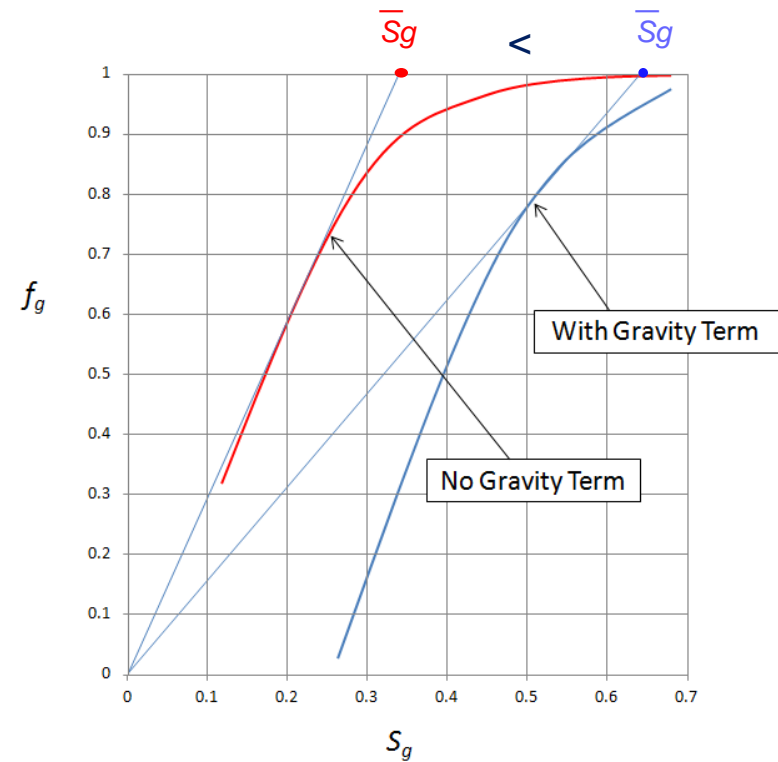
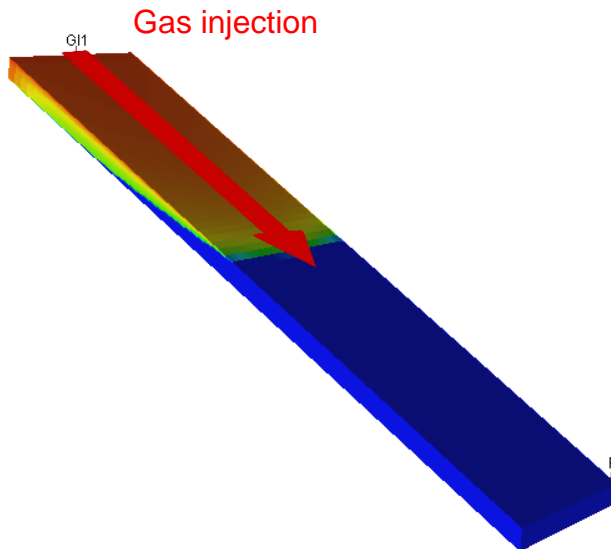
$$f_g = \frac{1 - \frac{k k_{ro} g \Delta \rho \sin \alpha}{q_t \mu_o}}{1 + \frac{k_{rg} \mu_o}{k_{ro} \mu_g}}$$

(Effect of Capillary force is neglected)

Where

$\Delta \rho$  = density difference,  $\rho_o - \rho_g$

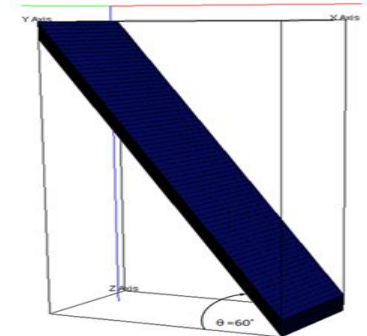
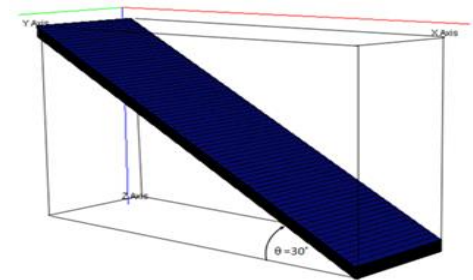
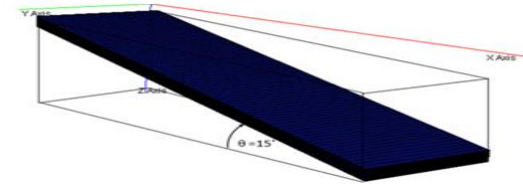
$\alpha$  = dip angle (positive down dip)



# Reservoir Model

- ECLISPE black-oil reservoir simulator (E100) is used in this study
- Undersaturated homogenous reservoir with 15, 30 and 60 degree dip angles
- The maximum simulation time is **100 years**
- The concession period is assumed to be **30 years**

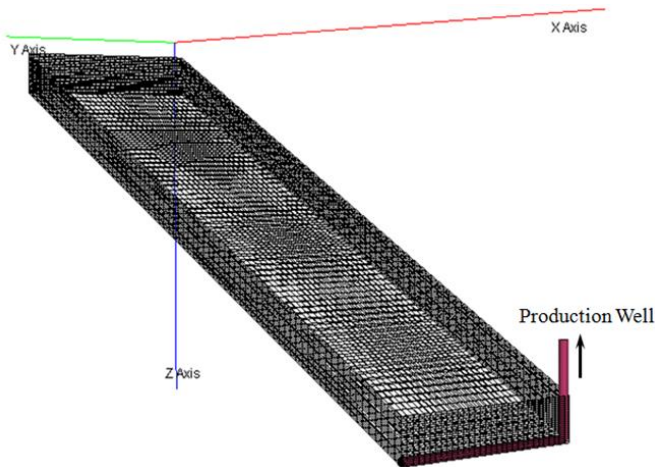
Parameter	Value	Units
Porosity	15.09	%
Horizontal permeability	32.529	mD
Vertical permeability	3.2529	mD
Top depth	5000	ft
<b>Production well constraints</b>		
Cut off oil production rate (STB/D)		100
Minimum bottomhole pressure (psia)		500
<b>Injection well constraint</b>		
Maximum bottomhole pressure (psia)		3300



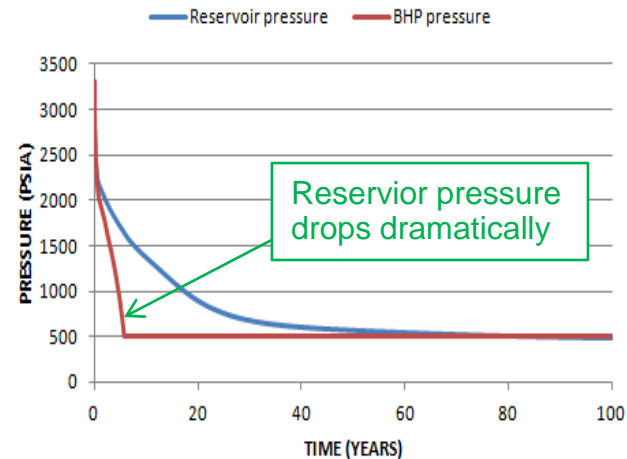
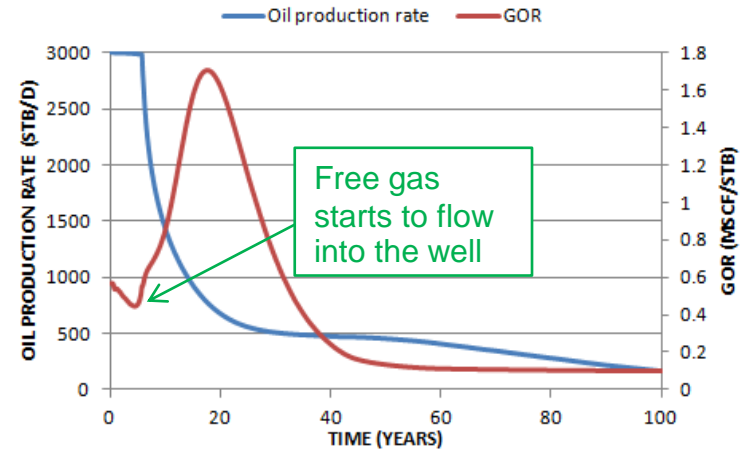
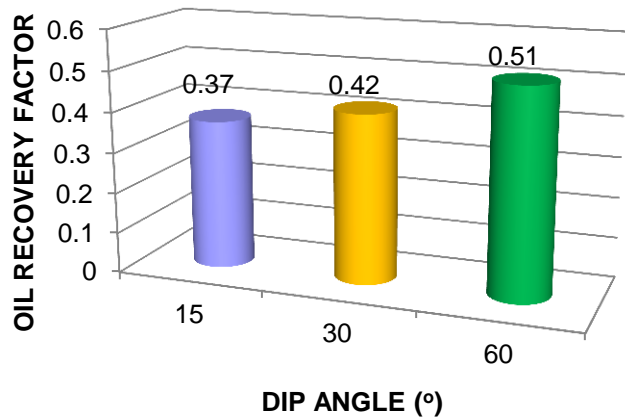


# Results and Discussion

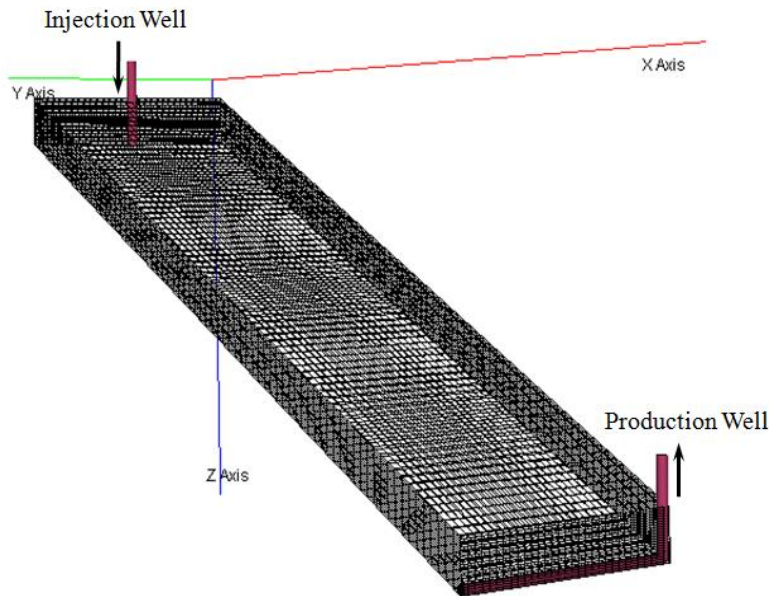
# Natural depletion (Base Case)



- Reservoir pressure declines rapidly
- Oil production declines due to the flow of gas that comes out of oil
- Oil recovery factor increases with higher dip angle

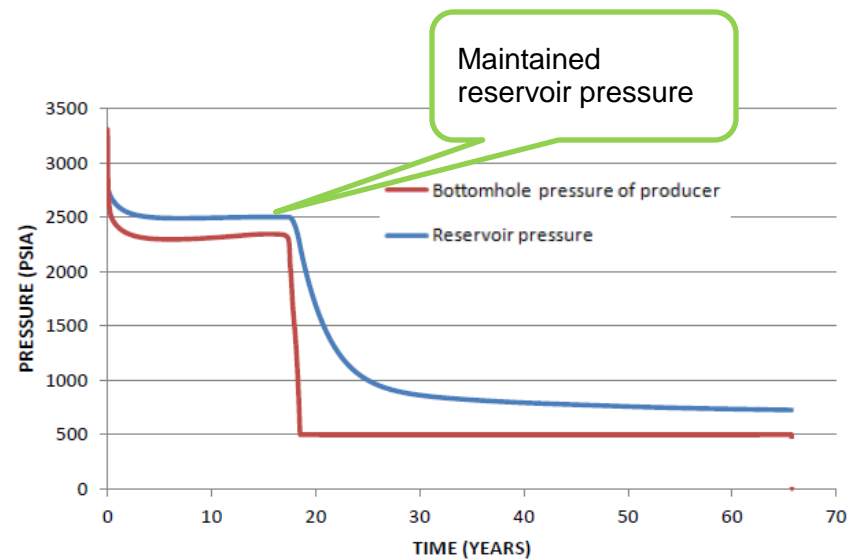
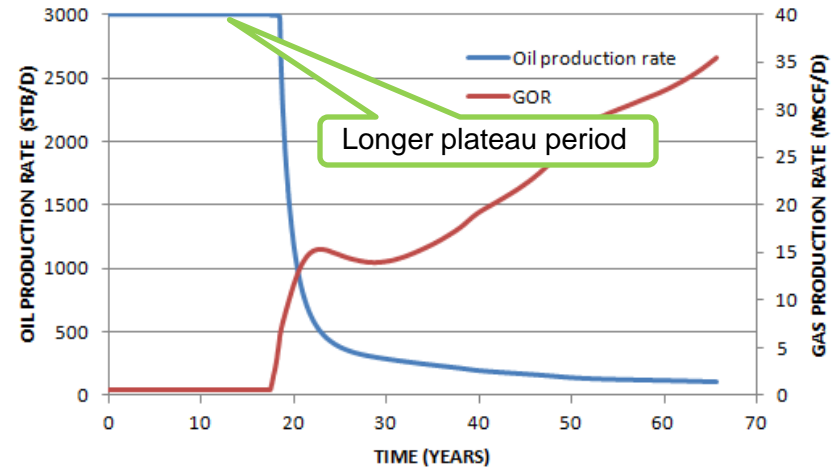


# Gas Assisted Gravity Drainage (GAGD)



## Benefit of GAGD

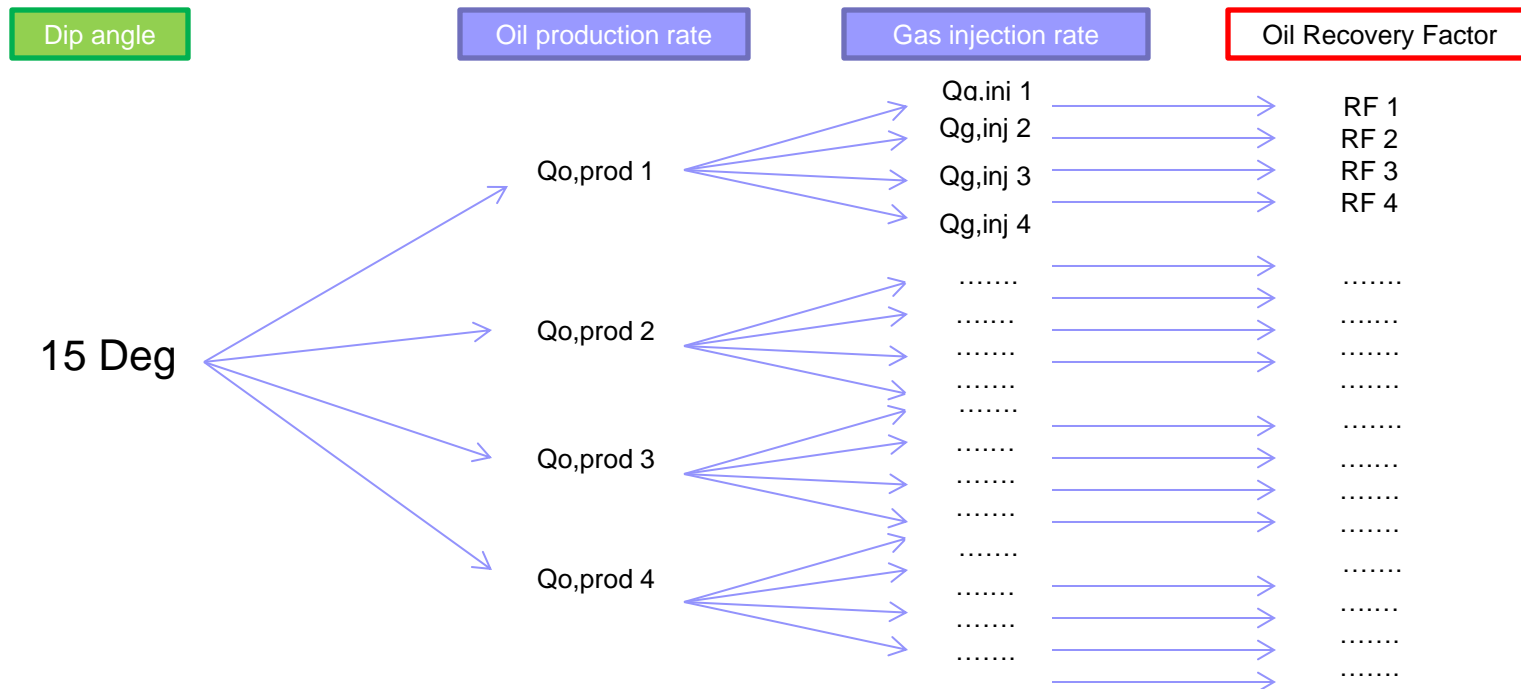
- Maintain the reservoir pressure
- Extend the plateau period
- Shorter production time
- Reduce flow of gas near the well bore



# Effect of oil production and gas injection rate

Two scenarios are used to study the effect of oil production rate and gas injection rate

- Vary oil production (gas injection rate based on oil production rate)
- Vary gas Injection rate with fixed oil production rate

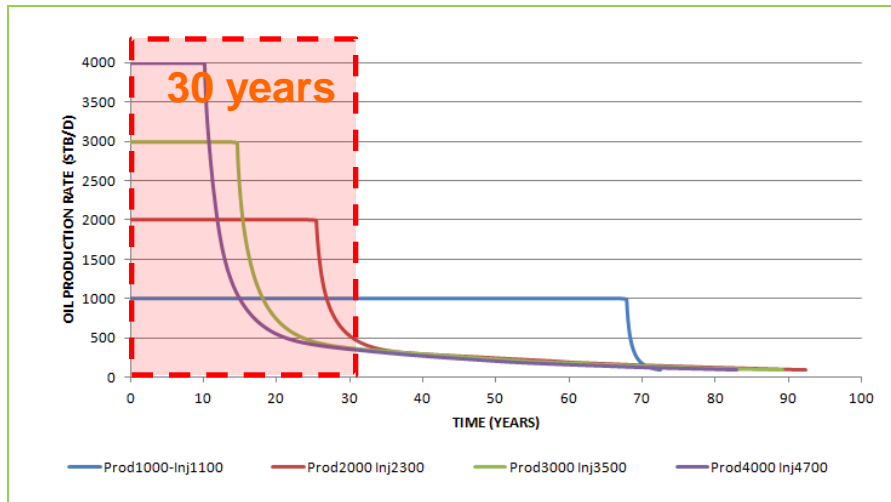


# Effect of oil production and gas injection rate

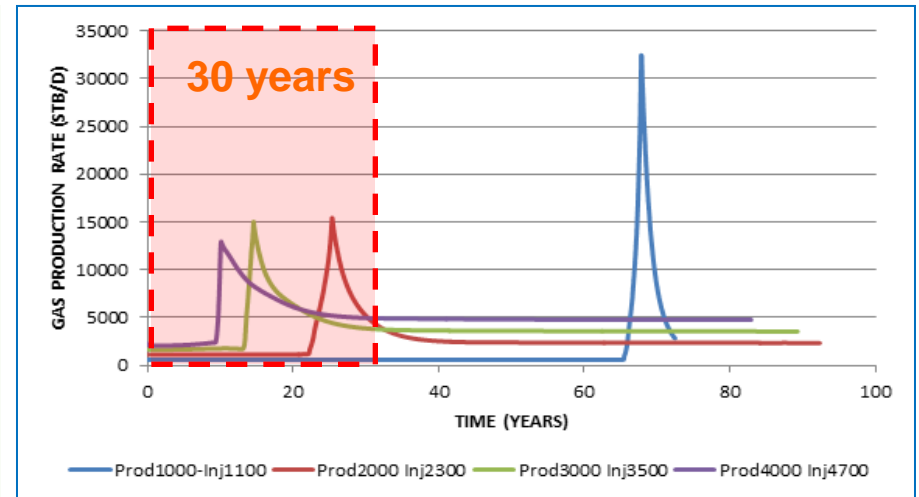
- For dip angle of 15 degrees

- $q_{o,prod} = 1000$  STB/D,  $q_{g,inj} = 1100$  MSCF/D
- $q_{o,prod} = 2000$  STB/D,  $q_{g,inj} = 2300$  MSCF/D
- $q_{o,prod} = 3000$  STB/D,  $q_{g,inj} = 3500$  MSCF/D
- $q_{o,prod} = 4000$  STB/D,  $q_{g,inj} = 4700$  MSCF/D

## Production profile



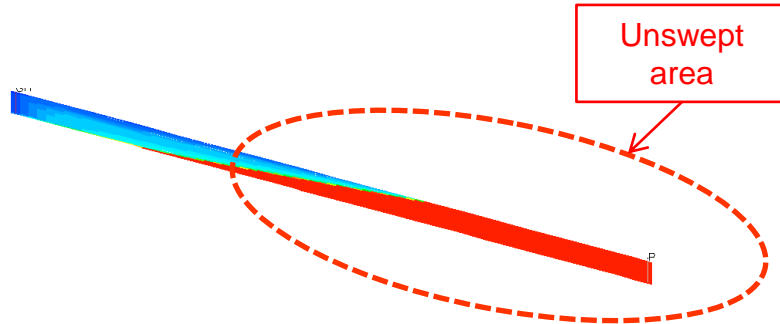
**Oil production rate**



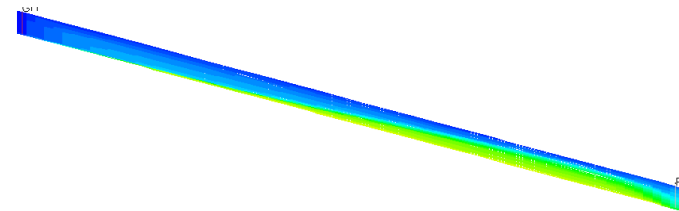
**Gas production rate**

- The higher production rate, the earlier gas breaks through

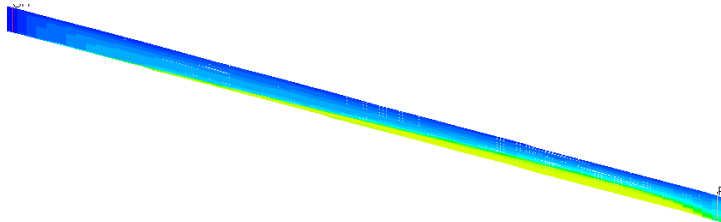
# Oil saturation distribution at 30 years



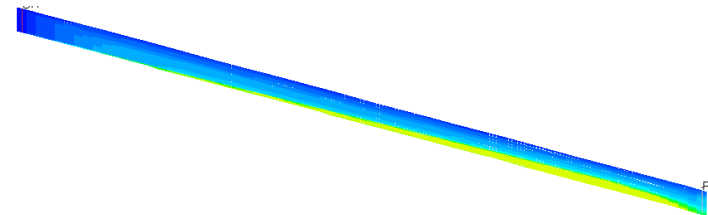
(a) Oil production rate: 1000 STB/D



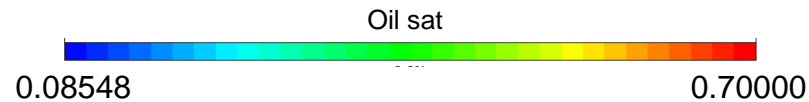
(b) Oil production rate: 2000 STB/D



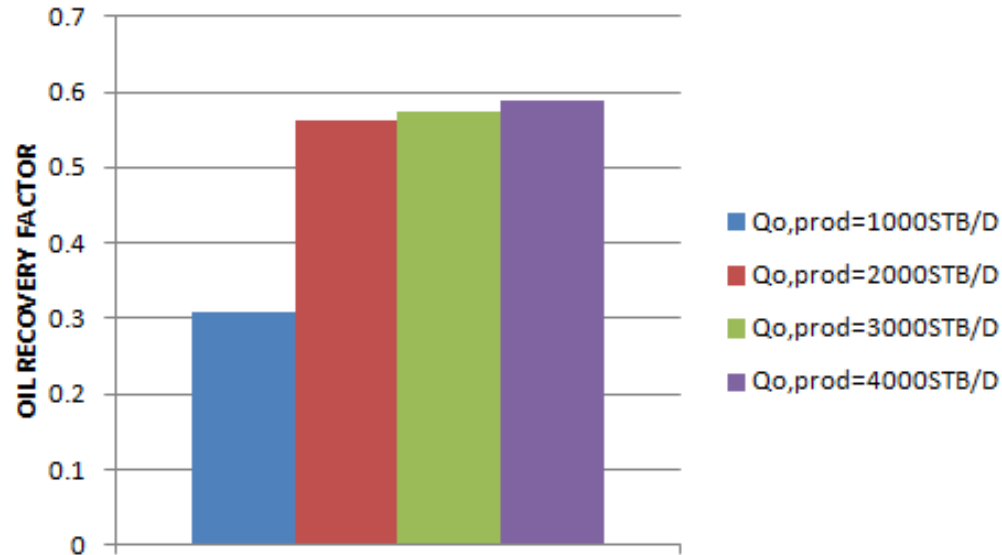
(c) Oil production rate: 3000 STB/D



(d) Oil production rate: 4000 STB/D



## Oil recovery factor at 30 years for 15-degree dip angle



### At the end of 30 years

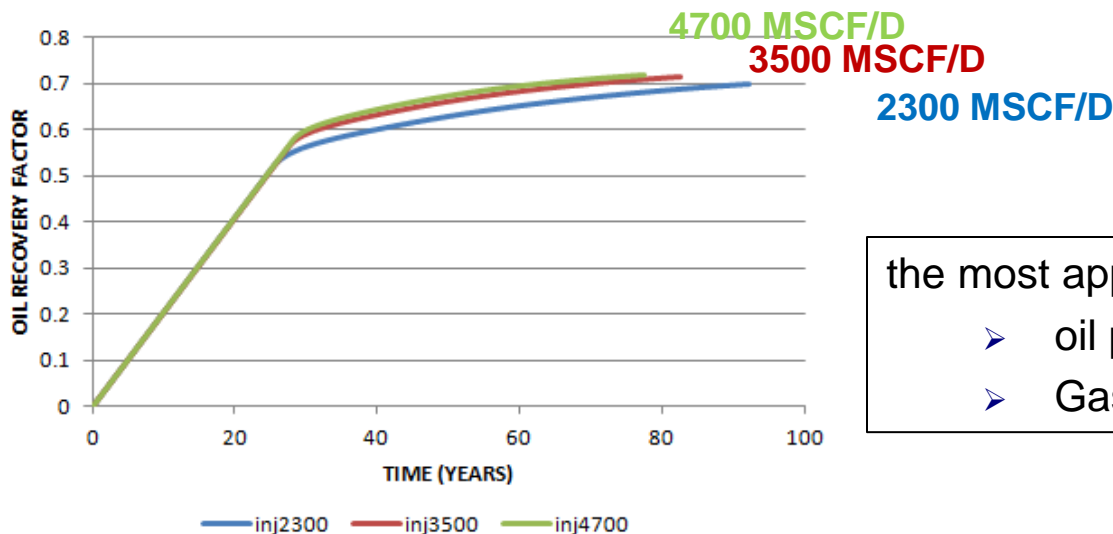
- Production rate of **2000**, **3000** and **4000** STB/D give comparatively high RF
- Production rate 2000,3000 and 4000 STB/D causes gas to break through within 30 years

# Effect of oil production and gas injection rate

## ■ For dip angle of 15 degrees

CASE	Oil production rate (STB/D)	Gas injection rate (MSCF/D)	RF (%)
1	2000	2300	56.28
2		3500	59.14
3		4700	59.80
4	3000	3500	57.29
5		4700	60.35
6		6000	61.40
7	4000	4700	58.89
8		6000	61.53
9		8000	63.14

- **Increasing injection rate** provides **higher oil recovery**
- **Small increase** in oil recovery when the injection rate is limited by the fracture pressure



- the most appropriate design parameter is
- oil production rate :4000 STB/D
  - Gas injection rate :6000 MSCF/D

# Effect of oil production and gas injection rate

- For dip angle of 30 degrees

the most appropriate design parameter is

- oil production rate :3000 STB/D
- Gas injection rate :4900 MSCF/D

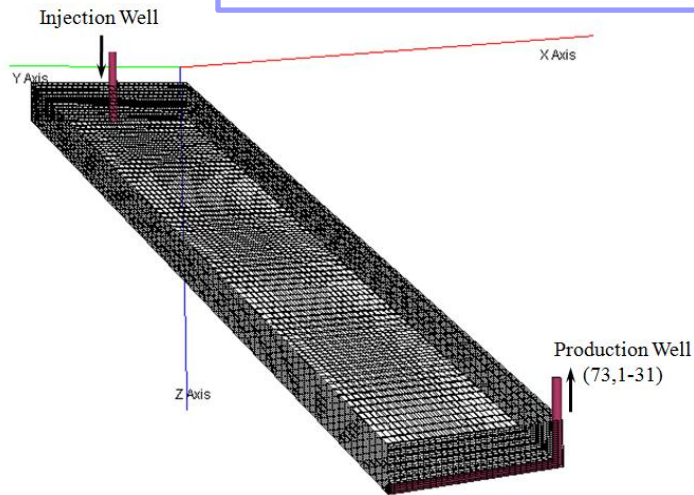
- For dip angle of 60 degrees

the most appropriate design parameter is

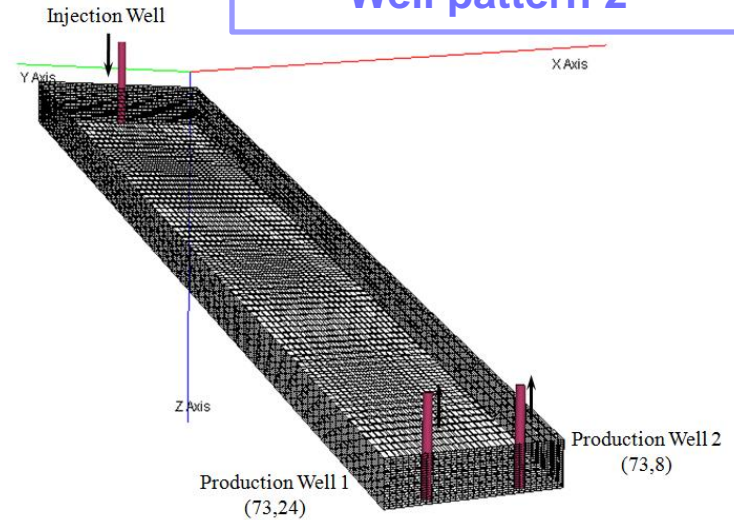
- oil production rate :3000 STB/D
- Gas injection rate :5400 MSCF/D

# Effect of well pattern

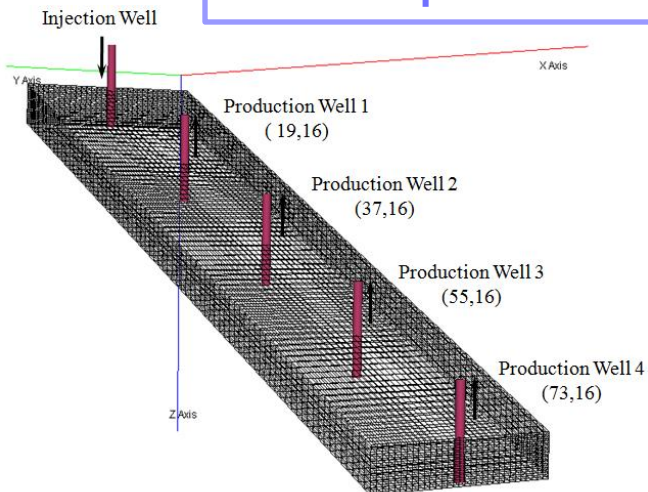
Well pattern 1



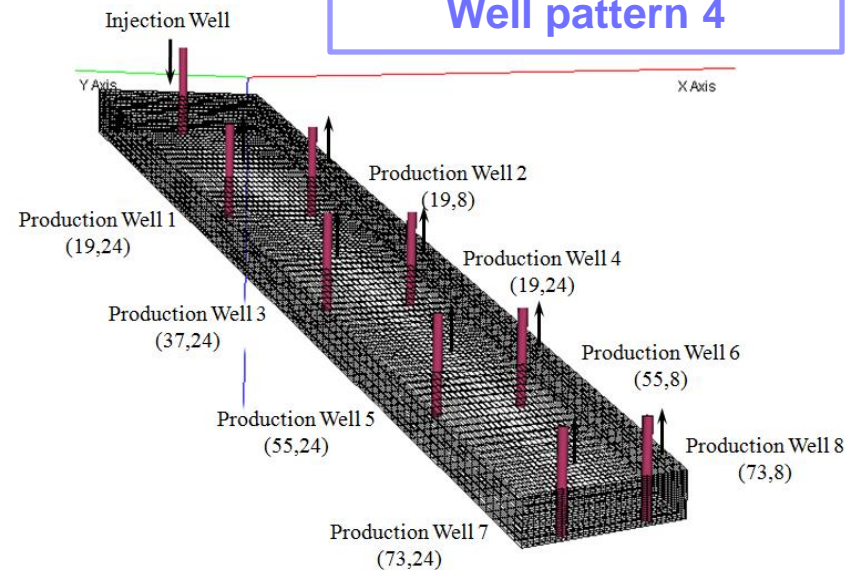
Well pattern 2



Well pattern 3

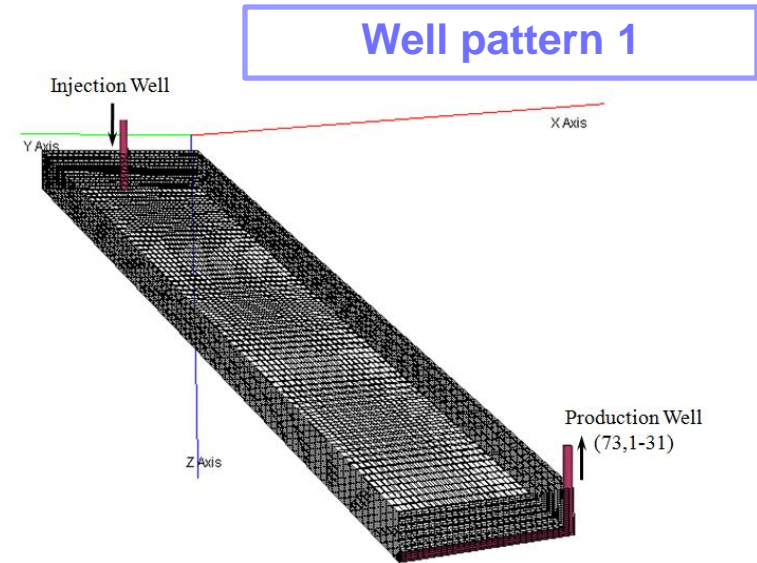
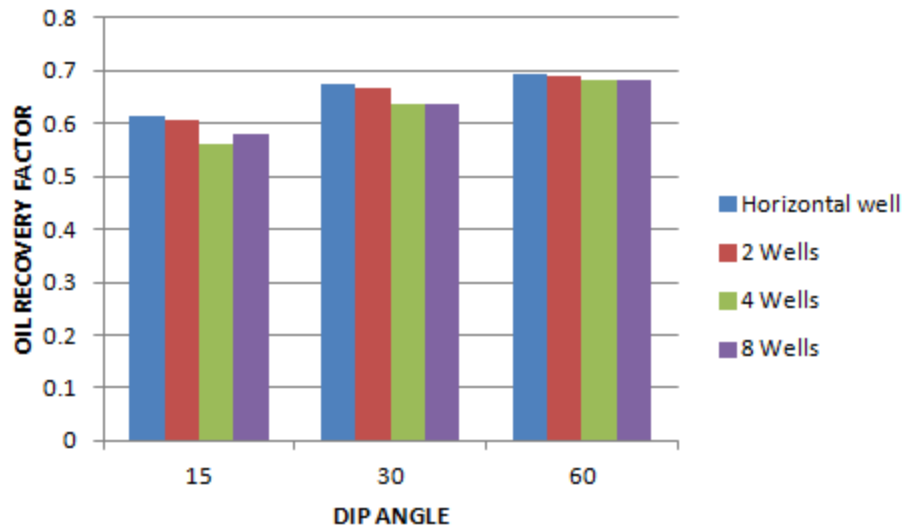


Well pattern 4



# Results of well pattern

- For dip angle of 15,30,60 degrees



- Well pattern 1 (Horizon well) provides the highest oil recovery at 30 years (0.61-0.69) because
  - Deeper location of producers provides longer and more stable oil production
  - High gas production in early time for well pattern 3 and 4 results in lower oil recovery

# Effect of relative permeability correlations

## At the end of production time

Dip angle	Model	Production time (years)	Cumulative oil production (MMSTB)	Cumulative gas production (BSCF)
15	ECLIPSE default	72.25	24.88	167.75
	Stone 1	72.58	24.92	168.50
	Stone 2	69.09	24.62	160.76
30	ECLIPSE default	49.67	25.30	96.90
	ECLIPSE	49.83	25.31	97.23
	Stone 2	44.42	24.91	87.30
60	ECLIPSE default	51.25	25.91	101.43
	Stone 1	51.58	25.96	102.12
	Stone 2	42.42	25.41	83.32

- Insignificant difference in oil production among these correlations for dip angle of 15, 30 and 60 degrees (around 1.2 to 2.2 %).
- Stone 1 gives slightly higher oil production than other correlations.
- Stone 2 model yields shorter production time.

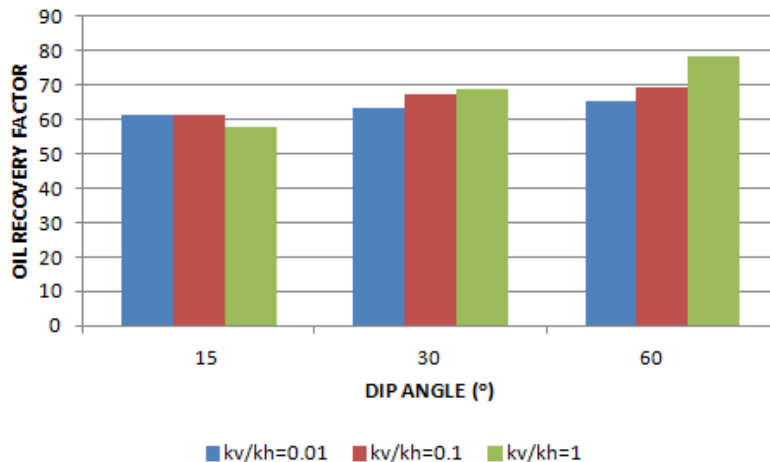
# Effect of vertical to horizontal permeability

Case	Vertical to horizontal permeability ratio	Vertical Permeability (md)	Horizontal Permeability (md)
1	0.01	0.32529	32.529
2	0.1	3.2529	32.529
3	1	32.529	32.529

## In small dip angle (15 degrees)

- Effect of gravity < capillary force
- Gas tends to bypass oil and breakthrough **earlier** when Increasing  $k_v/k_h$
- Lower RF when increasing  $k_v/k_h$

## At 30 years



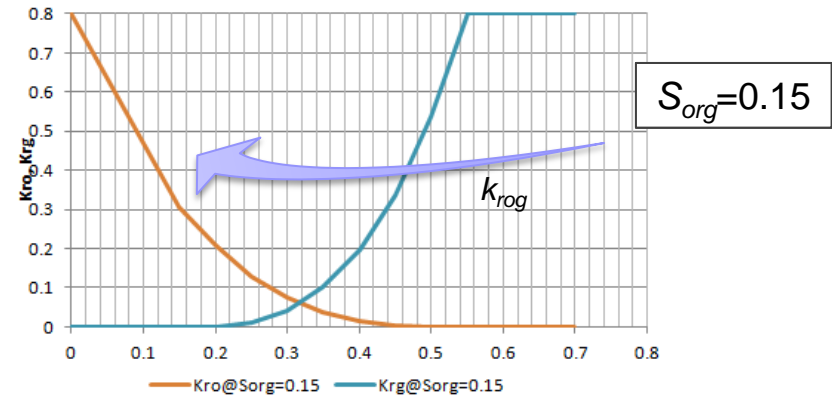
## In high dip angle (30 and 60 degrees)

- The effect of gravity > capillary force
- Gas breakthrough occur **later** when  $k_v/k_h$  is higher
- Higher RF when increasing  $k_v/k_h$

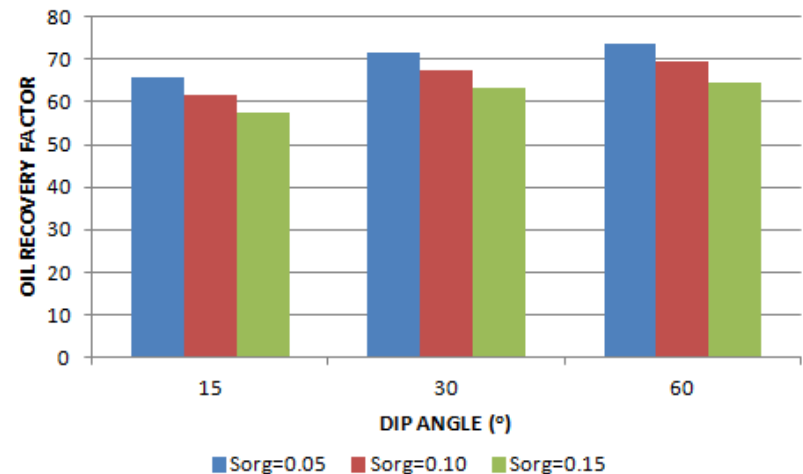
# Effect of relative permeability to oil and gas

- Residual oil saturation ( $S_{org}$ ) is used as a study parameter to change  $k_{rog}$ 
  - 0.05
  - 0.10
  - 0.15

- Increasing  $S_{org}$  causes
  - $K_{rog}$  shifts to the left
  - Lower oil recovery factor
  - Difference in oil recovery factor obtained from the sets of  $S_{org}$  is up to 9.41%



At 30 years



# Conclusion

- GAGD considerably increases oil production comparing to that of natural depletion
- Reservoir dip angle affects the oil recovery. An increase in dip angle enables gravity effect to improve the stability of flood front and increase gas sweep efficiency
- Oil production rate is a key parameter in GAGD process.
  - Very low production rate results in a stable gas flood front and high oil recovery. However, it takes impractically long production time
  - Higher production rate accelerates oil production, but it also causes early gas breakthrough, resulting in poor sweep efficiency
- When production rate is fixed, increasing gas injection rate provides higher oil recovery.
  - Once gas injection rate is so high that the injector BHP exceeds the fracture pressure, oil recovery is insignificantly increased.

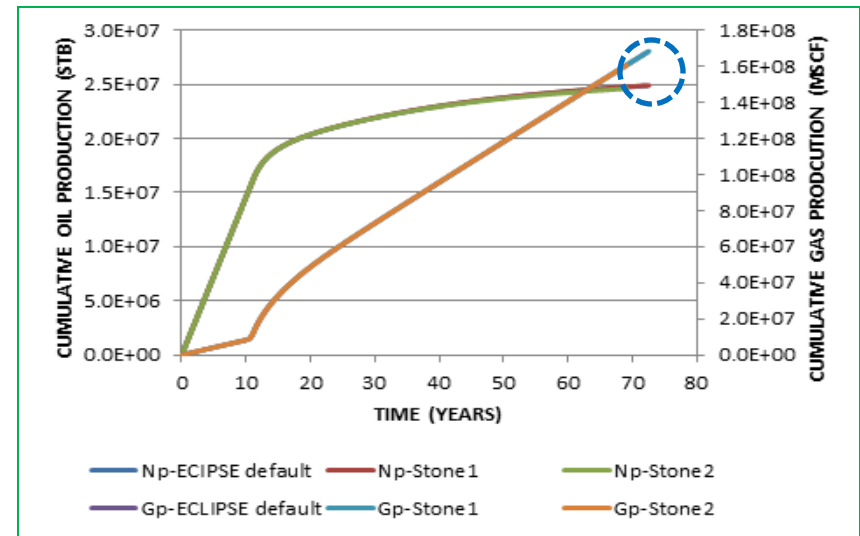
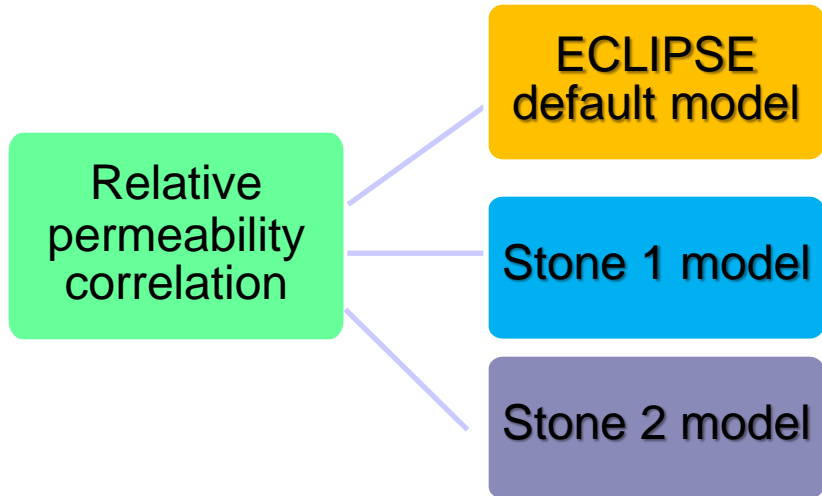
# Conclusion

- In dipping reservoirs, in order to delay gas breakthrough and maximize volumetric sweep efficiency.
  - gas injector should be located at the most updip location
  - production well should be placed at the most downdip location
- Increasing vertical to horizontal permeability ratio significantly increases oil recovery, improves displacement efficiency.
- insignificant difference in oil production among three study correlations for every dip angle.
- Decrease in residual oil saturation in gas-oil system results in higher oil recovery and longer production time.

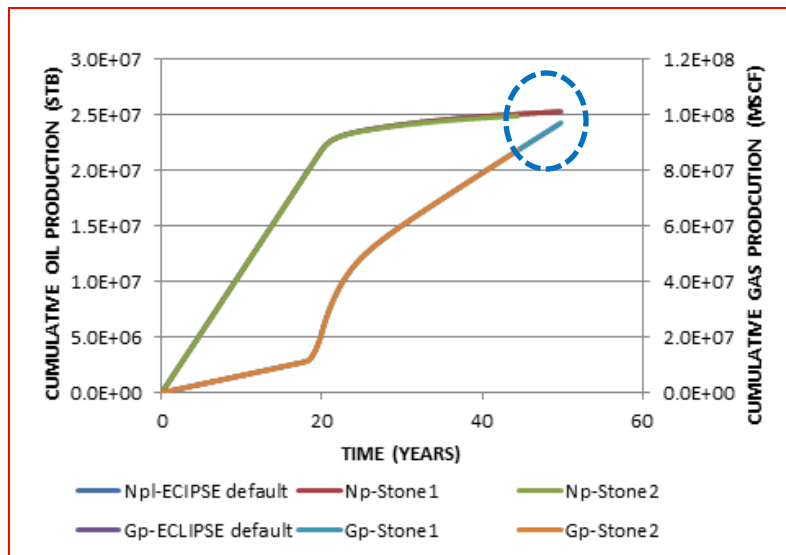


Q & A

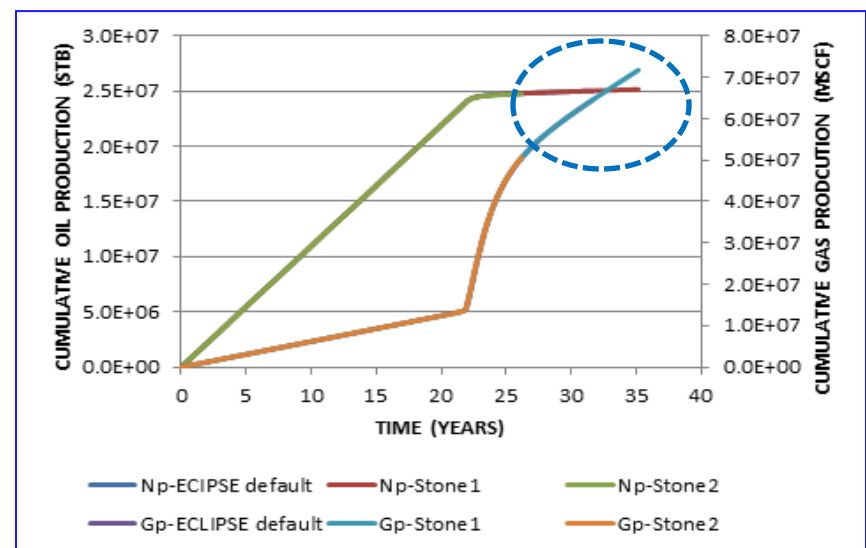
# Effect of relative permeability correlations



15 degrees

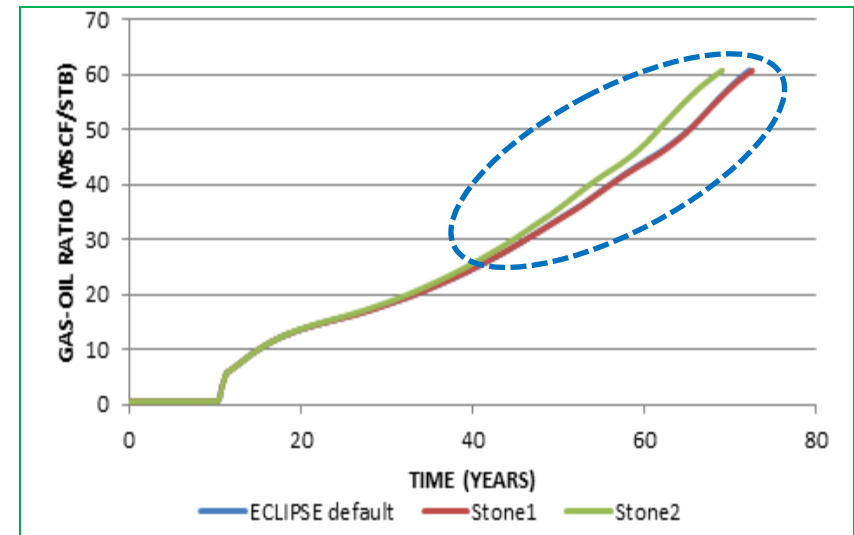
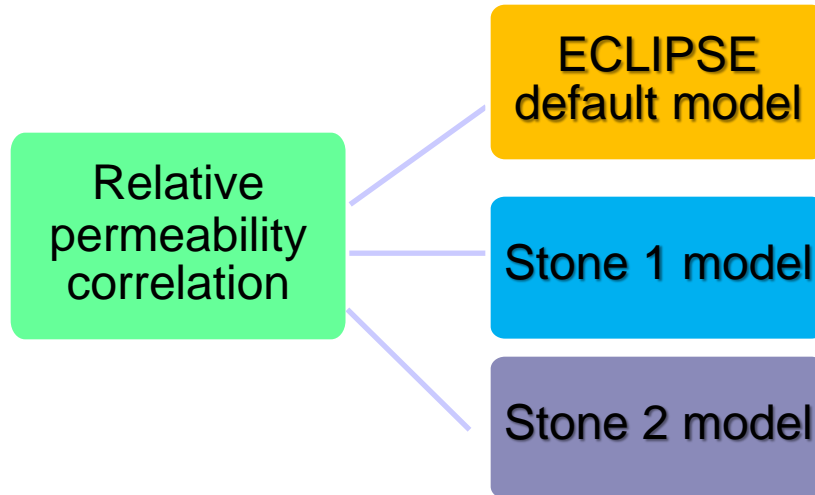


30 degrees

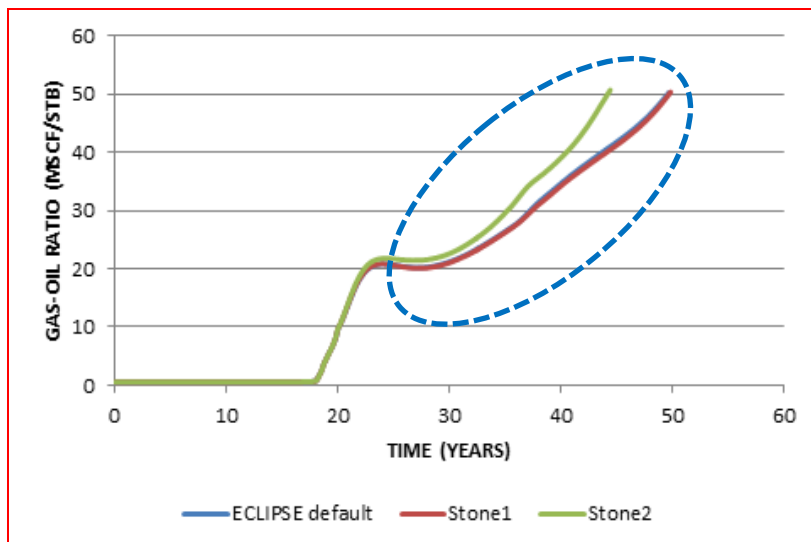


60 degrees

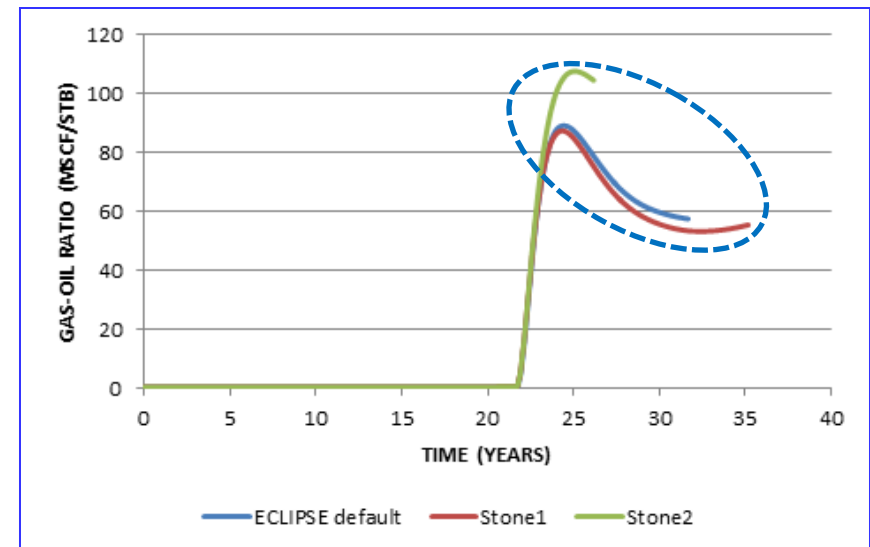
# Effect of relative permeability correlations



15 degrees



30 degrees



60 degrees

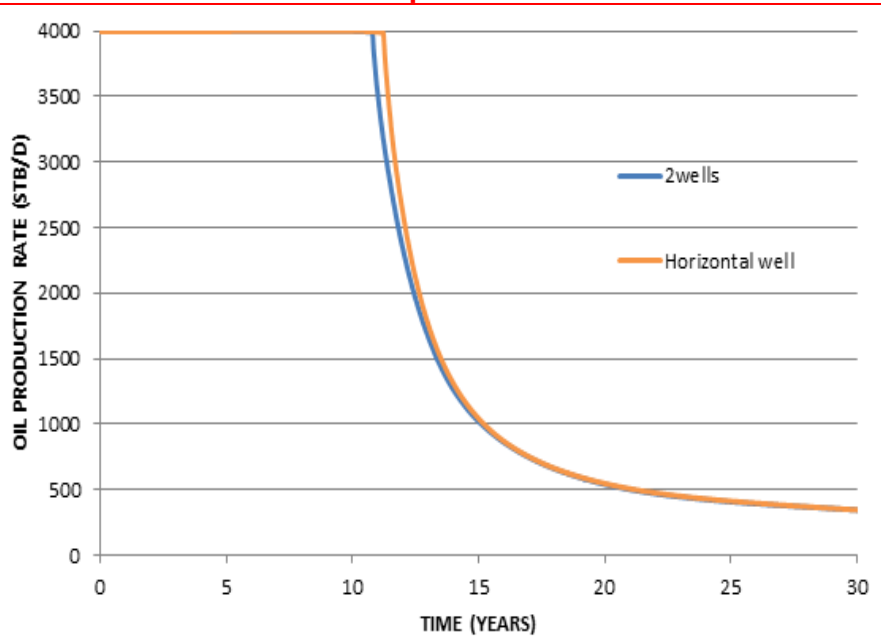


# Reservoir Model

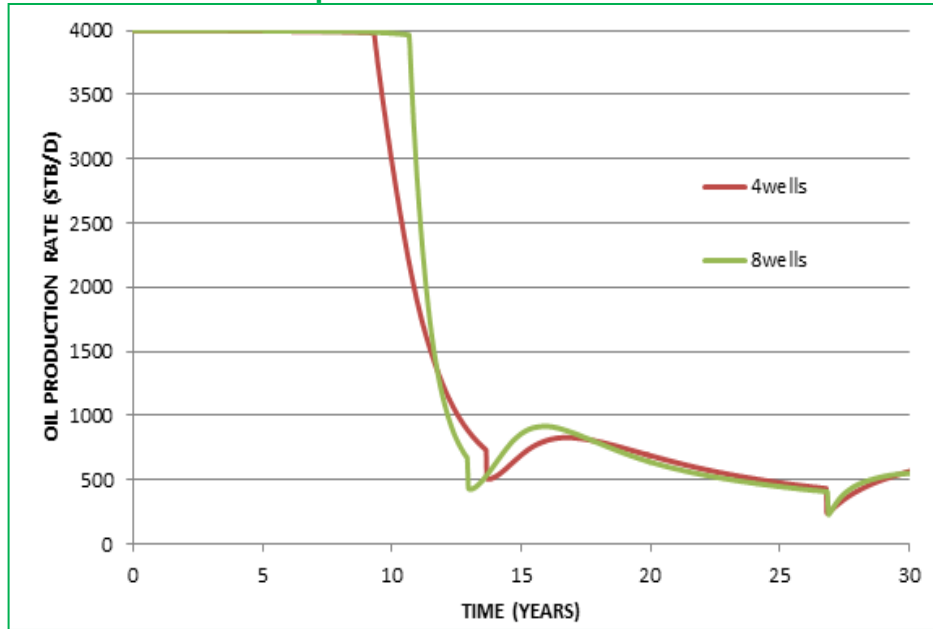
# Results of well pattern

- Production profile for dip angle of 15 degrees

Well pattern 1 and 2



Well pattern 3 and 4



- Oil production decline faster in well pattern 3 and 4 due to gas production at early time
- The deeper location of producer, the longer plateau period and the later gas breaks through

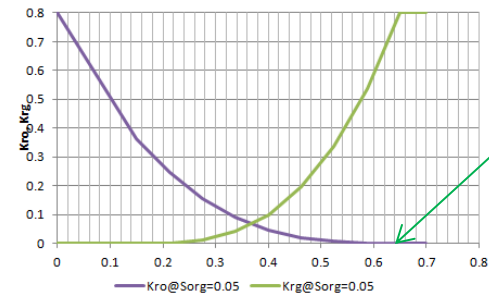
# Effect of relative permeability to oil and gas

- Residual oil saturation ( $S_{org}$ ) is used as a study parameter to determine the effect of different relative permeability to oil and gas
- Three values of  $S_{org}$  are used : 0.05, 0.10, 0.15

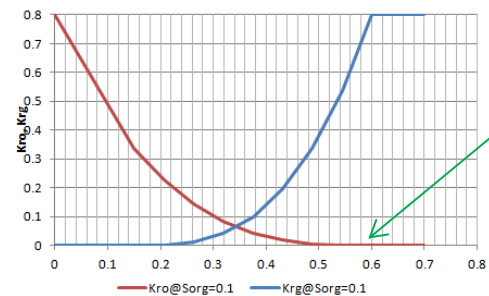
From Corey Correlation in oil-gas system

$$k_{ro} = \left( \frac{S_g - S_{wi} - \underline{S_{org}}}{1 - S_{wi} - \underline{S_{org}}} \right)^{N_o}$$

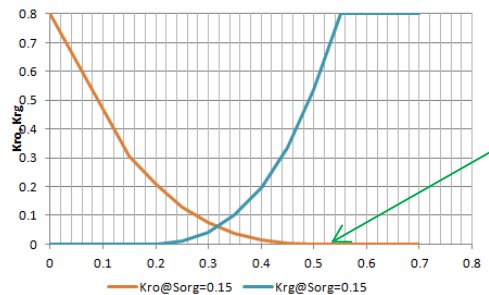
$$k_{rg} = \left( \frac{S_g - S_{gc}}{1 - S_{wi} - \underline{S_{org}} - S_{gc}} \right)^{N_g}$$



$S_{org} = 0.05$



$S_{org} = 0.10$



$S_{org} = 0.15$

# Effect of oil production and gas injection rate

- For dip angle of 60 degrees

CASE	Oil production rate (STB/D)	Gas injection rate (MSCF/D)	At 30 years			
				RF (%)		BOE (MMSTB)
1		3700		64.57		24.57
2	3000	4900		67.51		25.50
3		6500		67.93		25.48
4	4000	4900		64.05		24.25
5		6500		66.77		25.10
6		8500		67.32		25.11

- **Increasing injection rate** provides **higher oil recovery**
- Once injection rate is limited by fracture pressure, increasing gas injection rate results in slight increase in oil recovery

**Case 2** is the most appropriate design parameter for 60-degree dip angle