# Integrated Halo Model And Hydrodynamic Simulation For Optimization Oil Production In Crystalline Fractured Reservoirs

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# Abstract

Basement formation is known as the unique reservoir in the world. The fractured basement reservoir was contributed a large amount of oil and gas for Vietnam petroleum industry. However, the geological modelling and optimization of oil production is still a challenge for fractured basement reservoirs. Thus, this study aims to introduce the efficient workflow construction reservoir models for proposing the field development plan in a fractured crystalline reservoir. First, the Halo method was adapted for building the petrophysical model. Then, Drill stem history matching is conducted for adjusting the simulation results and pressure measurement. Next, the history-matched models are used to conduct the simulation scenarios to predict future reservoir performance. The possible potential design has four producers and three injectors in the fracture reservoir system. The field prediction results indicate that this scenario increases approximately 8 % oil recovery factor compared to the natural depletion production. This finding suggests that a suitable field development plan is necessary to improve sweep efficiency in the fractured oil formation. The critical contribution of this research is the proposed modelling and simulation with less data for the field development plan in fractured crystalline reservoir. This research's modelling and simulation findings provide a new solution for optimizing oil production that can be applied in Vietnam and other reservoirs in the world.


# Highlights

- The novel approach for granite basement modelling and reservoir simulation
- Halo method could solve the limitation for grantie fratctured modelling
- Drill stem matching is necessary for fractured modelling

# Introduction

Crystalline basement fractured reservoirs (CBFRs) are known as matrix rocks with fractures and act as fluid storage (Dang et al. 2011). Therefore, fractures play a crucial role in CBFRs. To understand the fracture characterization, the analog outcrop and subsurface data such as seismic, well logs, Drill stem test, coring data are obtained and analyzed. Then, a petrophysical model is constructed to estimate the distribution of them for the whole reservoir (Nguyen et al. 2011).

However, the geological modelling of CBFRs cannot be processed as conventional sandstone reservoirs. The fracture system is difficult to distribute in 3D model. The Halo model was adapted for solving the problem about fracture distribution in the basement reservoir to address this issue. The structural halo model is a mainly based modeling approach that uses seismically imaged faults and top surface reservoir for distributing a porosity network (Darmadi et al. 2013). It is a simple but powerful application to characterize a discrete fracture network model without complex geostatistical modelling (Guttormsen, 2008). The advantage of the Halo model is suitable for our study.

Moreover, the challenge of oil production in CBFRs is the big issue to prevent these reservoirs from being explored and produced more efficiently. The CBFRs have fractures and faults in different forms to affect fluid flow (Nguyen et al. 2011). Therefore, the simulation process is necessary for understanding reservoir behavior in CBFRs.

Recently, Zuo et al. (2019) proposed the using method for fracture detection to numerical simulation in synthetic and outcrop models. These scholars considered the semi-analytical model and Embedded Discrete Fracture Model (EDFM) to conduct the reservoir simulation model. Later, Yang (2020) was used a horizontal well system and EDFM for development fractured reservoirs. These authors stated that the geometry of fractures has a strong influence on pressure and saturation profile. Several studies proposed the useful for pressure and rate transient analysis (Dejam et al. 2018; Xing et al. 2018). In reservoir characterization,researchers around the world was used seismic and well log information for better understand the fractured granite reservoir (Basin et al. 2018; Bawazer et al. 2018; Bonter and Trice 2021; Glaas et al. 2021). Many works develop and offer an efficient modelling workflow for fractured reservoirs (Vo Thanh et al. 2019; Shiqian et al. 2020; Zhang et al. 2021). For detail, Vo Thanh et al. (2019) was used Artificial Neural network and geostatistical for $CO_2$ storage in a fractured basement in offshore Vietnam.

Regarding the history matching aspect, Li et al.(2021) was proposed the efficient history matching procedure for well spacing optimization in natural fractured reservoir. Similarly, Awad et al. (2020) conducted the history maching process for a fractured reservoir in Iraq.

However, the field development plan is the critical issue for fractured reservoirs because this process would decide the strategy for oil production in reservoir. The field development plan is popular in sandstone and carbonate reservoirs. Therefore, many researchers already proposed a field development plan for optimization hydrocarbon production (Babadagli 2007; Yang et al. 2017; Al-Mudhafar et al. 2018; Ayoub et al. 2018; Izadmehr et al. 2018; Mudhafar et al. 2019; Oludele et al. 2019; Dada et al. 2021; Sales et al. 2021). These studies was conducted in conventional reservoirs. However, a field development plan for crystalline fractured basement reservoir has less study to focus on this special reservoir. Thus, our work proposed the proper method by integrating the halo model for geological model construction and developing the field production for fractured crystalline reservoirs in offshore Vietnam.

Firstly, geological background is proposed for introduction the study area. Then, data and methodology are described in detail. Next, halo model was used for porosity and permeability distribution in fracture system. Then, the Drill stem test history matching process is performed to verify the hydrodynamic model using bottom hole pressure measurement. The reservoir history matched model is utilized for the field development plan by conducting hydrodynamic simulation scenarios such as well placement, gas lift rate, water injection, field production rate, tubing head pressure. The suitable design is proposed by oil recovery performance. Figure 1 illustrates the schematic of this study.

The main different between this study and previous work is the integrated halo method for construction petrophysical model. Also, our study proposed an efficiently process for improving oil production in fractured basement reservoir. The manual history matching process could be achieved by reduction permeability.  Due to simple and easily applied in this research, the proposed study could be adopted other crystalline basement reservoir in offshore Vietnam or other basin in the world.

# Geological Background

The Cuu Long basin is an Early Tertiary rift basin located off the southeast coast of Vietnam. The covers an area of approximately 150,000 $km^2$(Vo Thanh et al. 2019). The regional structural features of the basin by Eocene-Oligocene time can be subdivided into four main structural elements as follows (Hung and Le 2004; Vo Thanh et al. 2020): northern Cuu Long Subbasin, southwest Cuu Long (or West Bach Ho) subbasin, southeast Cuu Long (or East Bach Ho) Subbasin and Rong-Bach Ho (or Central) High. In the offshore Vietnam, the fractured basement reservoirs are deposited under the unconformities and on the highs of uplifted blocks that were weathering and crystalline. These fractured basement reservoirs were located below by younger sequences that played an essential role for source rocks and cap rocks (Dang et al. 2011).

In addition, Nguyen et al. (2008) found that the pore structure of the fractured crystalline reservoir in offshore Vietnam had the  high heterogeneity and complexity. Those pores resulted from various processes such as heat shrinkage and expansion of magmatic bodies, tectonic movements, hydrothermal impacts, and weathering. The porosity range from 2% to 5% represents a good reservoir quality. In Le et al. (2008), the porosity of the Dragon oil field was distributed from 0.22% to 15.04%, average 2.87%, which was obtained by core data analysis (Dang et al. 2011).

Also, the fractured basement reservoir in Cuu Long Basin is defined as fractured reservoir type C because fractures, faults and vugs system contributed to the porosity distribution. It is recognized as empty pores in the reservoirmatrix (Dang et al. 2011). The  location of study area is illustrated in **Figure 2**.

# Data And Method

This study used well log and seismic data from a fractured granite basement reservoir in Cuu Long Basin, offshore Vietnam. Firstly, three exploration wells have wireline logs, markers, cores, Drill stem test (DST), and petrophysical interpretation. Secondly, the seismic input data consists of structural depth maps fault sticks from seismic interpretation results. The fault system was used for structural construction model. Then, the petrophysical information was used to distribute in 3D geological model. Then, the Initial oil in place (OIIP) was calculated for fractured reservoirs. Next, the DST was used for history matching hydrodynamic model. Then, the history matching model was adapted to conduct the simulation scenarios for optimization of oil production in crystalline basement reservoirs. The flowchart of this study was exhibited in Figure 3.

### 3.1.1 Petrophysical Modelling method

The modelling approach is used Halo model for this study. For detail, the halo model is a structural modeling method that utilizes fault and top of fractured reservoir to determine a porosity network distribution. Also, this is a useful method to characterize a discrete fracture network system. The Halo model has not used complex geostatistical techniques for distributecture elements in fractured crystalline systsystems .A fault in the halo model is recognized as a stress-releasing fracture around fault because of tectonic induced deformation (Darmadi et al. 2013). The Halo Model is a recent methodology of crystalline basement modeling that better describes the reality of basement rock (Figure 4). In this model, porosity is distributed along with fault systems as a result of fault-associated fractures. Porosity at the fault location is considered the maximum porosity due to the greatest damage (strongest stress). These values decrease laterally with distance away from the fault plane and vertically with depth from the top of the basement. The calculation of porosity Halo model is following equation:

$$Lateral\_Porosity\_Distribution(LPD) = 10^{(-2.3*Rel.DistancetoFault/MaxDistancetoFault)} \quad (1)$$

$$Vertical\_Porosity\_Distribution(VPD) = Porosity\_Max\left(1 - a*\ln(Depth)\right) \quad (2)$$

$$Final\_Porosity = LPD*VPD*Porosity\_Max \quad (3)$$

Where a in equation (2) is the factor that obtain from porosity and depth relationship in the target reservoirs. This relation is expressed as followed:

$$\mathrm{Depth} = \mathrm{a.e}^{\mathrm{b.Porosity}} \quad (4)$$

The Depth stands for the distance from top of basemen. Also, a and b is are constant factor from the equation. In addition, we need to distribute the permeability in 3D model for dynamic simulation. Due to the limitation of this research, the permeability modelling was used the following equation(O.Jones 1975):

$$Permeability = Permeability\_\max*\left(\frac{Porosity}{Porosity\_\max}\right)^3 \quad (5)$$

## 3.2 Hydrodynamic simulation

Until now, one exploration well, BM-1X, and two appraisal wells, BM-2X, BM-3X have been drilled in the study area. The available reservoir engineering well data for crystalline basement reservoirs, including DST and PVT from all exploration, appraisal wells, are summarized in Table1. Data from these wells has been incorporated into the OIIP and Reserves estimation for the target reservoir.

Table 1. The information of PVT and DST for simulation study

| Reservoir | Data type | Exploration/ Appraisal Wells | | |
|---|---|---|---|---|
| | | BM-1X | BM-2X | BM-3X |
| Crystalline Basement | DST | DST#1 | DST#1 | DST#1 |
| | PVT | No | Surface Samples | Bottom Hole and Surface Samples |

# 3.2.1 PVT data

The PVT data used for the simulation model were generated from the PVT analysis results conducted at the Vietnam Petroleum Institute (VPI) for all the appraisal wells penetrating the crystalline reservoir. Figure 5 summarizes the critical PVT parameters such as Formation Volume Factor, Oil and Gas Viscosity, Solution Oil Gas Ratio used in the simulation model.

### 3.2.2. Oil Properties

During DST operations, surface samples from the crystalline fractured basement reservoir were taken and analyzed using traditional PVT analysis. The critical properties acquired, including bubble point (Pb) pressure, gas-oil ratio, formation volume factor, oil viscosity, and produced oil gravity, are listed below in Table 2.

Table 2. Fractured Basement Reservoir PVT Properties

| Properties | TL-2X - DST#1 |
|---|---|
| Gravity (API 60$^{o}$F) | 24.5 |
| Pb (psia) | 1,130 |
| Rs (scf/stb) | 183 |
| FVF @ Pres (rb/stb) | 1.128 |
| Viscosity @ Pb (cp) | 6.924 |

# 3.2.3. Rock-Fluid Properties

The oil-water permeability tables used in the simulation were obtained from spcecial core analysis from White Tiger filed in  Cuu Long basin. The relative permeability data is presented in figure 6.

Also, the initial residual water saturation ( $S_{wir}$,) was set at 15% as reference to White Tiger oil fields. Also, the fractures in the system have a huge equivalent radius comparing to the pore throats of inter-granular rocks. Thus, the capillary pressure in fractures must be highly smaller than that in inter-granular rock pore throats. Also, considering the sizeable vertical thickness of the basement reservoir, it is reasonable to assume the gravity effect to dominate the reservoir performance and capillary force to be negligible. Thus, the capillary pressure was neglected in this reservoir simulation study.

#### 3.2.4. Hydrodynamic simulation

The hydrodynamic simulation model of Eclipse Black oil (E100) was used for this study. Firstly, the history matching of reservoir model was used DST data for pressure matching in two wells (TL-2X, TL-3X). The DST history matching model was used for future prediction to optimize oil production in crystalline basement reservoirs. Then, the multiple simulation scenarios will be conducted to propose a reasonable strategy for reservoir monitoring. The criteria for the selected design is provided the high oil recovery for optimizing field development plan.

The field development plan is the crucial step for improving oil recovery in the hydrocarbon field. Thus, this study would present an interesting workflow for a static geological model to optimize oil production in a fractured crystalline reservoir.

The detail of possible scenario for improving oil production in fractured crystalline reservoir is elaborated as follows:

- **Scenario 1:** Sensitivity analysis on injection and production well locations considering aquifer support and no aquifer support.
- **Scenario 2:** The gas lift application might have some effects on improving oil production
- **Scenario 3:** The water injection is implemented for reservoir pressure management and enhancing oil production
- **Scenario 4:** The field production rate analysis is also considered for optimization oil production in the reservoir
- **Scenario 5:** Analysis the tubing head pressure is affected on oil production rate performance for crystalline basement reservoir.

## Result And Discussion

# 5.1 Geological modelling results

Similar to other crystalline basement reservoirs, most of the pore volume exists within fractures, while the fracture distribution is entirely related to the existence of visible lineaments, as interpreted from seismic data.

Porosity distribution in this study was based on the Halo concept. The reservoir properties are known to decay with distance away from the fault and also with increasing depth. Therefore, high porosity values are observed in the upper zone of the basement and along fault planes. Also, in the vertical direction, porosity decreases as the distance from the top of the basement increases. This parameter is designated as vertical porosity. The vertical porosity versus depth represented by minimum, most likely, and maximum curves are presented in Table 3 and Figure 7. Based on this information, the final porosity of crystalline basement reservoirs was exhibited in Figure 8.

Table 3. The relationship between depth and porosity

| Case | The functions of porosity according to the Distance from top of basement |
|---|---|
| Max | $Depth = 28141.40e^{-113.83Poro}$ |
| Most Likely | $Depth = 13441.19e^{-135.80Poro}$ |
| Min | $Depth = 4118.71e^{-166.47Poro}$ |

Regarding the permeability models, based on relationship between the porosity and permeability on equation (5). From the DST data and porosity calculation, the porosity ($\Phi_{max}$ ) and permeability ($K_{max}$) maximum were estimated as follows: $K_{max}$ = 1000 mD and $\Phi_{max}$= 7%. Figures 9 illustrate the horizontal permeability distribution of the crystalline basement structure.

The porosity and permeability of this research has only 556,776 cells with 195,251 active cells, which is small enough to be used in the dynamic model, thus, no upscaling was required.

# 5.2 Hydrodynamic simulation models

## 5.2.1 DST matching

The initial model (before any modifications) shows quite optimistic results for both DSTs in TL-2X and TL-3X when performing DST matching. They should have resulted from very high permeability in the fracture system. Thus, a global permeability reduction was applied to get a better downhole pressure matching. While performing permeability reduction, the bottom-hole pressure behavior in TL-3X was much better than in TL-2X. It suggests that those two wells belong to different zones. Figure 10 present the visualization about permeability reduction for this study. A good match was acquired after multiply the TL-3X zone’s permeability by a factor of 0.2 and TL-2X zone’s permeability by a factor of 0.07.  Figure 11 shows the bottom-hole pressure matching results for both TL-2X and TL-3X. It is indicated the excellent performance matching between simulated and measurement data. Thus, the history matched model could be used for investigating the oil production performance in this research.

### 5.2.2 Field Development Plan based simulation scenarios

The DST pressure matched reservoir simulation model was used to determine production and injection well locations, investigate the impact of an aquifer, and the effect of water injection and gas lift on field performance and its ultimate recovery for a fractured crystalline reservoir. All of the scenarios would be conducted in 30 years oil production life-cycle of the oil field.

#### 5.2.2.1 Scenario 1: Well placement for injection and production considering aquifer support

Based on fractures distribution, 07 producer and 06 injector candidates were introduced. Several simulation runs were made to find the optimum locations and number of wells for development. The first step was to determine the optimum producer locations assuming 4 producers (P) (out of 7 candidates) and 3 injectors (which were 1I, 2I, and 3I). Next, sensitivity runs were made for both scenarios: with and without flank aquifer.  Using aquifer size of 10 times, OIIP is prevalent practice for basement simulation models in other nearby fields, which was also used in this model. Additional assumptions for these runs were Tubing Head Pressure (THP) of 250 psia, gas-lift rate of 3MMSCFD/Well, and field production rate was capped at 12,000 STB/D.

Figure 12 illustrates the location of well producers and injectors for simulation scenario 1. This scenario will be investigated total 8 cases for well location of producers and injectors.

Figure 13 illustrate the field production performance by varying the well placement for producers and injectors for aquifer and no aquifer support. It can easily be observed that the case Case 1 & Case 1A achieving the best recovery factor for either with or without aquifer support (Figure 13a and Figure 13b). The 4 producers (1P, 2P, 3P, and 4P) were then used in the sensitivity runs to find the optimum locations for injectors. 3 out of 6 injector candidates were picked to run in both with and without aquifer scenarios. The injected volume was set as such the voidage equals to one. All other control points are the same as the above cases. The well location injector sensitivity indicated that the case (1I, 2I, and 3I) has excellent performance in field production total and oil recovery (Figure 13c and Figure 13d). Overall, the well producers (1P, 2P, 3P, and 4P) and injector (1I, 2I, and 3I) with aquifer support will give the highest oil production for the target crystalline fractured basement reservoirs

#### 5.2.2.2 Scenario 2: considering gas lift application for improving oil production performance

Several simulations run with different GasLift rates to investigate the impact of gas lift on field performance for the case while no aquifer support existed. Case 4 used an injection rate with 4 MMSCFD that shows the highest result. However, the improvement is not significant for an additional 1MMSCFD to the base case (Case 1). Thus, a base case is still recommended for our simulation study. This work was investigated the gas lift rate for simulation study purposes. However, the gas lift operation is strongly dependent on well process. Also, the well model would be a better illustration of gas lift. The simulation study provides the possible option for a field development plan in fractured crystalline reservoirs. The simulation study for gas lift application is illustrated in Figure

#### 5.2.2.3 Scenario 3: water injection effect

In order to make sure that water injection plays a vital role in-field performance, the two base cases were set to run without water injection. The simulation results clearly show that the recovery factor is reduced drastically when no water injection is applied. The simulation results are exhibited in Figure 15. This result is indicated the critical water flooding on oil field development in fractured crystalline reservoirs. The water injection will support maintaining reservoir pressure to accelerate oil production. Also, the water injection provides the waterfront sweeps the oil towards the production well.

Besides that, the water injection time and water volume injection were investigated in this work. The simulation results advise that the beginning water injection application is the best solution for oil production crystalline basement reservoirs. The later water injection would decrease the oil recovery efficiency. It is clear indicated in Figure 16a. In addition, the voidage injection was also the critical factor in the water-flooding operation. In this work, the voidage injection volume increased to lead to improving the oil recovery factor. Figure 16b is the evidence for our finding. However, the voidage injection volume is dependent on the reservoir connectivity and characterization of the specific field. Thus, this parameter should be carefully considered for the field development plan in a case by case.

#### 5.2.2.3 Scenario 4: production rates

The next study is to look at the effect of changing plateau rate. Production constraints were set at 10,000 and 14,000 STBD then compared to Case 1. The plateau is more extended when the rate is reduced and shorter as the rate increases, as expected. Not much different in EUR is observed for production rates constraints. This scenario found that the field production rate does not affect field production development plans in crystalline basement reservoirs. The simulation results are clear illustration in Figure 17. However, the field production rate is not a strong influence in the simulation investigation for this work. However, the field production rate might be carefully for specific well operation in each field, especially the field with complex reservoirs such as crystalline basement reservoirs.

#### 5.2.2.3 Scenario 4: Tubing head pressure

Sensitivity runs were made to see the impact of tubing head pressure (THP) on production. Same assumptions as in Case 1 were used, except the variation of THP. A little change in the recovery factor is observed when the THP increased to 430 psia as less drawdown in the well. Thus, THP should be carefully considered for field development in crystalline fractured basement reservoir. The simulation results was a highlight in figure 18.  Tubing head pressure is considered for simulation study because it can monitor for field operation. The well operator could be followed the guideline from the field development plan. On the other hand, the practical operation might be changed to the specific situation. However, the simulation study supports smoothing the well process that is our objective to conduct investigation tubing head pressure.

# Comparative analysis

To verify the crucial and feasibility of the workflow proposed in this research, a comparative analysis of the simulation results was also conducted and highlighted in Table 4. The simulation results of this research are compared by crystalline basement reservoir in Cuu Long basin, namely i) X field which have been successfully explored and optimization oil production, recently in Viet Nam (Ba et al. 2019). In our work, the simulation scenarios consider less wells than previous study. The main contribution of this study is novel approach of Halo model for geological modellng to get sucessul DST matching for future development plan. Also, this study did not use the long production history but our effort is better than previous work by proposing the comprehensive plan for oil production in granite basement reservoir. In the other hand, the detail of comparison is exhibited in Table 4.

Table 4. Comparison this work and previous study

| Oil Field | Field development method | Oil Recovery improvement |
|---|---|---|
| X field | 10 producers 4 injector | 10-13% |
| This study | 4 producers 4 injectors | 10-24% |

This comparison indicates that our method has an improvement than previous study. The Halo method is one of the key factor for our research. The geological models consider the fracture length for distribution porosity and permeability in granite basement reservoir in this study.

# Conclusions

This study proposed the new approach for integrated halo model and hydrodynamic simulation for improving oil production in the crystalline fractured basement reservoirs. The key message could be delivered as following:

- The Halo method is useful for construction the geological model in crystalline basement reservoirs. This method could be used in the construction fractured basement model with limitation data. This idea is very useful for current situation of oil and gas industry with low oil price.
- The DST matching plays an important for verification the geological model in the early stage exploration and production of fractured basement reservoirs
- This study was used DST matching for proposing the field development plan.

- The total oil recovery with natural depletion is ranges from 10–24%. Also, the production with support pressure from water injection or aquifer could increase the oil recovery from 18–36%
- Water injection (volume and timing) depends on reservoir connectivity and aquifer sizes. Also, Water injection is supported for maintaining reservoir pressure to improve oil production in target reservoir.
- The recovery in fractured crystalline basement is function of:

  OIIP or Movable oil
  Additional energy support
  Connectivity between injectors and producers
  Connectivity between reservoir and aquifer
  volume of aquifer
  Production wells with multiple fracture
  Production constrained as THP, Gaslift application, Volume of injected water
- The reservoir model should be updated frequently with new data to improve the technical solution.
- The geological model should update whenever the fracture data is available
- The proposed modelling method could be used in the early stage exploration and production hydrocarbon in crystalline fractured basement reservoir.

# Declarations

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**Conflicts of interest:**

The author declare no conflict of interest.

# References

1. Al-Mudhafar WJ, Rao DN, Srinivasan S (2018) Robust Optimization of Cyclic CO2 flooding through the Gas-Assisted Gravity Drainage process under geological uncertainties. J Pet Sci Eng 166:490–509. https://doi.org/10.1016/j.petrol.2018.03.044
2. Awad F, Jang A, Lee H et al (2020) Effect of fracture characteristics on history matching in the Qamchuqa reservoir: a case study from Iraq. Carbonates Evaporites 35:1–20. https://doi.org/10.1007/s13146-020-00607-3
3. Ayoub J, Llc JA, Gao S et al (2018) Optimization of Gas Lift Throughout the Well Lifecycle in Unconventional Reservoirs. In: Abu Dhabi International Petroleum Exhibition & Conference. Abu Dhabi, UAE

4. Ba NT, Thanh HV, Sugai Y et al (2019) Applying the hydrodynamic model to optimize the production for crystalline basement reservoir, X field, Cuu Long Basin, Vietnam. J Pet Explor Prod Technol. https://doi.org/10.1007/s13202-019-00755-w
5. Babadagli T (2007) Development of mature oil fields - A review. J Pet Sci Eng 57:221–246. https://doi.org/10.1016/j.petrol.2006.10.006
6. Basin Q, Ma F, Yang W et al (2018) Characterization of the reservoir-caprock of the large basement reservoir in the Dongping field,Qaidam Basin, China. Energy Explor Exploit 36:1498–1518. https://doi.org/10.1177/0144598718772317
7. Bawazer W, Id AL, Kinawy MM (2018) Characterization of a fractured basement reservoir using high-resolution 3D seismic and logging datasets: A case study of the Sab ' atayn Basin, Yemen. PLoS One
8. Bonter DA, Trice R (2021) An integrated approach for fractured basement characterization: the Lancaster Field, a case study in the UK. Pet Geosci 25:400–414
9. Dada MA, Mellal M, Makhloufi A (2021) A field development strategy for the joint optimization of flow allocations, well placements and well trajectories. Energy Explor Exploit 39:502–527. https://doi.org/10.1177/0144598720974425
10. Dang CTQ, Chen Z, Nguyen NTB, Bae W (2011) Improved Oil Recovery for Fractured Granite Basement Reservoirs: Historical Lessons, Successful Application, and Possibility for Improvement. In: SPE European Formation Damage Conference. The Netherlands
11. Darmadi Y, Harahap A, Achdiat R et al (2013) Reservoir Characterization of Fractured Basement Using Seismic Attributes, Dayung Field Case Study, South Sumatra Indonesia. In: Proceedings of the Indonesian Petroleum Association Thirty-Seventh Annual Convention and Exhibition
12. Dejam M, Hassanzadeh H, Chen Z (2018) Semi-analytical solution for pressure transient analysis of a hydraulically fractured vertical well in a bounded dual-porosity reservoir. J Hydrol 565:289–301. https://doi.org/10.1016/j.jhydrol.2018.08.020
13. Glaas C, Vidal J, Genter A (2021) Structural characterization of naturally fractured geothermal reservoirs in the central Upper Rhine Graben. J Struct Geol 148:104370. https://doi.org/10.1016/j.jsg.2021.104370
14. Hung N, Du, Le H Van (2004) Petroleum Geology of Cuu Long Basin - Offshore Vietnam. In: proceedings of AAPG International Conference. Barcelona, Spain, September 21–24
15. Izadmehr M, Daryasafar A, Bakhshi P et al (2018) Determining influence of different factors on production optimization by developing production scenarios. J Pet Explor Prod Technol 8:505–520. https://doi.org/10.1007/s13202-017-0351-1
16. Le HV, Pham BT (2008) oil reservoir management, control and regulation of production process in fractured basement reservoir of white tiger oil field. Practices and Experiences. The 2nd international conference-Petrovietnam 2008 (p. 203). Vung Tau: Science and Technics Publishing House
17. Li Q, Wu J, Chang C et al (2021) The Application of Integrated Assisted History Matching and Embedded Discrete Fracture Model Workflow for Well Spacing Optimization in Shale Gas Reservoirs with Complex Natural Fractures. Geofluids

18. Mudhafar WJ, Al, Rao DN, Srinivasan S (2019) Geological and production uncertainty assessments of the cyclic CO 2 – assisted gravity drainage EOR process: a case study from South Rumaila oil field. J Pet Explor Prod Technol 9:1457–1474. https://doi.org/10.1007/s13202-018-0542-4
19. Nguyen KT, Karoevich KA, Ogly KK, Le TD (2008) Regarding the problem of enhancing oil recovery for basement reservoir of the white tiger oil field. The 2nd international conference-Petrovietnam 2008 (p. 218). vung tau: Science and Technics Publishing House
20. Nguyen NT, Dang CTQ, Bae W (2011) Geological Characteristics and Integrated Development Plan for Giant Naturally Fractured Basement Reservoirs. In: Canadian Unconventional Resources Conference. Calgary, Alberta, Canada
21. O.Jones F (1975) A Laboratory Study of the Effects of Confining Pressure on Fracture Flow and Storage Capacity in Carbonate Rocks. 21–27
22. Oludele T, Iloka O, Yawale C (2019) Field developmental plan analysis: a case study of 'x' reservoir. J Pet Explor Prod Technol 9:2185–2203. https://doi.org/10.1007/s13202-019-0622-0
23. Sales L, Jäschke J, Stanko M (2021) Early field planning using optimisation and considering uncertainties Study case: Offshore deepwater field in Brazil. J Pet Sci Eng 207:109058. https://doi.org/10.1016/j.petrol.2021.109058
24. Shiqian X, Yuyao L, Yu Z et al (2020) A History Matching Framework to Characterize Fracture Network and Reservoir Properties in Tight Oil. J Energy Resour Technol 142:. https://doi.org/10.1115/1.4044767
25. Vo Thanh H, Sugai Y, Nguele R, Sasaki K (2019) Integrated work flow in 3D geological model construction for evaluation of CO 2 storage capacity of a fractured basement reservoir in Cuu Long Basin, Vietnam. Int J Greenh Gas Control 90:102826. https://doi.org/10.1016/j.ijggc.2019.102826
26. Vo Thanh H, Sugai Y, Sasaki K (2020) Impact of a new geological modelling method on the enhancement of the CO2 storage assessment of E sequence of Nam Vang field, offshore Vietnam. Energy Sources Part A Recover Util Environ Eff 42:1499–1512. https://doi.org/10.1080/15567036.2019.1604865
27. Xing C, Yin H, Liu K et al (2018) Well Test Analysis for Fractured and Vuggy Carbonate Reservoirs of Well Drilling in Large Scale Cave. Energies 11:. https://doi.org/10.3390/en11010080
28. Yang H, Kim J, Choe J (2017) Field development optimization in mature oil reservoirs using a hybrid algorithm. J Pet Sci Eng 156:41–50. https://doi.org/10.1016/j.petrol.2017.05.009
29. Yang Z, Wang Y, Zhang X et al (2020) Numerical Simulation of a Horizontal Well With Multi-Stage Oval Hydraulic Fractures in Tight Oil Reservoir Based on an Embedded Discrete Fracture Model. Front Energy Res 7:. https://doi.org/10.3389/fenrg.2020.601107
30. Zhang K, Zhang J, Ma X et al (2021) History Matching of Naturally Fractured Reservoirs Using a Deep Sparse Autoencoder. SPE J
31. Zuo L, Tan X, Yu W, Hu X (2019) Fracture Detection and Numerical Modeling for Fractured Reservoirs. Energies 1–15. https://doi.org/10.3390/en12030386

# Figures

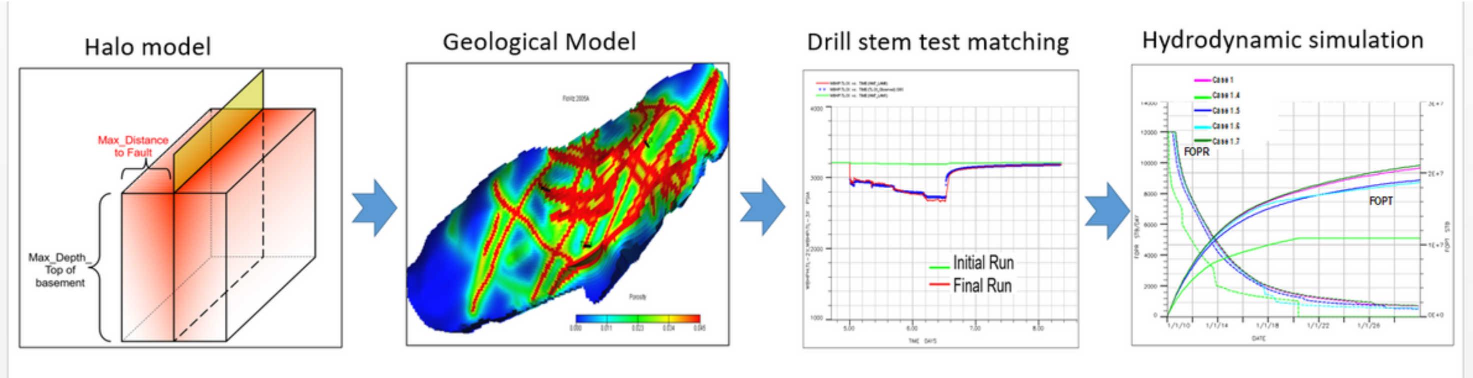



**Figure 1**

The schematic of general workflow in this work


**Figure 2**

Location of study area

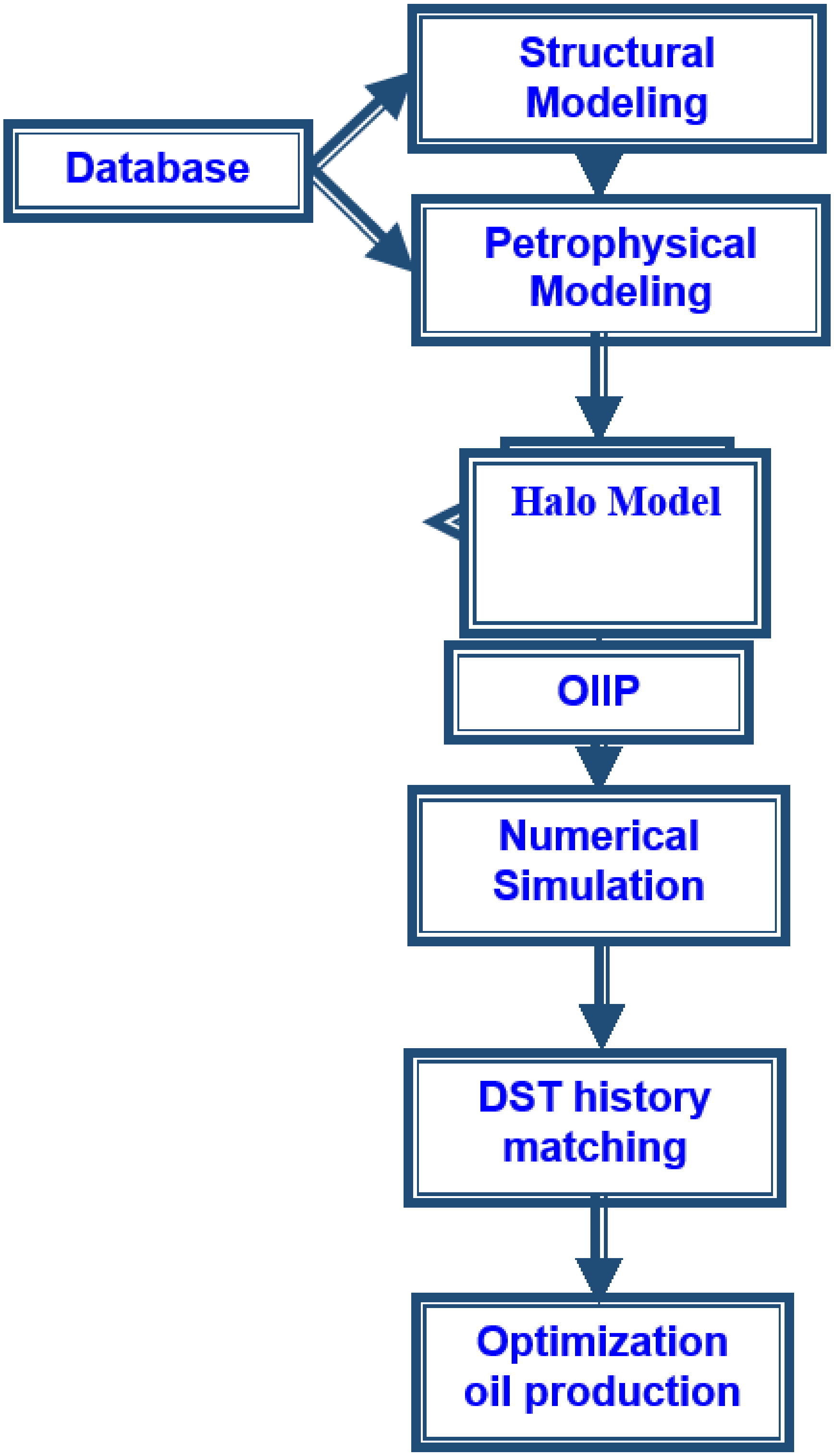



**Figure 3**

The flowchart of this work

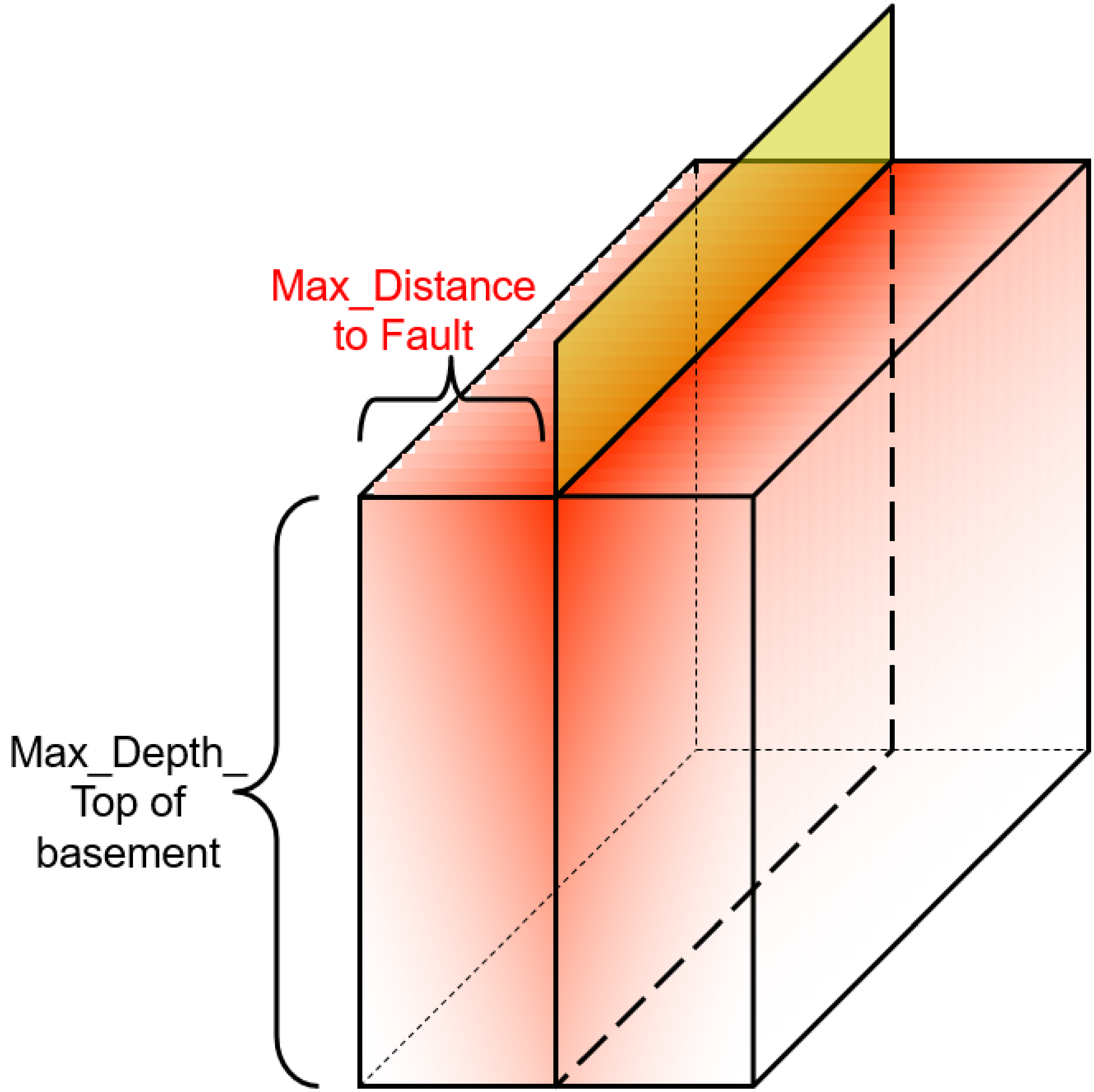
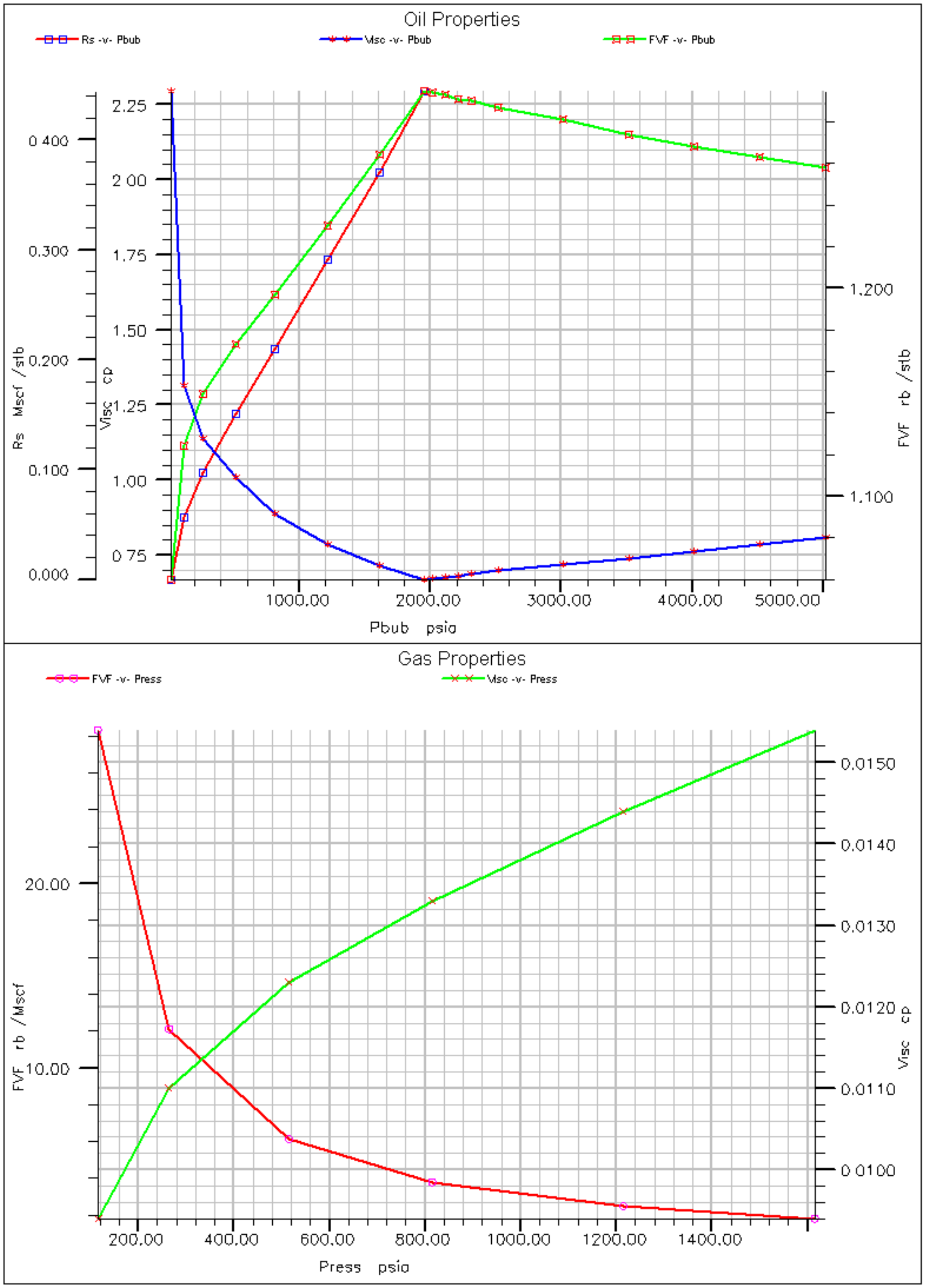


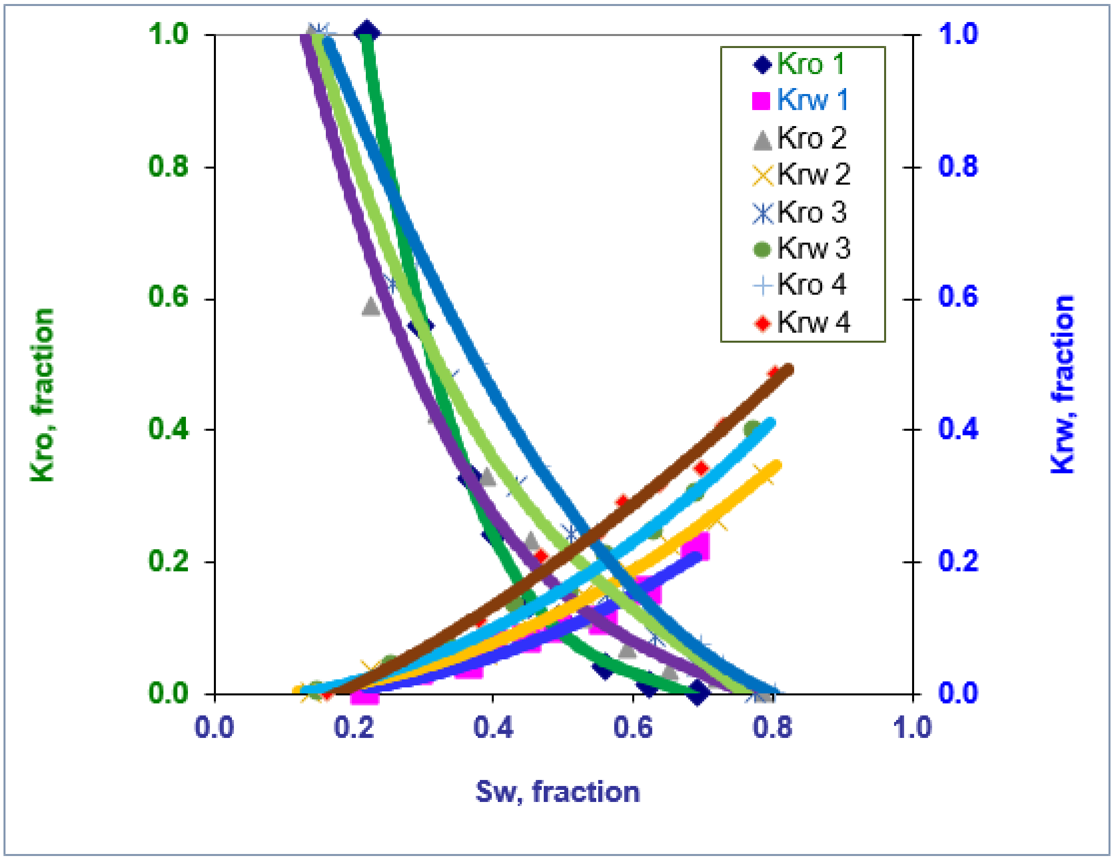

**Figure 4**

Schematic for principal of Halo method



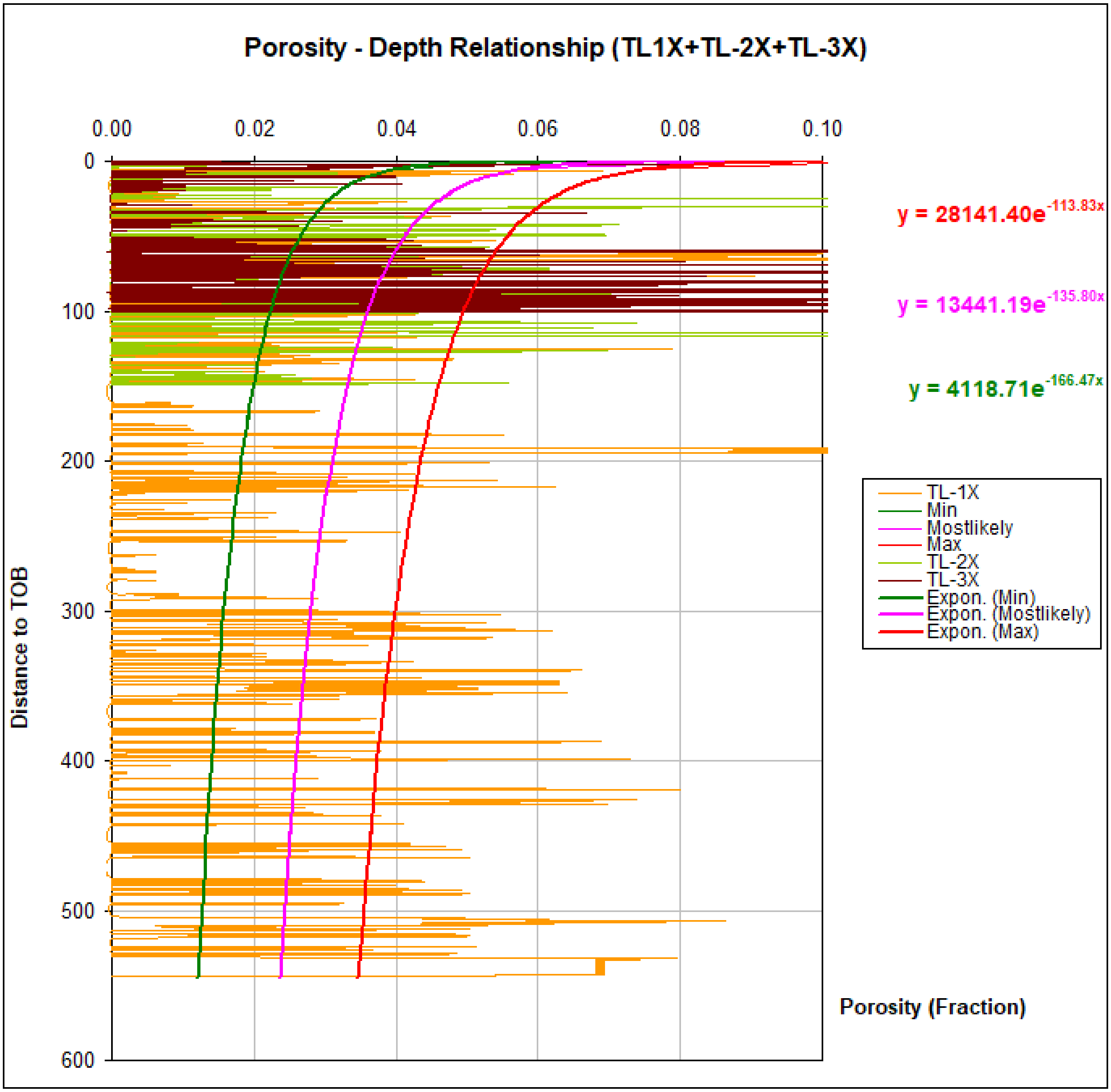

## Figure 5

The oil (top) and gas (bottom) properties for simulation study




## Figure 6

Relative permeability curves for this research




## Figure 7

Vertical porosity distribution in Halo model

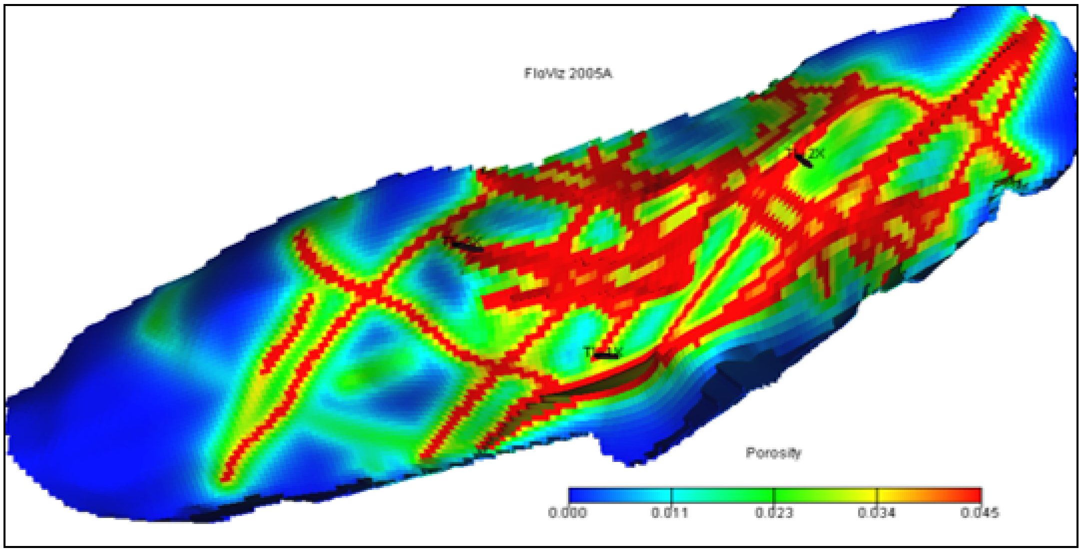



**Figure 8**

Porosity distribution for crystalline fractured reservoirs

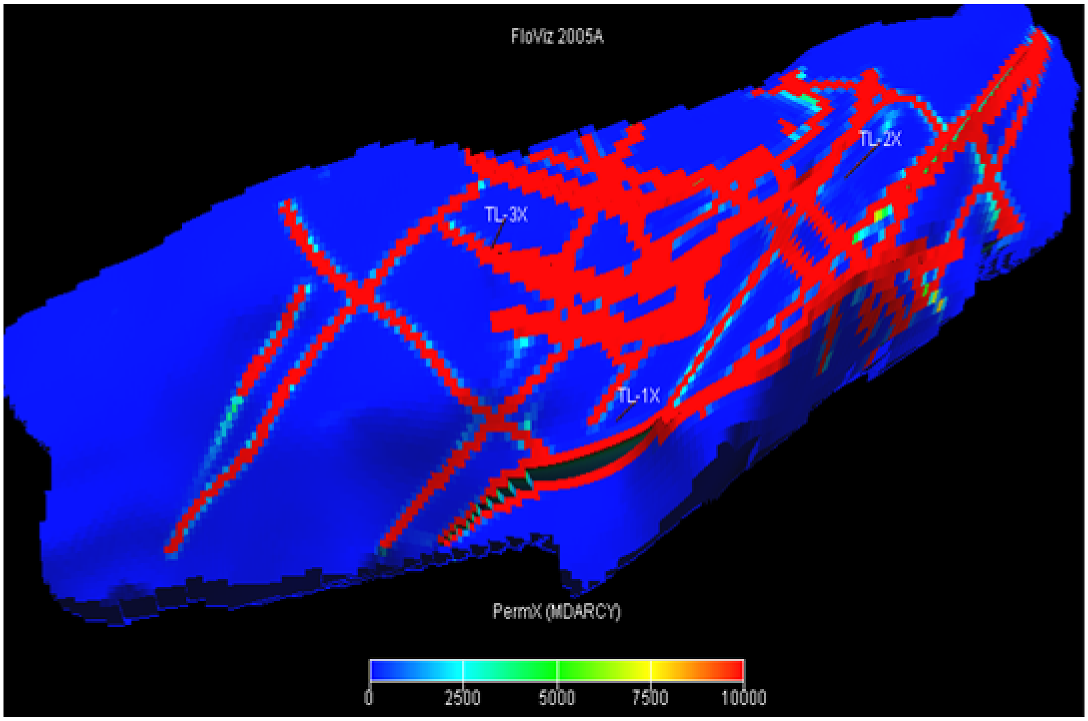



**Figure 9**

Permeability distribution for this study

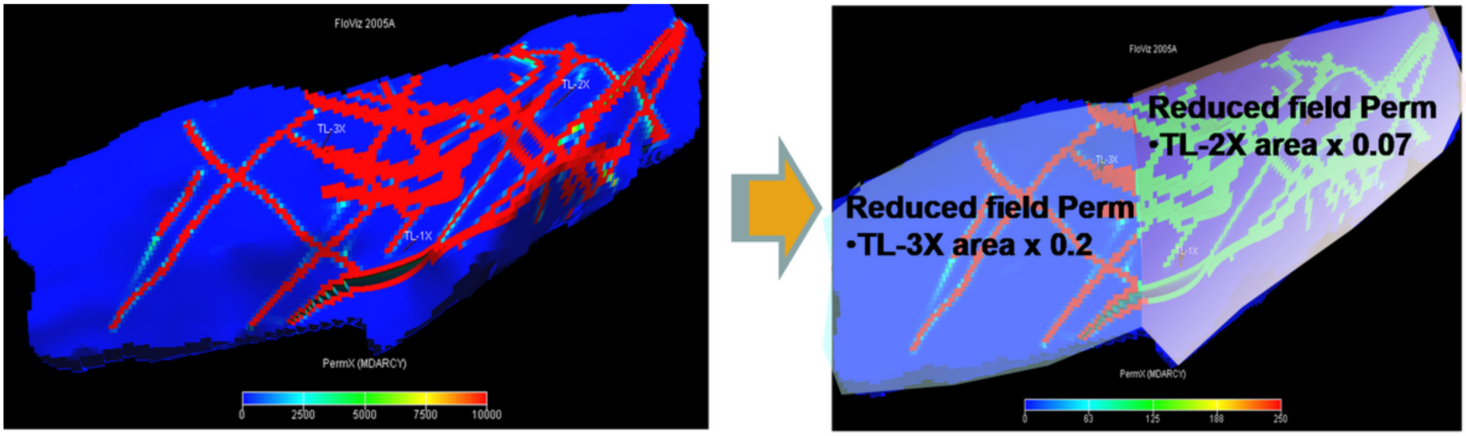
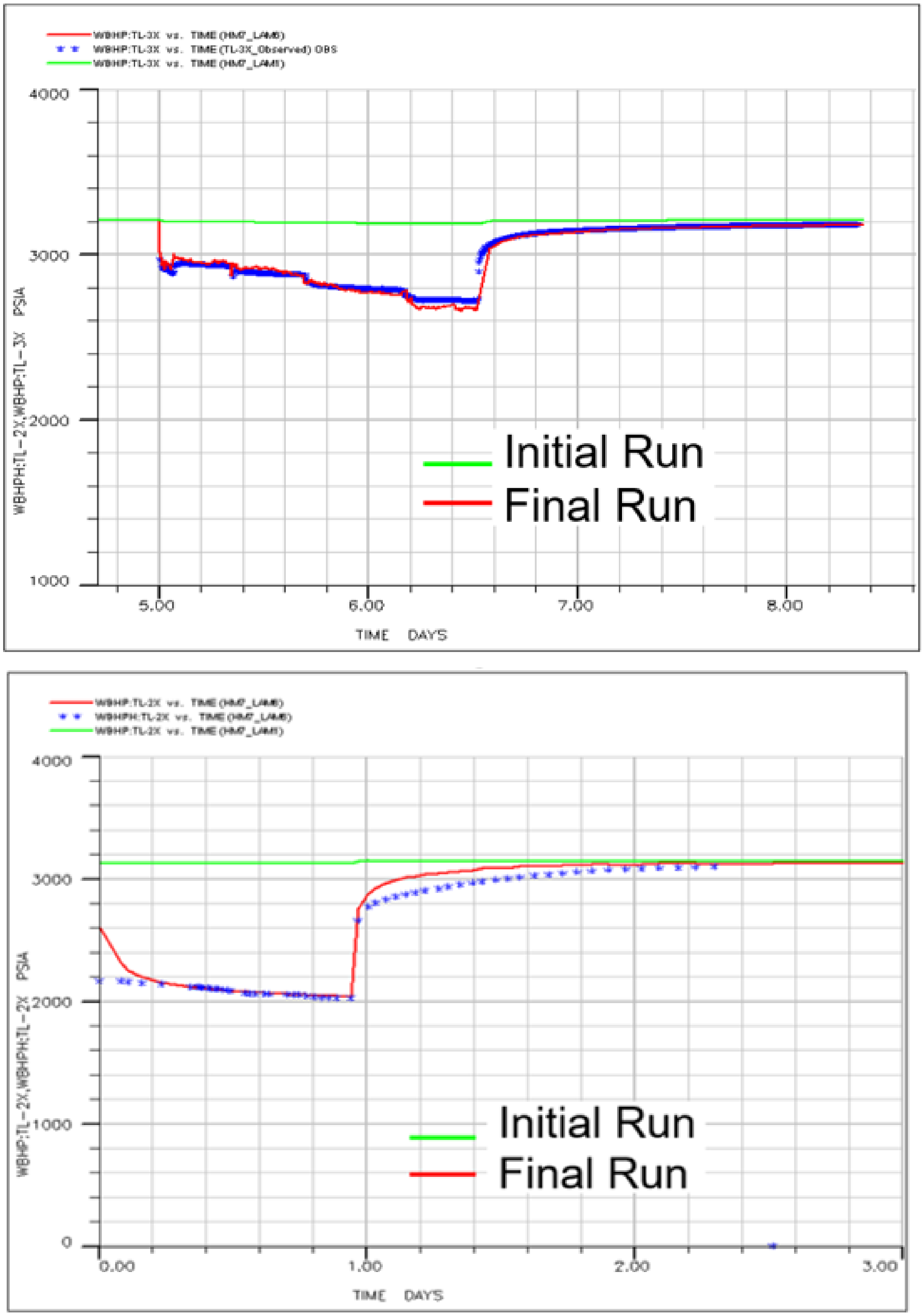



**Figure 10**

Permeability reduction for DST matching process




## Figure 11

DST matching for two wells in this work

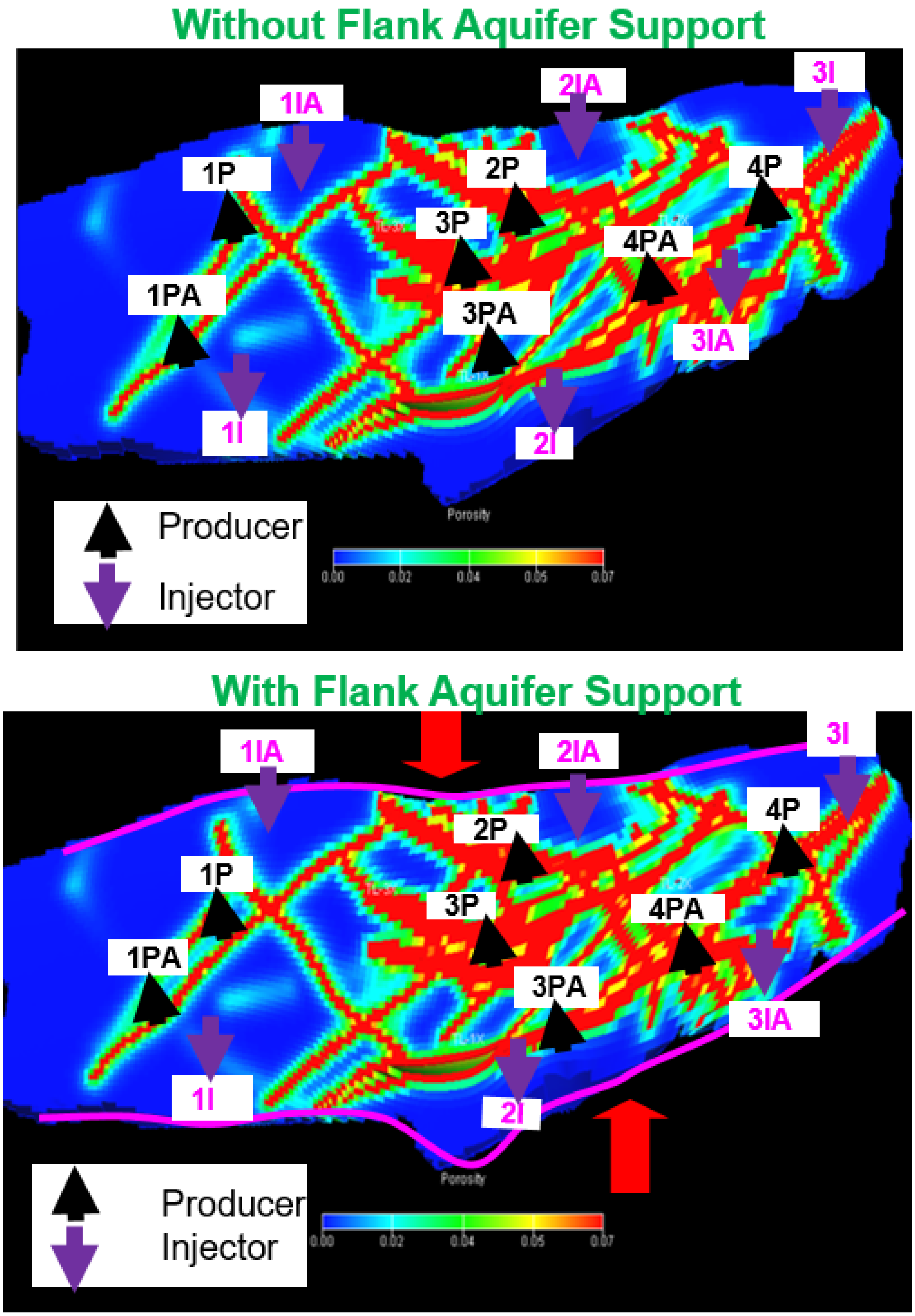
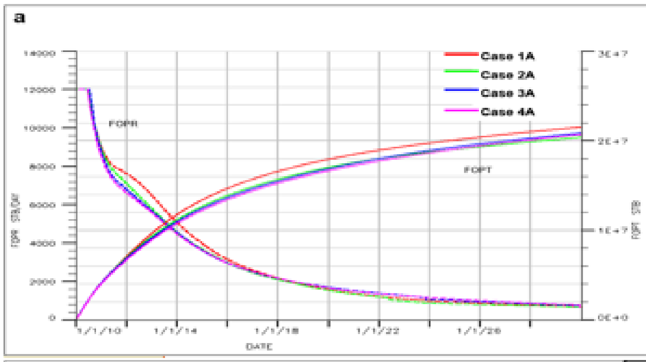


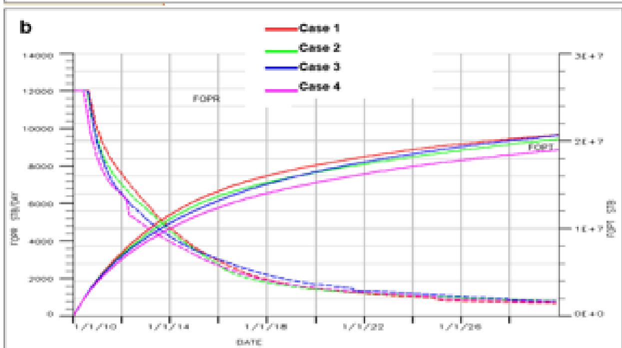

**Figure 12**

Well location demonstration for producers and injectors a



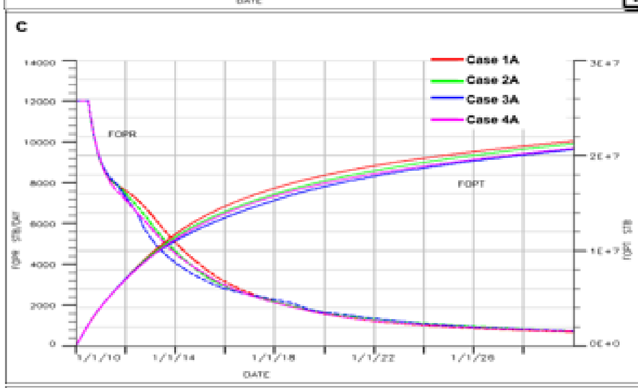

| Case | With Flank Acquifer | |
|---|---|---|
| | FOPT | RF |
| | MMSTB | % |
| Case 1A: 1P,2P,3P,4P | 21.5 | 35.6 |
| Case 2A: 1PA,2P,3P,4P | 20.3 | 33.8 |
| Case 3A: 1P,2P,3PA,4P | 20.8 | 34.5 |
| Case 4A: 1P,2P,3P,4PA | 20.6 | 34.3 |

b



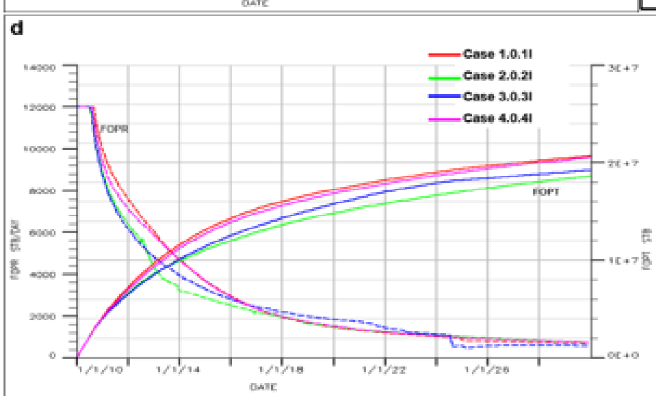

| Case | No Flank Acquifer | |
|---|---|---|
| | FOPT | RF |
| | MMSTB | % |
| Case 1: 1P,2P,3P,4P | 20.7 | 34.4 |
| Case 2: 1PA,2P,3P,4P | 20.2 | 33.4 |
| Case 3: 1P,2P,3PA,4P | 20.6 | 34.2 |
| Case 4: 1P,2P,3P,4PA | 19 | 31.4 |

c




| Case | With Flank Acquifer | |
|---|---|---|
| | FOPT | RF |
| | MMSTB | % |
| Case 1A: 1I,2I,3I | 21.5 | 35.6 |
| Case 1A.1: 1I,2IA,3I | 21.2 | 35.2 |
| Case 1A.2: 1I,2IA,3IA | 20.6 | 34.1 |
| Case 1A.3: 1IA,2I,3I | 20.7 | 34.4 |

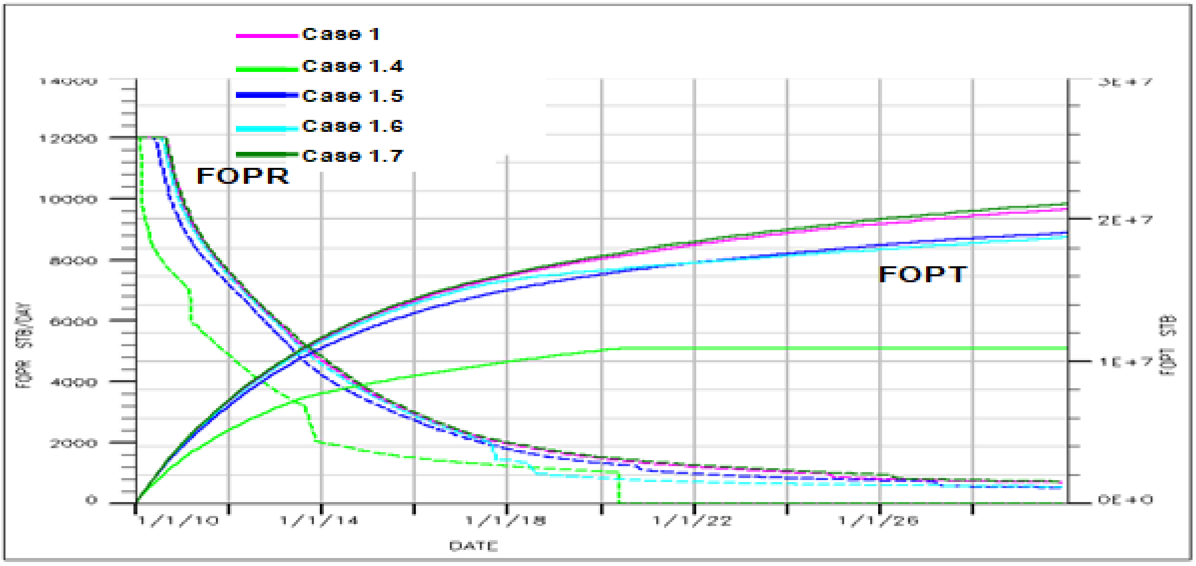
d




| Case | No Flank Acquifer | |
|---|---|---|
| | FOPT | RF |
| | MMSTB | % |
| Case 1: 1I,2I,3I | 20.7 | 34.4 |
| Case 1.1: 1I,2IA,3I | 18.6 | 30.8 |
| Case 1.2: 1I,2IA,3IA | 19.2 | 31.9 |
| Case 1.3 1IA,2I,3I | 20.6 | 34.1 |

## Figure 13

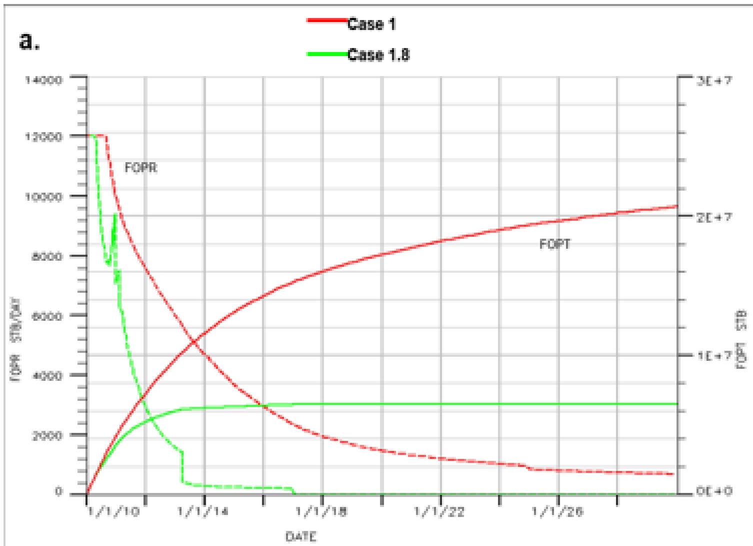
Field production performance for well placement study



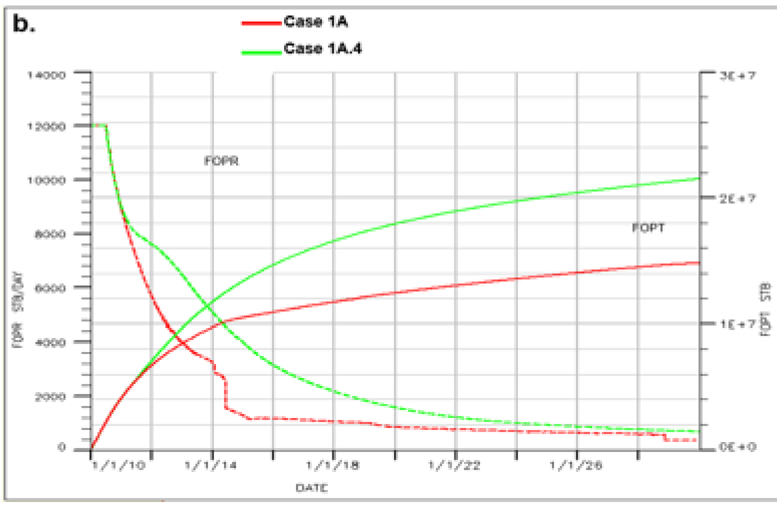

| Case | No Flank Acquifer | | |
|---|---|---|---|
| | Well Gaslift Rate | FOPT | RF |
| | MMscf/d | MMSTB | % |
| Case 1 | 3 | 20.7 | 34.4 |
| Case 1.4 | 0 | 10.9 | 18.1 |
| Case 1.5 | 1 | 19 | 31.5 |
| Case 1.6 | 2 | 18.7 | 31 |
| Case 1.7 | 4 | 21.1 | 34.9 |

**Figure 14**

The field production performance for gas lift application




| Case | No Flank Acquifer | |
|---|---|---|
| | FOPT MMSTB | RF % |
| Case 1.0 | 20.7 | 34.4 |
| Case 1.8 (No Water Inj.) | 6.4 | 10.1 |




| Case | Flank Acquifer | |
|---|---|---|
| | FOPT MMSTB | RF % |
| Case 1A | 21.5 | 35.6 |
| Case 1A.4 (No Water Inj.) | 14.8 | 24.5 |

**Figure 15**

Water injection effect comparing with simulation scenario no water injection for both case aquifer support and no aquifer support

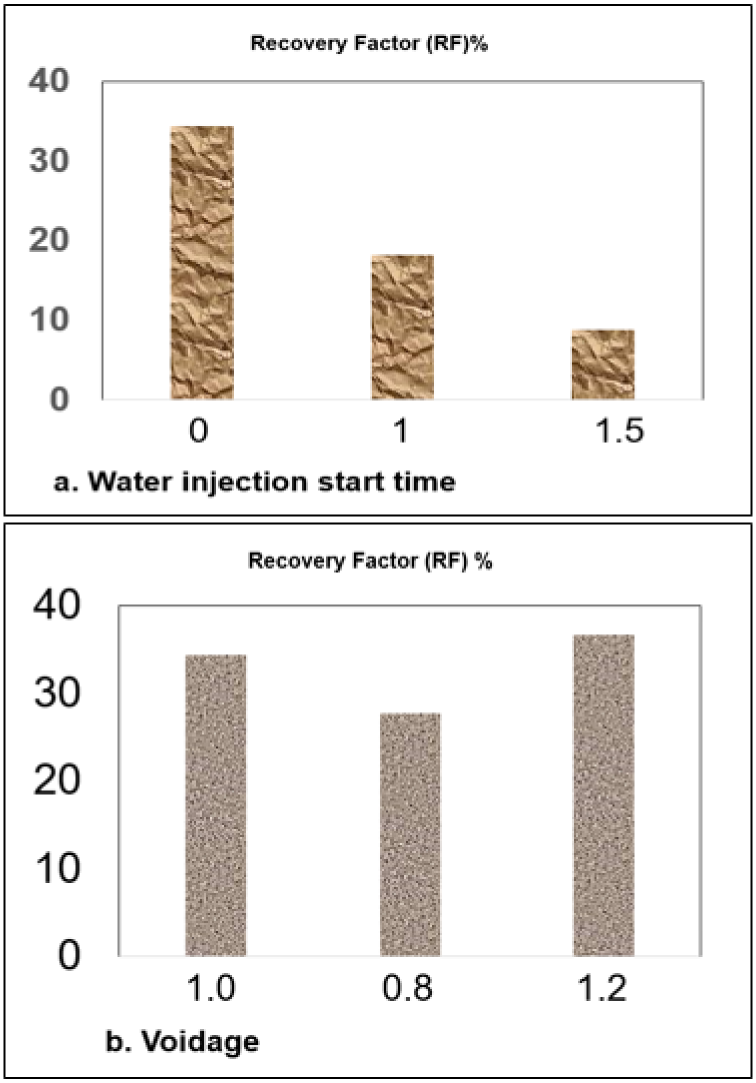



**Figure 16**

The water injection time (a) and voidage volume effect to field production performance

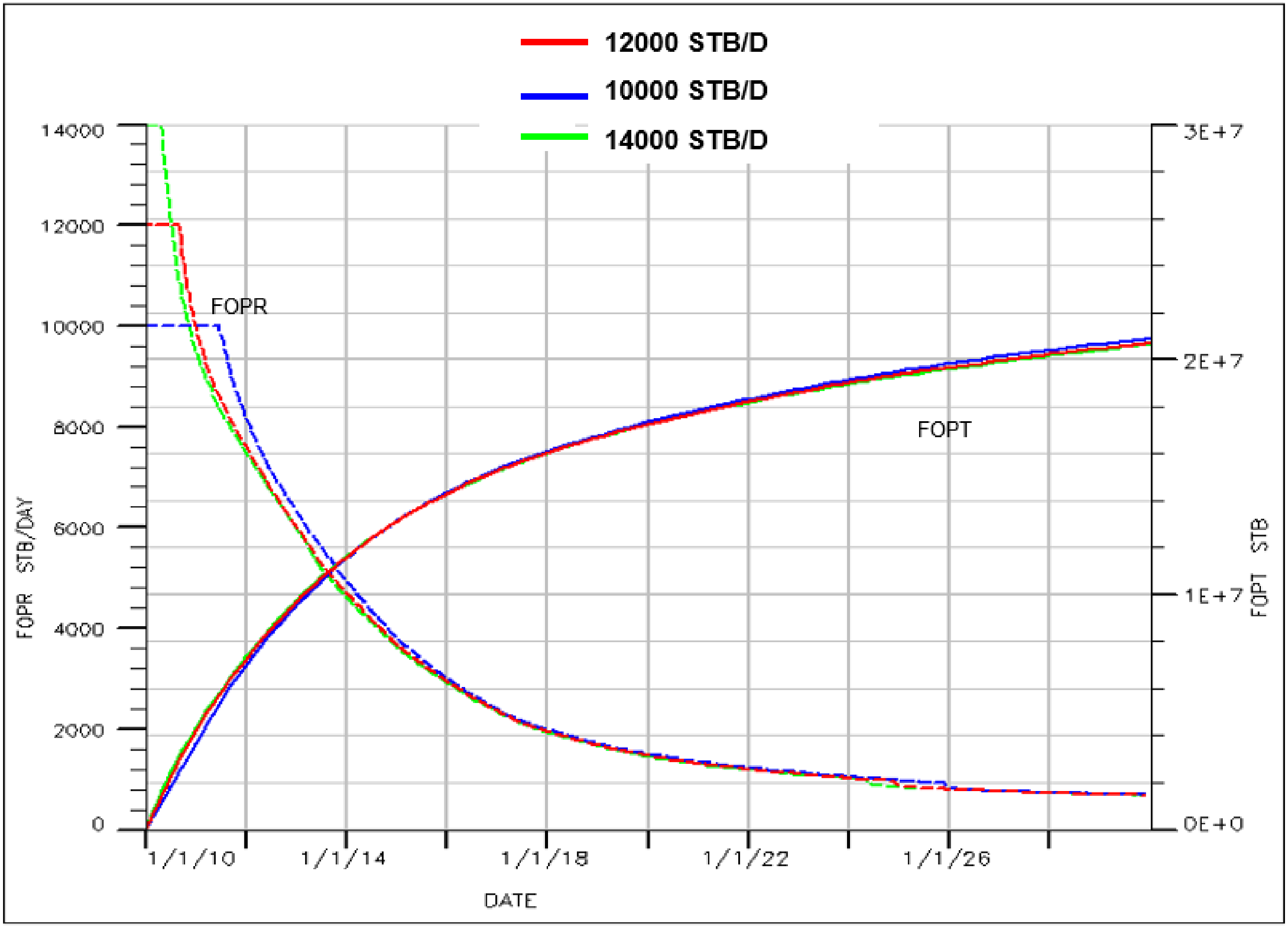



**Figure 17**

Production rates affected oil recovery performance.

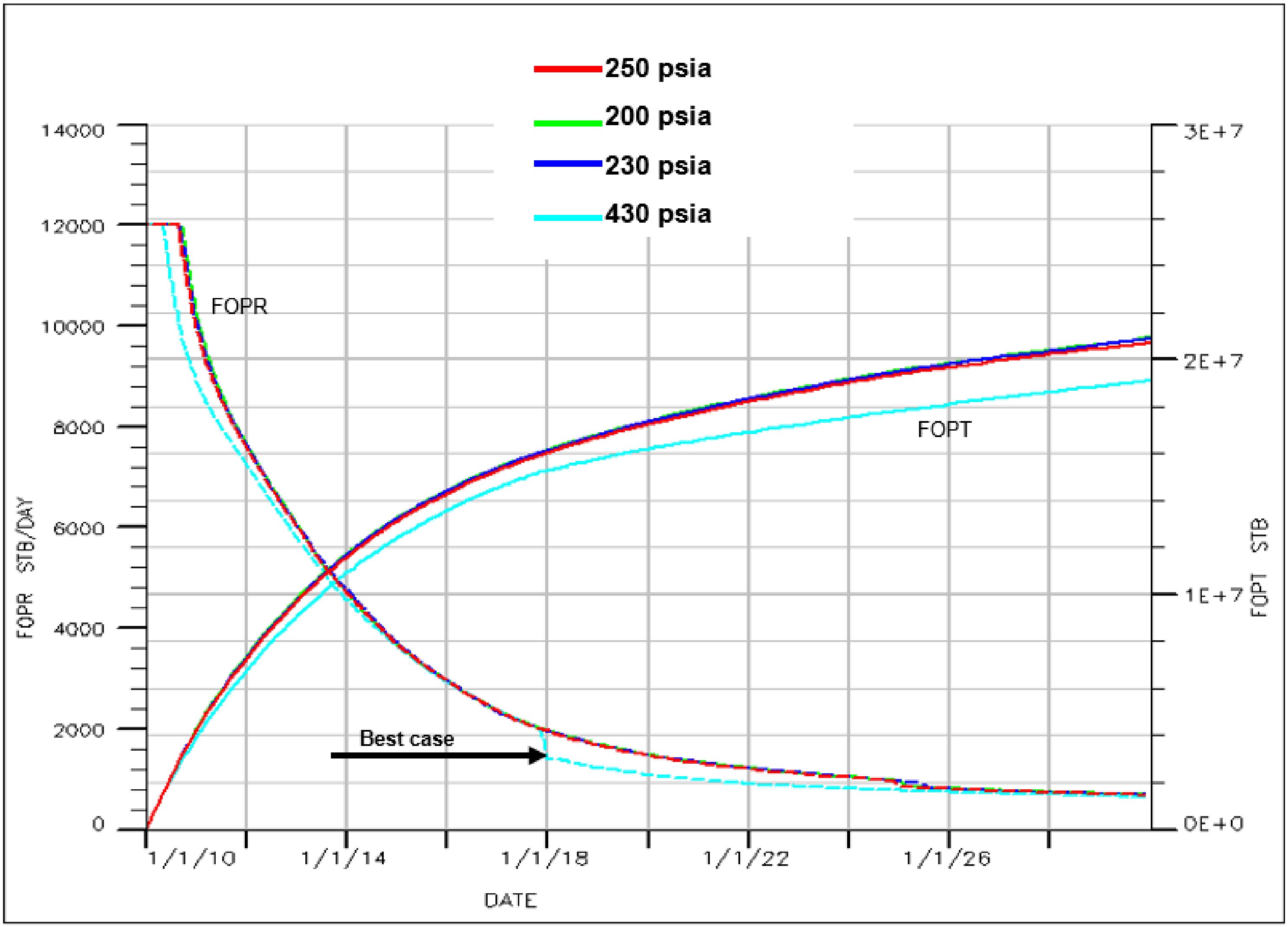



**Figure 18**

Tubing head pressure effect on oil recovery performance