NTNU – Trondheim
Norwegian University of
Science and Technology

History Matching of Production and 4D Seismic Data

- Application to the Norne Field

Tianjiao Yan

Petroleum Geoscience and Engineering
Submission date: April 2014
Supervisor: Jon Kleppe, IPT

Norwegian University of Science and Technology
Department of Petroleum Engineering and Applied Geophysics

Acknowledgement

The five years I spent at NTNU is the most important part of my life. When I look back, there are lot of things I wish I could handle better, however, I consider myself extremely lucky to be a part of NTNU. It provided me, an excellent environment for learning and opportunity to interact with genius teachers and fellow students.

I want first to thank my supervisor Jon Kleppe, who is such a respectable professor at NTNU for providing me guidance and incredible support during my master thesis work. He is a very approachable and friendly person and I can feel optimism and self-confidence with his support.

Likewise, I would like to thank Professor Alexey Stovas, for helping me with the seismic data interpretation. Assistant Professor Jan Ivar Jensen, for providing me help with reservoir simulation. Richard Rwechungura, for helping me with history matching. They provide me guidance and valuable suggestions and feedbacks throughout my master thesis work.

In addition I would like to thank my parents, my father Guanqun Yan and my mother Fang Dong for trusting me and giving me unconditional support. I am also grateful to my boyfriend Zhaolong Liu for his tall and handsome. Thanks to them for being always there for me in highs and lows in this period and always in my life.

Thank you all for let me feel satisfied and peaceful at this moment.

Yan Tianjiao

23.04.2014

Abstract

History matching is the procedure to build a model as close as possible to nature. Reservoir models, constrained to seismic response, as well as flow response, can provide a better description of the reservoir and thus more reliable forecast. 4D seismic have the potential to provide the fluid contact with time, estimating the fault seal and locate the bypass fluids. This thesis focus on history matching use production data and time-lapse seismic, with application to the Norne field in the Norwegian Sea.

This work first describes a methodology for history matching. The parameters selected for study are permeability in x- and z-direction and fault transmissibility. The approach is manual and modified by trial and error procedure. Sensitivity analysis is applied before history matching. Results show the cumulative oil production profile has the great impact on permeability and fault transmissibility. Adjustment of permeability is used to track the oil near- and far from the wellbores and control the water movement between cells and to improve the water cut match. Fault transmissibilities are used to control the fluid flow direction and to guide the water flood.

In the seismic interpretation study part, Time-lapse seismic surveys is used to qualitatively track the water-oil contact movement and to understand the flood direction. Time-lapse seismic surveys of the Norne field acquired in 2001 and 2004 is qualitatively used to test the accuracy of base case and modified simulation model.

There are several recommendations for future work on the history matching of Norne field E-segment. Factors like relative permeabilities and vertical barriers transmissibility which is used to control the water rise should be considered in order to improve the accuracy of reservoir model. Communications between different segments should be take into consideration in order to improve the reservoir model accuracy for the entire Norne field. The precision of qualitative use of 4D seismic can be improved by convert the simulation model to synthetic seismic model and then compare with the original 4D seismic data.

Contents

1. Introduction

1.1 Objectives

History matching is the method to build a model as close as possible to nature. This model is modified until it reproduces the observed production data, furthermore, it should be able to make realistic predictions about the future production performance of the reservoir [1].

This thesis work is concentrated on the E-segment of the Norne field. The main objective is to history match the simulation model. The thesis consists of a theory part and an application part. The theory part contains an insight into methods of history matching and time-lapse seismic follow up by a detailed description of the Norne E-segment. The application part is consists of manual approach of real production data history matching and combination of 4D seismic interpretation.

Eclipse100 reservoir simulator is used to run the simulation. Petrel, Office, Floviz and GL-view are used to visualize the reservoir model and properties. Based on earlier sensitivity studies, permeability and fault are the parameters selected to be adjusted in order to give the best possible match [2]

4D seismic interpretation is used to reduce the uniqueness of the history matching procedure. The correspondence between the simulation model and the observed seismic data has been evaluated by creating synthetic seismic from the simulation model and compare it visually the observed seismic data. Qualitative comparison of oil-water contact movement give a better understanding of flooding patterns and water rise.

1.2 History Matching

Once a reservoir simulation model has been constructed, the reliability of the model should be tested by testing the difference between the data defining the reservoir in the numerical model and the actual values of the reservoir. The way to test accuracy of the model is to simulate past performance of the reservoir and to compare the simulation results with actual, historical data. Significant difference between the simulated- and observed well and reservoir performance will cause correspondingly errors in the simulation. Therefore adjustments to the simulation model are made in order to minimize the difference. Modeling the past performance identifies the weaknesses in data and then the accuracy of the model is improved by modifications. Changes that are made in the model make it to simulate close to historical performance, and make the model consistent with geological description of the reservoir.

History matching can improve the reservoir description and data acquisition program such as porosity, permeability, fluid distribution and fluid movement. Sometimes history matching can lead to discovery of a major operating problem – casing leaks, improper allocation of fluids to wells, etc. If the quality is good, the model is accepted to predict forecasts. Reservoir performance can be complex with numerous interactions, which makes history matching time-consuming and expensive [3].

Production data are the most common type of reservoir data and currently towards 4D seismic data integration. Matching seismic data allows reservoir engineers to have better understanding of reservoir fluid movement during the production period therefore reduce the non-uniqueness of history matching processing.

1.3 Time-Lapse Seismic

Time-lapse seismic is defined as repeated seismic surveys such as two- or three-dimensional conventional seismic data, repeated four components (4C), VSP and cross well seismic. These data acquired at different times over the same area, with the objective of monitoring changes occurring in a producing hydrocarbon reservoir over time [1] [4].

The basic observation for using 4D seismic data was originally observed from rock physics experiments: the density of a rock as well as overall elastic modulus of a rock change with the type of fluid in the pores, when effective pressure acting on the rock and the temperature around the rock is alter. Due to the change in elastic modulus, the rock becomes more or less resistant to wave-induced deformations. Therefore, velocities of seismic waves as they travel through a rock will experience an increase or decrease in magnitude. Changes in reservoir properties such as saturation and fluid pressure as a result of oil and gas production, water or gas injection are recorded in different moments since detectable changes in seismic attributes are observed. Changes in external variables such as ambient noise, recording equipment, etc. can also be recorded [5] [6] [7].

4D seismic method involves acquisition, processing, and interpretation of repeated seismic surveys over a producing hydrocarbon field. The first survey is usually called the base-line survey and the repeated survey is called the monitor survey. Ideally, the base survey is a 3D data set acquired before production from the stated field and monitor survey is acquired after some time of production. By comparing the difference between repeated 3D seismic data sets recorded at different times provides large amount information about the evolution in space and time of distribution of hydrocarbons inside reservoirs. The difference should be close to zero, except where reservoir changes have occurred [8] [4].

Before using seismic time-lapse data for history matching, the following issues should be assessed [9]:

- The time-lapse seismic must be reliable. This means that there should be a lower difference for the non-producing zone when compared to a detectable signal.
- The petro-physical model must reflect a reasonable change compared to reality.
- Petro-elastic modeling (PEM) has to be designed for each field. PEM makes an effective link between the fluid and rock property and the elastic and seismic property.

In the context of 4D reservoir management, the reservoir production data can be utilized along with the seismic data to improve the reservoir model through history matching. This technique allows a quantitative, rather than a visual, interpretation of 4D seismic results. The resulting improvement provides a direct linkage to reservoir management tools, so that, the knowledge gained from the 4D study can be better used to manage the reservoir future performance [1]. 4D seismic data can be used both quantitatively and qualitatively, and qualitative 4D seismic matching is used in this thesis. 4D seismic data not only provides information about the dynamic process occurring in the reservoir while production takes place but also provides information about the spatial lithology heterogeneity where dynamic changes occur [1]. Time-lapse seismic is now an efficient tool to improve drainage and total recovery, monitoring contacts and detecting partially flushed zones, to terminate marginal wells and prevent wells from being drilled into a flushed zone, a complementary tool for the infill drilling of producers and injectors, and recent parameter estimation[10].

2. HISTIRY MATCHING THEORY

2.1 General History Matching

2.1.1 The Objective Function

History matching involves a construction of an initial model with an initial approximation of the reservoir parameters, followed by a systematic process to minimize an objective function that represents the mismatch between observed and simulated responses [3].

The definition of objective function depends on the observed variable available, and is defined as the amount of discrepancy between observation data such as seismic survey, reservoir production historical data, field pressure, and the simulator response for a given set of parameters. For the composition it is necessary to know the distance between the simulated curves and observed data related to each parameter included in the process [1].

There are three most common formulas for calculating the objective function [1]:

- Least-Square Formulation:

$$F=(d^{obs}-d^{cal})^T(d^{obs}-d^{cal}) \qquad (2.1)$$

Where d_{obs} represents the vector containing the observed (measured) data and d_{cal} the response of the system, as predicted by forward modeling is the vector containing the calculated (simulated) data.

- Weighted Least-Square Formulation:

$$F=(d^{obs}-d^{cal})^T w(d^{obs}-d^{cal}) \qquad (2.2)$$

The weighted least-square formulation is equal to the least-square formulation apart from a vector w, which contains the weighting terms. w is a diagonal matrix that assigns individual weights to each measurement.

- Generalized Least-Square Formulation:

$$F=\frac{1}{2}(1-\beta)\{(d^{obs}-d^{cal})^T C_d^{-1}(d^{obs}-d^{cal})\}+\frac{1}{2}\beta\{(\alpha-\alpha_{prior})^T C_\alpha^{-1}(\alpha-\alpha_{prior})\} \qquad (2.3)$$

Where α is the reservoir parameters, α_{prior} is the reservoir parameters of the previous model; The β factor is a weighting factor which expresses the relative strength of our belief in the initial model and C_d is the covariance matrix of the data, C_d provides information about the correlation among the data. $C\alpha$ is the covariance matrix of the parameters of the mathematical model.

Incorporating time-lapse seismic information into history matching as additional dynamic data could provide images of fluid movements between wells [9]. It also reduces the extent of non-uniqueness of traditional history matching. When matching production and seismic data together without a priori information, this simplified form can be expressed as follows

$$F=\frac{1}{2}\sum_{j=1}^{nseries}\frac{w_j^P}{ntime_j}\sum_{i=1}^{ntimes_j}\left(\frac{d_{i,j}^{obs}-d_{i,j}^{cal}(\alpha)}{\sigma_{i,j}^P}\right)+\frac{1}{2}\sum_{j=1}^{ndata}\frac{w_j^P}{nvalues_j}\sum_{i=1}^{nvalues_j}\left(\frac{S_{i,j}^{obs}-S_{i,j}^{cal}(\alpha)}{\sigma_{i,j}^S}\right)\text{........(2.4)}$$

where: n_{series} is the number of production data series to be matched, n_{timej} is the number of measurement times, σ_d and σ_S are standard deviation on production and seismic data errors respectively, n_{data} is the number of seismic data series to be matched, n_{values} is the number of observed seismic data values, S_{obs} and S_{cal} are observed and computed seismic data value respectively, and w are weighting coefficients.

2.2 Manual History Matching

In most cases manually history matching is a procedure of trial and error. Reservoir engineers run simulation for historical period and compare the results for actual field data to analyze the difference between simulated and observed value such as gas-oil ratio, water cut, and bottom-hole pressures and manually adjust simulation input at a time in order to minimize the difference to improve the match. The quality of this type of history matching largely depends on the engineer's experience and the amount of the budget. The process can have several solutions. This is a problem that makes future prediction non-unique which is also critical input needed for making business decisions. Some of these decisions include development drilling, facility upgrades, work over schedules, stimulation, water flooding and installing artificial lifts [1].

Usually, manual history matching means extensive work with a reservoir and relevant data if the reservoir has a long production history and perhaps multiple re-completions. A number of consistencies in the database should be detected and corrected. On the other hand, manual history matching can result in an improved understanding of the drive mechanisms and flooding pattern of the reservoir, for instants, improve in identifying wells, which suffer from poor cementation [11].

2.3 Automatic History Matching

Reservoir history matching problems are generally characterized by a very large number of unknown parameters. Since reservoirs are usually very heterogeneous, there are hundreds of thousands of grid blocks in a typical reservoir simulation model to estimate reservoir parameters in high resolution. Therefore, manual history matching is often not reliable for long periods and is always associated with many uncertainties, and computers are employed to automatically vary the parameters. This procedure is called computer aided or semi-automatic history matching. Semi-automatic history matching is defined as construction of an initial model with an initial approximation of the reservoir parameters， which then goes through a systematic process reduction of an objective function that represents the mismatch between observation and calculated response by perturbing the relevant parameters [8]. The main purpose of computer aided parameter estimation is to decrease the “human” tasks like simulation model modifications, run simulations, comparison of observed and simulation data, etc. associated with the process [1]. In these types of approaches, the computer program used for changing some parameters in order to minimize the objective function.

Most automatic history-matching methods do not permit simultaneous matching of two or more kinds of data. In practice, pressure normally would be matched first. Then GOR or WOR would be matched by automatic modification of either rock or pseudo-relative permeability functions. For a match of pressure, the model grid generally will be divided into arbitrary areas. The simulator will modify multiplying factors one value for each area that will raise or lower all permeability and/or porosities uniformly. The reservoir variables or parameters are automatically changed to achieve a match. It is generally not feasible to have a multiplying factor for every permeability or porosity value in the model [12].

The procedures for Automatic History Matching (AHM) will depend on the characteristics of the computer program. Generally AHM will include the following steps: First, to devise a numerical model of the reservoir, and simulate the aquifer in addition to the reservoir if water drive is significant. Then select the variables to be modified by the automatic history matching package. It is important to select variables that have the strongest effect on the objective function. Reservoir parameters must be realistic. Then assign the best current reservoir description to the model by setting up the observed data and assigning scaling factors to the observed data. During the AHM process reservoir mechanics and reservoir geology description should be taken into consideration.

2.3.1 Gradient Based Methods

The algorithm to minimize the objective function that measures the difference between the simulator response and the observed field data start with the initial guess of body parameters and the process is iteratively advanced until the best fit is obtained between the calculated and observed data. Several optimization algorithms are developed for this purpose. These algorithms are usually classified depending on whether they use the gradient of the objective function or not. [4]

Gradient-based history-matching techniques are becoming more widely used as appropriate software becomes commercially available [13][14][15].

The gradient of the objective function is defined as:

$$\nabla F \equiv \left(\frac{\partial F}{\partial \vec{\alpha}}\right)^T \qquad (2.5)$$

Where α is the model parameter vector.

Some widely used gradient-based methods are the Steepest Descent method, the Gauss-Newton method, the Levenberg-Marquardt algorithm, the Conjugate Gradient method and Sequential Quadratic Programming (SQP). Gradient -based methods are used to obtain a local minimum of the objective function. By calculating the gradient of the algorithm could determine the direction for optimization search and the let the function converge towards the local minimum. Some gradient methods require Jacobin (first derivative) while other methods require also the second derivative (the Hessian). To approximate the Hessian, one needs the sensitivity coefficients, which are the derivatives of the data. This sensitivity matrix is mathematically defined as $J_{ij}=\partial d_i/\partial \alpha_i$, where i run over data space, j runs over model space and α is the model parameter vector.

The main assumptions for gradient-based method are [1]:

− The objective function F is smooth,

− It is possible to compute∇F,

− The objective function is varying linearly with parameter changes.

The main disadvantages of using gradient-based methods are [1]:

− The possibility of converging to a local minimum in the objective function rather than a global minimum.

− Long computing time required to perform the gradient and calculation computationally expensive since some of them involve the computation of sensitivities.

2.3.2 Non-gradient Based Method

In contrast to gradient-based methods, non-gradient based methods may be able to find global minimum. Only objective function evaluations are used to find optimum point. Gradient and Hessian of the objective function are not needed. Non-gradient based methods require a large amount of simulation runs to converge, and are usually limited to smaller scale problems. It is able to seek the optimum point for objective functions that do not have smooth first or second derivatives.

Some well know non-gradient based methods are: Evolutionary algorithms, Simulate annealing, Scatter and Kalman filter methods.

2.4 General procedure for history matching

Normally, the general procedure one could follow in history matching includes the following steps [16]:

1. Define the objectives of the history matching process.

2. Determine the method to use in history match.

3. Acquire model input data, especially the history of field performance. Determine which data should be matched during the history matching process and the criteria to be used to describe a successful match.

4. Determine the reservoir data that can be adjusted during the history match and the confidence range for these data.

5. Run the simulation model with the best available input data. During the pressure match stage of the history match the reservoir voidage rates (oil rate plus free-gas rate plus water rate at reservoir conditions) are specified. During the saturation stage of history match, oil rates for an oil reservoir and gas rates for a gas reservoir at standard conditions are specified.

6. Compare the results of the history match run with the historical production data chosen in Step 3.

7. Make adjustments to the model. Consult with geologic, drilling, and production operations personnel, etc. Change the reservoir data selected in Step4 within the range of confidence.

8. Continue with Step 5 through 7 until the criteria established in Step 3 are met and a satisfactory match of observed data is achieved.

2.4.1 Strategies for History Matching

A universally accepted strategy for history matching does not exist. One of the general guidelines that can lead to a history match toward successful completion is presented in table 2.4.1 below.

The first two steps in the table take precedence over the last two. If the first two steps cannot be achieved, there is possible the model is inadequate, which may be due to wrong model selection, the reservoir is poorly characterized, or field data is inaccurate or incomplete [18].

Table 2.4.1 Suggested History Matching Strategy [17]

Step	Remarks
1	Match volumetrics with material balance and identify aquifer support which gives an insight into the data adjustments required for the history match.
2	Match reservoir pressure. Pressure may be matched both globally and locally. The match of average field pressure establishes the global quality of the model as overall material balance. The pressure distribution obtained by plotting well test results at given points in time shows the spatial variation associated with local variability of field performance.
3	Match saturation dependent variables. These variables include water-oil ratio (WOR) and gas-oil ratio (GOR). WOR and GOR are often the most sensitive production variables in terms to both breakthrough time and the shape of the GOR or WOR curve.
4	Match well flowing pressures.

2.4.2 History Matching Parameters

A fundamental concept of history matching is the concept of a "hierarchy of uncertainty" [17], which is a ranking of model input data quality that lets the modeler determine which data is most and least reliable. Changes to model input data are then constrained by principle that the least reliable data should be changed first.

Relative permeability data are typically placed at the top of hierarchy of uncertainty because they are modified more often than other data. Changing a variety of input parameters, including relative permeability endpoints and fluid contacts, may modify initial fluid volumes.

Those reservoir and aquifer properties appropriate for alteration, in approximate order of decreasing uncertainty are: (1) Aquifer transmissibility, k_h, (2) Aquifer storage, (3) reservoir transmissibility, Relative permeability and capillary pressures functions. The following additional properties must sometimes be altered, but they usually are known with acceptable accuracy: (5) reservoir porosity and thickness, (6) structural definition, (7) rock compressibility, (8) reservoir oil and gas properties, (9) water/oil contacts (WOC) and gas/oil contacts (GOC), and (10) water properties.

How changes in some history match parameters affect matches of saturation and pressure gradients is presented in Table 2.4.2

Table 2.4.2 Influence of Key History Matching Parameters [17]

Parameter	Pressure Match	Saturation Match
Pore volume	ΔP/Δt	*
Permeability thickness	ΔP/Δx	ΔS/Δx
Relative permeability	Not used	ΔS/Δx andΔS/Δt
Rock compressibility	*	Not used
Bubble point pressure	ΔP/Δt	*
*Avoid changing if possible		

2.4.3 Evaluating the History Match

Typically, observed and calculated parameters are compared by making plots of pressure vs. time, production rate or injection rate vs. time, gas-oil ratio (GOR), water-oil ratio (WOR), water-gas ratios (WGR) water vs. time or water cut vs. time. Other comparisons should be made if data are available include: and model fluid saturations vs. well log saturations and chemical tracer concentration vs. time.

Pressure is usually the first dynamical variable to be matched during the history matching process. Average pressure is affected by fluid volumes in place, size of aquifer, and the degree of communication between the reservoir and the aquifer. Pressure interference data can be especially useful if they are accurate enough to yield independent estimates of between well permeability thickness. Pressure drawdown is affected most by horizontal permeability and skin effects.

Oil production rates are usually the most accurate data available. The modeler specifies one rate, and then verifies the rate is entered properly by comparing observed cumulative production with model cumulative production. After the rate of one phase is specified, the rate of all other phases must be matched by model performance. Gas production may not be measured accurately if the gas has been flared. Injection data tend to be less accurate than production data, either because measurement errors or because fluids are lost to other intervals as a result of casing leaks or flow behind pipe. Errors in production data may occur for the same reasons, but they are usually discovered and corrected. If volumes are measured at central sites and not at individual wells, allocation back to wells will be a potential source of error. Where production or injection is commingled, allocation to individual zones will be a source of error.

However, a poor match of water cut and gas oil ratio will also cause a poor match for the average pressure. Phase ratios such as GOR and WOR are sensitive indicators and provide information about pressure depletion and front movements. Matching historical WOR, GOR or WGR is usually the best way to confirm the validity of estimates of effective zonation and zonal continuity. When the reservoir is on an early stage of depletion, or if for any other reasons there are no direct data defining water or gas movement, one must rely heavily on core analysis, logs, and knowledge of the depositional environment to develop zonation and to estimate continuity. Water cut and gas oil ratio depend primarily on draw- down, i.e. again on permeability, but also on the fluid contacts, and the thickness of the transition zone (which depends on capillary pressure). The shape of the curves after breakthrough depends on the relative permeability curves, but the breakthrough time depends mainly on the end-points of these curves, i.e. the effective permeability with only one of the phases flowing.

2.4.4 Deciding on a Match

The understanding of the objectives is the standard for deciding if the match is acceptable. The accuracy of the history match should be better than, or at least comparable to, the accuracy required in predictions.

Pressure may be considered matched if the difference between calculated and observed pressures is within ±10% drawdown. Pressure matches for individual wells are often acceptable if model and well pressures agree to within ±50 psi [±345 kPa] on average. In some reservoirs such as most gas reservoirs and many high-permeability reservoirs, a match must be much better than ±50 psi [±345 kPa] to be acceptable [17].

Another sensitive indicator of the quality of a history match is the match of WOR, GOR or water cut. There are three factors that should be considered: 1. Breakthrough time 2. The magnitude of the difference between observed and calculated values 3. Trends. Each factor should be improved by adjustment the model. [19]

2.5 Integration of Time-lapse Seismic Data to Manual History Matching

4D seismic surveys have several areas of application when we used to aid in manual history matching. Simulation to seismic modeling is used to validate and optimize geologic models and simulation models [20]. A synthetic 4D seismic response can be compared either qualitatively or quantitatively with the actual 4D response. The results are used to update the simulation model to match both the seismic data and production data. The procedure is shown in figure 2.5.

The effects of 4D can be result of changes in both saturation and pressure in the reservoir. Qualitative interpretation is usually easier than quantitative. Change of saturation can be used to evaluate the 4D seismic data in terms of sweep, to identify bypassed oil, baffles, flood fronts, and contact movement. Interpreted pressure changes can be used to infer connectivity, fault seal and compartmentalization.

Qualitative interpretation of the 4D response establishes templates for manually updating the geologic and flow-simulation models. Those temples are used to guide reservoir placement and to adjust flow parameters such as fault transmissibility or permeability multipliers. The result of model updates are then compared visually with the 4D response.

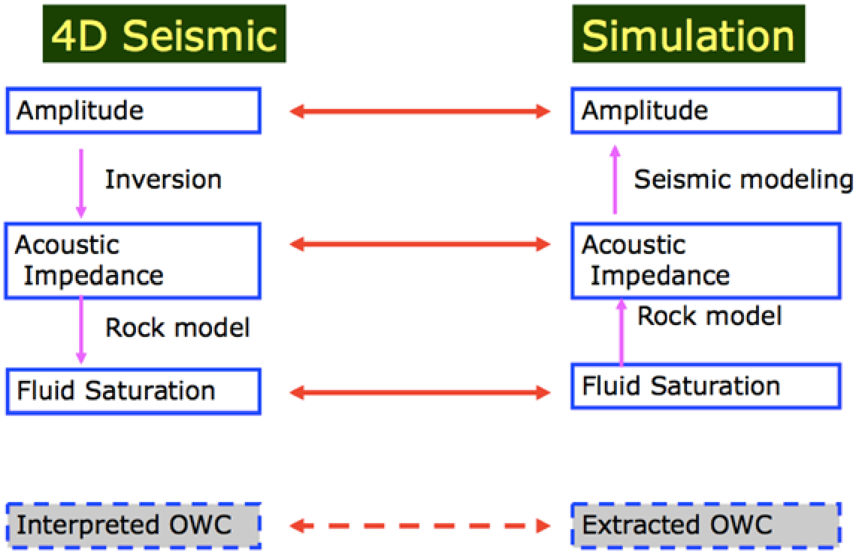


Figure 2.5 Qualitative use of 4D seismic in model updating

3. THE NORNE FIELD

3.1 General Field Information

Norne is an oil and gas field situated in the blocks 6608/10 and 6508/10, belongs to the southern part of the Nordland II sector in the Norwegian Sea. It is located about 85 kilometers north of the Heidrum and 200 km west of Brønnøysund as shown in figure 3.1.1.[21]

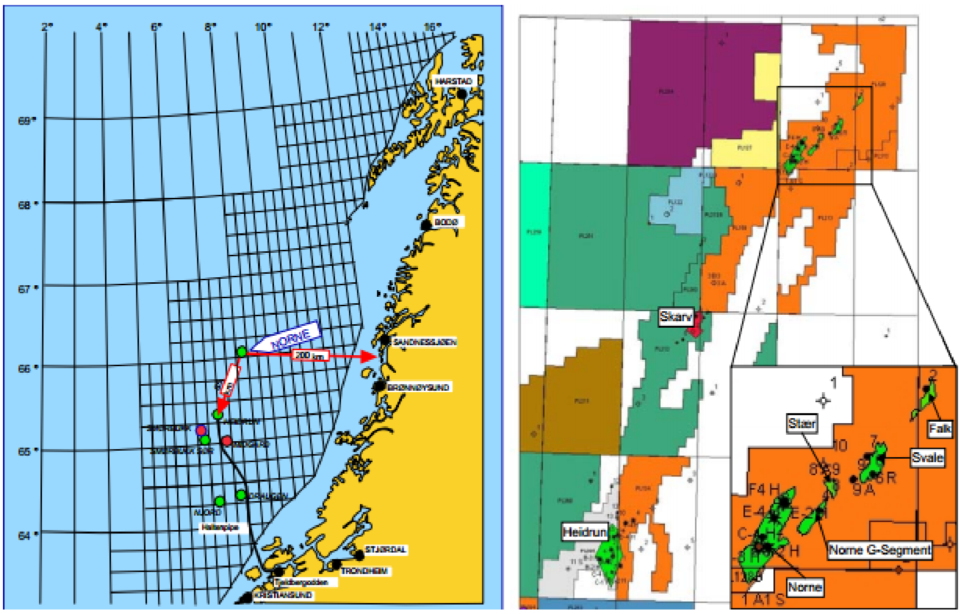


Figure3.1.1 Norne field location[21]

The Norne field was first discovered at 1991. Development drilling began in August 1996. Oil production started in November 1997 and gas production started in 2001. It is operated by Statoil and owned by a partnership of Statoil ASA (39.1%), Petoro AS (54.0%) and Eni Norge AS (6.9%). [21]

The Norne field consists of two separate compartments: The Norne Main Structure consists of Norne C, Norne D and E-segment and contains 97% of oil in place. The other is the Northeast Segment consists of Norne G-Segment. The Norne field segments is shown in figure 3.1.2 [22]

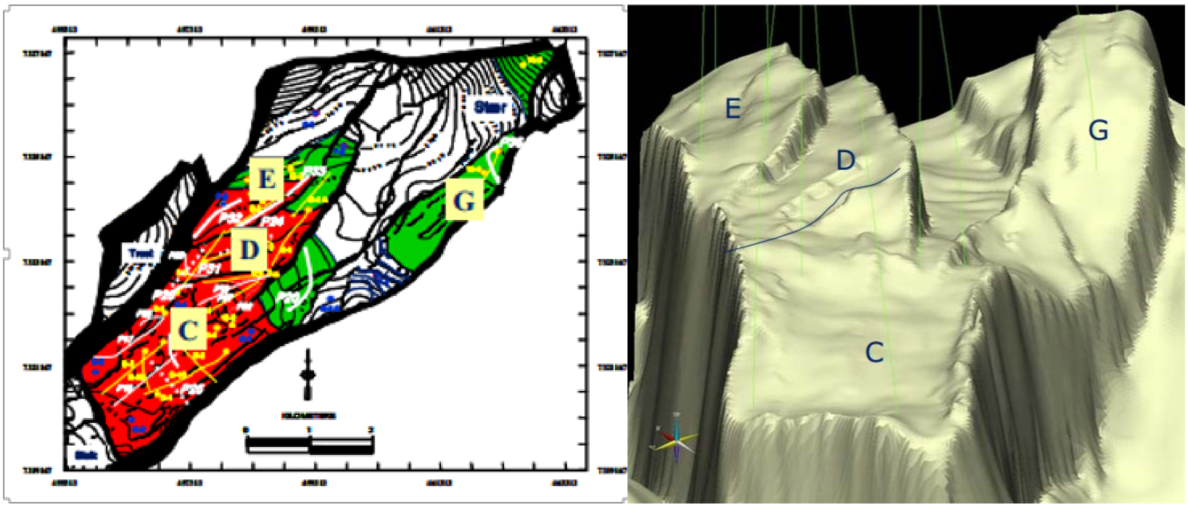


Figure 3.1.2 The Norne field segments. The 4 main fault blocks are denoted C. D, E and G [21]

The horst block is approximately 9km x 3km and the water depth is approximately 380 meters. The crest of reservoir is about 2,525m below mean sea level (MSL). Reservoir pressure is close to hydrostatic and the formation pressure is 273bar with a temperature of 98°C at a reference depth of 2,639m below MSL. The oil/water contact is defined at 2,688m. [23]

3.2 Field Geology

The reservoir is subdivided into four main different formations from top to base: Garn, Ile, Tofte and Tilje as shown in figure 3.2.1

Based on the discovered well, 6608/10-2, hydrocarbons were found in the lower-to Middle-Jurassic sandstones. Total hydrocarbon column is 135m and consisted of an oil column of 110m thick and overlying gas cap. Approximately 80% of oil reserve on the Norne Main Structure is located at Ile- and Tofte formation and free gas is primarily located in the Garn formation. [19]

The hydrocarbon source rocks are believed to be the Spekk formation from Late Jurassic and the coal bedded Åre formation from Early Jurassic.

The reservoir sandstones are dominated by fine- grained and well to very well stored sub-arkosic arenites which are buried at 2500-2700m depth and affected by digenetic processes. The reservoir quality is generally good although it is reduced by mechanical compaction. The porosity is 20-30% and permeability can varies from 20 to 2500md.

The entire reservoir thickness, from Top Åre to Top Garn formations, varies over the field, from 260m in the southern parts to 120m in the northern parts. The decrease in thickness is caused by increased erosion.

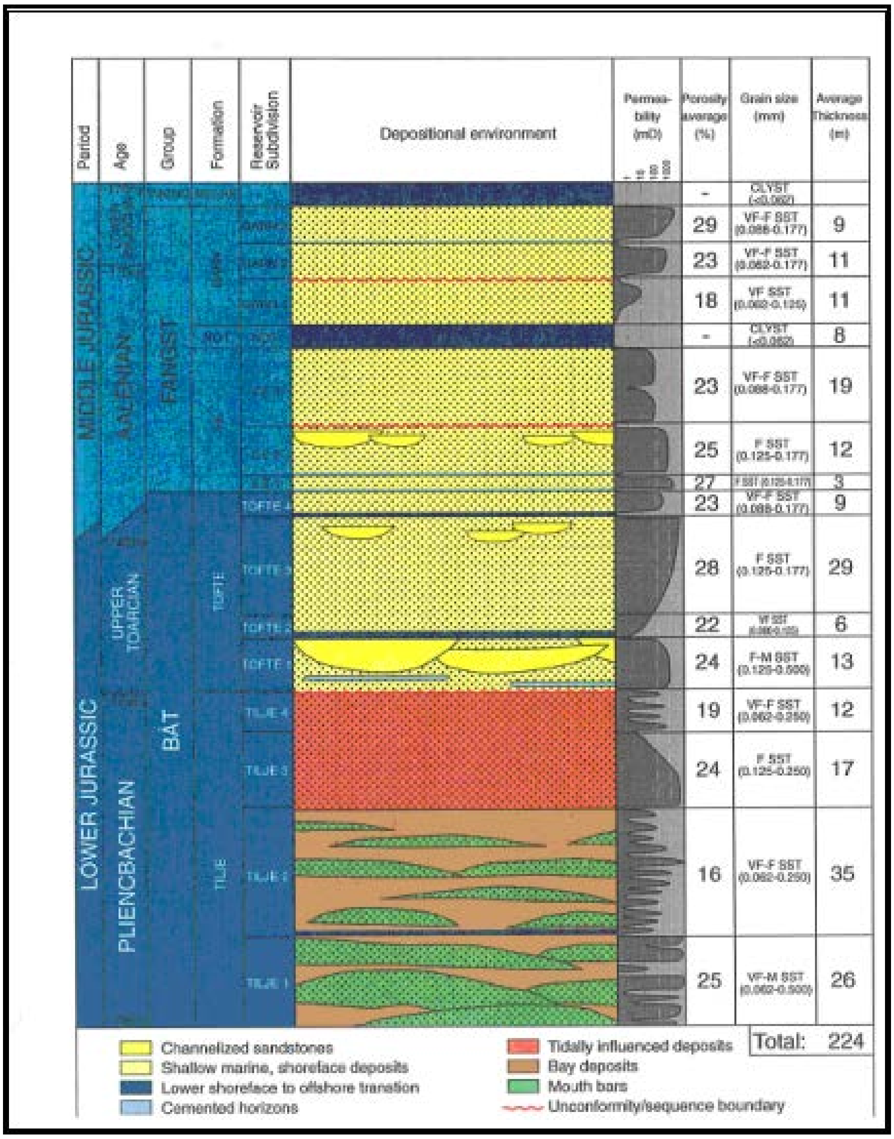


Figure 3.2.1 Strati graphical sub-division of the Norne reservoir [24]

The Melke formation is nearly non-permeable act as the cap rock, which seals the reservoir and traps the reservoir fluid in place. As shown in figure 3.2.2 the Norne reservoir is relative flat with a gas filled Garn Formation and the gas oil contact in the vicinity of the Not Formation clay stone. The northern flank dips towards north-northwest with an oil leg in the Garn Formation. The Not formation also behaves as a cap rock, preventing communication between the Garn and the Ile Formations. [22] The fluid contacts of Norne cross section is shown in figure 3.2.3

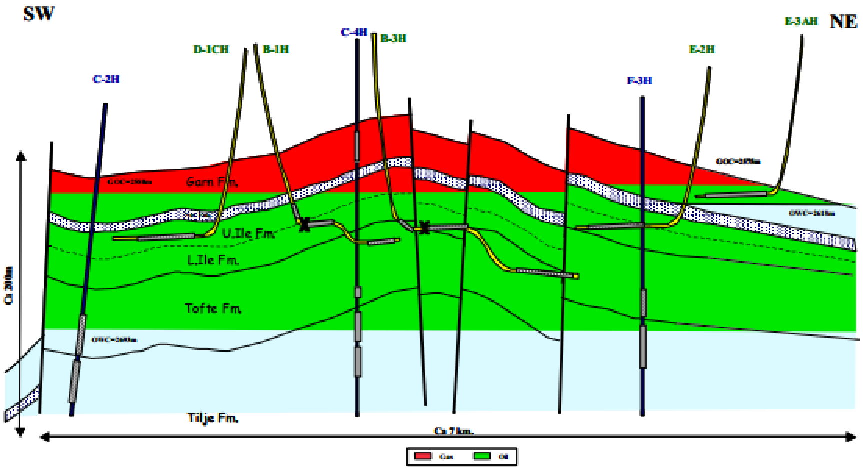


Figure 3.2.2 NE-SW running structural cross section through the Norne Field with initial fluid contacts and current drainage strategy [24]

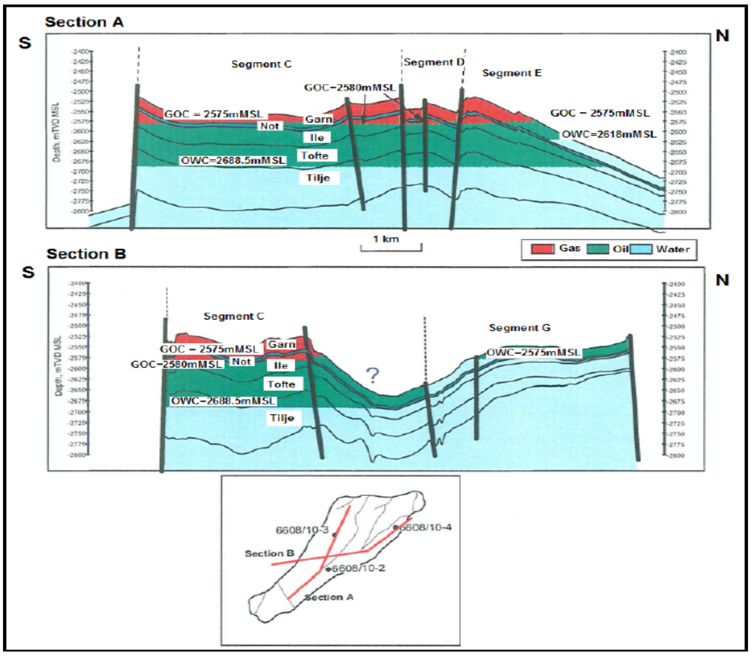


Figure 3.2.3 Norne cross section with fluid contacts [24]

3.3 Reservoir Communications

The Norne reservoir contains both faults and stratigraphic barriers which may affect vertical and lateral flow. It is important to consider the effect they have on the fluid flow to enhance the drainage strategy.

Faults could be discovered by studying the seismic data. Transmissibility multipliers have been assigned to each subarea of the fault plans. The fault plans are divided into sections which follow the reservoir zonation to describe the faults in reservoir simulation model. These are functions of fault rock permeability, fault zonation width, the matrix permeability and the dimensions of grid blocks in the simulation model.

Several stratigraphic barriers are present in the field. Their lateral extent and thickness variation are assessed using cores and logs. The continuous stratigraphic barriers resulting in less vertical flow is listed in Table 3.3.1 below [25].

Comment:

- Garn3/Garn2, carbonate cemented layer at top Garn 2
- Not formation, claystone formation
- Ile 2.1.1/Ile 1.3, carbonate cementations and increased clay content at base Ile3
- Ile 1.2/ Ile 1.1, carbonate cemented layers at base Ile 2
- Ile 1.1/ Tofte 2.2, carbonate cemented layers at top Tofte 4
- Tofte 2.1.1/Tofte 1.2.2, significant grain size contrast
- Tilje3 /Tilje 2, claystone formation

Pressure distribution in the field clearly indicates influence the stratigraphic barriers have on flow within the reservoir. Most obvious barriers to flow are the NOT formation, the carbonate cemented layers which separate Ile 1 and Tofte 4 formations, and the claystone which separate Tilje 3 and Tilje 2 Formations.

Table 3.3.1 Stratigraphic barriers and layers in Norne field

Layer	Formation	Stratigrafic Barriers/Layers
1	Garn3	Carbonate cemented layer
2	Garn2	
3	Garn1	
4	NOT	Claystone formation
5	Ile 2.2	
6	Ile2.1.3	
7	Ile 2.1.2	
8	Ile 2.1.1	Carbonate cementations and increased clay content
9	Ile 1.3	
10	Ile 1.2	
11	Ile 1.1	Carbonate cemented layers
12	Tofte 2.2	Carbonate cemented layers
13	Tofte 2.1.3	
14	Tofte 2.1.2	
15	Tofte 2.1.1	Significant grain size contrast
16	Tofte 1.2.2	
17	Tofte 1.2.1	
18	Tofte 1.1	
19	Tilje 4	
20	Tilje 3	Claystone formation
21	Tilje 2	
22	Tilje 1	

3.4 Subsea System

Subsea production facilities will comprise five well templates - three for production, one for water injection and one for combined gas and water injection. Each template has four slots and the capacity to tie in additional satellite wells. Flexible flow-lines and risers are specified. A multifunctional umbilical will be used to control and monitor the subsea system, to distribute chemicals and hydraulic fluid, as well as to supply power. The templates are being installed in northern and southern groups, placed about 4,000m apart. Water depth varies between 370-390m. One production and one water-injection template will make up the northern group. These installations are tied back to the production ship by two nine-inch production lines, one nine-inch water-injection line and one control and service umbilical. The southern group comprises two production templates, a combined water-/gas-injection line and two controls and service umbilical. The templates in each group are positioned so that the rig can enter all the slots without the need for anchor handling. [23]

The field is being developed with a floating production and storage vessel. Six subsea wellhead templates 4 for production and 2 for injection named B, C, D, E and K are connected to the vessel.（see figure 3.4.1）Template K was placed on the sea bottom in 2005, 150-200 meters south of B, C and D templates. Each template has 4 well slots available; 3 for production and 1 for injection or production. The first production well K-3 H is planned to be drilled during summer of 2006. [26]

The well stream is carried by flexible risers to the vessel, which rotates around a cylindrical turret anchored to the sea floor. The vessel has storage tanks for stabilized oil and a processing plant is located on the deck of the ship.

All well slots produced oil in January 2006 the Norne Field, approximately 15000 Sm3/d, and all 8 injection wells were used for water injection. 68 mil Sm3 oil has been produced since the production started, which is approximately 43% of the oil in place or 76% of recoverable reserves.

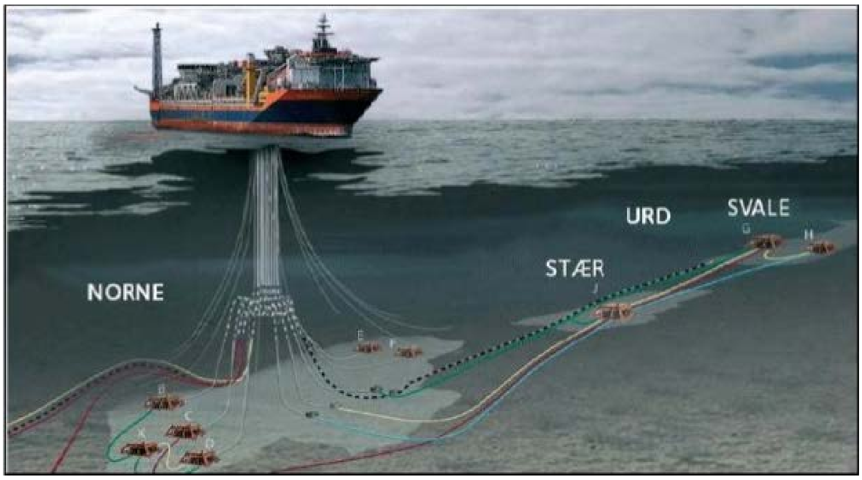


Figure 3.4.1 Development of the Norne Field [21]

3.5 Wells

The first well[25] discovered oil and gas on the Norne field was well 6608/10 - 2. Drilling started on the 28th of October 1991. The objectives were to test the hydrocarbon potential of the Fangst Group of Middle Jurassic age, and to see if it was equivalent to the Rogne Formation in the Viking Group. The second exploration well 6608/10 - 3 confirmed the result of hydrocarbons in the discovery well. Well 6608/10 - 4 was the first exploration well to be drilled on the North - East area. Its purpose was to prove the presence of oil in the Middle Jurassic sandstones in the G - segment. The first development well to be drilled on the Norne Field was Well 6608/10 - D - 1 H. The plan was to drill it as a producer in the Ile and Tofte Formations in the southern part of the field. As this was the first well to be drilled in this area, results from the well was important for the further development of the field and numerous tests were performed. The production started on 7th of November 1997 and this well marks the start of the life of the Norne Field. The well was shut the 1st of September 2002.

3.5.1 Exploration wellbores

To test the hydrocarbon potential in the sandstones and appraise oil accumulation in different formations, 4 exploration wells were drilled. Several intervals were perforated and tested. An overview of the exploration wells is presented in Table 3.5.1 below.

Table 3.5.1: Exploration wellbores [28]

Name	UTM coordinates	Entry Date	Completion Date	Purpose
6608/10 - 2	7321933.62N - 457994.68E	28.10.1991	29.01.1992	WILDCAT
6608/10 - 3	7324321.37N - 458426.47E	07.01.1993	11.03.1993	APPRASIAL
6608/10 - 3R	7324321.37N - 458426.47E	08.08.1995	17.08.1995	APPRASIAL
6608/10 - 4	7324847.23N - 462006.74E	15.12.1993	06.03.1994	WILDCAT
Name	Status	Contents	TVD (m)	HC Formation
6608/10 - 2	Plugged & Abandoned	Oil & Gas	3677	Fangst and Båt
6608/10 - 3	Susp. Reentered later	Oil & Gas	2920	Fangst and Båt
6608/10 - 3R	Plugged & Abandoned	Oil & Gas	2920	Fangst and Båt
6608/10 - 4	Plugged & Abandoned	Oil & Gas	2800	Melke and Garn

3.5.2 Development wells

Active development wells in the Norne Field in December 2009 were shown in table 3.5.2. The wells are completed in different formations depending on the drainage strategy.

Table 3.5.2 Active development wells in the Norne Field [28]

Well Name	Completion date	Drill Permit	Wellbore purpose	Wellbore Contents
6608/10-B-1 BH	2006	2634-P	Production	Oil
6608/10-B-2H	1997	1239-P	Production	Oil
6608/10-B-3H	1999	1590-P	Production	Oil
6608/10-B-4DH	2004	2423-P	Production	Oil
6608/10-C-1H	1998	1422-P	Injection	Water
6608/10-C-2H	1998	1501-P	Injection	Water
6608/10-C-3H	1999	1570-P	Injection	Water
6608/10-C-4AH	2004	2342-P	Injection	Water
6608/10-D-1CH	2003	2335-P	Production	Oil
6608/10-D-2H	1998	1249-P	Production	Oil
6608/10-D-3BY2H	2005	2580-P2	Production	Oil
6608/10-D-3BY1H	2005	2580-P1	Production	Oil
6608/10 D-4AH	2003	2218-P	Production	Oil
6608/10 E-1H	1999	1591-P	Production	Oil
6608/10 E-2CH	2008	2915-P	Production	Oil
6608/10 E-3CH	2005	2551-P	Production	Oil
6608/10 E-4AH	2000	1727-P	Production	Oil
6608/10 F-1H	1999	1584-P	Injection	Water
6608/10 F-2H	1999	1638-P	Injection	Water
6608/10 F-3H	2000	1669-P	Injection	Water
6608/10-F-4AH	2007	2898-P	Injection	Water
6608/10-K-1H	2006	2772-P	Production	Oil
6608/10-K-3H	2006	2743-P	Production	Oil
6608/10-K-4H	2007	2830-P	Production	Oil
Oct-08		3103-P	Production	Oil
Oct-08		3106-P	Production	Oil

3.6 Resources and recoverable reserves

Approximately 80% of the oil reserves on the Norne main structure is located in the Ile and Tofte formation. The free gas is mainly located in the Garn Formation. The most likely in place volumes and official recoverable reserves for the Norne Field are as table 3.6.1

Table 3.6.1 In place volumes in 2004 [27]

		PDO	Official RNB 2006
Oil in place, STOIIP	x 10^6 Sm^3	164.2	157.0
Gas in place (free & solution)	x 10^9 Sm^3	29,9	29.8
Recoverable oil reserves	x 10^6 Sm^3	72,4	87.4
Recoverable gas reserves	x 10^9 Sm^3	-	13.65

The in-place volume estimates from 2006 are 157 MSm3 oil in place (OIIP) and 29.8 BSm3 gas in place (GIIP). As of June 2010, 83.7 MSm3 of oil and 6.1 BSm3 of gas have been produced, resulting in an oil recovery factor of 53.3%， which makes Norne one of the highest recovery fields on the Norwegian continental shelf. Reserved in Norne fiels 2010 is listed in table 3.6.2

Table 3.6.2 Reserves in Norne field 31.12.2010 [28]

Reserves inclusiv sold and delievered volumes						***Reserves***				
field	***Oil***	***Gas***	***NGL²***	***Condensate***	**Sum o.e**	***Oil***	***Gas***	***NGL²***	***Condensate***	**Sum o.e**
	mill Sm^3	**bill Sm^3**	**mill tonn**	**mill Sm3**	**mill Sm3**	**mill Sm3**	**mrd Sm3**	**mill tonn**	**mill Sm3**	**mill Sm3**
NORNE	93.4	11.7	1.7	0.0	108.2	8.8	5.5	0.9	0.0	16.1

3.7 Drainage Strategy

The main goal was to develop the Norne Field such that the economic optimum production is reached.

The field is developed only with horizontal producers now. As shown in figure 3.7.1, to accelerate the build-up of well potential until plateau production was reached, some of the first producers were drilled vertical to some deviated. All these wells have been sidetracked to horizontal producers. [19] The horizontal oil producers in Tofte and Lower Ile formation will be plugged and sidetracked and drilled horizontal in upper Ile Formation just below the Not Formation shale when the water cut becomes high (>90%) resulting in problems to lift the liquid.

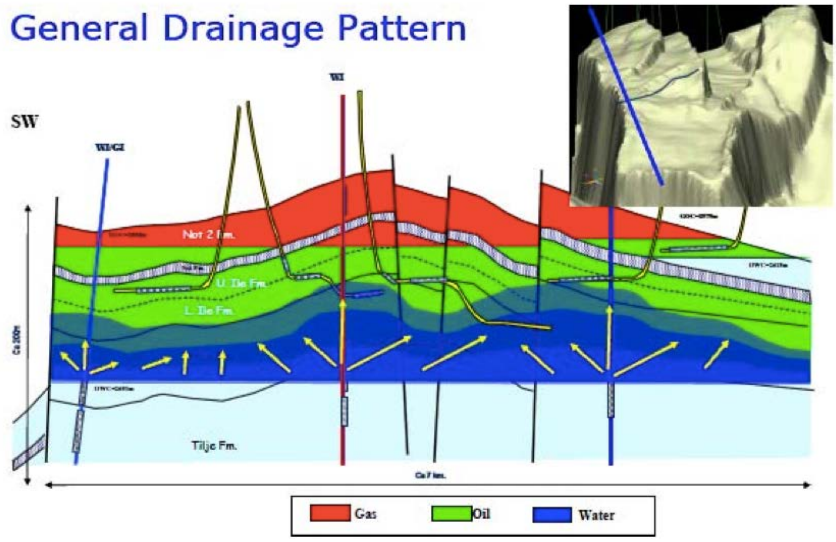


Figure 3.7.1 General Drainage Pattern[21]

The pre - start drainage strategy was to maintain the reservoir pressure by re - injection of produced gas into the gas cap, and injects water into the water zone. During the first year of production, the gas cup was experienced in high pressure and the Not shale is sealing over the Norne Main Structure, there is no communication across the Not formation during the production. The gas injection was changed to inject in the water zone and the lower part of the oil zone. Injection fluids have been both gas and water up to 2004, in 2005 the gas injection was ended and the oil was produced only by water injection as a drive mechanism. Further, since the prediction of gas flow in the reservoir became more uncertain, a higher GOR than expected caused the production to be restricted by gas handling capacity. Gas export was started in order to obtain a balanced gas and water injection strategy, and prevent further increase in GOR. (The wells on template F have only injected water while the wells on the C - template have injected both water and gas again in 2006 to prevent pressure depletion in the gas cap. Figure 3.7.2)

The horizontal oil producer in Tofte and lower Ile formation will be plugged and sidetracked and drilled horizontal in Upper Ile Formation just below the Not Formation shale when the water cut become too high(over 70%-80%) resulting in problems to lift the liquid.

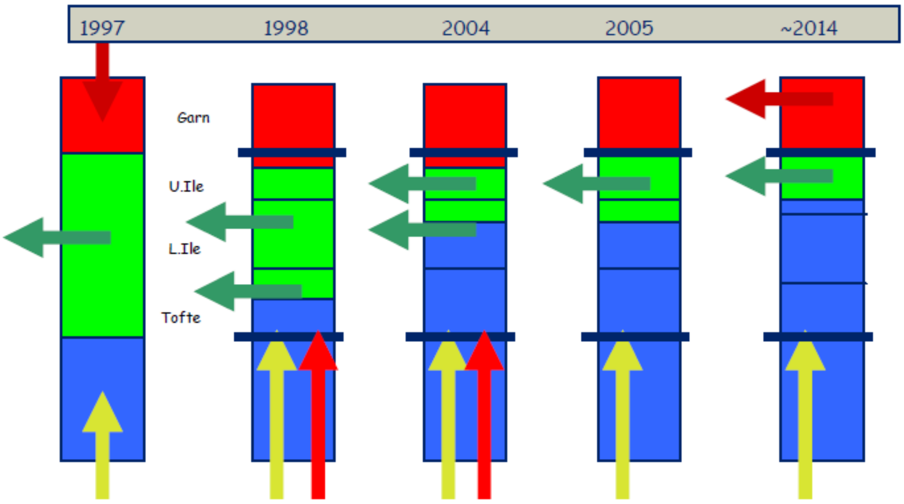


Figure 3.7.2 Drainage strategy for the Norne Field. Vertical arrows are injection streams, horizontal arrows are production streams. Blue is for water, green for oil and red for gas. [25]

3.8 Time-lapsed seismic reservoir monitoring

The Norne Field is a flat horst structure and a change in fluid contacts during production has to be monitored by the difference in seismic signals from the reservoir zone from year to year.

The initial seismic survey on the Norne Field was acquired in 1992. A dual source and three streamers separated by 100m were used. The next five surveys, shot for time-lapsed purposes, have been collected in 2001, 2003, 2004, 2006 and 2008. All surveys were acquired with the WesternGeo Q-Marine system. A single source and six steerable streamers separated by 50m were used in all monitor surveys. It was decided not to steer to repeat the feathering of the base survey. Instead all lines were acquired as close as possible to a zero feather, because this is much easier to repeat time - lapse changes in the reservoir between the different years are identified by use of these data. The first monitoring survey was done in 2001 to monitor the oil-water contact and drainage of the field. This survey was named ST0113, this was considered as the base Q-survey and all the new surveys repeat this geometry as accurately as possible. In June 2003 a second survey named ST0305 was acquired. It covered 85 km^2 and it was allowed time - lapse changes in the reservoir between 2001, 2003 to be identified. In July 2004, the 3rd

Q - marine survey over Norne ST0409 was shot. This was acquired as identically as possible to the 2001 and 2003 surveys, but covered a larger area of $146km^2$. In July/August 2006 the 4th Q - marine survey over Norne ST0603 was shot. This was acquired as identically as possible to the 2004 survey. [28] The survey area is shown in figure 3.8.1. 4D data with difference between 2001 and 2006 are shown in Figures 3.8.2.

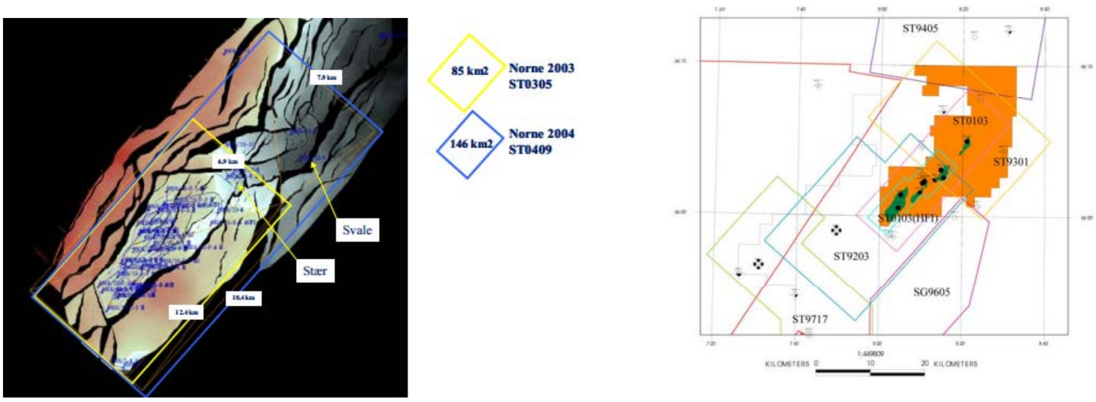


Figure 3.8.1: Seismic surveys in the Norne Field area [29]

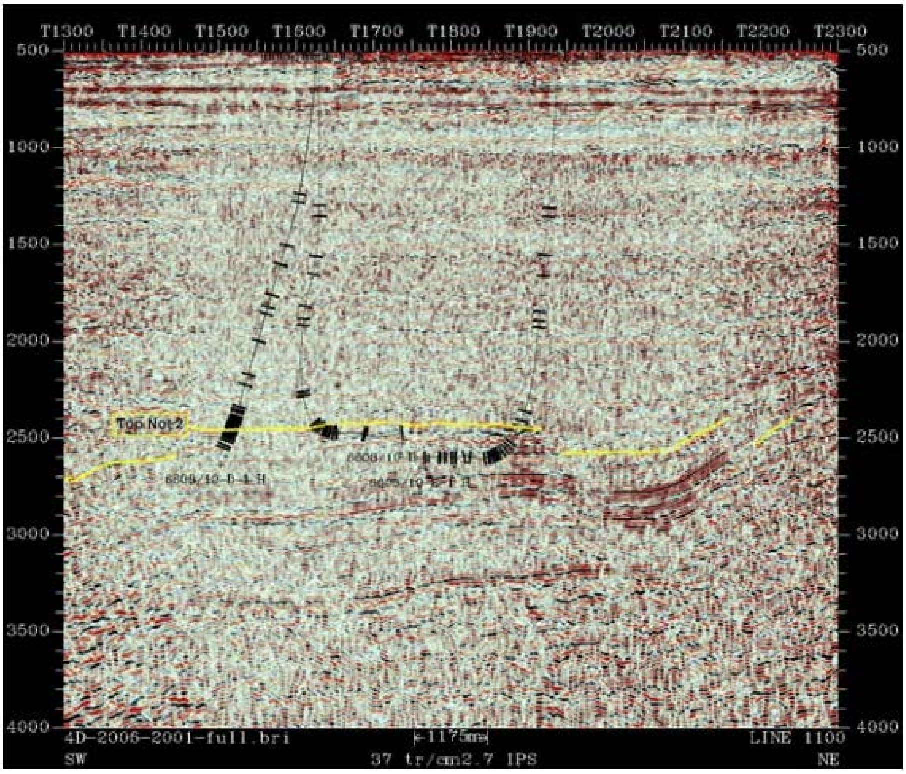
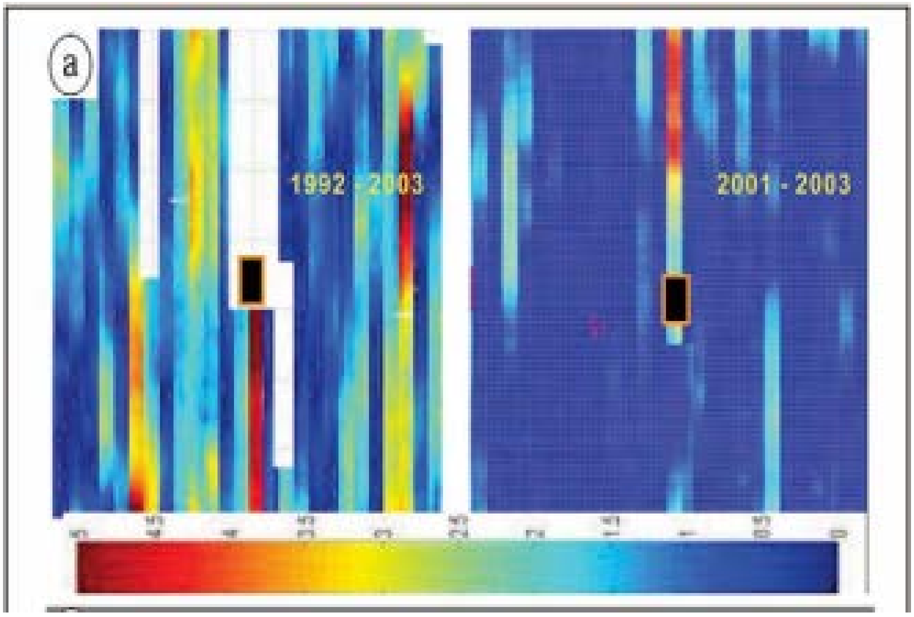


Figure 3.8.2: 4D Seismic, line number 1100, 2001-2006 [25]

Figure 3.8.3 shows the feathering difference between the base survey and the Q-acquisitions in 2003, and between the Q-acquisitions in 2001 and 2003. Much larger feathering differences are seen with the base survey than between the Q-marine surveys. As seen in Figure 3.8.4, this clearly influences the amount of non-repeatable noise in the 4D data. The repeatability between the Q-marine surveys is clearly better than between the base and Q-surveys. Average nrms for base versus Q is approximately 40%, the corresponding number for Q versus Q is 19-21%. [29]



3.8.3 Left is feathering difference between base and 2003, and right is difference between 2001 and 2003[29]

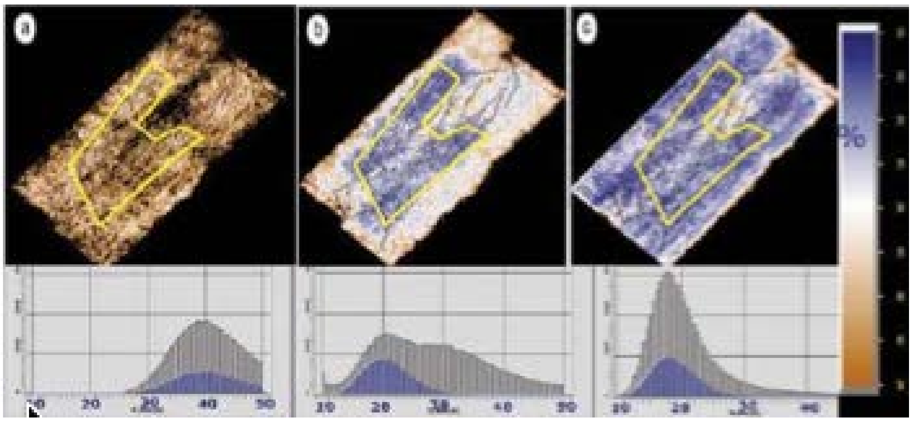


Figure3.8.4. The nrms maps and nrms histograms measured on the 4D data in overburden of (a) base and 2001, (b) 2001 and 2003, and (c) 2003 and 2004. Blue data points in the histogram are related to the yellow polygon on the map.

Changes in acoustic impedance are due to pressure or saturations changes, which lead to a different velocity. Therefore, 4D seismic data at Norne field has been used to observe the difference in amplitude and acoustic impedance. Results have been used to adjust the simulation model [28]. The 4D results have indicated changes in the saturations, which the simulation model did not predict. The pressure or saturation change is shown as variable density, while the 4D cube is put on top as wiggle. In order to do this, it is important that both the 4D data and the interpretations are made in either depth or time. It is possible to convert the cubes between depth and time by use of a velocity cube. Figure 3.8.5 shows 4D seismic overlaid interpretation of pressure changes from 2001 until 2006.

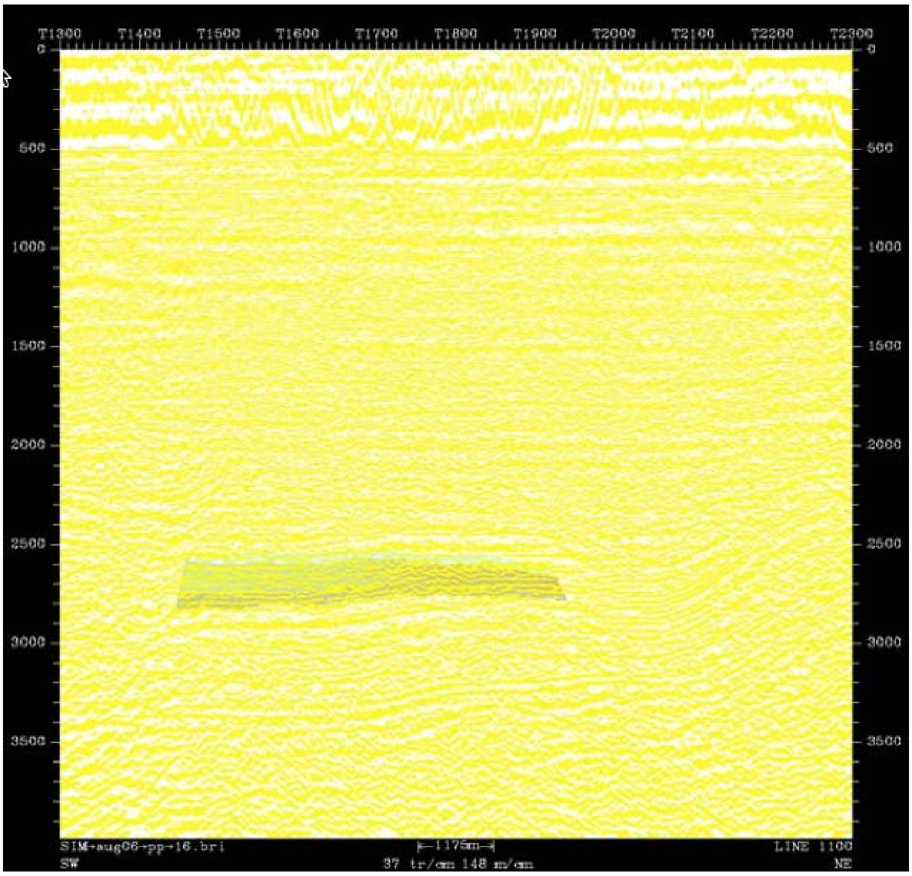


Figure 3.7.7 4D seismic overlaid interpretation of pressure changes from 2001 until 2006[25]

4D seismic is an important tool in connection with well planning. By studying the water saturation changes in the reservoir, water flooded areas can be located and avoided as possible well locations. The 4D seismic can also be utilized in the work of history matching by comparing real seismic with synthetic seismic created from the simulation output. Agreement and disagreement between the simulation model and the historical data can be discovered from such a comparison.

As mentioned above, synthetic seismic can be made from simulation programs. A program, which generates seismic pictures from the Eclipse simulation is developed by Alexey Stovas at NTNU. The software enables the ability to compare real seismic with synthetic seismic. Differences found from comparisons can tell something about accuracy of the Eclipse simulation.

4. THE NORNE FILED SIMULATION CASE

4.1 Introduction

The reservoir model was developed based on a 2004 geological model, which is interpretation of the 4D seismic surveys ST0103, ST0305, ST0409. The simulation grid was based on updated fault polygons and new structural and isochore maps. Isochore maps were generated for every individual reservoir zone. They were constructed based on reservoir zonation data, available sedimentological data and overall gross reservoir thickness variations determined by seismic data.

The interactive Reservoir Analysis Package (IRAP) was used for reservoir modeling. Grid cell sizes of 50x50 meters were used to represent the reservoir. Major faults in the field were modeled using true dips, while small faults less than 20 meters by simple addition. Wells in the field are treated as deviated wells, by employing true vertical depths and deviation data.

4.2 Description of the Norne Simulation Model

4.2.1 Grid

The simulation model has grid dimensions 46x112x22 with blocks of approximately 80-100m in x-and y-direction consists of 113344 grid cells of which 44927 are active.

It has a rotation angle of 52.9 degrees. Maximum point is located at depth -2439 and minimum point is at – 3090. The thesis concentrates on Norne-E segment which consists of 8646 active grids and composed of 11x52x22 blocks. The reservoir was divided into 22 reservoir zones for modeling. Some of the boundaries between zones were selected as sequence boundaries and maximum flooding surfaces. Other boundaries were based on lithology or defined on porosity/permeability from wells 6608/10-2 and 6608/10-3. Surrounding wells were used for correlation of boundaries. The model's UTM coordinates is shown in Table 4.2.1. Table 4.2.2 illustrates the current reservoir zonation, which is used in the simulation model in the Eclipse software.

The root mean squares (RMS) have been used for generating the grid and populating the grid with petro-physical properties.

Table 4.2.1 Simulation model UTM coordinates and depth

Axis	Min	Max	Delta
X	455465.75	462761	7295.27
Y	7319112.25	7327079	7966.75
Depth	-3090.13	-2439.11	651.02

Table 4.2.2 The current reservoir zonation

Layer	Formation	Layer	Formation
1	Garn 3	12	Tofte 2.2
2	Garn 2	13	Tofte 2.1.3
3	Garn 1	14	Tofte 2.1.2
4	Not	15	Tofte 2.1.1
5	Ile 2.2	16	Tofte 1.2.2
6	Ile 2.1.3	17	Tofte 1.2.1
7	Ile 2.1.2	18	Tofte 1.1
8	Ile 2.1.1	19	Tilje 4
9	Ile 1.3	20	Tilje 3
10	Ile 1.2	21	Tilje 2
11	Ile 1.1	22	Tilje 1

4.2.2 Reservoir properties

Porosity, permeability and net-to-gross (NTG) properties are imported from the geological model. Vertical permeability is set to a ratio of horizontal permeability and the stratigraphical barriers. The following figures (4.2.2.1 to 4.2.2.4) show reservoir properties: porosity, permeability and NTG cross section through producer E-3H.

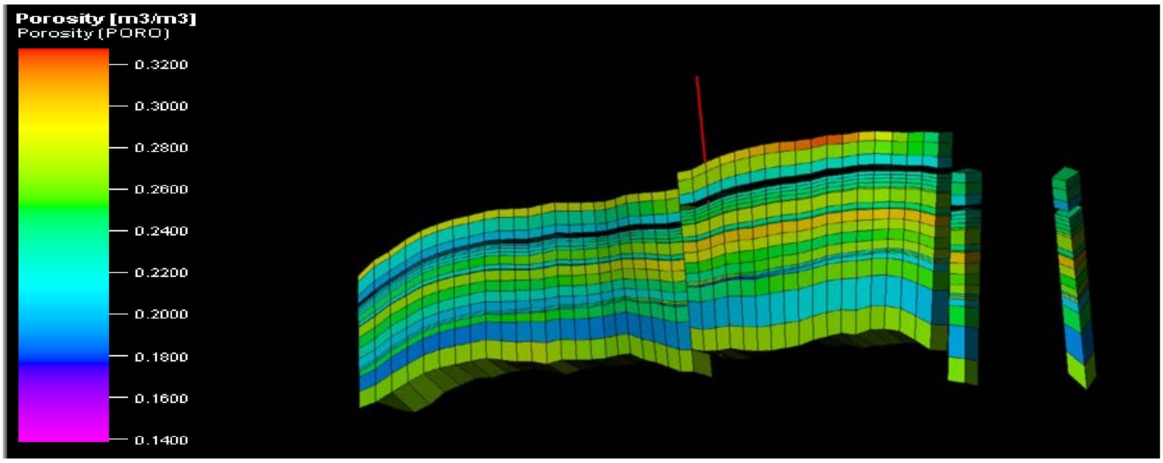


Figure4.2.2.1, reservoir porosity, view from north to south, cross section i=12 through the producer E-3H

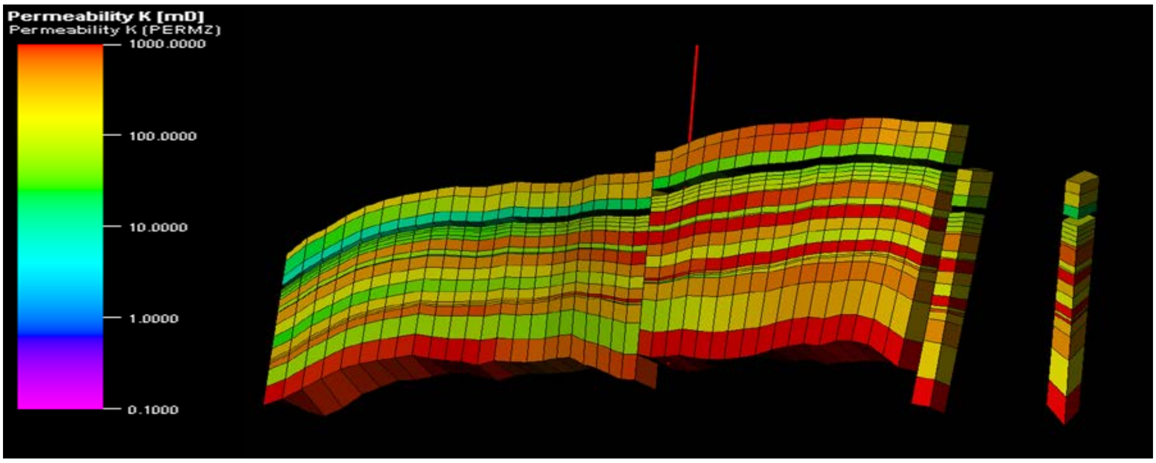


Figure4.2.2.2, horizontal permeability, view from north to south, cross section i=12 through the producer E-3H

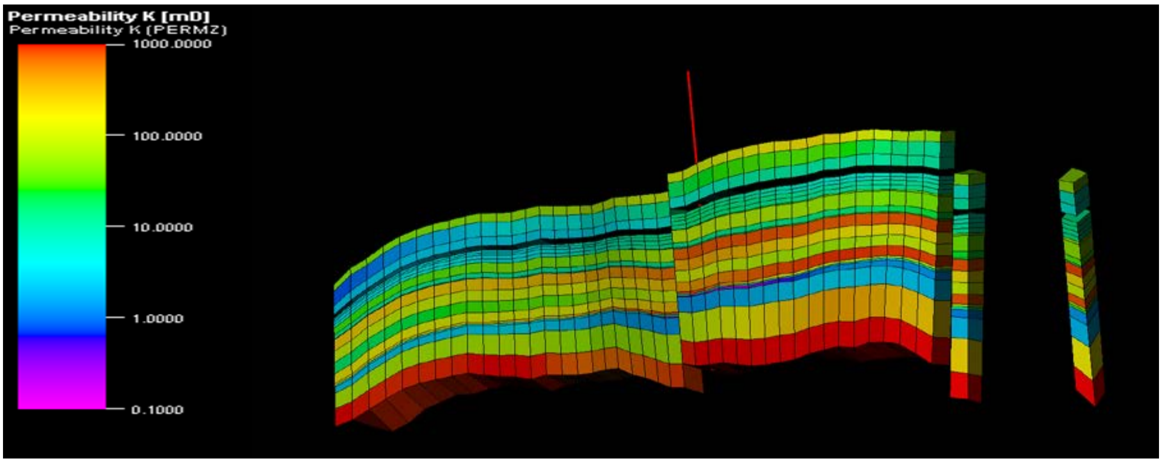


Figure 4.2.2.3, vertical permeability, view from north to south, cross section i=12 through the producer E-3H

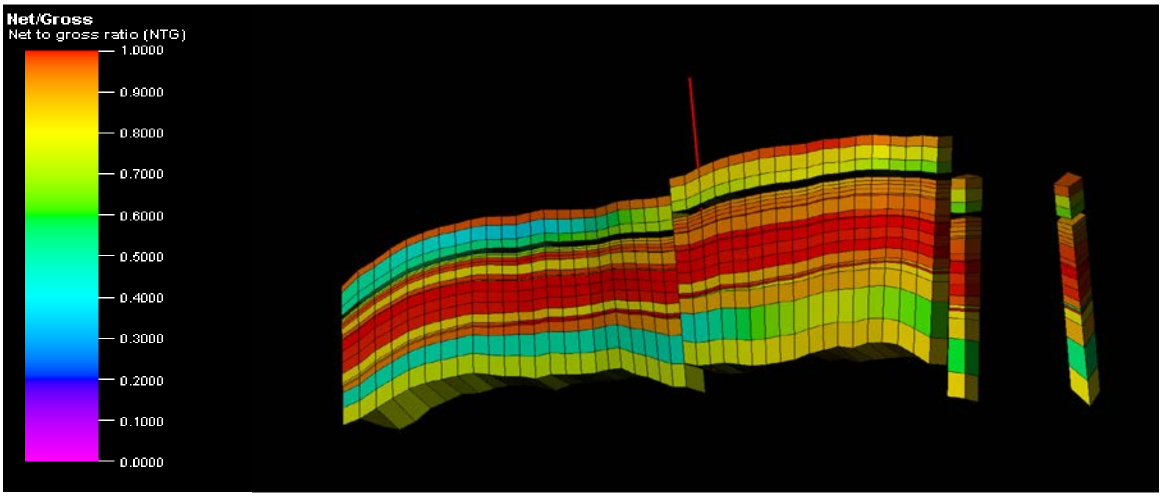


Figure 4.2.2.4, reservoir NTG, view from north to south, cross section i=12 through the producer E-3H

Initial saturations are shown in figure (4.2.2.5 to 4.2.2.7) below:

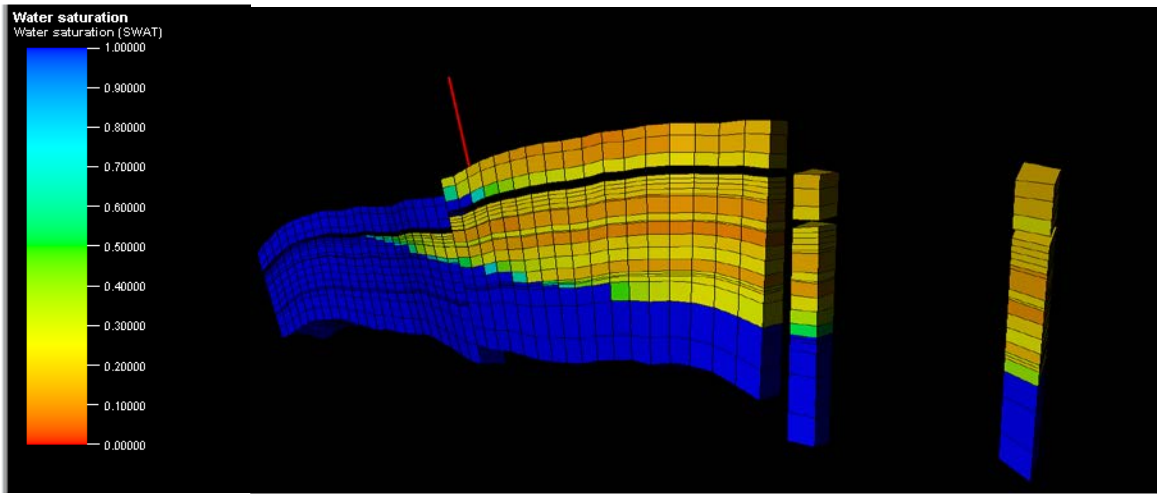


Figure 4.2.2.5 Initial Water saturation, view from north to south, cross section i=12, through the producer E-3H

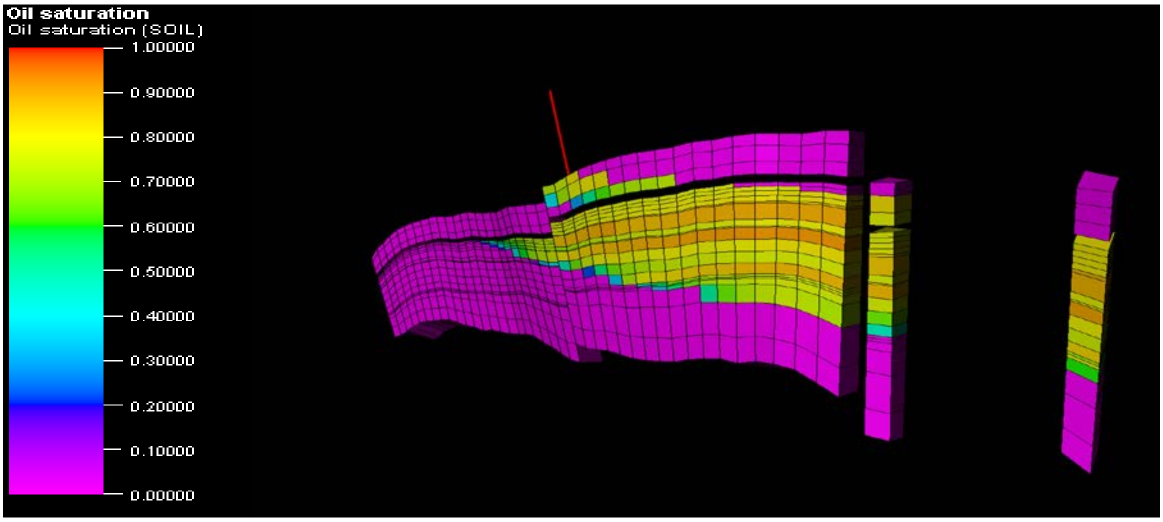


Figure4.2.2.6 Initial oil saturation, view from north to south, cross section i=12, through the producer E-3H

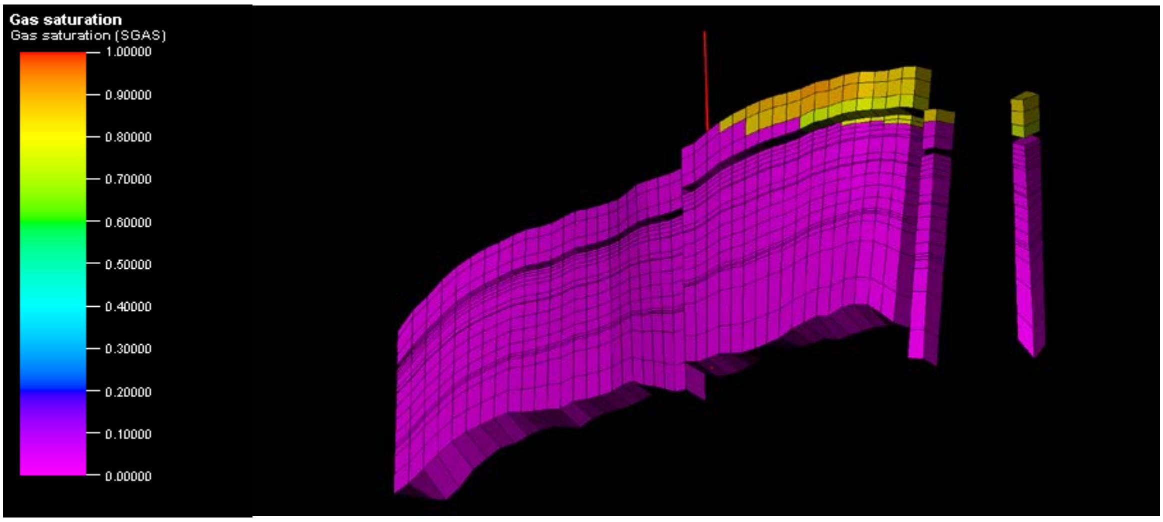


Figure 4.2.2.7, Initial gas satuation, view from north to south, cross section i=12, through the producer E-3H

4.2.3 Fluid Contacts

The fluid contact in reservoir simulation model is given in Table 4.2.3.1

Table 4.2.3.1 Fluid contact in the reservoir simulation model

Datum	Pressure	WOC	GOC	Segment	Formation
m	bar	m	m	-	-
2582.0	268.56	2692.0	2582.0	C and D	Garn
2500.0	263.41	2585.5	2500.0	G	Garn
2582.0	269.46	2618.0	2582.0	E	Garn
2200.0	236.92	2400.0	2200.0	G	Ile and Tilje
2585.0	268.77	2693.3	2585.0	C and D and E	Ile and Tilje

4.2.4 Wells

The field has been developed 7 wells, three oil producers (E-2H, E-3H, E-3AH) with 2 side tracks and two water injectors (F-1H, F-3H). Wells data are list in Table 4.2.4.1, Wells on Norne E segment are shown in the figure 4.2.4.2. Figure4.2.4.3 shows the perforation of E-3AH and distribution of E-3H and E-3AH on layer 2. Figure 4.2.3.4 shows the perforation of E-2H. Figure 4.2.4.5 and 4.2.3.6 shows PERMZ of layer 2 and layer 9 respectively.

Table 4.2.4.1 Wells data

Well Name	Well Type	Start Production	End Production
E-3H	Producer	01 August 1998	01 May 2000 (stop production)
E-2H	Producer	01 November 1999	01 January 2004 (still producing)
E-3AH	Producer	01 December 2000	01 January 2004 (still producing)
F-1H	Injector	01 May 1999	01 January 2004
F-3H	Injector	01 September 2000	01 January 2004

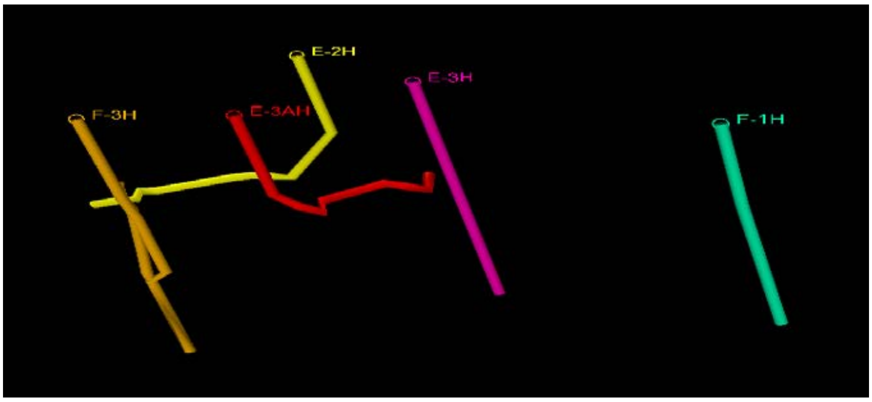


Figure 4.2.4.2 Wells on Norne E-segment

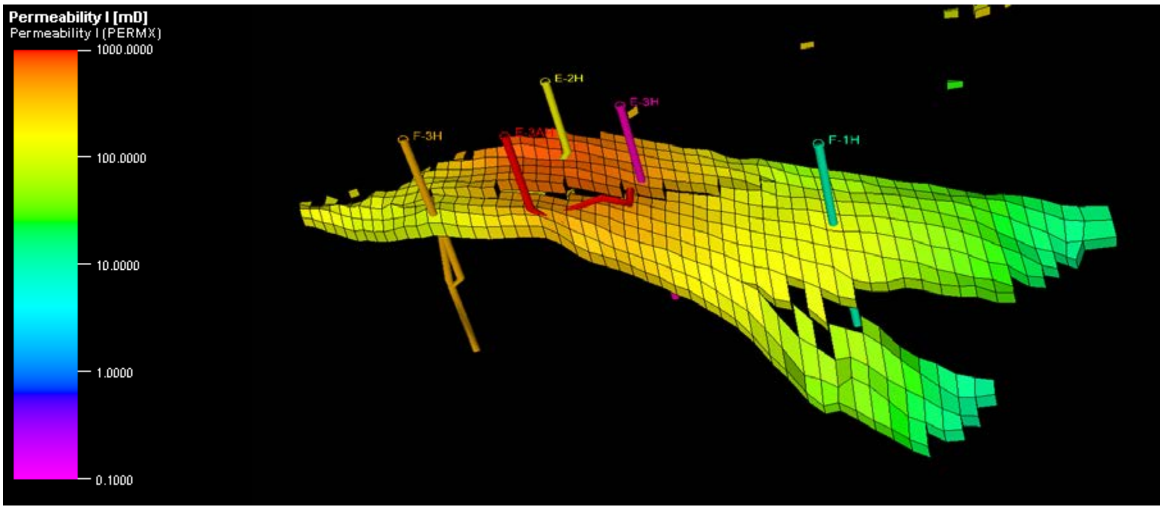


Figure 4.2.4.3 PERMX for layer 2

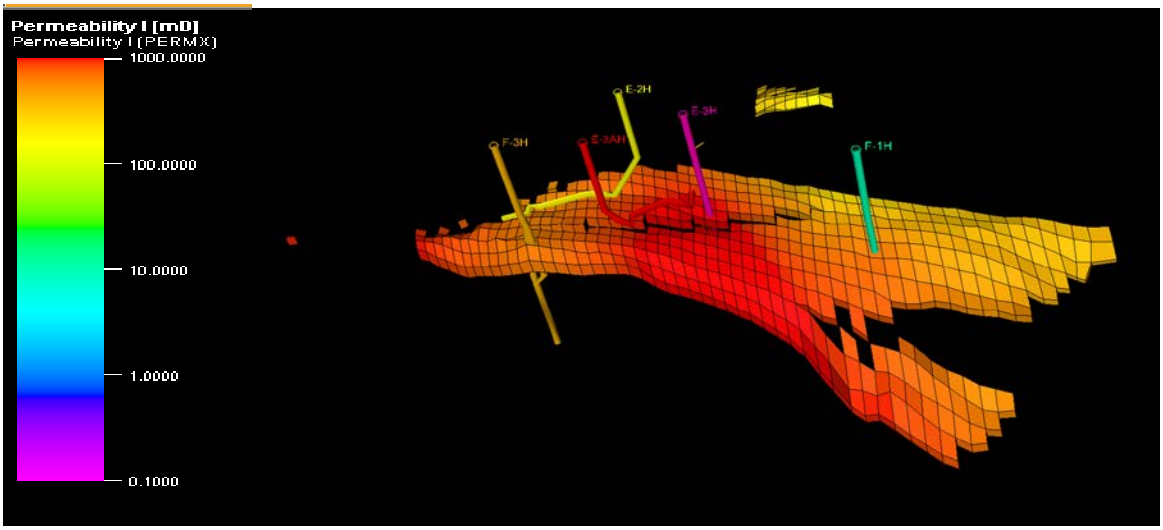


Figure 4.2.4.4 PERMX for layer 9

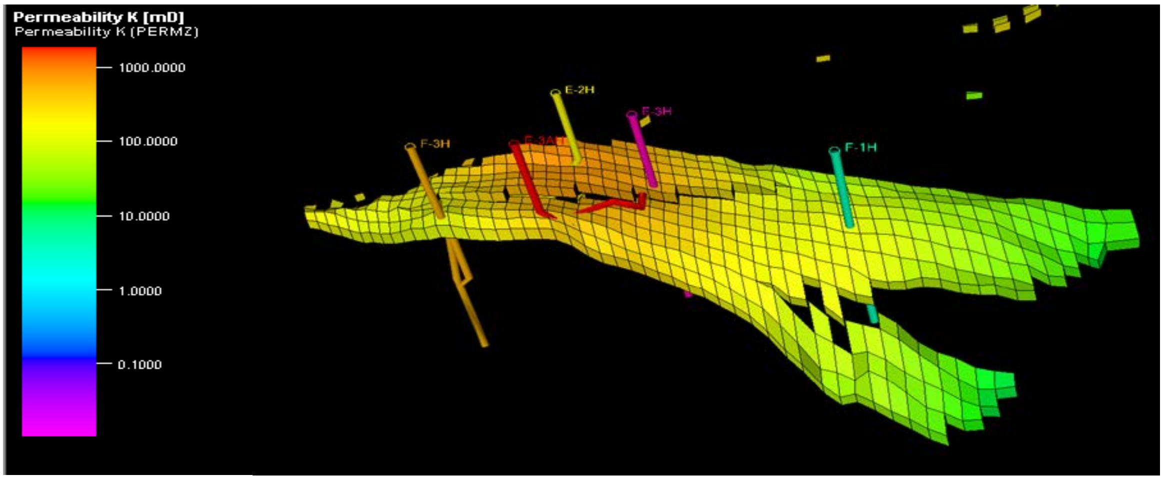


Figure 4.2.4.5 PERMZ for layer 2

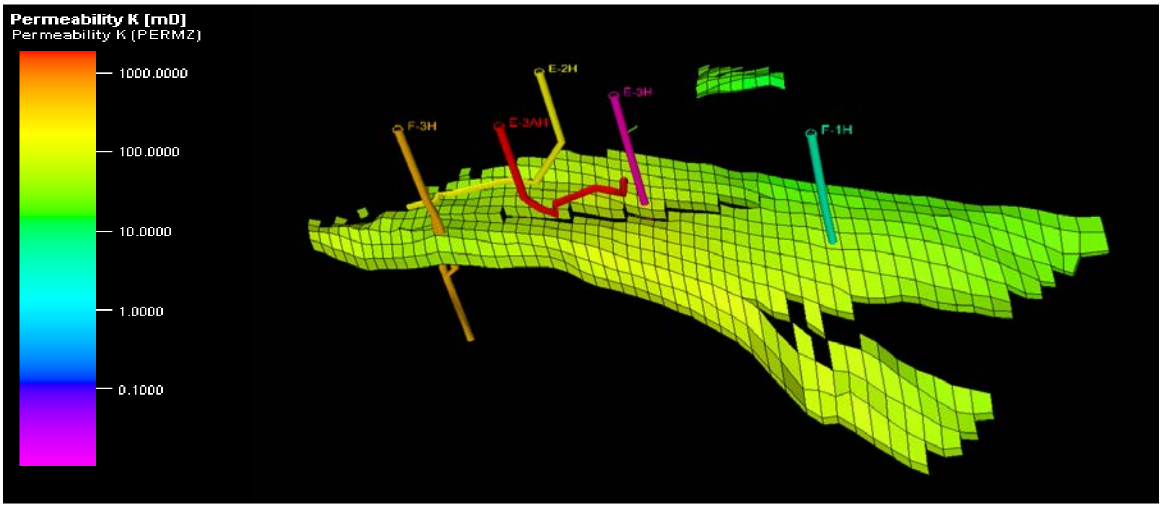


Figure 4.2.4.6 PERMZ for layer 9

4.2.5 Faults

The faults were done by dividing the fault planes into sections that followed the reservoir zonation. Then each subarea of the fault planes needed to be assigned transmissibility multipliers. These are a function of rock permeability, fault zone width, matrix permeability (host rock) and dimensions of the grid blocks in the simulation model [25] Figure 4.2.5.1 illustrates this, and the equation for the transmissibility multiplier is given below.

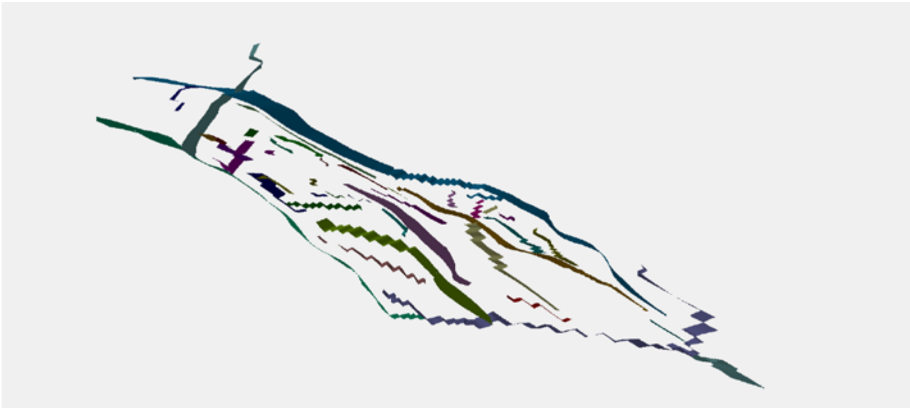


Figure 4.2.5.1 Faults in the 2004 simulation model

Faults influence flow in a reservoir simulation model in two ways. First, they change the connectivity of sediment logical flow units. Faults generally increase the overall vertical connectivity of a reservoir and decrease the overall horizontal connectivity, but the precise influence of fault displacements on reservoir connectivity is complex, as seismic data cannot resolve details of fault structure: what appears to be a single fault on seismic often comprises multiple fault strands which can have a significantly different effect on flow unit connectivity than a single strand.

Faults in reservoirs are sampled either at low resolution by seismic or at a high resolution by wells. Seismic interpretation provides information about the locations and displacements of large faults, but cannot resolve the small scale structure within the fault zone. Wells sample faults at a particular point in a reservoir, and cored faults provide direct samples from which fault zone properties can be measured. Fault zones are complex heterogeneous and anisotropic volumes of varying composition and thickness, and a well samples only a single line through a zone. Predicting flow through a fault requires a model of fault zone structure at a resolution, which cannot be obtained from either data source.

Faults transmissibility are considered sealing in the base case and individually adjusted when history matching using the ECLIPSE keyword MULTFLT. The MULTZ and MULTFLT keywords are transmissibility multipliers in the z-direction and across a fault, respectively. [25]

Fault transmissibilites, MULTFLT is used in the Norne full field model but not the Norne E-segment model. The value of MULTFLT can be seen in Table 4.2.5.2

Table 4.2.5.2 MULTFLT Norne E-segment model

Fault name	MULTFLT
E_01	0.01
E _01_F3	0.01
DE_1	3.9
DE_B3	0.00075
DE_2	0.015
DE_0	20
EF	1.0
m_north	1.0
m_west	1.0

4.3 Provided data

Basically there are two kinds of data supplied, production data and seismic data. Also reports showing different development stages of the field have been provided. The released data includes:

1) Reservoir simulation model of full field in Eclipse format, with historical data

2) All wells including well picks, and well position time-depth conversion and well logs.

3) The reservoir is been producing since 1997, oil rates, water and gas rates are available for each well. WHP and BHP are also recorded.

4) Production data for each well up to 2006 are given for history matching purpose.

5) 4D seismic data in 2001 is used as base case and three monitors in 2003, 2004 and 2006 for E-segment are available.

6) Difference in saturation and pressure in each cell from 2003 and 2004 inverted seismic data.

7) Interpreted top reservoir horizon.

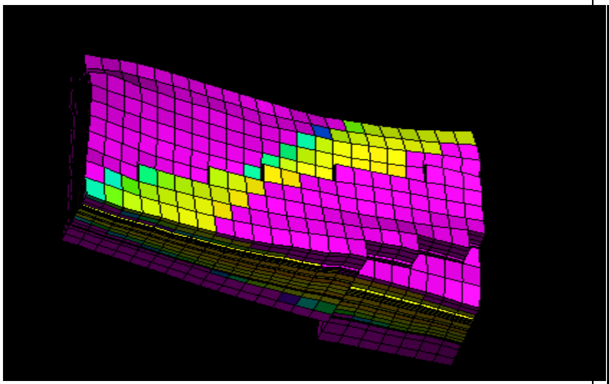
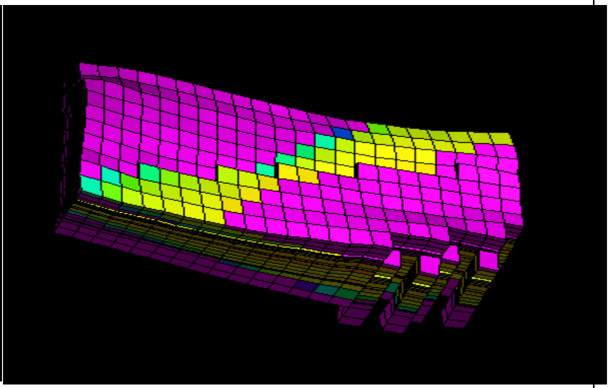
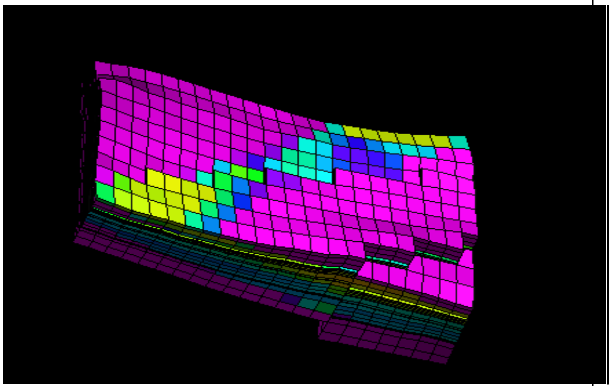
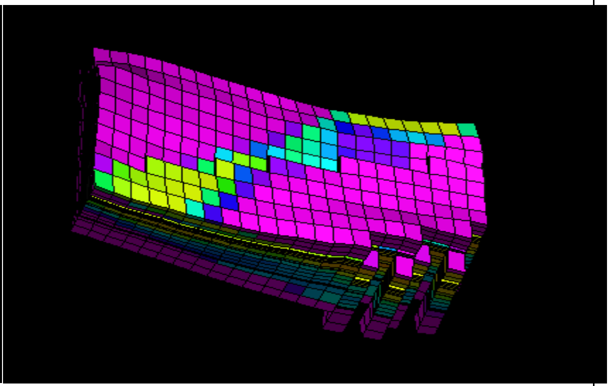
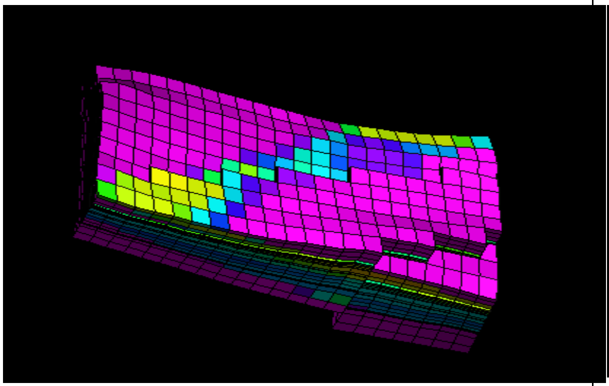
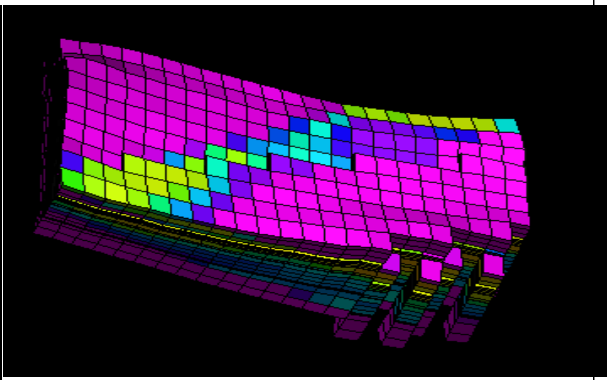
8) Interpreted faults.

9) Petro-elastic model.

4.4 Quality control of Norne E-segment model

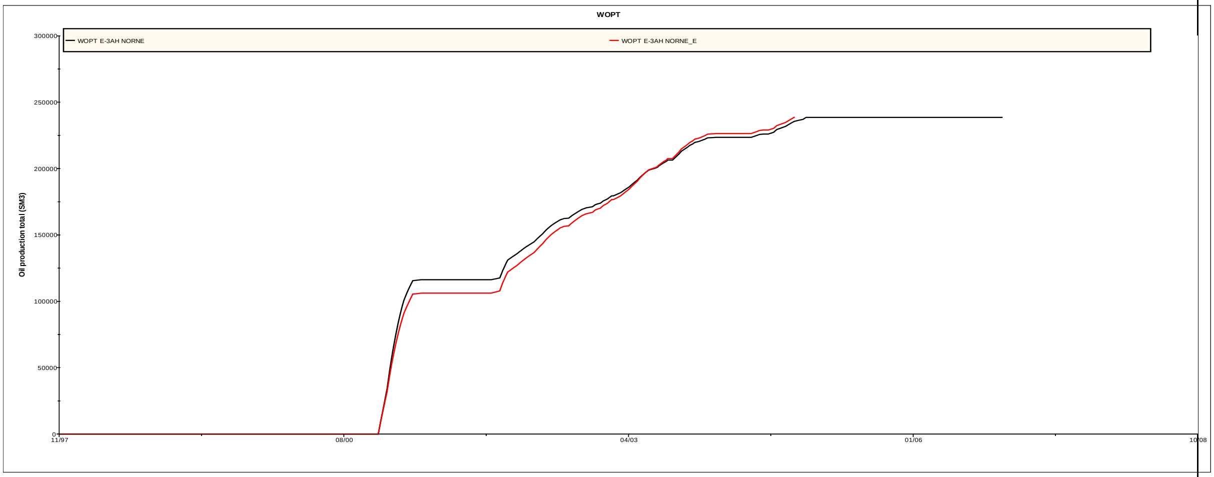
The model used in this thesis is the Norne E-segment model which is separated from the Norne whole field model. A checking should be done before history matching in order to ensure the quality of the E-segment model when isolated and compared to when it was attached to rest of field. The referred match is illustrated in table 4.4.1 and 4.4.2

Table 4.4.1Oil saturation match at different times

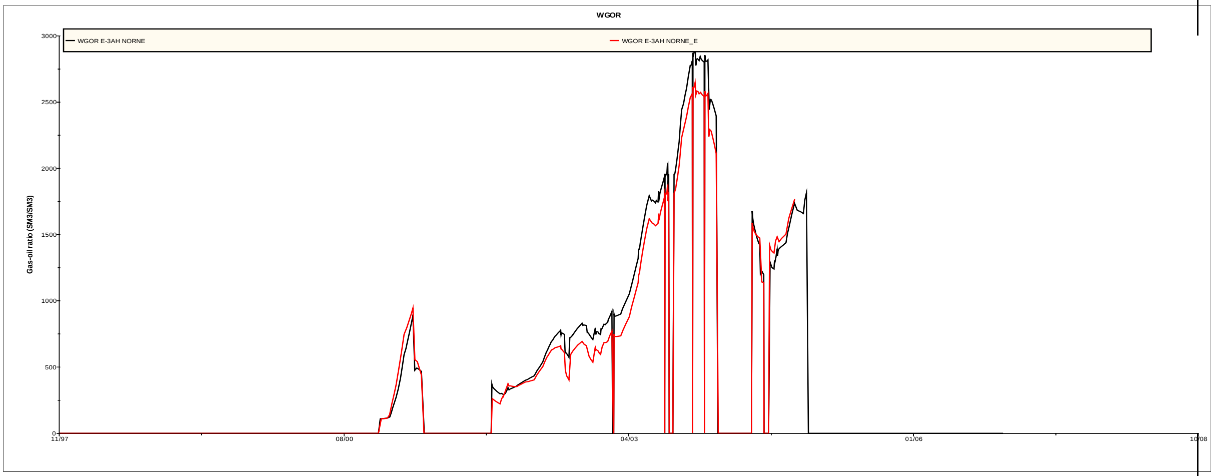
A Section from E-segment run in Full Field Model	A Section from E segment run in Separated E-segment Model
 06 November 1997	 06 November 1997
 02 January 2003	 02 January 2003
 19 January 2004	 19 January 2004

During the production process, a good match was obtained when a section was sliced from isolated segment and compared with the same section in attached segment. The quality testing was also done to the production well E-3AH. In the figure 4.4.2 The red line represents the full field model and the black line represents the separated E-segment. However, little differences exists, the quality is still good.

Table 4.4.2 Well E-3AH matching between the separated E-segment and attached E – segment.



Total Oil Production of Well E-3AH



Well gas-oil ratio: E-3AH

5. HISTORY MATCHING THE NORNE SIMULATION MODEL

5.1 The Base Case

Manual history matching is used as matching procedure in this thesis. The objective is to validate the reservoir model to reduce the uncertainties on reliable forecasts, not to simply fit the data. Therefore, the model should not only reproduce production data by numerical simulation, but also must be consistent with the geological knowledge of the reservoir. It is senseless to allocate an extremely high or low value which is impossible to have in reservoir real production life, reasonable modification is required. The manual history matching procedure is start with a base model and modifies reservoir properties by trial and error to adjust simulation results with the production history performance of the field. Production data will be matched due to lack of pressure data and the consistency of model is checked against the initial geological description during the matching procedure. Permeability and faults transmissibility is modified in order to meet the historical performances. History matching will be on a detailed level, individual well located on E segment will be history matched since the change in well production is obvious compared to the change in field production.

The history matching covers the period from production start 1998 to the revision stop at August 22 2004. The period from August to June 2005 is used as a check of prediction of model. From the figure 5.1.1 to 5.1.3, the Norne reservoir simulation model produces less oil except several months between year 2000 and year 2001 than reservoir actually produced in history because of Water Cut (WCT) is higher than history during that period.

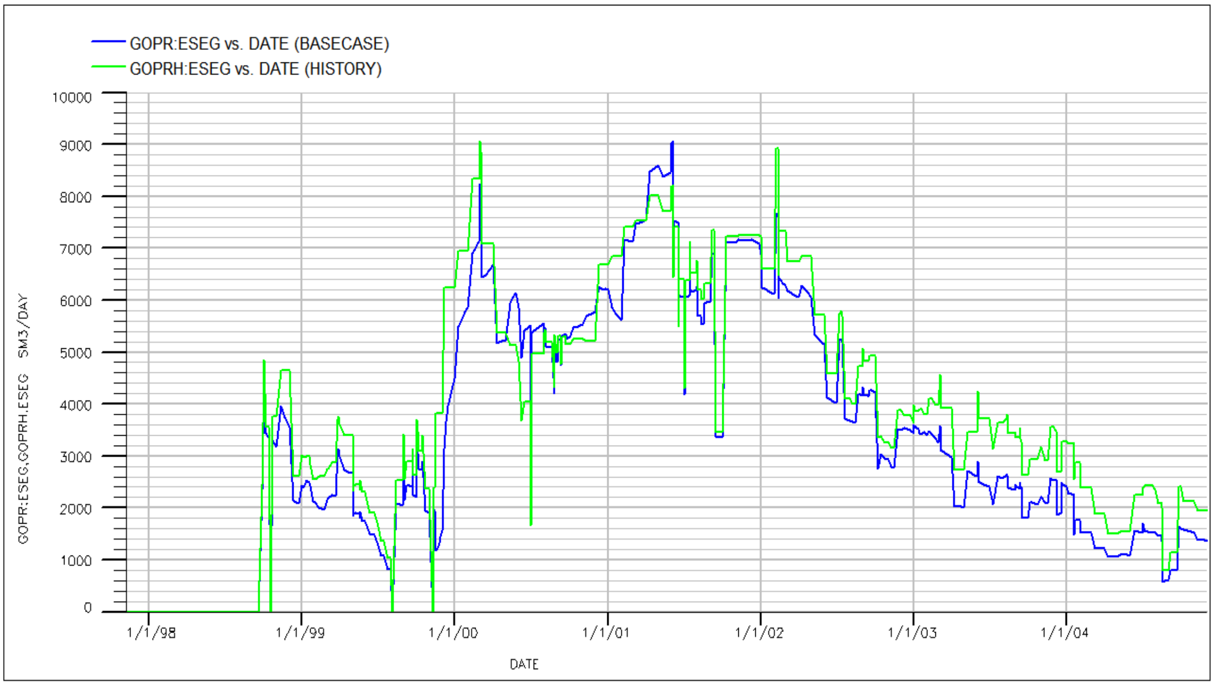


Figure 5.1.1 OPR for the base case and history Norne E-segment. Green=History value, Blue=model value

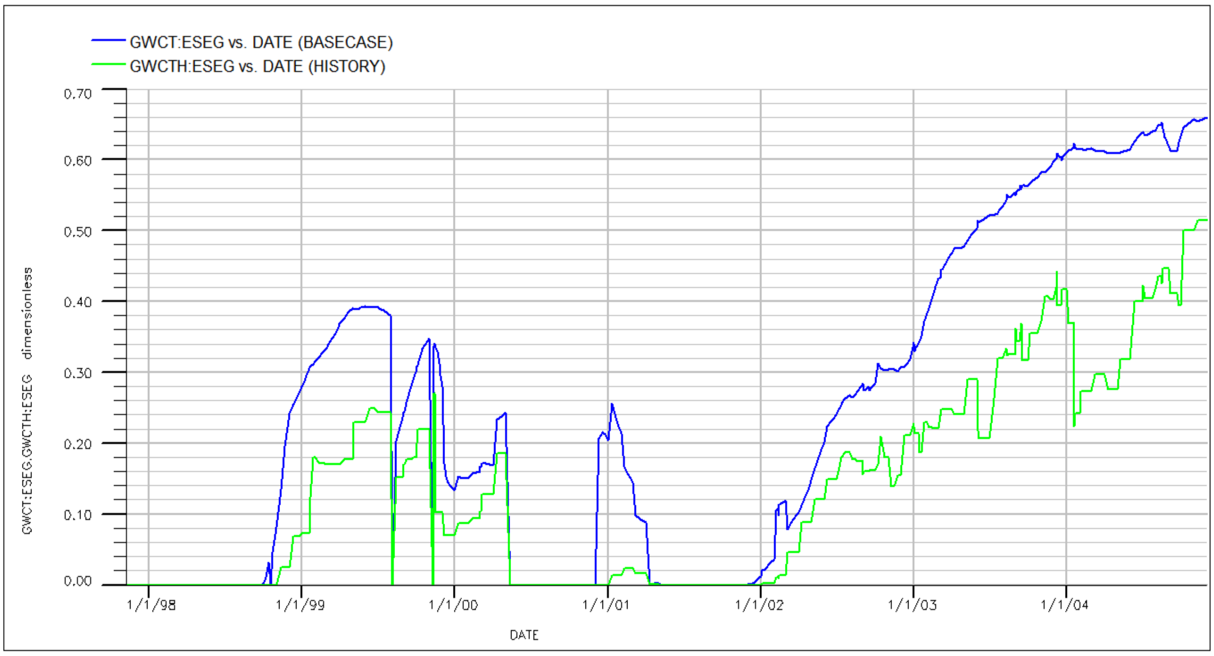


Figure 5.1.2 WCT for the base case and history Norne E-segment. Green=History value, Blue=model value

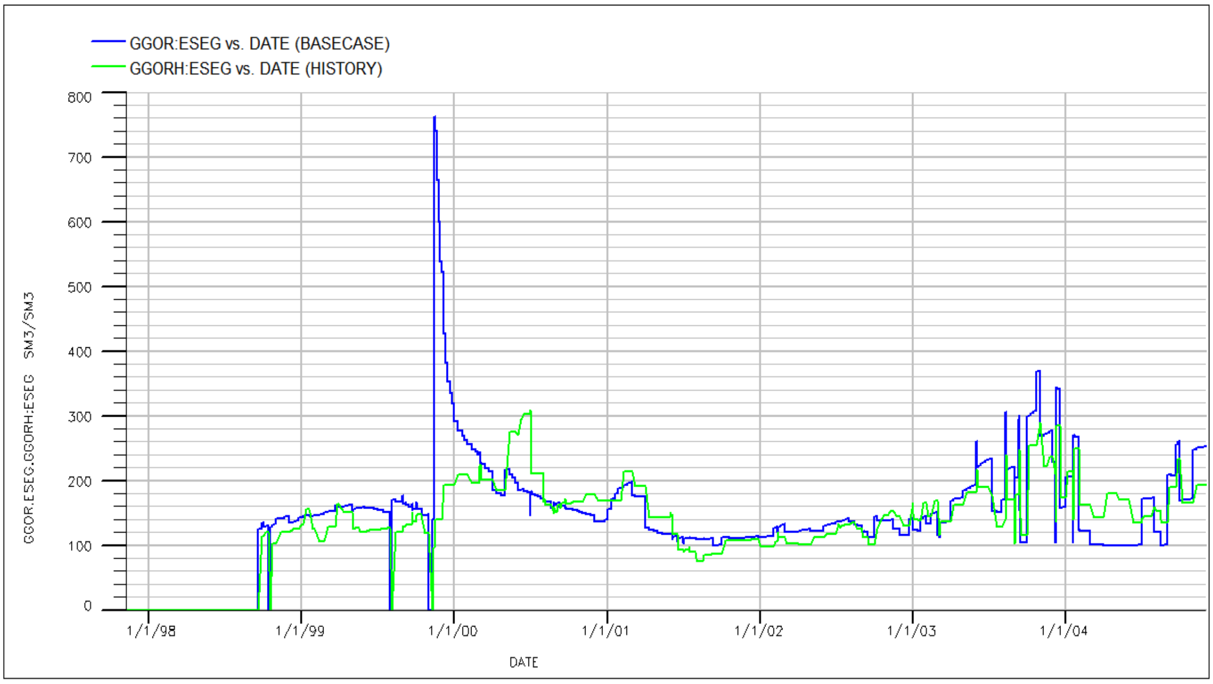


Figure 5.1.3 GOR for the base case and history Norne E-segment. Green=History value, Blue=model value

5.2 History Matching Norne Cases

5.2.1 Case1: Adjustment of PERMZ

First modification is to adjust vertical permeability (PERMZ) around the wellbore. First, cells to be modified are determined by using the Floviz software, each layer around wellbore are checked during the production period. The range of PERMZ is from 0.0106 to 1884.8177. The reservoir PERMZ distribution around the wellbore is shown in figure 4.2.4.5 and 4.2.4.6 in Chapter 4. Figure 4.2.2.3 shows the PERMZ difference in each layer.

As it is shown in base case figure, the water cut curve should be reduced in order to increase the oil production rate and cumulative oil production. The largest source of water in the simulation model is considered to be the underlying aquifer and water injection.

A sensitivity analysis of PERMZ is used to check if PERMZ have an obvious impact on cumulative oil production. PERMZ is multiplied a factor of 0.1, 0.2, 5, 10 to analyze the sensitivity of the wells, and the basecase is without alternations. Results of sensitivity analysis is shown in figure 5.2.1.1 to 5.2.1.5

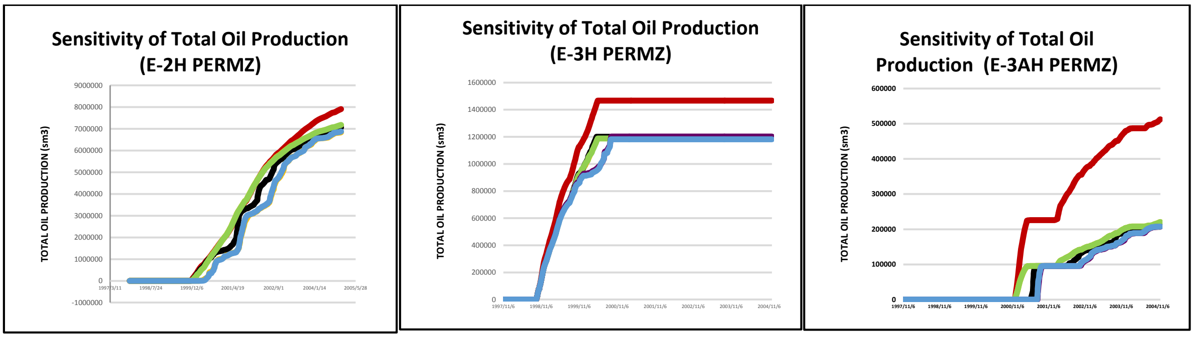


Figure 5.2.1.1 Sensitivity of total oil production by changing PERMZ of well E-2H.Red=History, Orange=Basecase, Blue=0.1xPERMZ, Green= 0.2xPERMZ, Black=5xPERMZ, Purple=10xPERMZ.

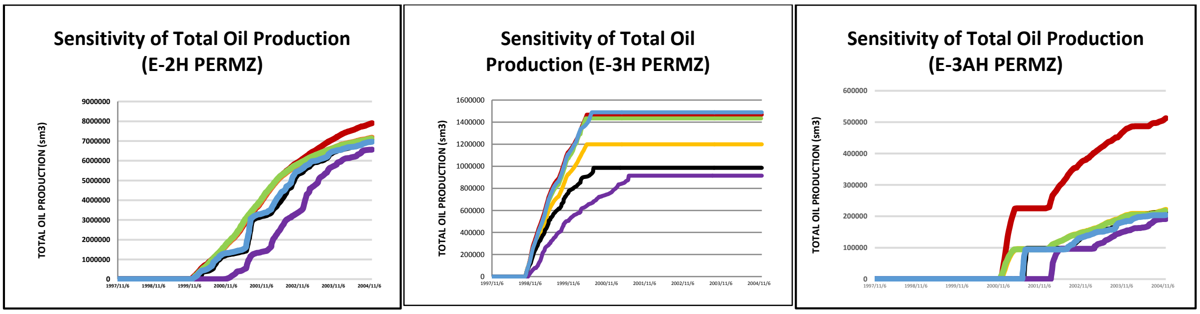


Figure 5.2.1.2 Sensitivity of total oil production by changing PERMZ of well E-3H.Red=History, Orange=Basecase, Blue=0.1xPERMZ, Green= 0.2xPERMZ, Black=5xPERMZ, Purple=10xPERMZ.

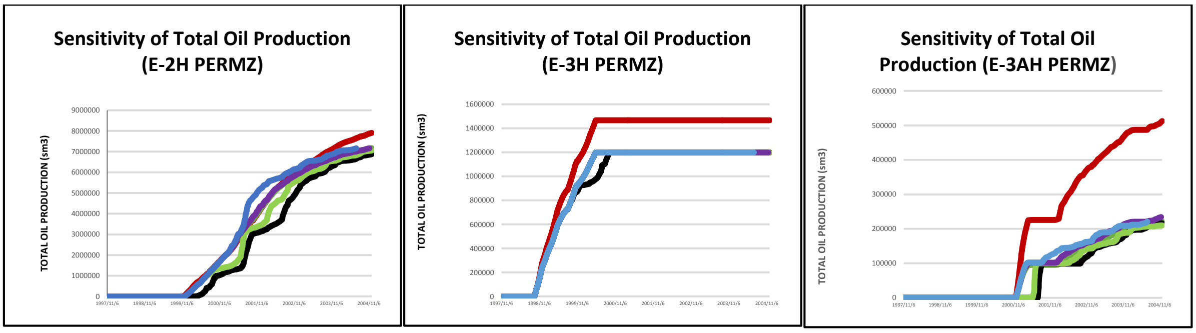


Figure 5.2.1.3 Sensitivity of total oil production by changing PERMZ of well E-3AH.Red=History, Orange=Basecase, Blue=0.1xPERMZ, Green= 0.2xPERMZ, Black=5xPERMZ, Purple=10xPERMZ.

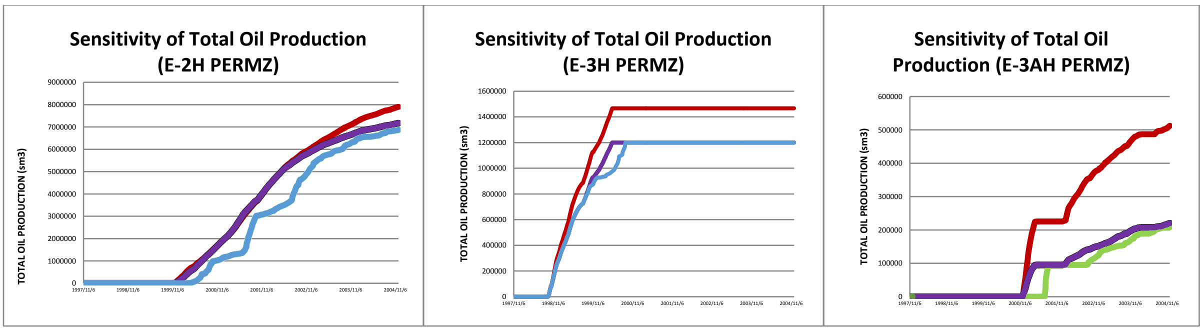


Figure 5.2.1.4 Sensitivity of total oil production by changing PERMZ of well F-1H.Red=History, Orange=Basecase, Blue=0.1xPERMZ, Green= 0.2xPERMZ, Black=5xPERMZ, Purple=10xPERMZ.

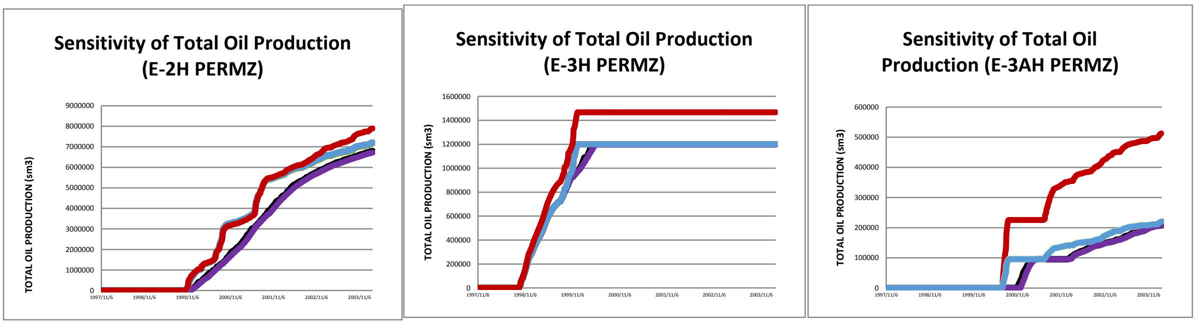


Figure 5.2.1.5 Sensitivity of total oil production by changing PERMZ of well F-3H.Red=History, Orange=Basecase, Blue=0.1xPERMZ, Green= 0.2xPERMZ, Black=5xPERMZ, Purple=10xPERMZ

As a conclusion of sensitive analysis, PERMZ affacts the cumulative oil production. Well E-2H is sensitive when the PERMZ around the production wells are altering. Well E-3H is highly sensitive when the PERMZ around the wellbore is altering and decreasing of PERMZ leads to increasing of comulative oil production. To change PERMZ of Well E-2H and E-3H have higher affection to the performances of other wells and to reduce the PERMZ value around wellbore of E-3H and E-2H could increase the cumulative oil producrtion for all wells and achieve a better match. E-3AH is neither sensitive nor have obvious affection on other wells. To change the permeability of two injection wells F-1H and F-3H give little affaction on production wells.

Altering of PERMZ around each wellbore is adjusted further. Oil and water production, oil and water production rates, water cut and gas oil ratio is taken into consideration when the suitability of PERMZ is tested. Water cut weighted more than the Gas Oil Ratio (GOR) when the best case is decided due to low quality of the history data for the gas. The case with best match is listed in Table 5.2.1.6.

The new field model with alternation in PERMZ is plotted with the basecase and history. Below is a plot of Oil production, WCT and GOR in figure 5.1.7 to 5.1.9. The most obvious change in the production data is the WCT. The new model has lower water cut. Detailed well behavior is plotted in figure 5.2.1.10 to 5.2.1.15.

Table 5.2.1.6 List of PERMZ modified in Case 1

Well name	PERMZ
E-3H	0.5
E-2H	0.01
E-3AH	3
F-1H	0.005
F-3H	0.005

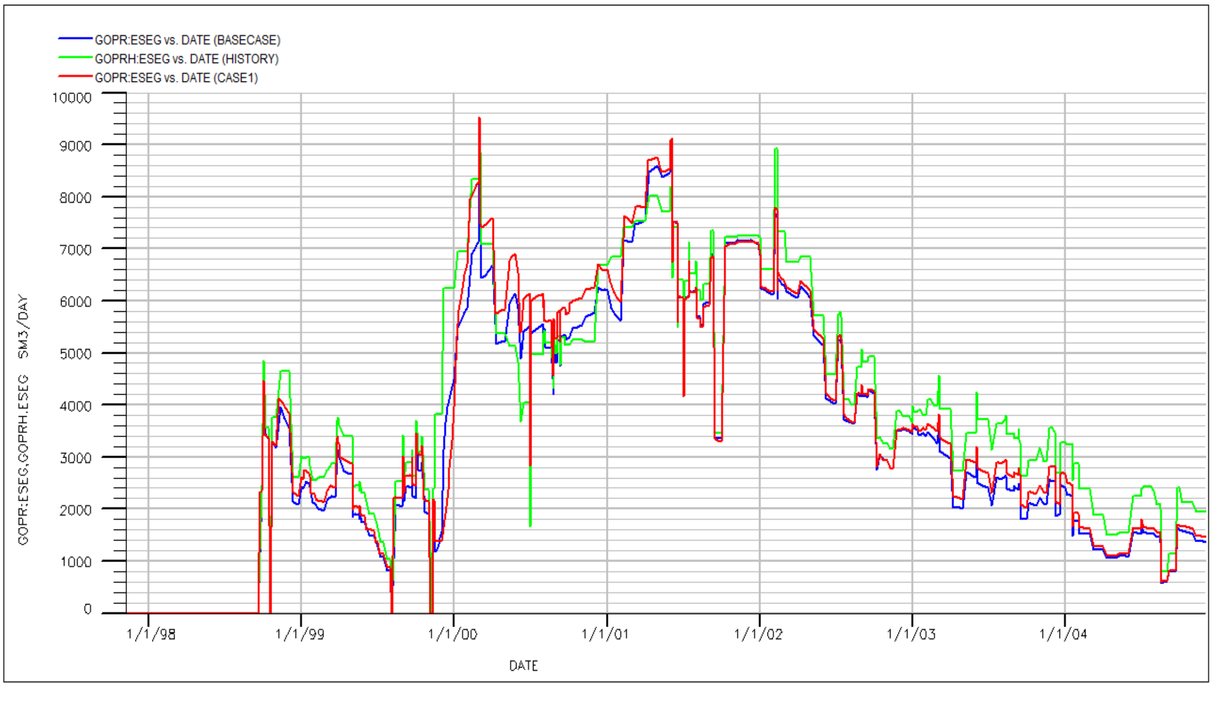


Figure 5.2.1.7 Oil Production rate E-segment. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

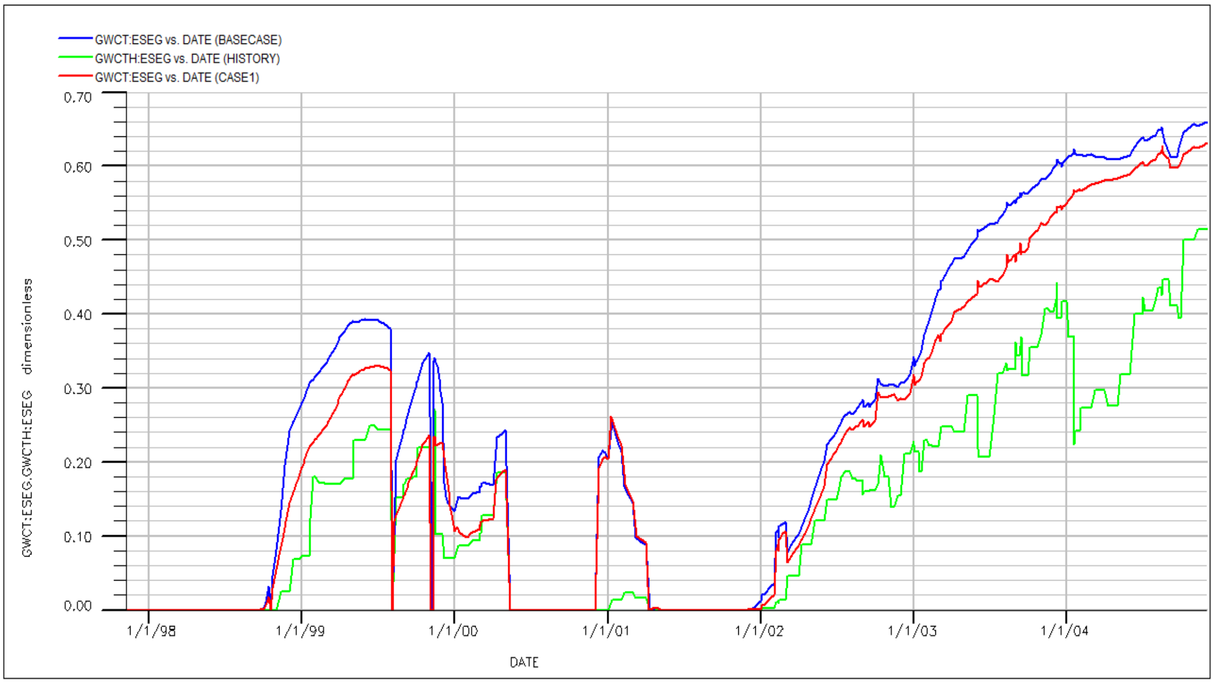


Figure 5.2.1.8 Water Cut E-segment. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

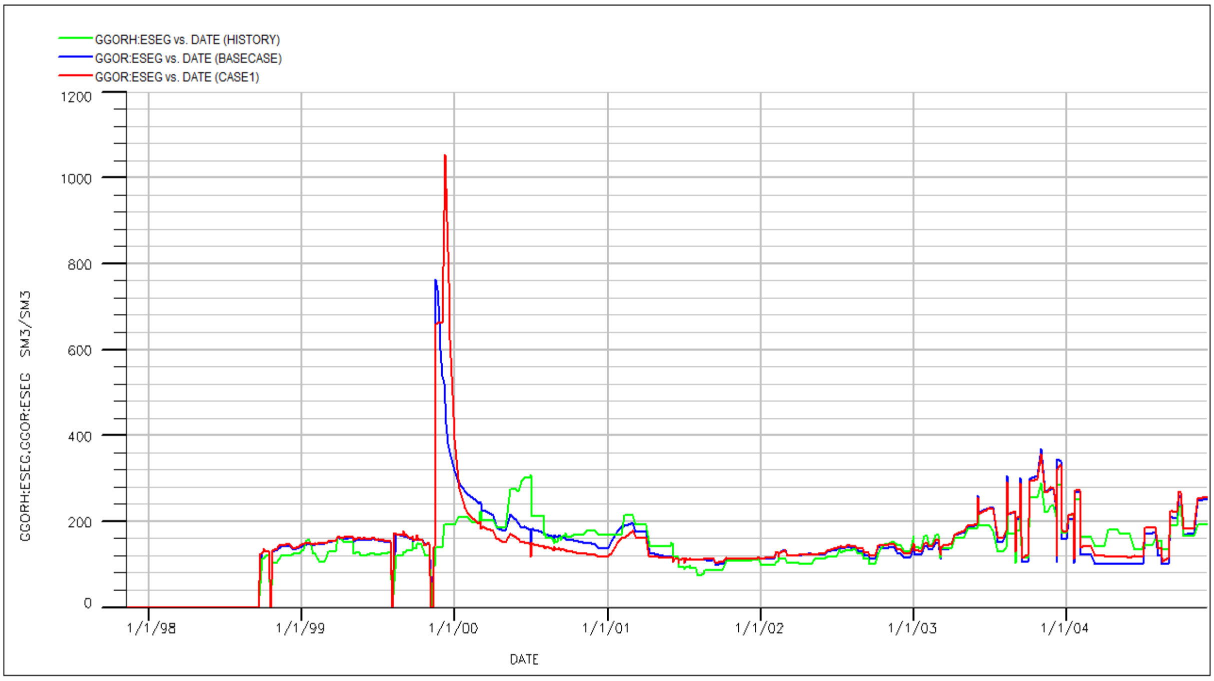


Figure 5.2.1.9 GOR E-segment. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

Figure 5.2.1.10 OPR E-2H. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

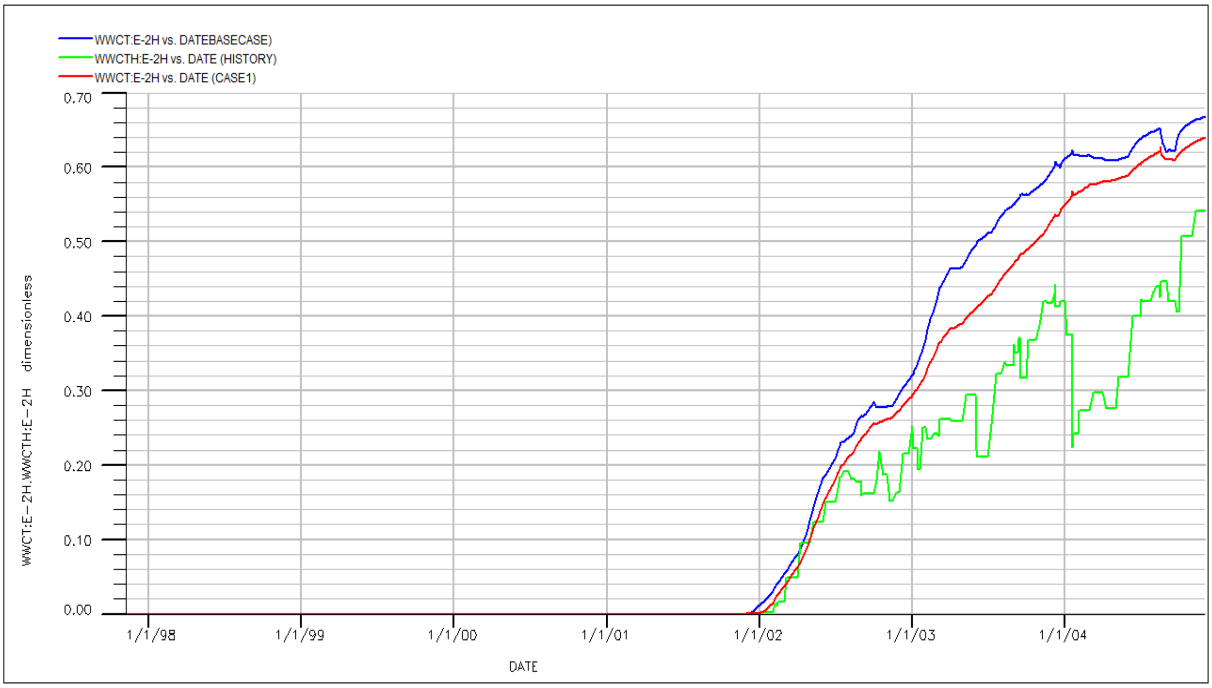


Figure 5.2.1.11 WCT (right) E-2H. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

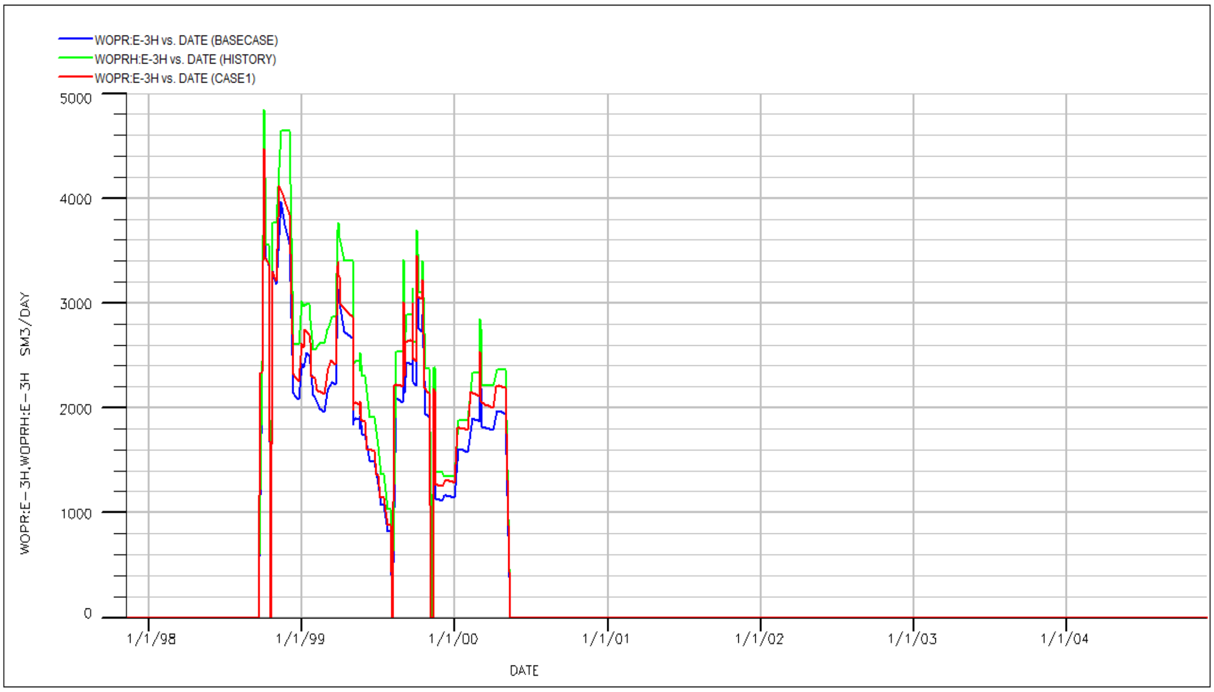


Figure 5.2.1.12 OPR E-3H. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

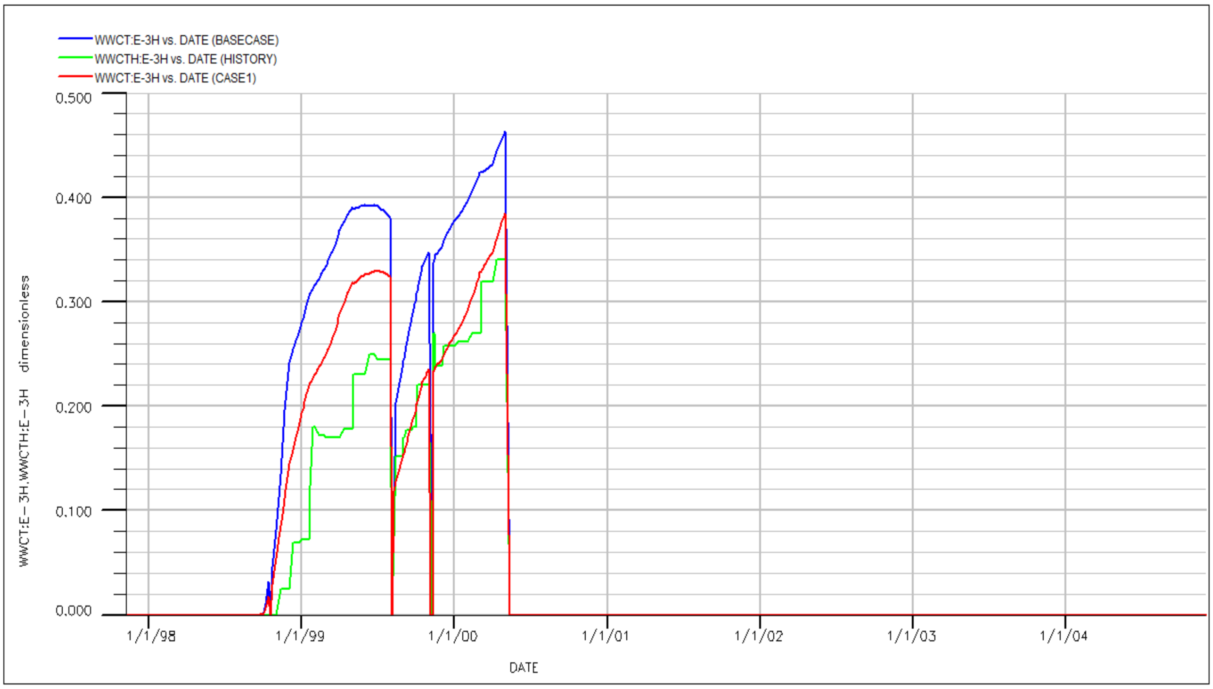


Figure 5.2.1.13 WCT E-3H. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

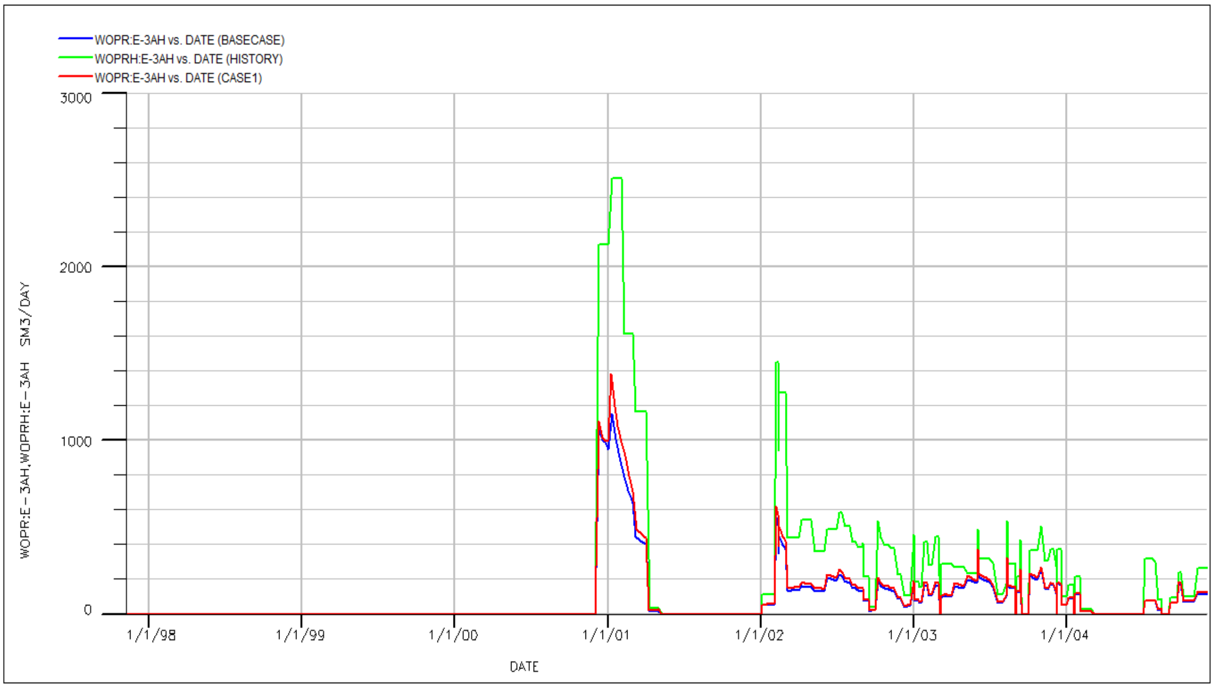


Figure 5.2.1.14 OPR E-3AH. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

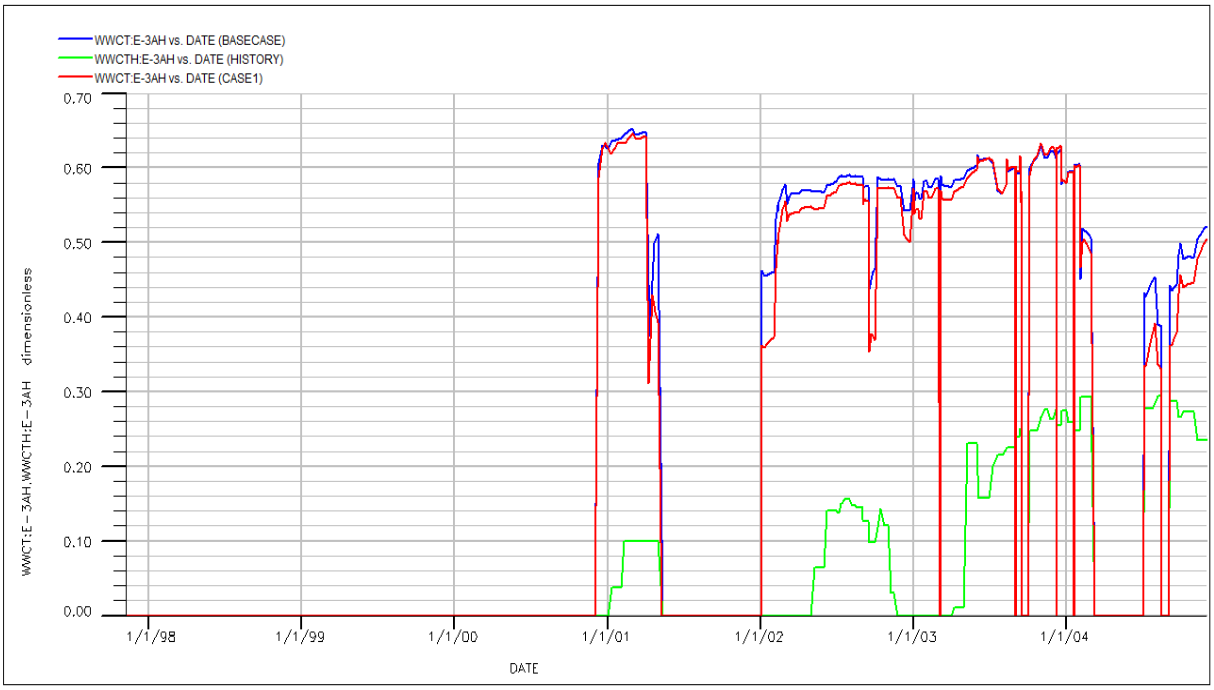


Figure 5.2.1.15 WCT E-3AH. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

5.2.2 Case2: Adjustment of PERMX

5.2.2.1 Case2a Adjustment of PERMX

Second case is to adjust horizontal permeability (PERMX) around the wellbore. The same procedure as first case is followed. The range of PERMX is from 0.9651 to 5933.2971. The reservoir PERMX performance around the wellbore and well connection is shown in figure4.2.4.3 and 4.2.4.4 in Chapter 4. Figure 4.2.2.2 shows the PERMX difference in each layer. PERMX around wellbore is supposed to be lower than permeability far from the wellbore due the oil production.

To analyze the sensitivity of the wells altering PERMX, a factor of 0.1, 0.2, 5 and 10 is multiplied to each well, and basecase is without alternations. Sensitivity analysis is shown in figure 5.2.2.1 to 5.2.2.5

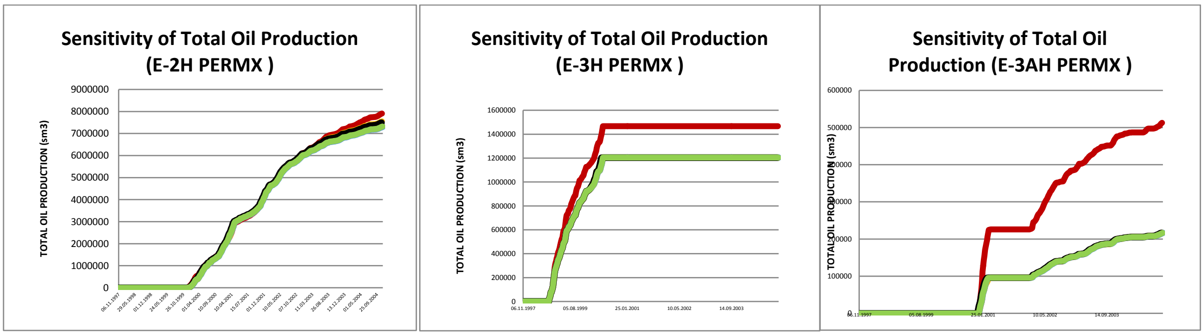


Figure 5.2.2.1 Sensitivity of total oil production by changing PERMX of well E-2H.Red=History, Orange=Basecase, Blue=0.1xPERMX, Green= 0.2xPERMX, Black=5xPERMX, Purple=10xPERMX.

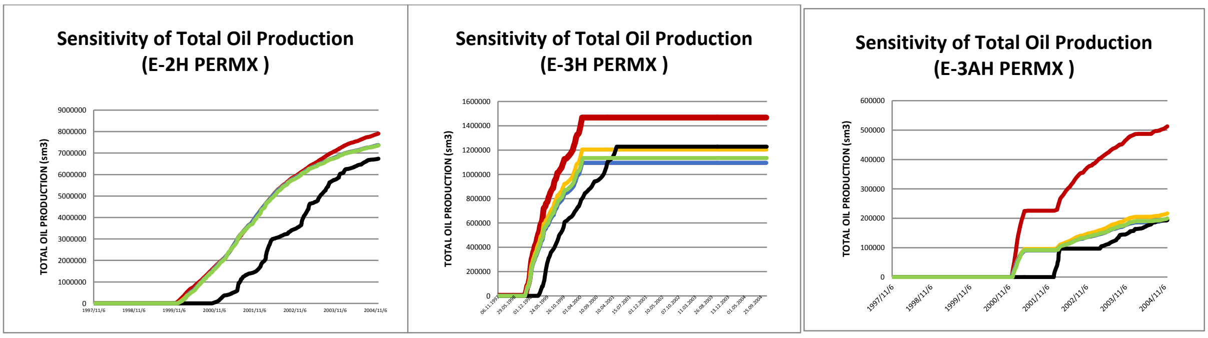


Figure 5.2.2.2 Sensitivity of total oil production by changing PERMX of well E-3H.Red=History, Orange=Basecase, Blue=0.1xPERMX, Green= 0.2xPERMX, Black=5xPERMZ, Purple=10xPERMX.

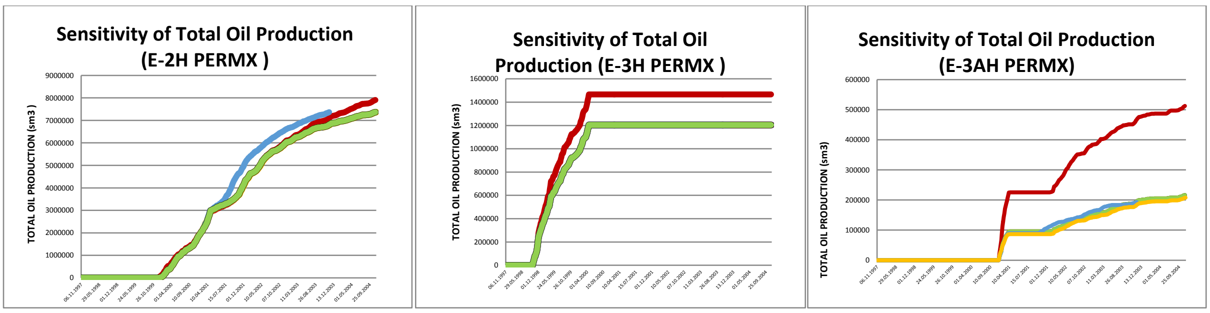


Figure 5.2.2.3 Sensitivity of total oil production by changing PERMX of well E-3AH.Red=History, Orange=Basecase, Blue=0.1xPERMX, Green= 0.2xPERMX, Black=5xPERMX, Purple=10xPERMX.

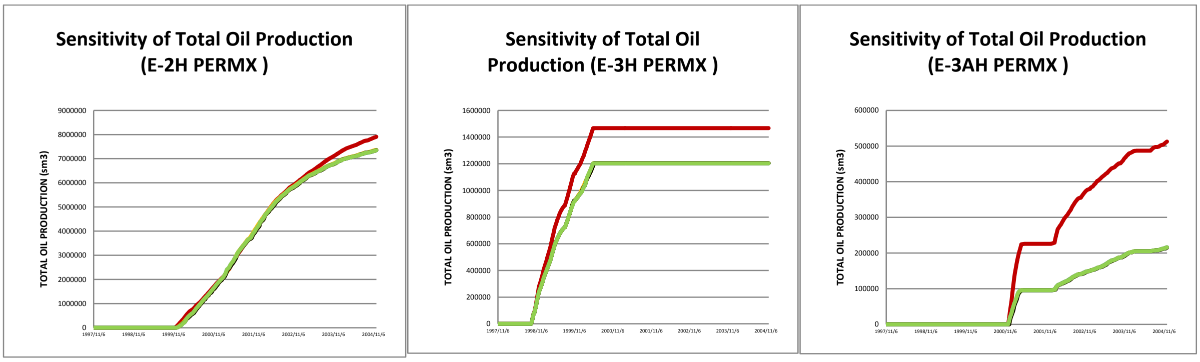


Figure 5.2.2.4 Sensitivity of total oil production by changing PERMX of well F-1H.Red=History, Orange=Basecase, Blue=0.1xPERMX, Green= 0.2xPERMX, Black=5xPERMX, Purple=10xPERMX.

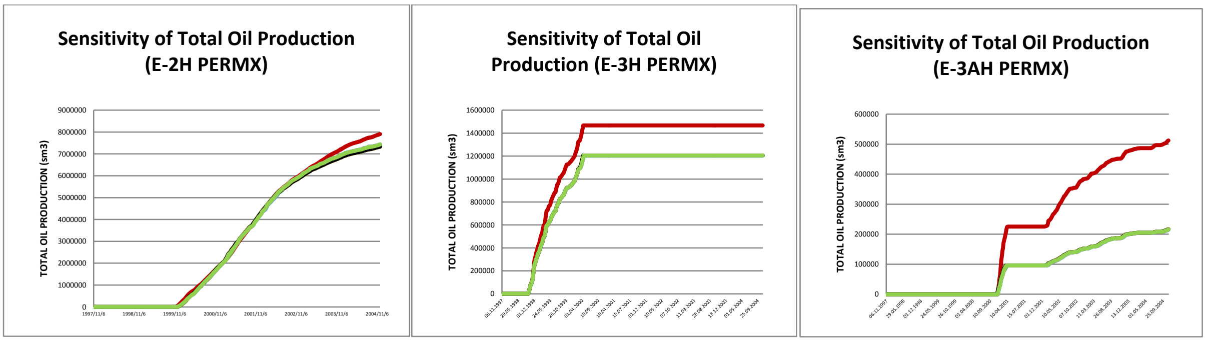


Figure 5.2.2.5 Sensitivity of total oil production by changing PERMX of well F-3H.Red=History, Orange=Basecase, Blue=0.1xPERMX, Green= 0.2xPERMX, Black=5xPERMX, Purple=10xPERMX.

As a conclusion of sensitive analysis, PERMX affacts the cumulative oil production, however the model does not as sensitive as the PERMZ case. Well E-2H is relative sensitive by altering PERMX around each production wells on E-segment. E-3H is sensitive if and only if PERMX around E-3H changes, however, E-3H have higher affection to the performances of other wells. E-3AH does not have great affection on other wells. To change the permeability of two injection wells F-1H and F-3H have little affaction on production wells.

In further consideration of adjustment, to reduce the horizontal permeability between the production and injection wells could reduce the quick flow of water toward the production wells and therefore prevent the early water breakthrough in to the production wells.The case with best match is listed in Table 5.2.2.6.

Table 5.2.2.6 List of PERMX modified in Case2a

Well name	PERMX
E-3H	1.25
E-2H	15
E-3AH	0.03
F-1H	0.3
F-3H	0.3

The new model with alternation in PERMX is plotted in figure 5.2.2.7 to 5.2.2.9. Detailed well behavior is plotted in figure 5.2.2.10 to 5.2.2.15.

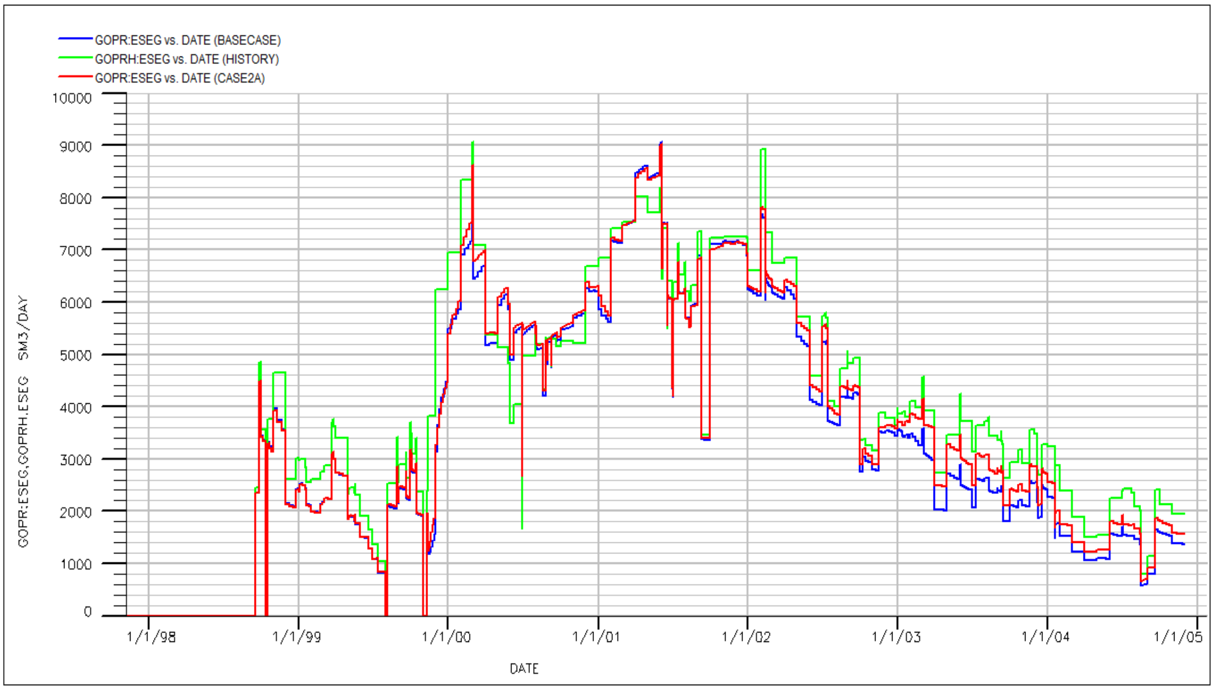


Figure 5.2.2.7 OPR E-segment. Green=History Data, Blue=Basecase Model Data, Red= History Matched data.

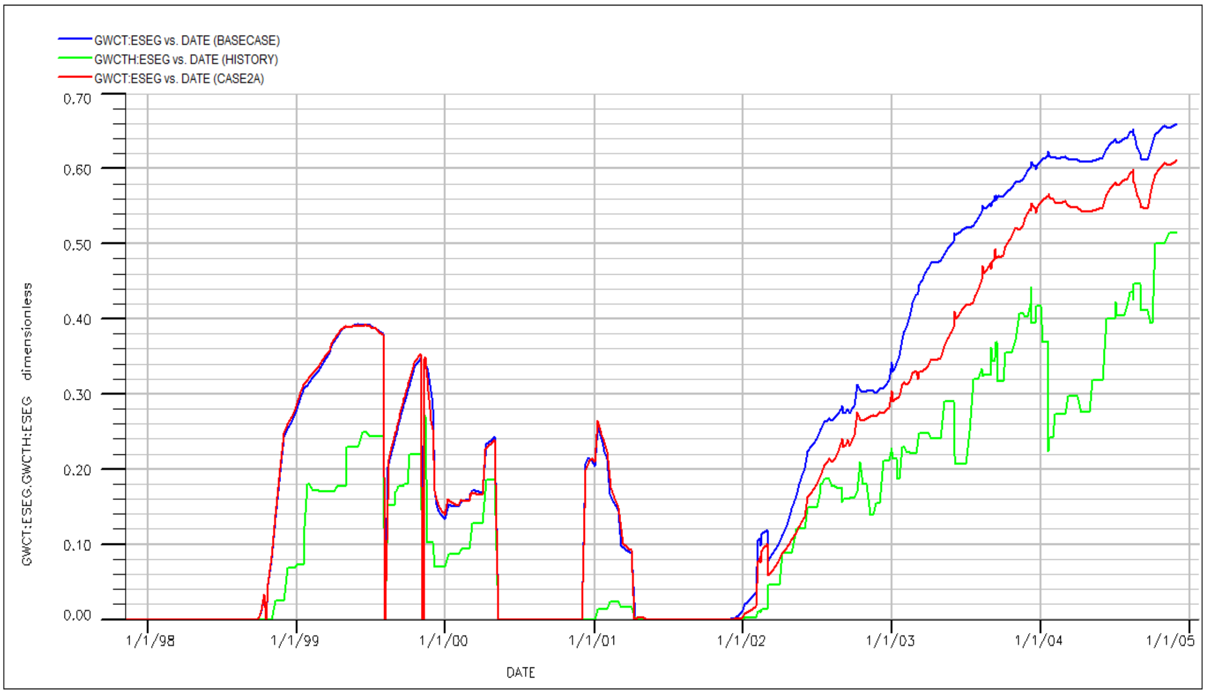


Figure 5.2.2.8 WCT E-segment. Green=History Data, Blue=Basecase Model Data, Red= History Matched data.

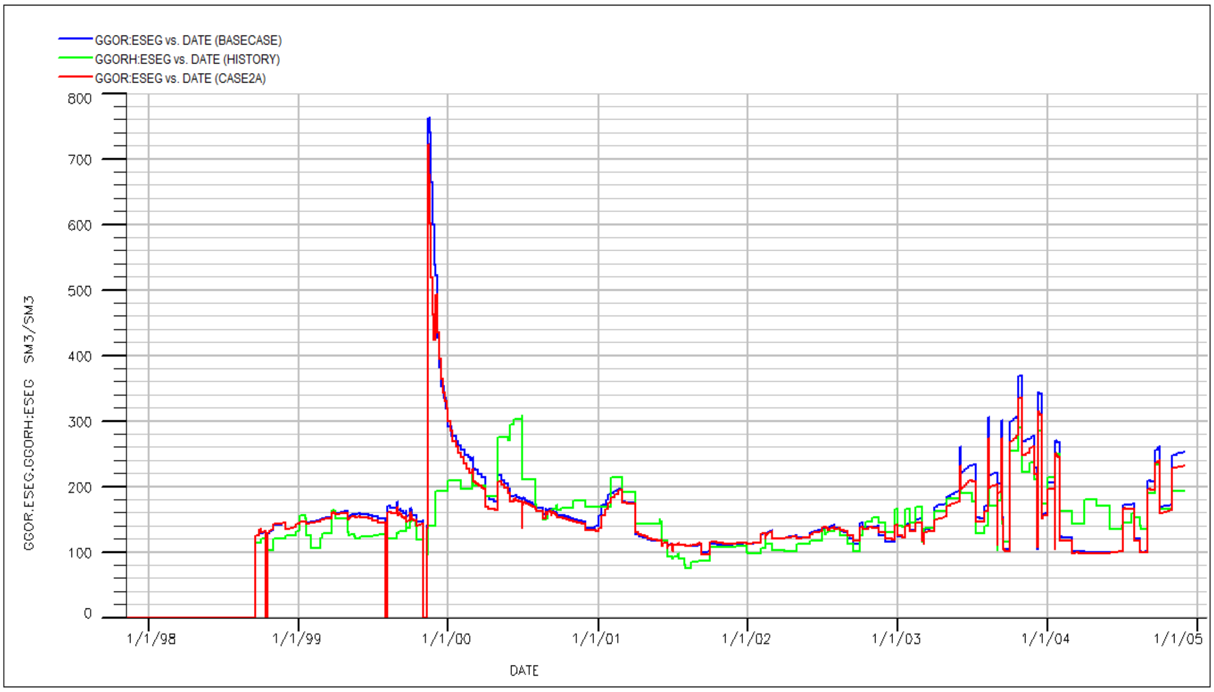


Figure 5.2.2.9 GOR E-segment. Green=History Data, Blue=Basecase Model Data, Red= History Matched data.

Figure 5.2.2.10 OPR E-2H. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

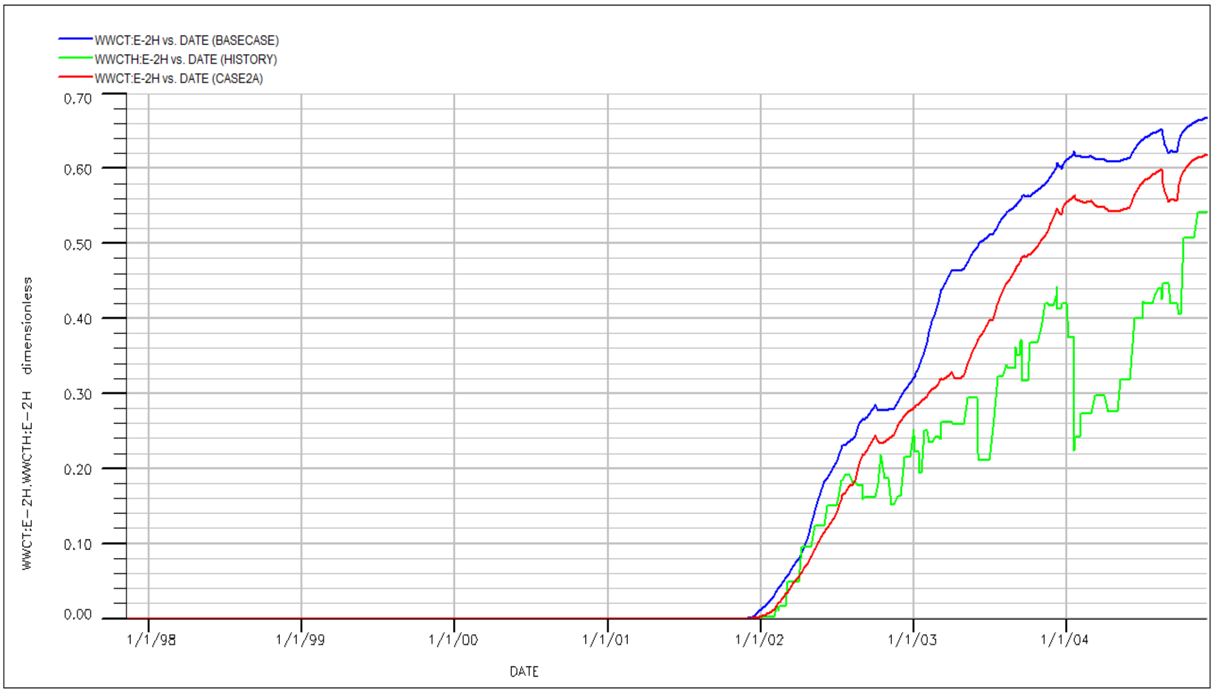


Figure 5.2.2.11 WCT E-2H. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

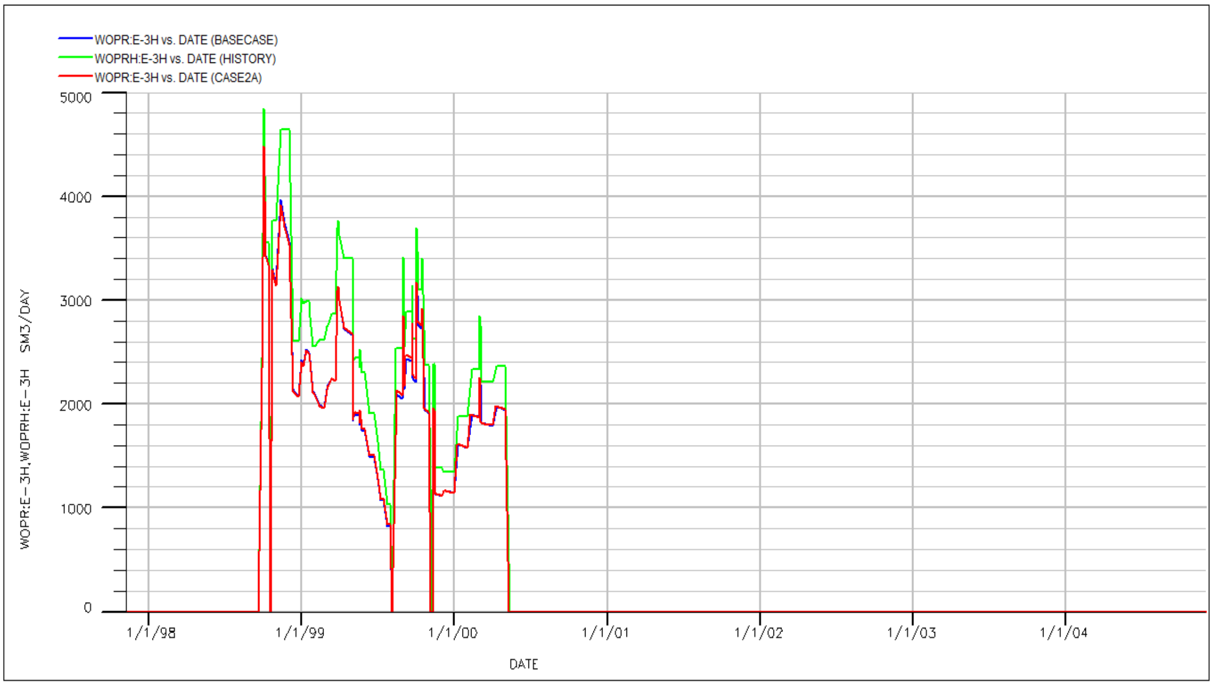


Figure 5.2.2.12 OPR for E-3H. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

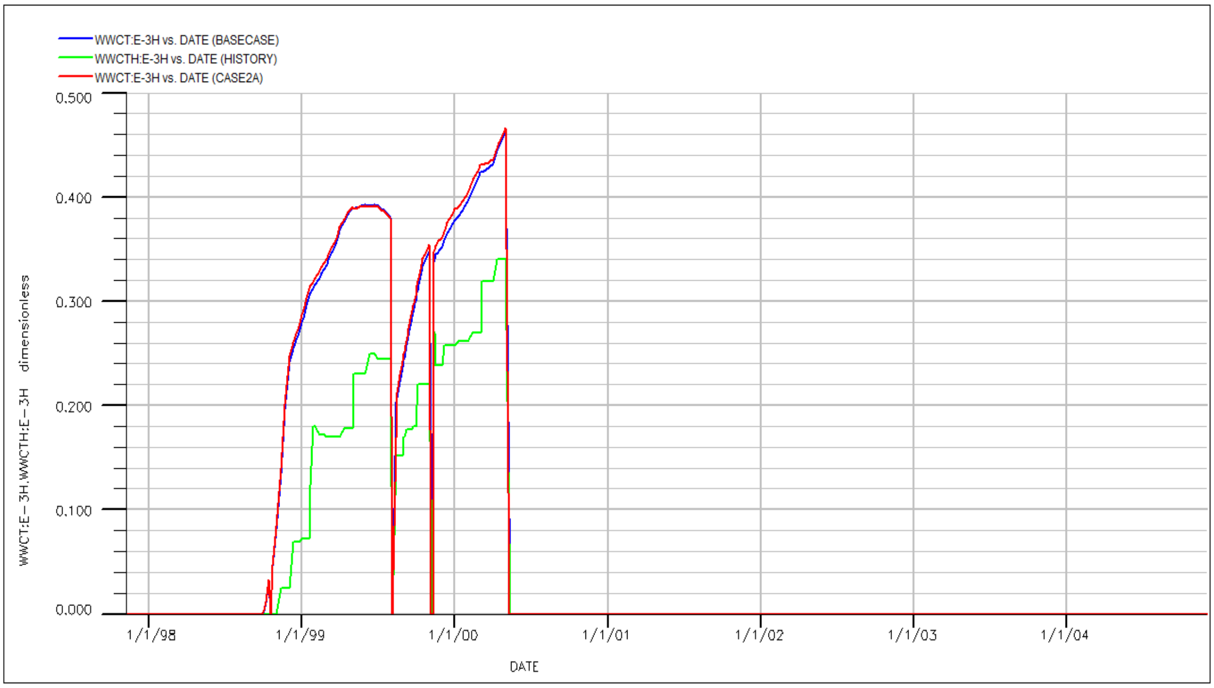


Figure 5.2.2.13 WCT for E-3H. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

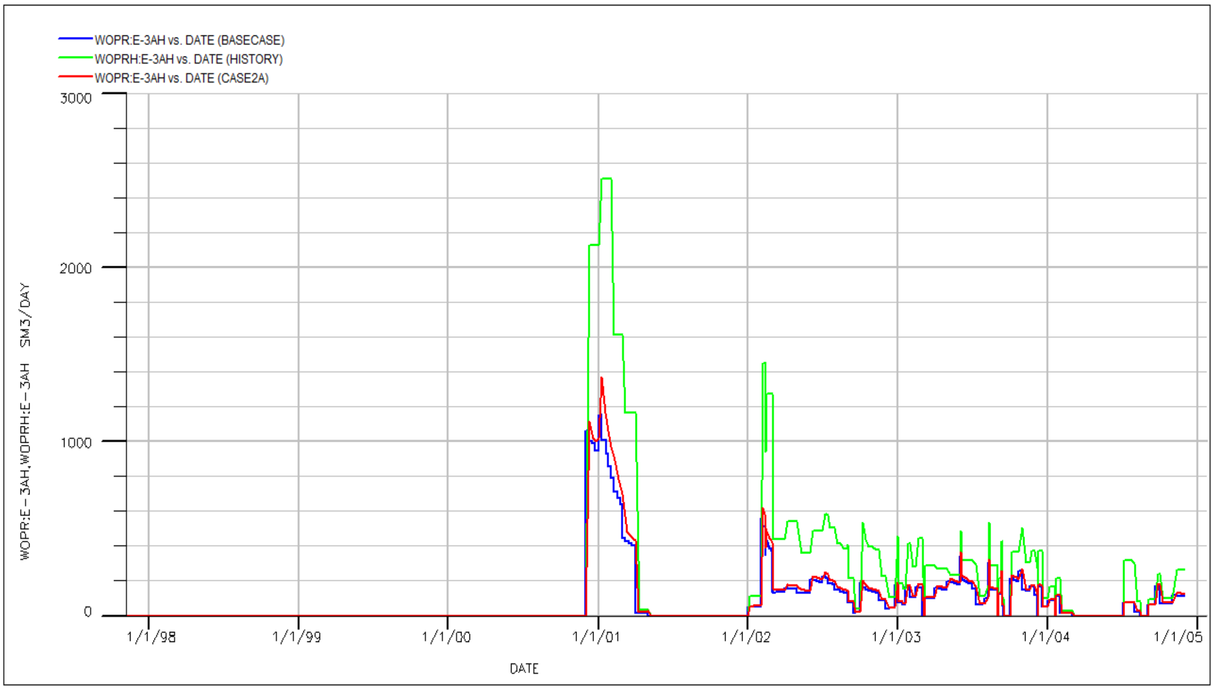


Figure 5.2.2.14 OPR E-3AH. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

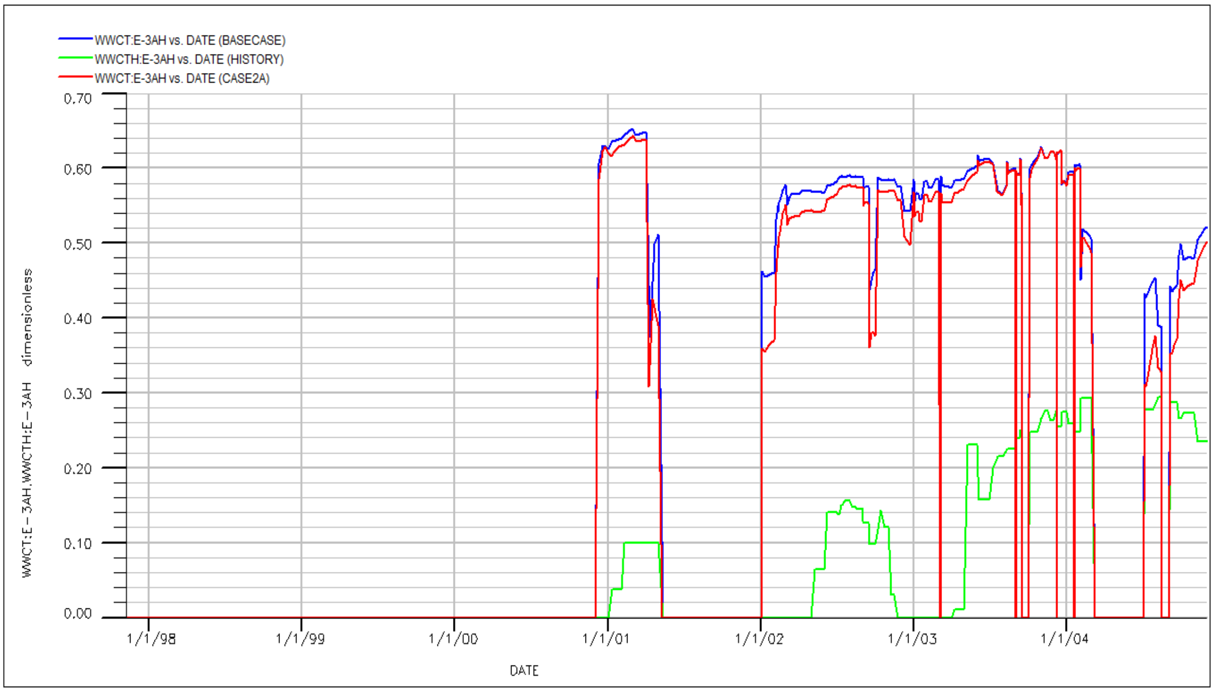


Figure 5.2.2.15 WCT for E-3AH. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

5.2.2.2 Case 2b: Combination of Case1 and Case 2a

The new case combines the adjustment of PERMZ and PERMX. Parameters modified are listed in Table 2.2.2.13

Table 2.2.2.16 List of parameters modified in Case2b

Well name	PERMZ	PERMX
E-3H	0.5	1.25
E-2H	0.001	15
E-3AH	3	0.03
F-1H	0.005	0.3
F-3H	0.005	0.3

The new model with alternation in PERMX and PERMZ is plotted in figure 2.2.17 to 2.2.19 and detailed well behavior is plotted in figure 5.2.2.20 to 5.2.2.25.

Figure 5.2.2.17 OPR E-segment. Green=History Data, Blue=Basecase Model Data, Red= History Matched data.

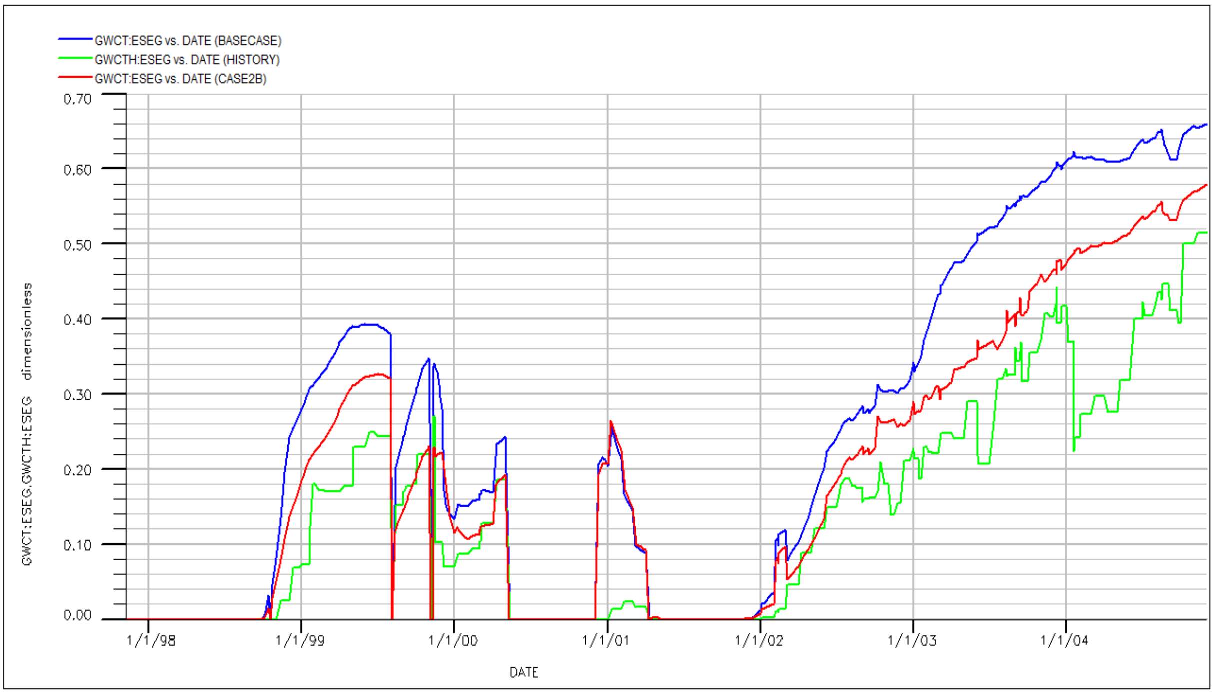


Figure 5.2.2.18 WCT E-segment. Green=History Data, Blue=Basecase Model Data, Red= History Matched data.

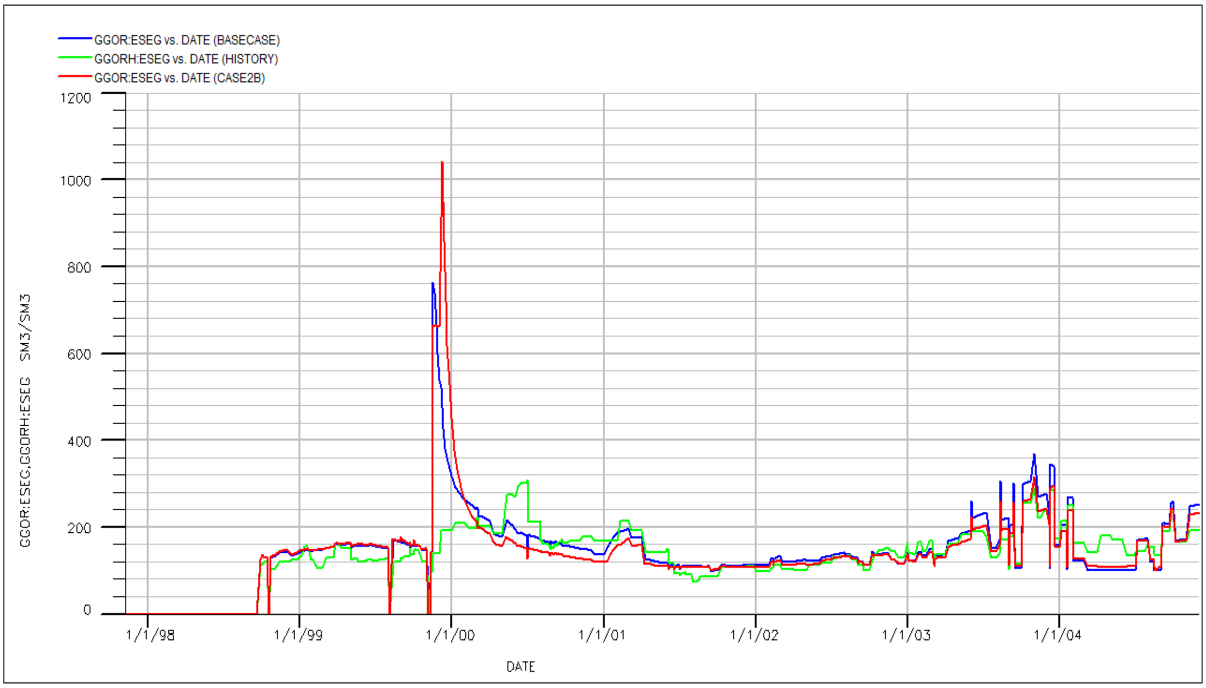


Figure 5.2.2.19 GOR E-segment. Green=History Data, Blue=Basecase Model Data, Red= History Matched data.

Figure 5.2.2.20 OPR E-2H, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

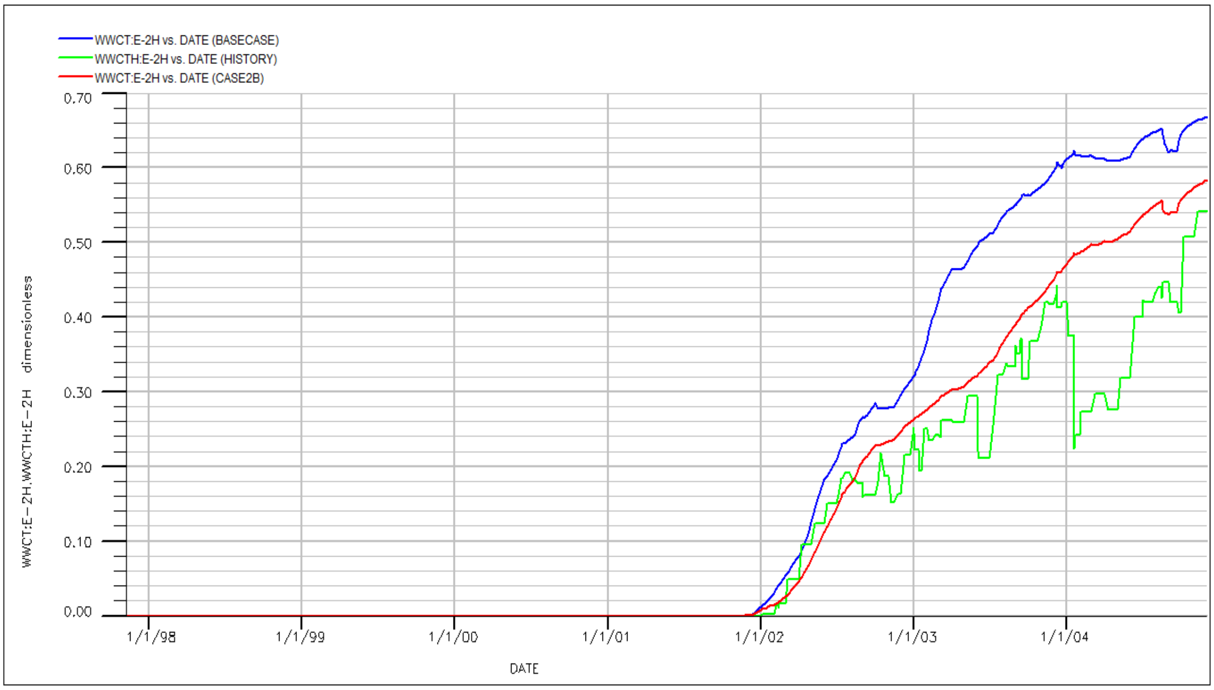


Figure 5.2.2.21 WCT E-2H Green=History Data, Blue=Basecase Model Data, Red= History Matched data

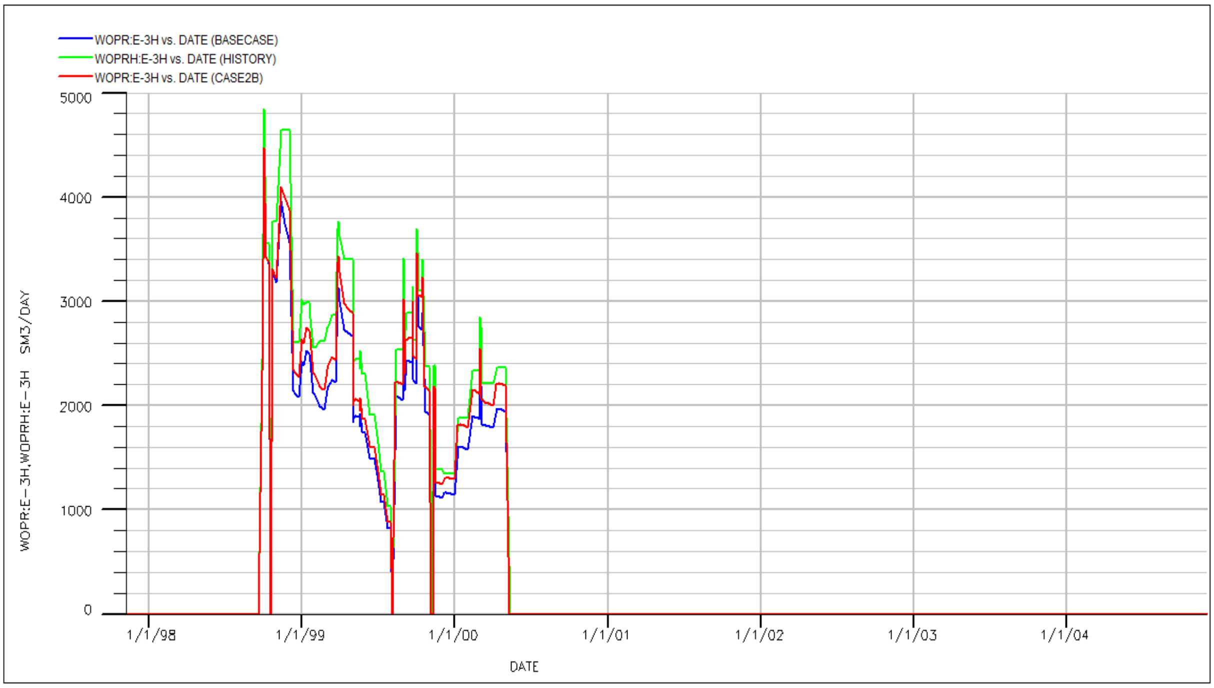


Figure 5.2.2.22 OPR E-3H, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

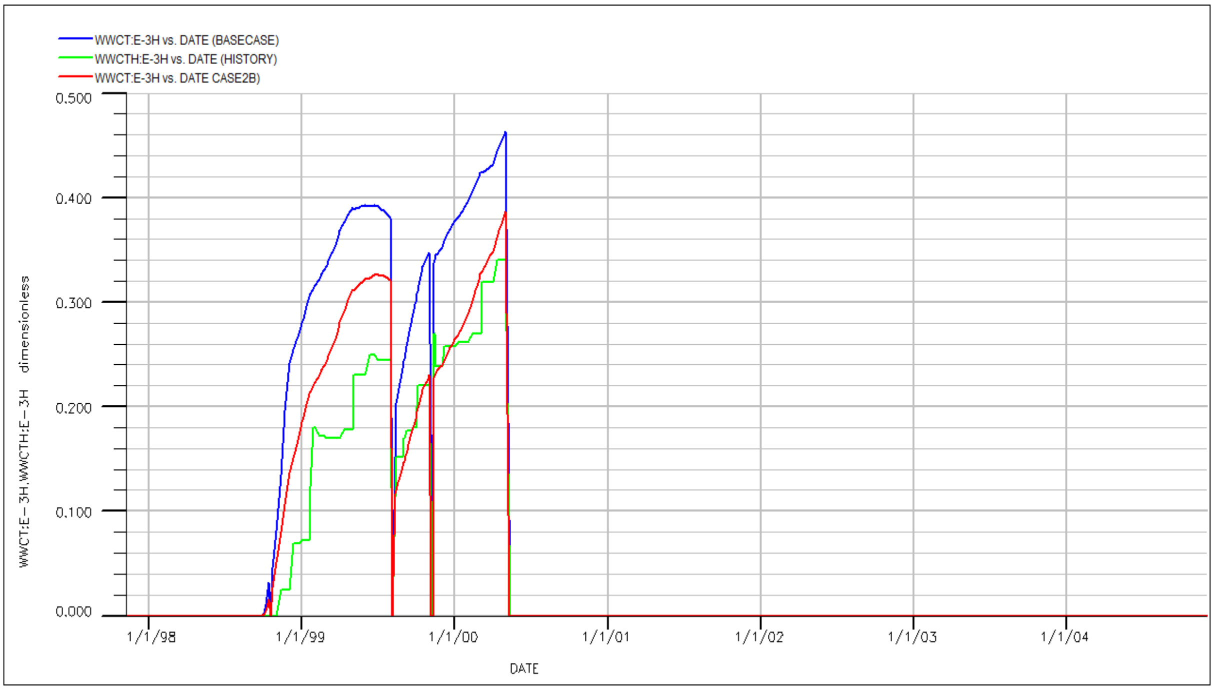


Figure 5.2.2.23 WCT E-3H, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

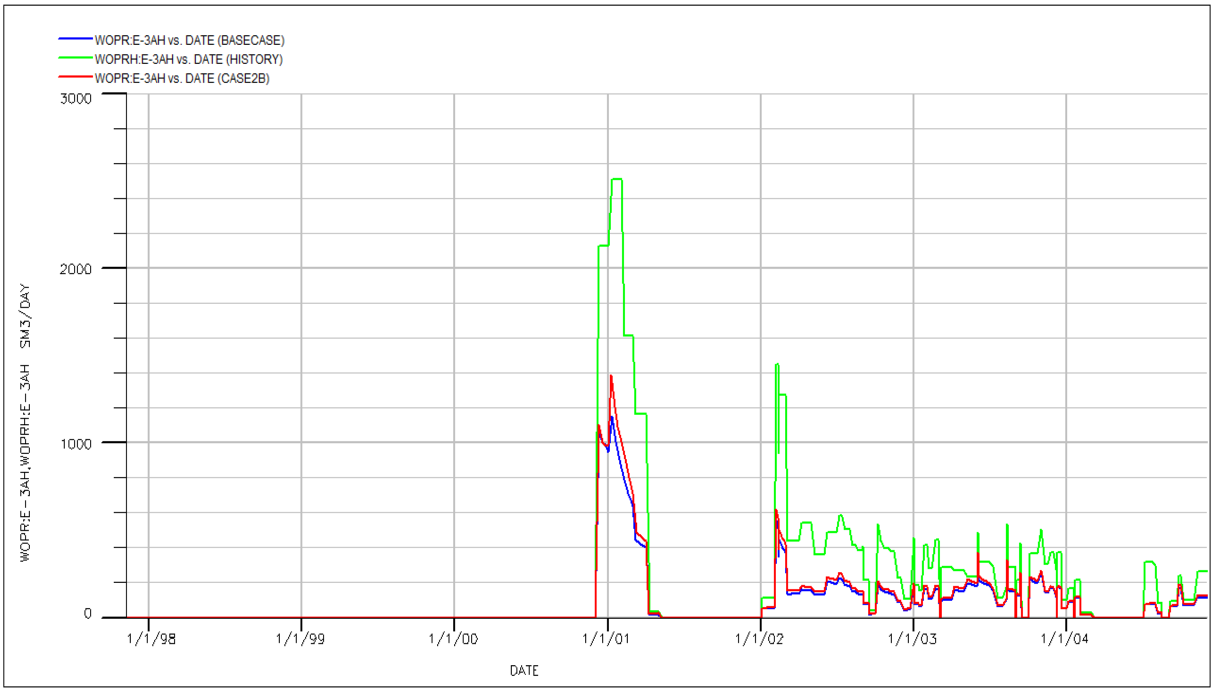


Figure 5.2.2.24 OPR E-3AH. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

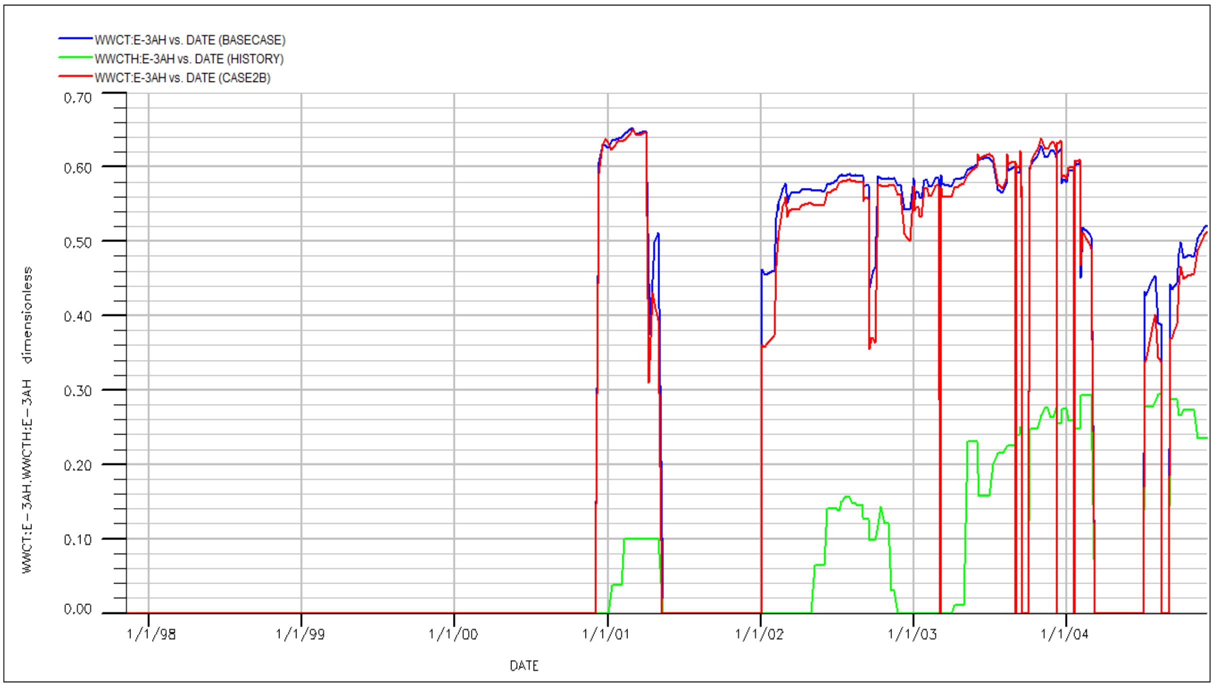


Figure 5.2.2.25 WCT E-3AH. Green=History Data, Blue=Basecase Model Data, Red= History Matched data

5.2.3 Case3: Adjustment of faults

5.2.3.1 Case3a: Adjustment of fault transmissibility

Local change in fault transmissibility was done in order to better match the production profiles of detail level of individual wells. This is done by including a fault multiplier in an input data file. All the faults on E-segment are listed in the fault multiplier input file and different multiplication values are tested. An invisible fault is a fault with value 1.0 while a fault with value 0 means totally sealed fault.

On the sensitive analysis part, the transmissibility of faults is given as a low and a high case. The high cases were multiplied a factor of 100 while low cases were multiplied a factor of 0.01 to alter the fault transmissibility. After simulating these cases, the WOPT for each well were studied and compared to history and basecase values. The target was to analysis the impacts that faults transmissibilities have on the well oil production.

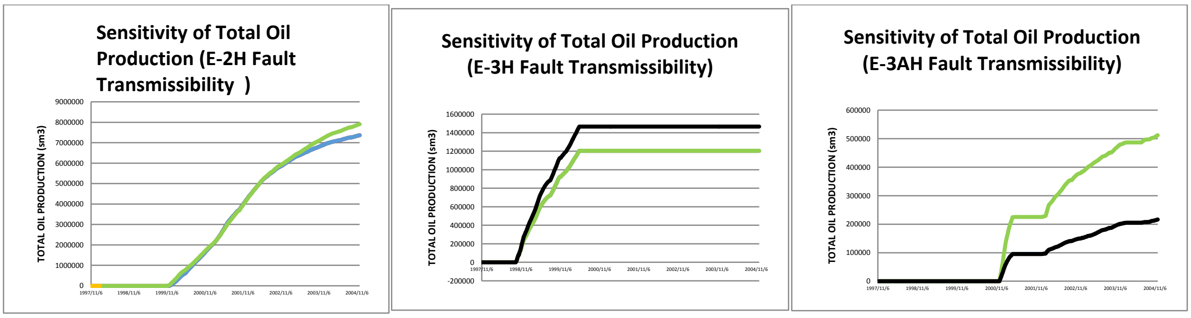


Figure 5.2.3.1 Sensitivity of Total Oil Production by changing transmissibility of Fault m_west. Green =History, Black=Basecase, Red=High case, Blue=Low case

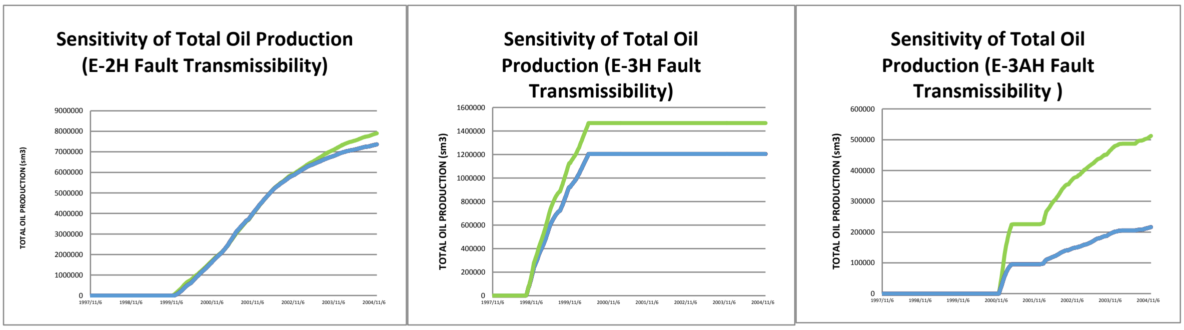


Figure 5.2.3.2 Sensitivity of Total Oil Production by changing transmissibility of Fault m_north. Green =History, Black=Basecase, Red=High case, Blue=Low case

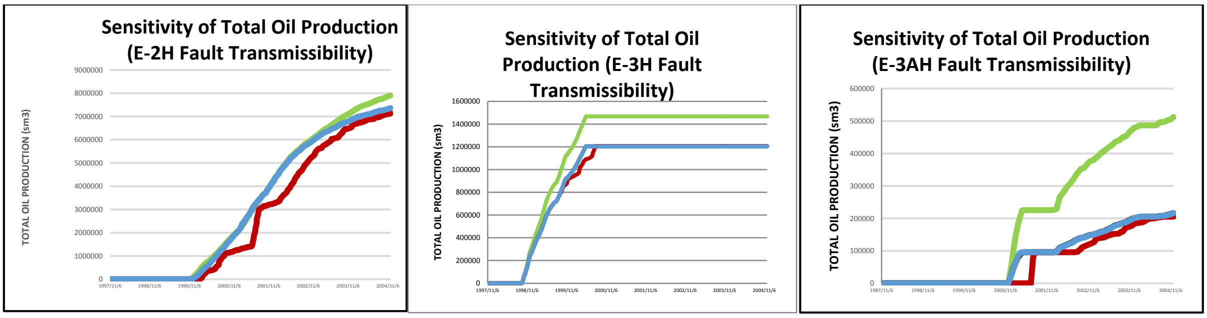


Figure 5.2.3.3 Sensitivity of Total Oil Production by changing transmissibility of Fault DE_2. Green =History, Black=Basecase, Red=High case, Blue=Low case

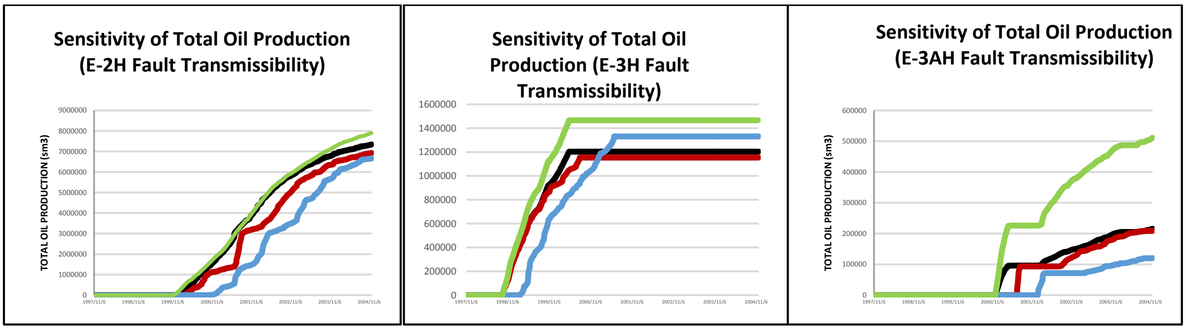


Figure 5.2.3.4 Sensitivity of Total Oil Production by changing transmissibility of Fault E_01. Green =History, Black=Basecase, Red=High case, Blue=Low case

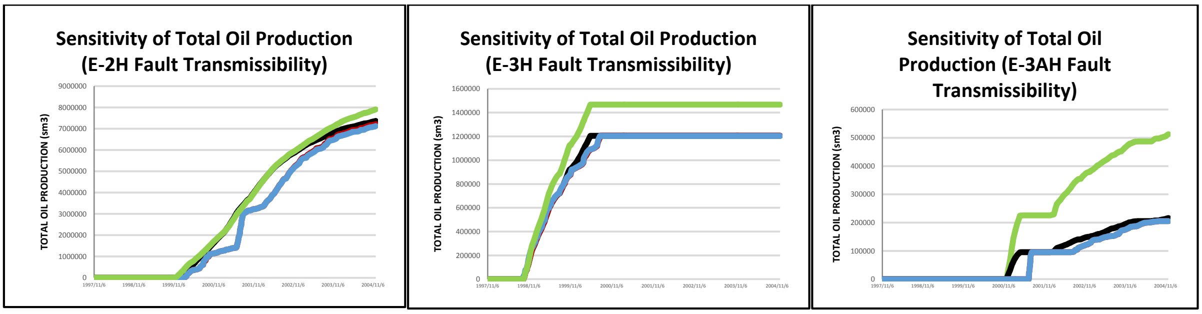


Figure 5.2.3.5 Sensitivity of Total Oil Production by changing transmissibility of Fault DE_1, Green =History, Black=Basecase, Red=High case, Blue=Low case

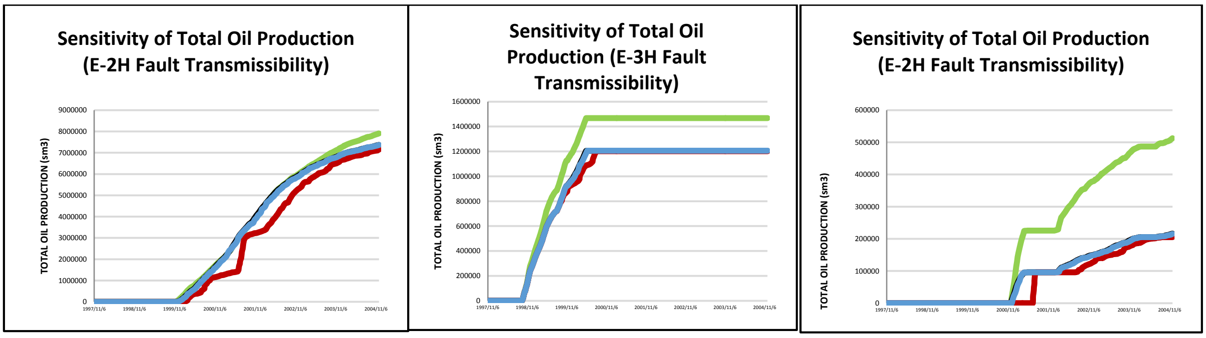


Figure 5.2.3.6 Sensitivity of Total Oil Production by changing transmissibility of Fault EF, Green =History, Black=Basecase, Red=High case, Blue=Low case

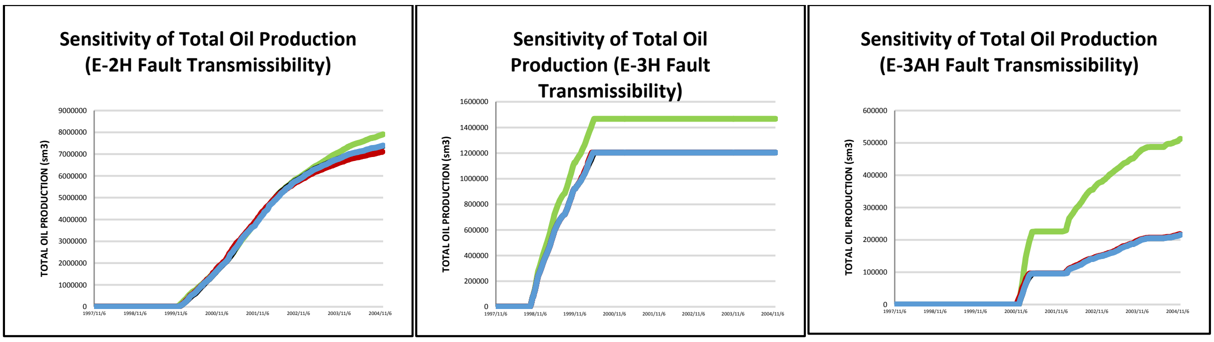


Figure 5.2.3.7 Sensitivity of Total Oil Production by changing transmissibility of Fault E_01_F3, Green =History, Black=Basecase, Red=High case, Blue=Low case

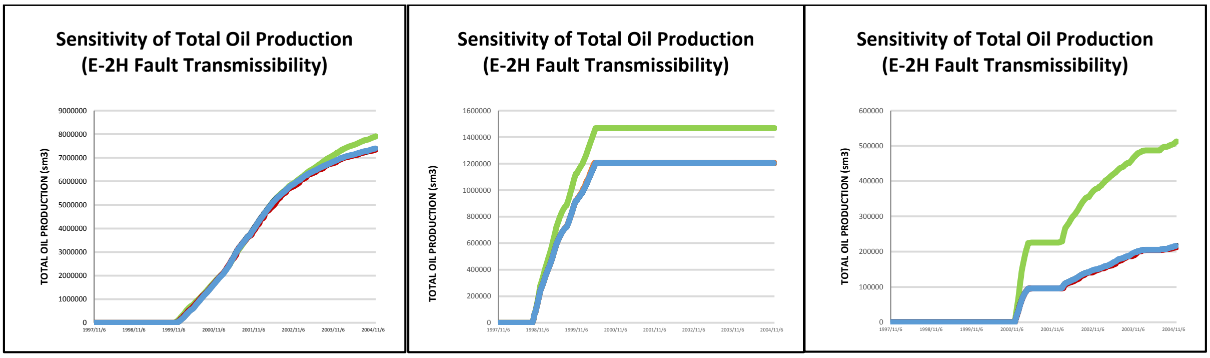


Figure 5.2.3.8 Sensitivity of Total Oil Production by changing transmissibility of Fault DE_B3, Green =History, Black=Basecase, Red=High case, Blue=Low case 3.8

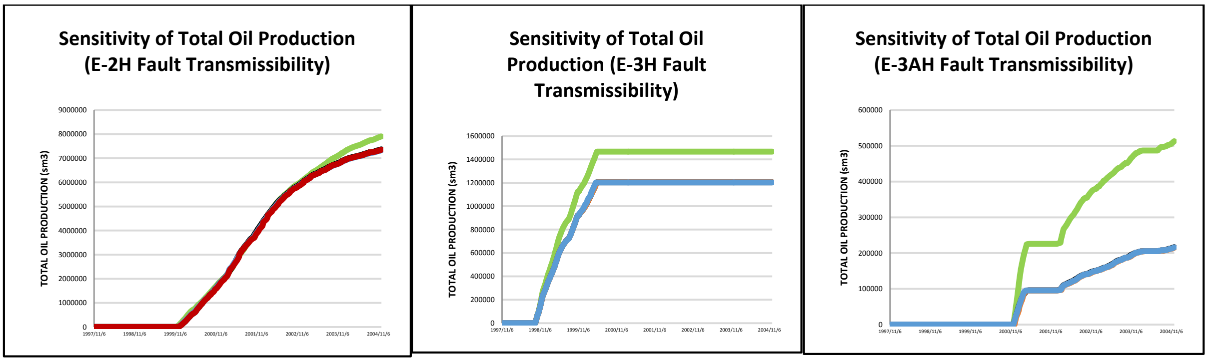


Figure 5.2.3.9 Sensitivity of Total Oil Production by changing transmissibility of Fault DE_0, Green =History, Black=Basecase, Red=High case, Blue=Low case

With respect to the sensitive analysis, communications across faults are considered to be sensitive. Total oil production of well E-2H is the most sensitive and highly sensitive when transmissibilities of fault E_01 and DE_1 are altered. Fault E_01 located through well E-3AH and E-3H and near well E-2H. Names and locations of fault on Norne E segment are shown in figure 5.2.3.10. Fault m_west and m_north is act as boundaries for E-segment and have little effect to three production wells. For fault DE_2, E_01_F3 and DE_B3, the performance could be improved by the modification to low cases.

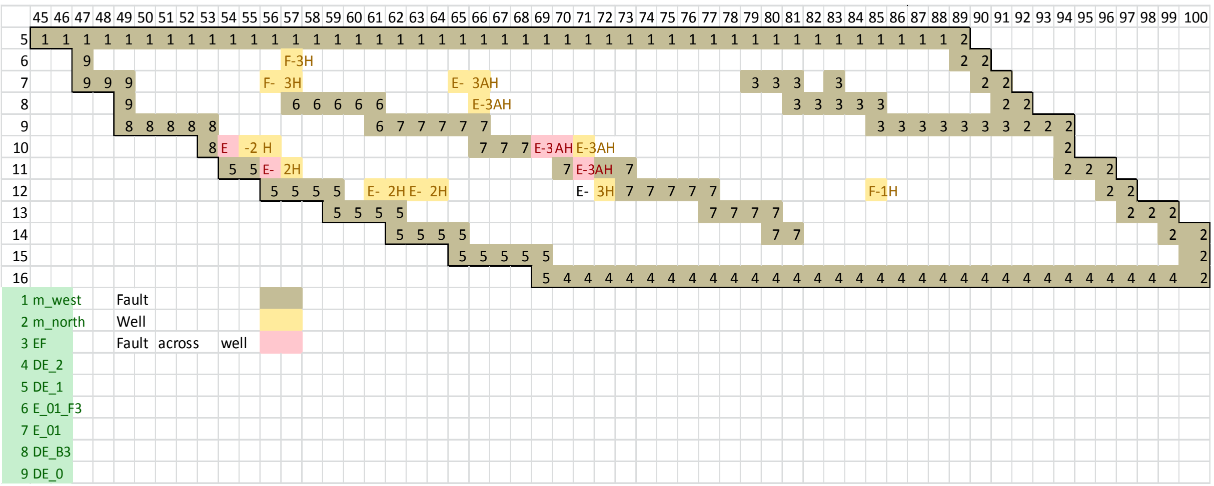


Figure 5.2.3.10 name and location of fault on Norne field.

How fault will affect the model flow performance is studied in the case below by Sintef [30]. Faults can either act as conduits for fluid flow in subsurface reservoirs or create flow barriers that severely affects fluid distribution and/or reduces recovery.[34] Faults affect the transmissibilities geometrically by introducing new connections between cell to cell and by changing the contact areas between two cells that close together over a fault surface. Fault transmissibility multipliers are used for reducing or increasing permeability for each cross-fault connection. The figure 5.2.3.11 to 5.2.3.14 shows the distribution of Norne pressure field and corresponding streamlines resulting from a two-phase incompressible flow calculation. Fault is act as internal boundaries. The flow is driven by a set of injection and production wells. Plot 5.2.3.11 and 5.2.3.13 shows the results obtained when all transmissibility multipliers equal unity which means faults do not impose a limiting condition to flow. The pressure field is smooth and the streamlines could pass through the faults. Plots 5.2.3.11 and 5.2.3.13 shows the results when the faults are completely sealing, the pressure distribution is discontinuous and streamline paths that shows fault is act as flow barriers.

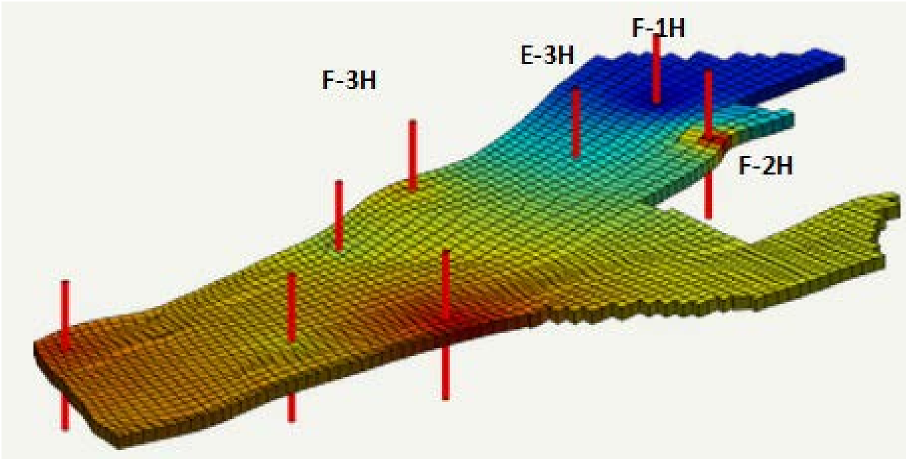


Figure 5.2.3.11 Pressure distribution on Norne field when fault multiplier set equal. [30]

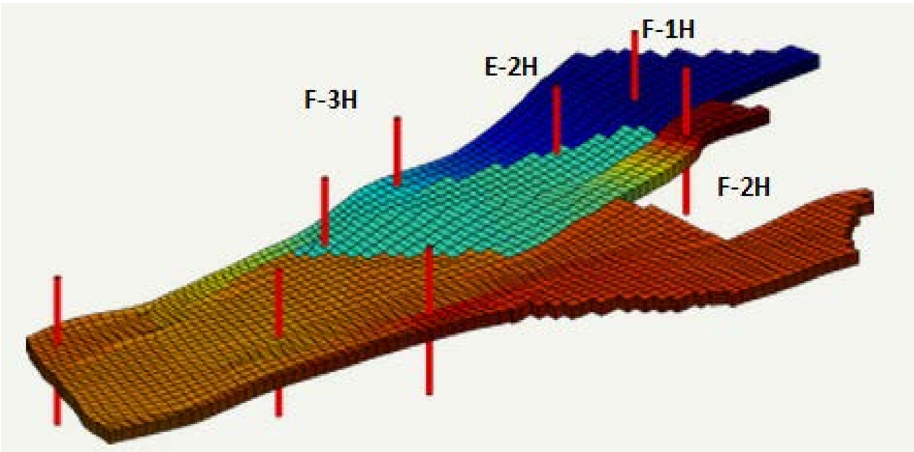


Figure 5.2.3.12 Pressure distribution on Norne field when faults are completed sealing. [30]

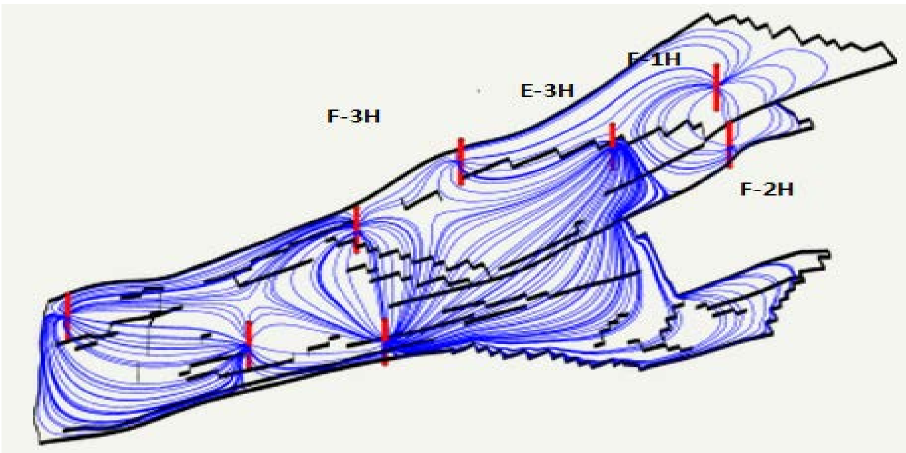


Figure 5.2.3.13 Reservoir flow distribution on Norne field when fault multiplier set equal. [30]

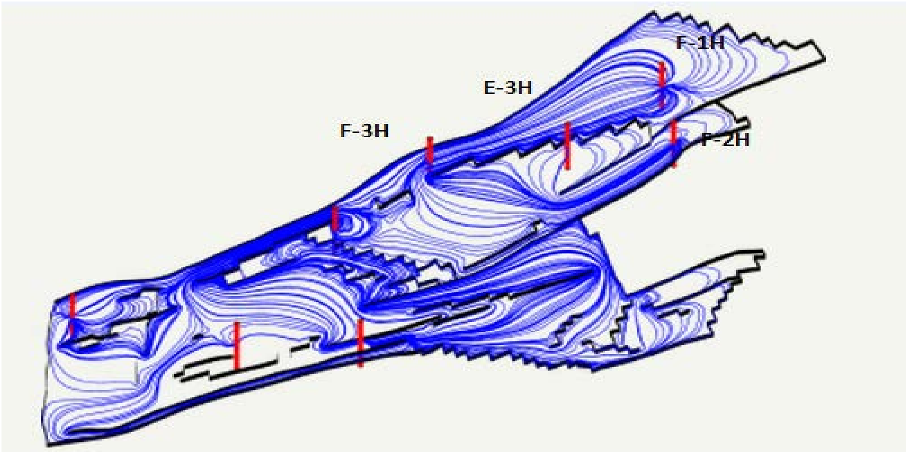


Figure 5.2.3.14 Reservoir flow distribution on Norne field when faults are completed sealing. [30]

As shown in figure 5.2.3.15, Part of water injection well F-1H floods towards well E-3H direction and may communicate across the fault E_01. Part of F-3H injection water may floods along the E_01_F3 and continue to E_01 and part of F_3H may floods along the m_west (the main fault) into C-segment. In order to reduce the water flood from injector F-1H into production well across the fault E_01, transmissibility of E_01 should be reduced.

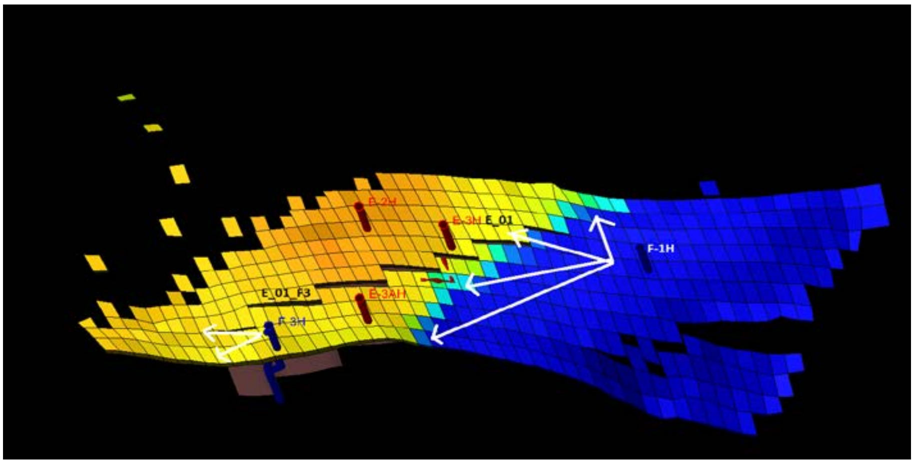


Figure 5.2.3.15 Flood of F-1H and F-3H before modification.

The matching process further was focused on fault multipliers. Trials and errors attempts were made to reduce the difference between simulation and history cases on faults, Table 5.2.3.16 shows list of multipliers of all faults in Norne field. The new model with alternation in fault transmissibility is plotted in figure 5.2.2.17 to 5.2.2.19 and detailed well behavior is plotted in figure 5.2.2.20 to 5.2.2.25.

Table 5.2.3.16 List of faults in Norne Fields

Fault name	multply
'm_west'	1
'm_north'	1
'DE_2'	0.01
'E_01'	0.015
'DE_1'	69
'EF'	1
'E_01_F3'	0.3
'DE_B3'	0.0015
'DE_0'	30

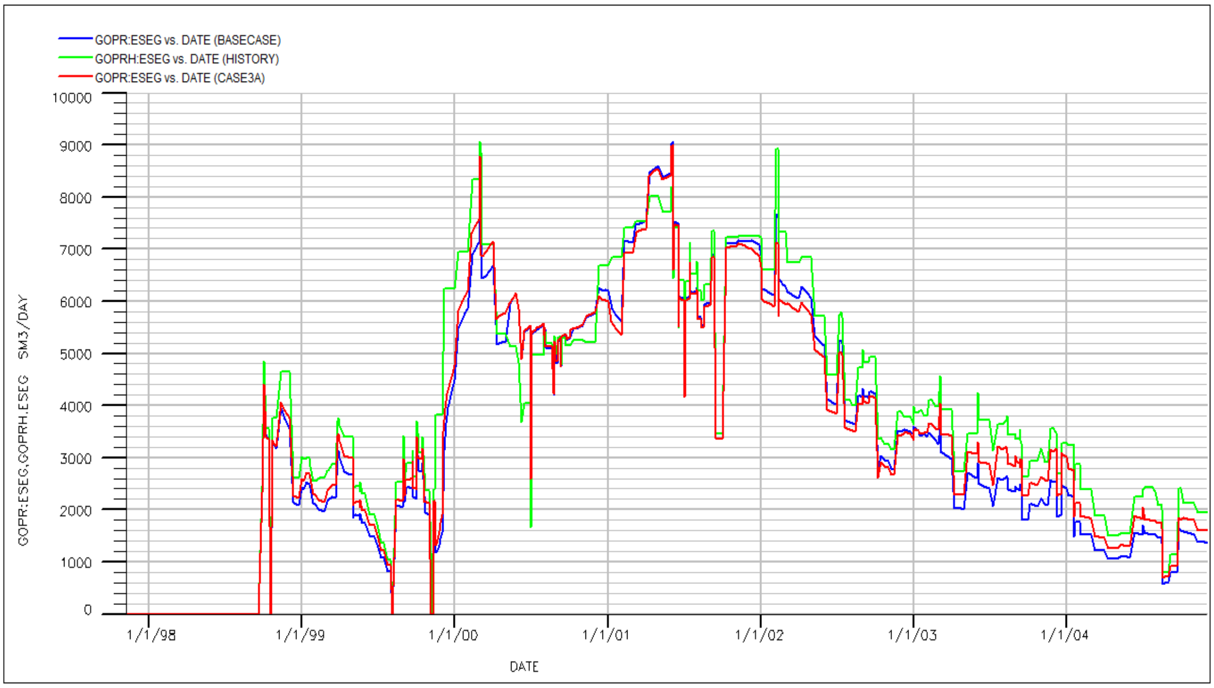


Figure 5.2.3.17 OPR E-segment Norne Green=History Data, Blue=Basecase Model Data, Red= History Matched data

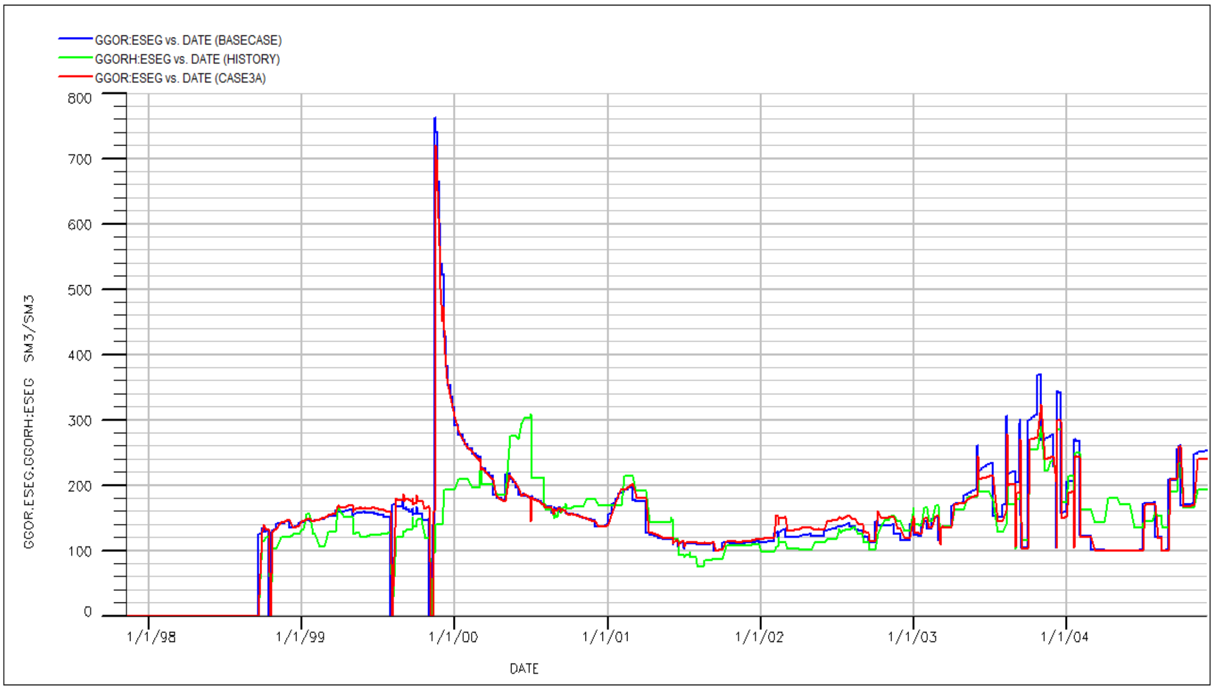


Figure 5.2.3.18 GOR E-segment Norne Green=History Data, Blue=Basecase Model Data, Red= History Matched data

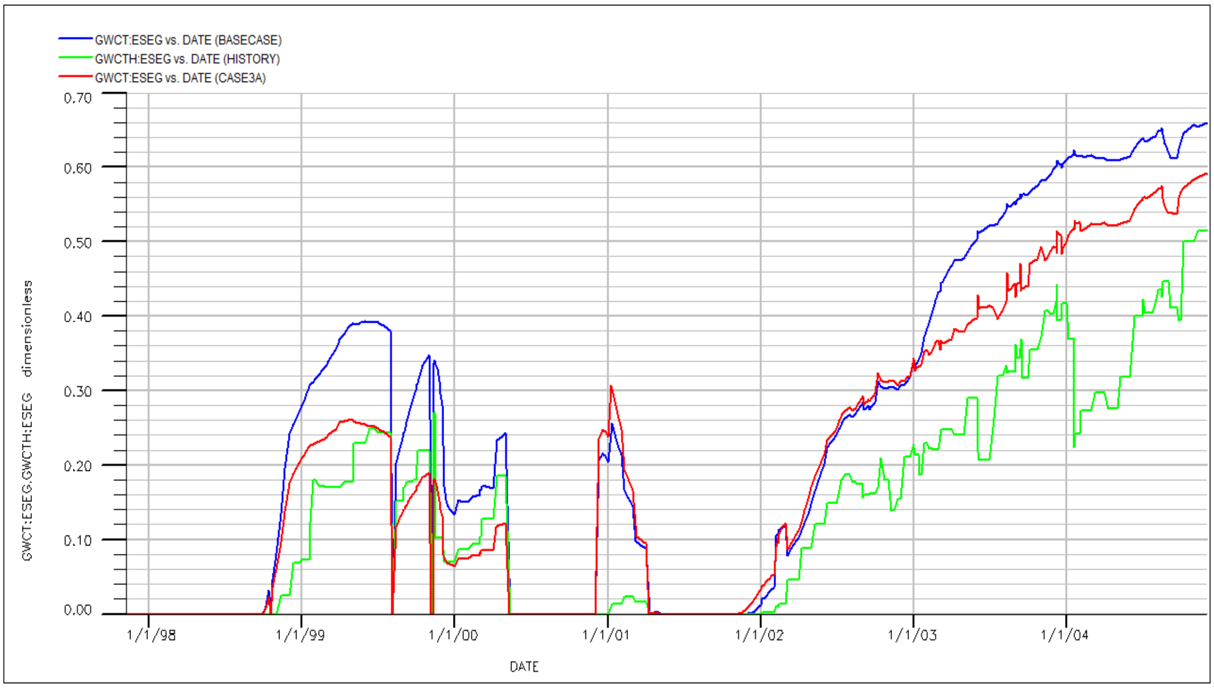


Figure 5.2.3.19 WCT E-segment Norne Green=History Data, Blue=Basecase Model Data, Red= History Matched data

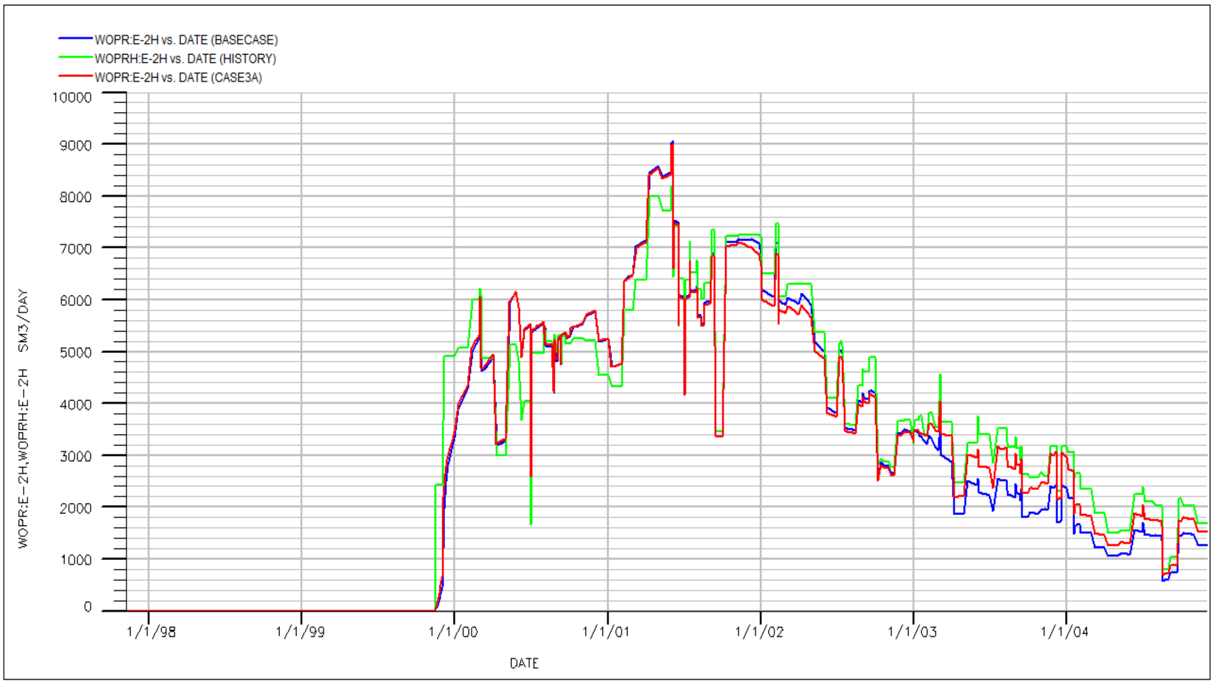


Figure 5.2.3.20 Well E-2H OPR Green=History Data, Blue=Basecase Model Data, Red= History Matched data

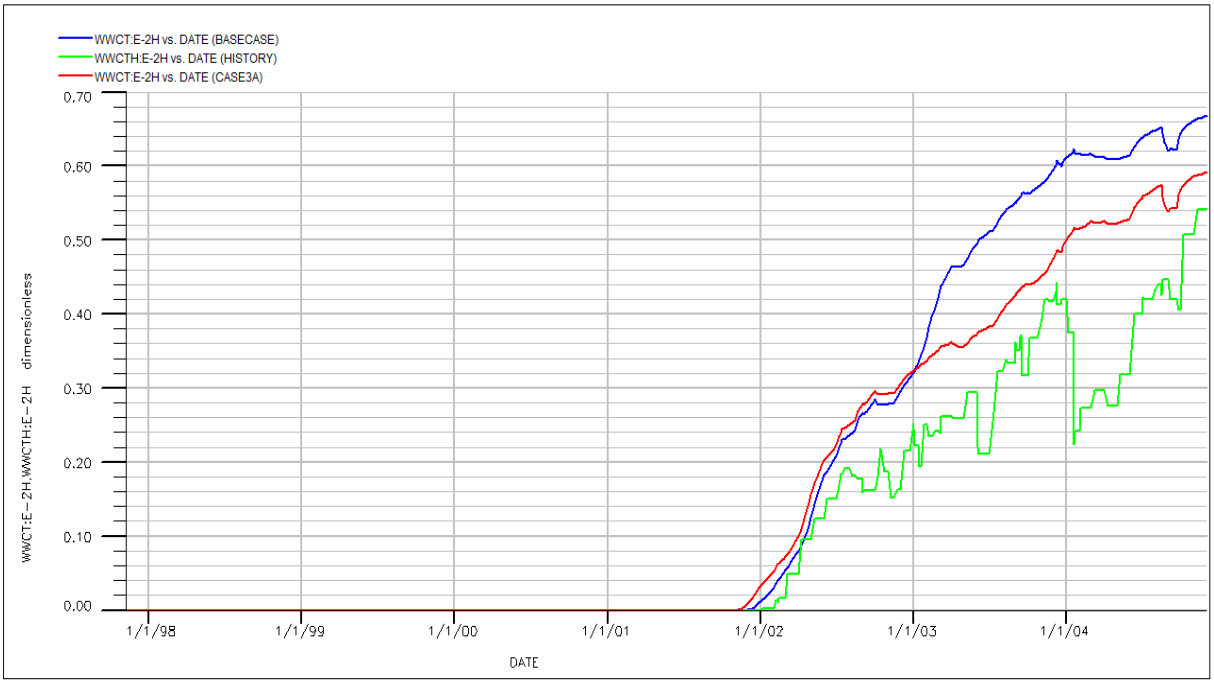


Figure 5.2.3.21 Well E-2H WCT Green=History Data, Blue=Basecase Model Data, Red= History Matched data

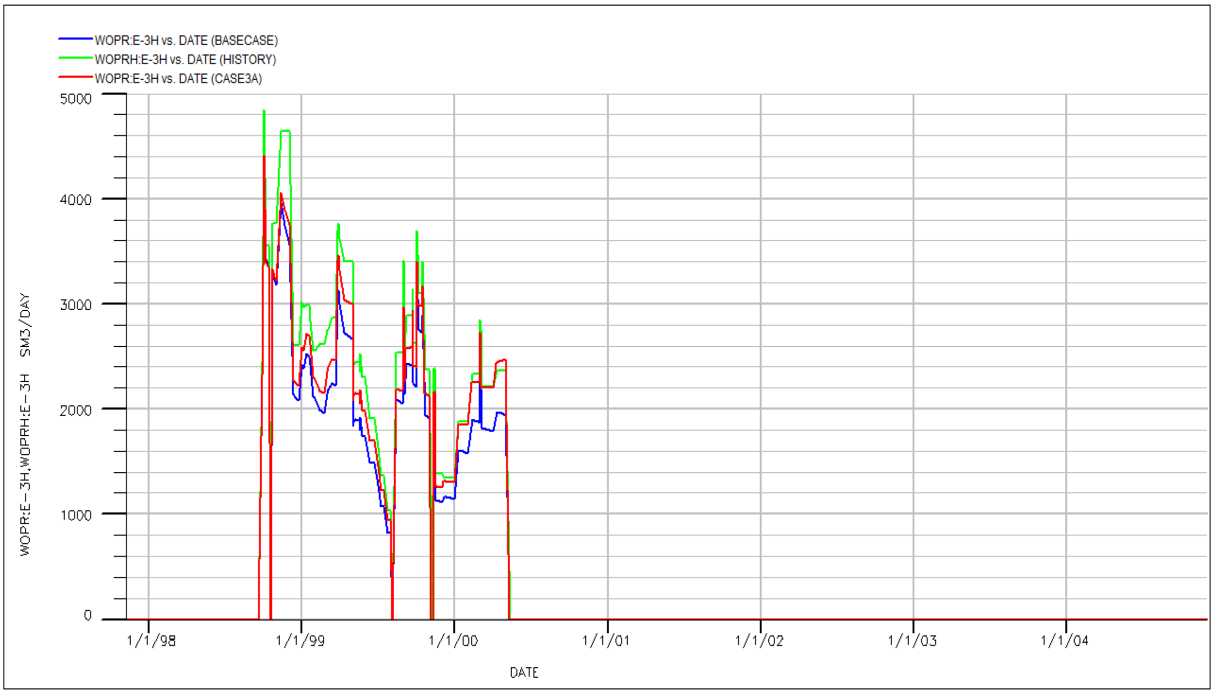


Figure 5.2.3.22 Well E-3H OPR Green=History Data, Blue=Basecase Model Data, Red= History Matched data

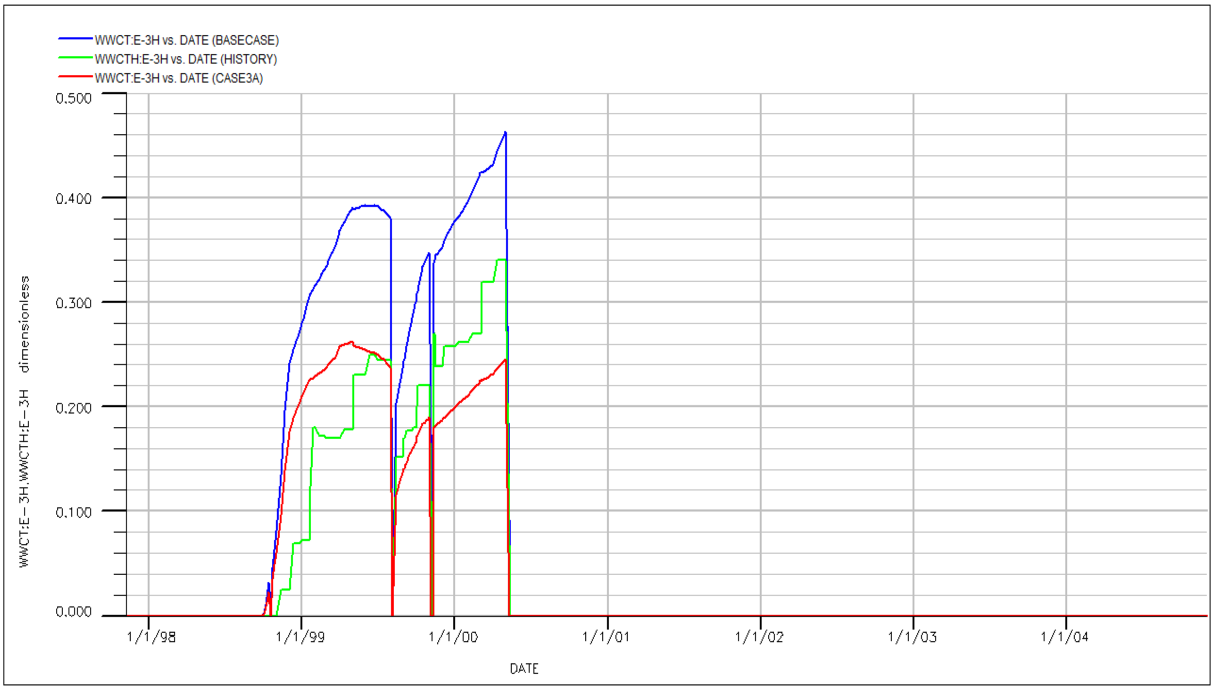


Figure 5.2.3.23 Well E-3H WCT Green=History Data, Blue=Basecase Model Data, Red= History Matched data

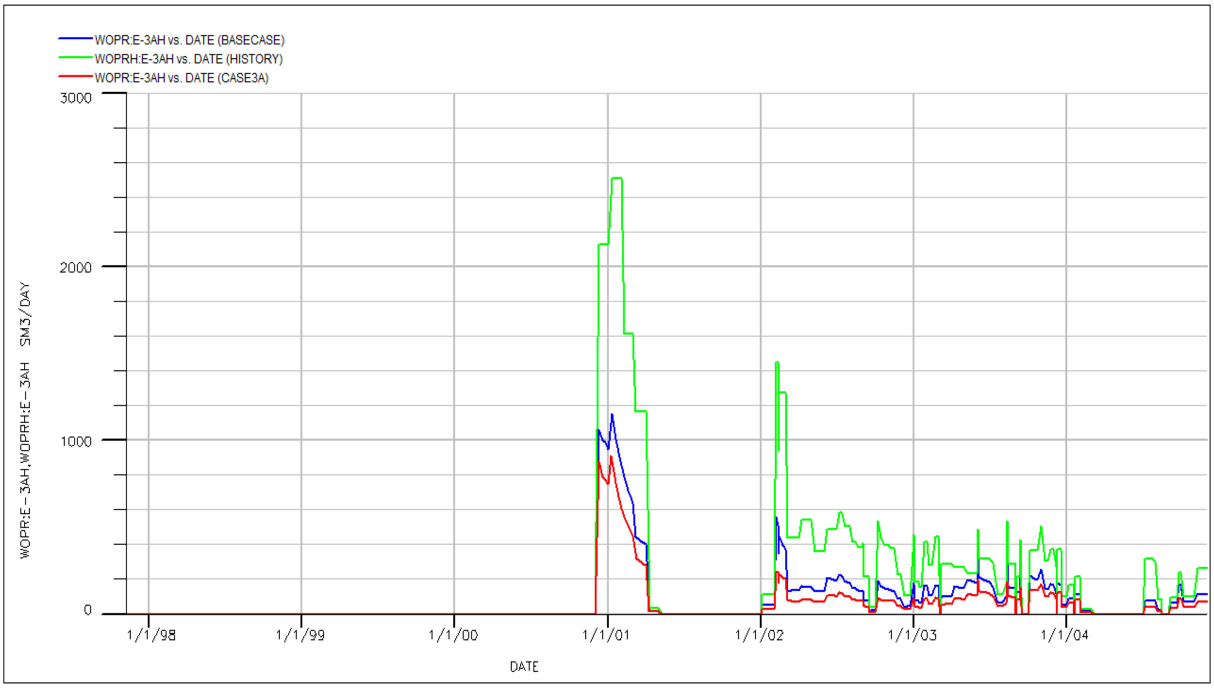


Figure 5.2.3.24 Well E-3AH OPR, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

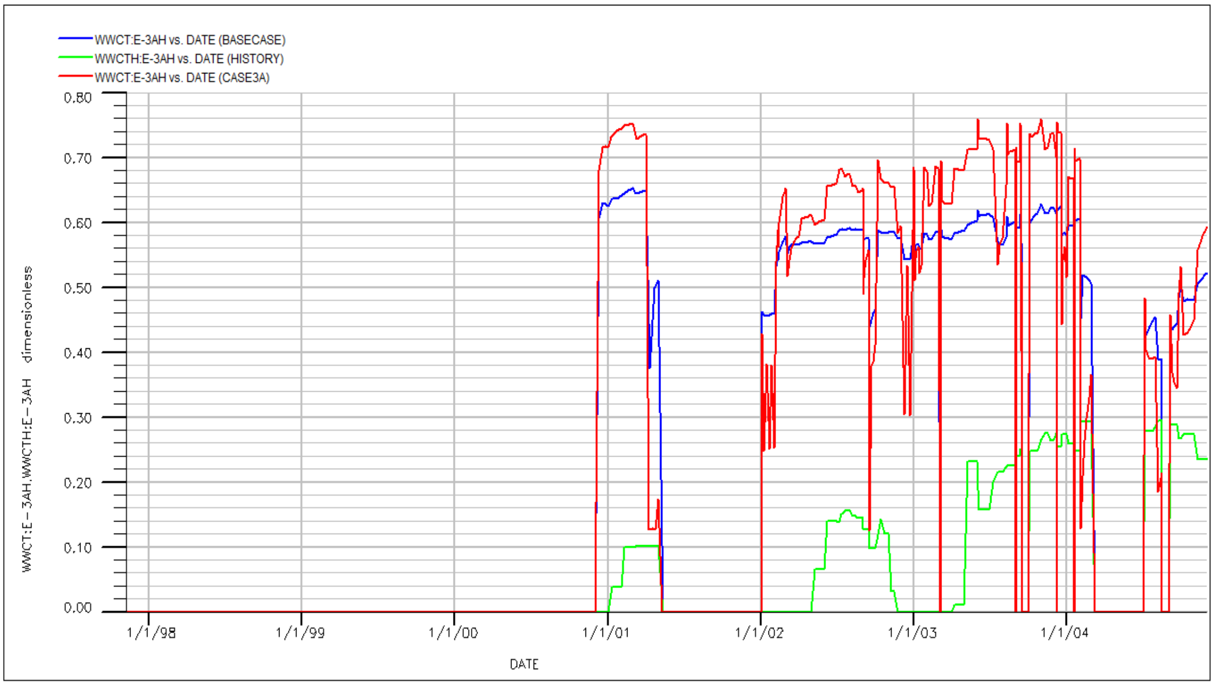


Figure 5.2.3.25 Well E-3AH WCT, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

5.2.3.2 Case 3B: Combination of Case 3a and Case 2b

The last case is to combine alternation in PERMX, PERMZ and fault transmissibility .The result of Oil Production Rate, Water Cut and Gas Oil Ratio on E-segment was plotted in figure 5.2.3.26 to 5.2.3.28. Detailed well behavior is plotted in figure 5.2.3.29 to figure 5.2.3.34.

Figure 5.2.3.26 Oil production rate on E-segment, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

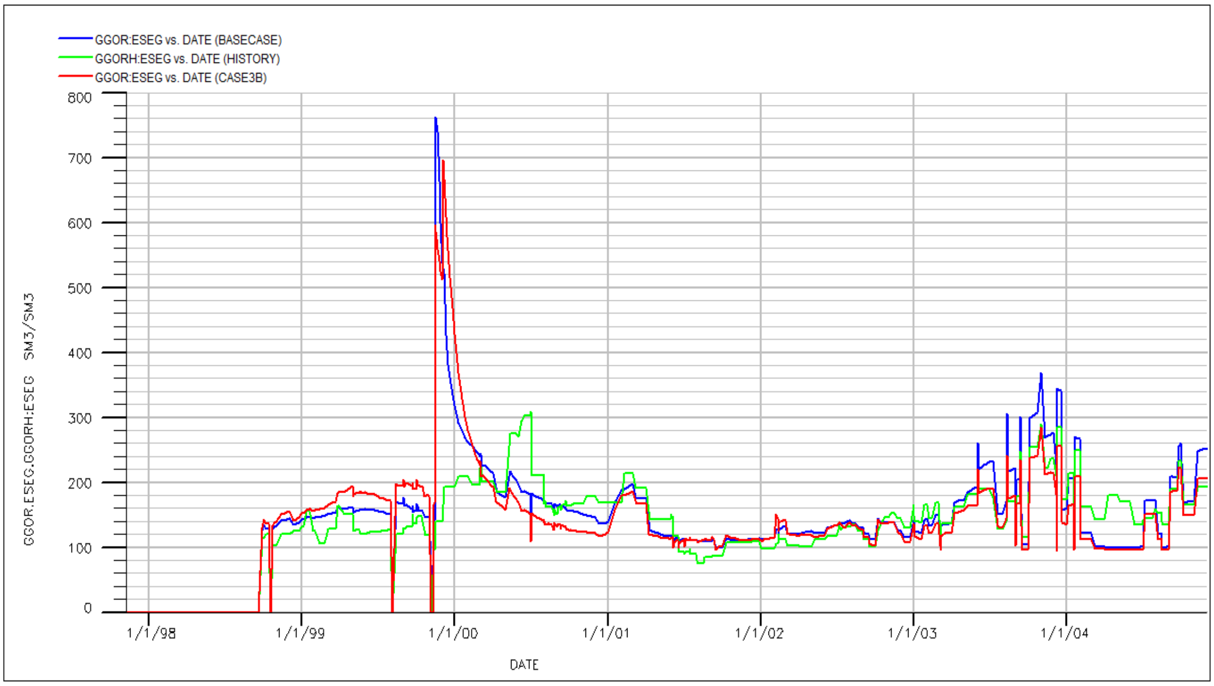


Figure 5.2.3.27 Gas oil ratio on E-segment, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

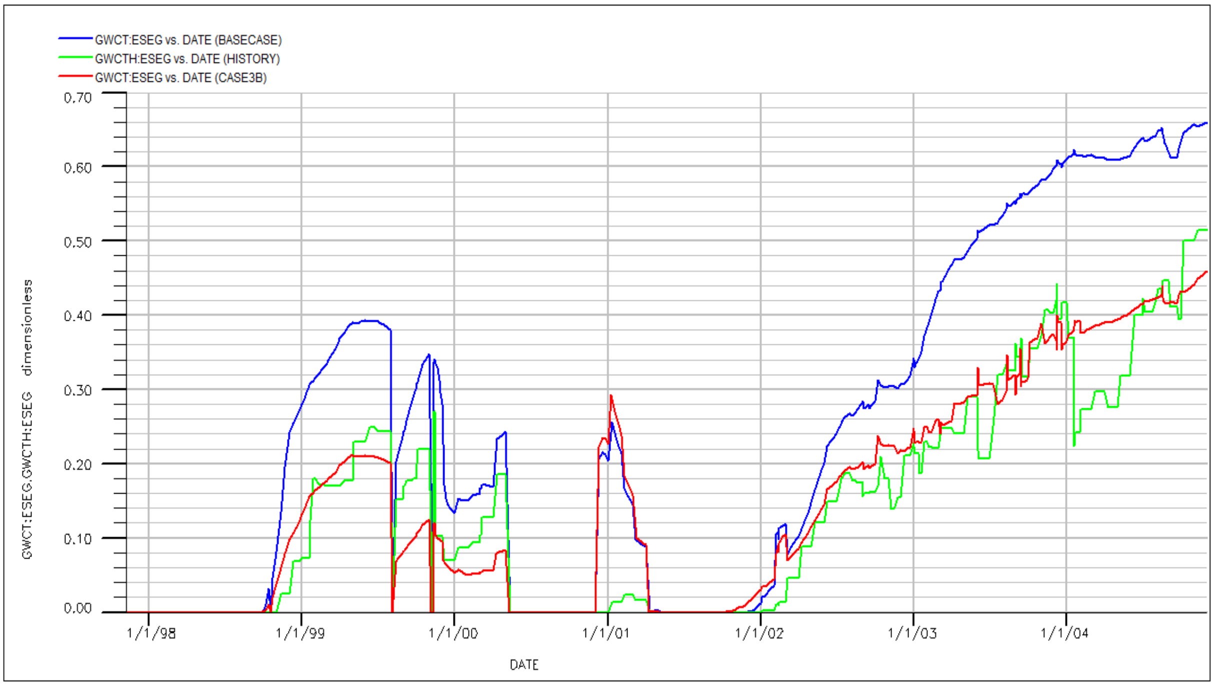


Figure 5.2.3.28 Water cut on E-segment, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

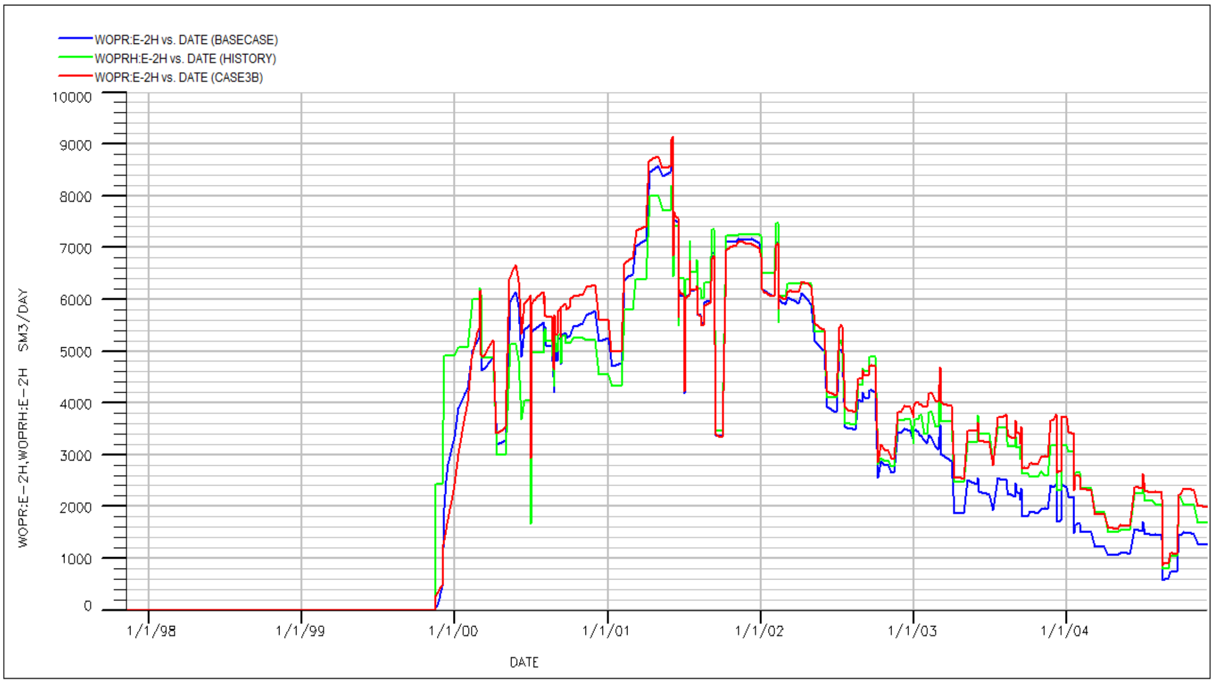


Figure 5.2.3.29 E-2H Oil production rate, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

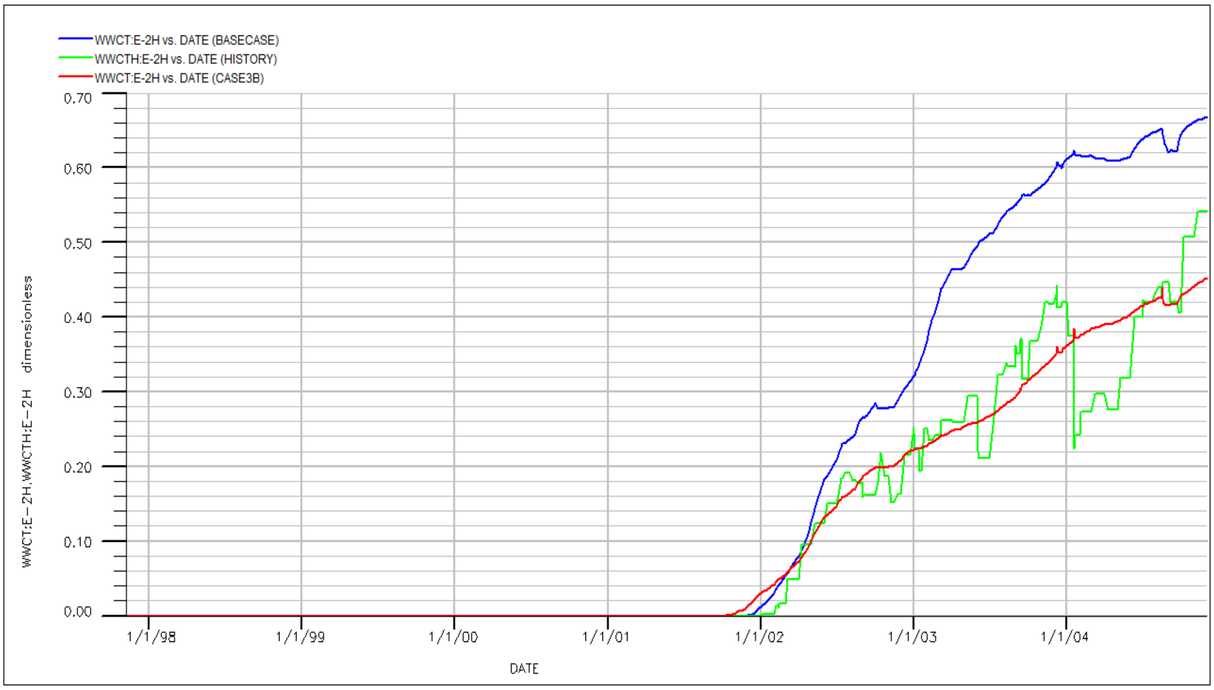


Figure 5.2.3.30 E-2H water cut, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

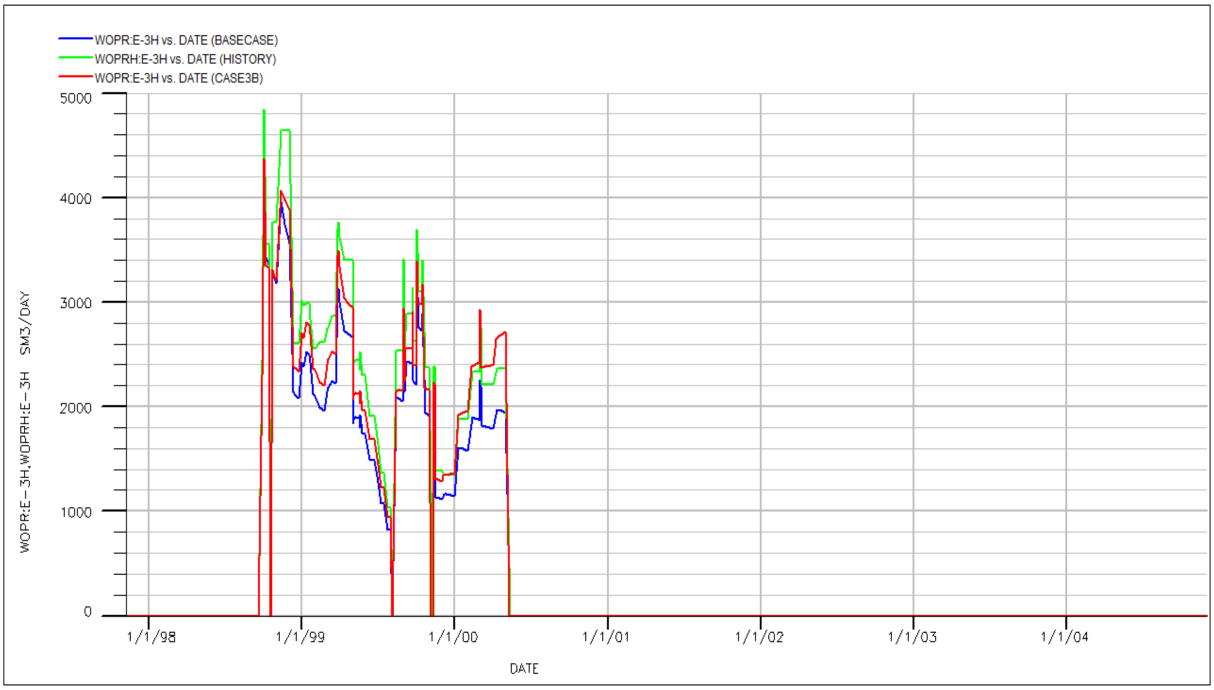


Figure 5.2.3.31 E-3H Oil production rate, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

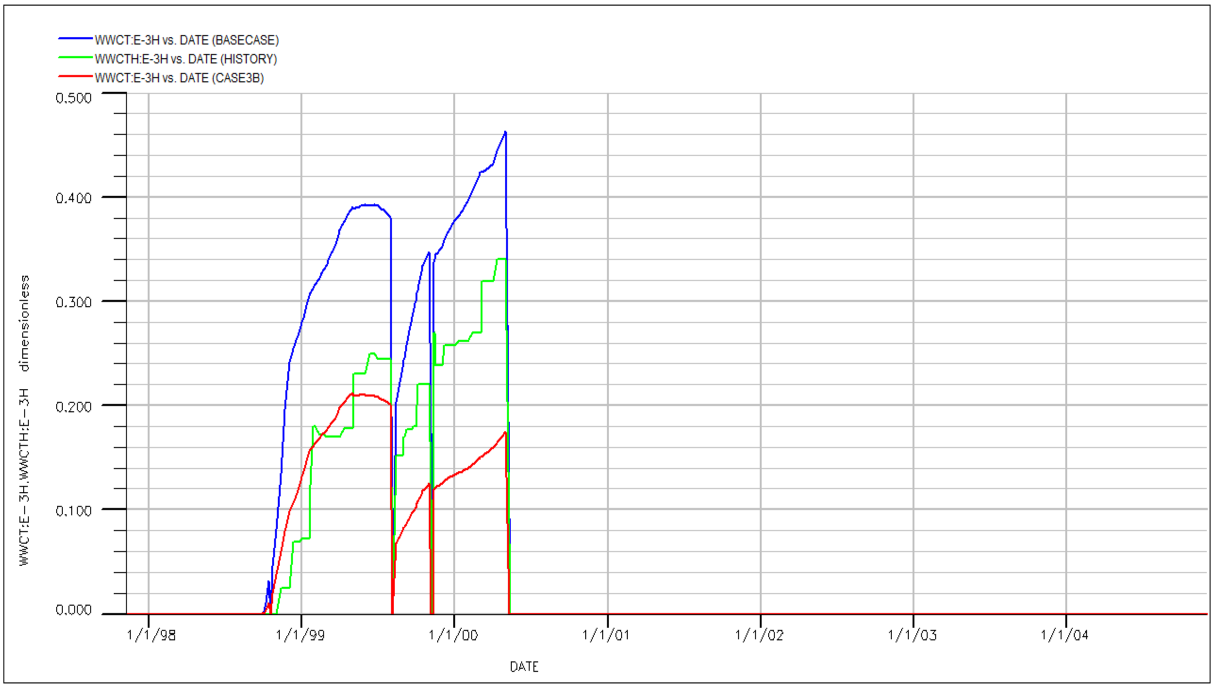


Figure 5.2.3.32 E-3H water cut, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

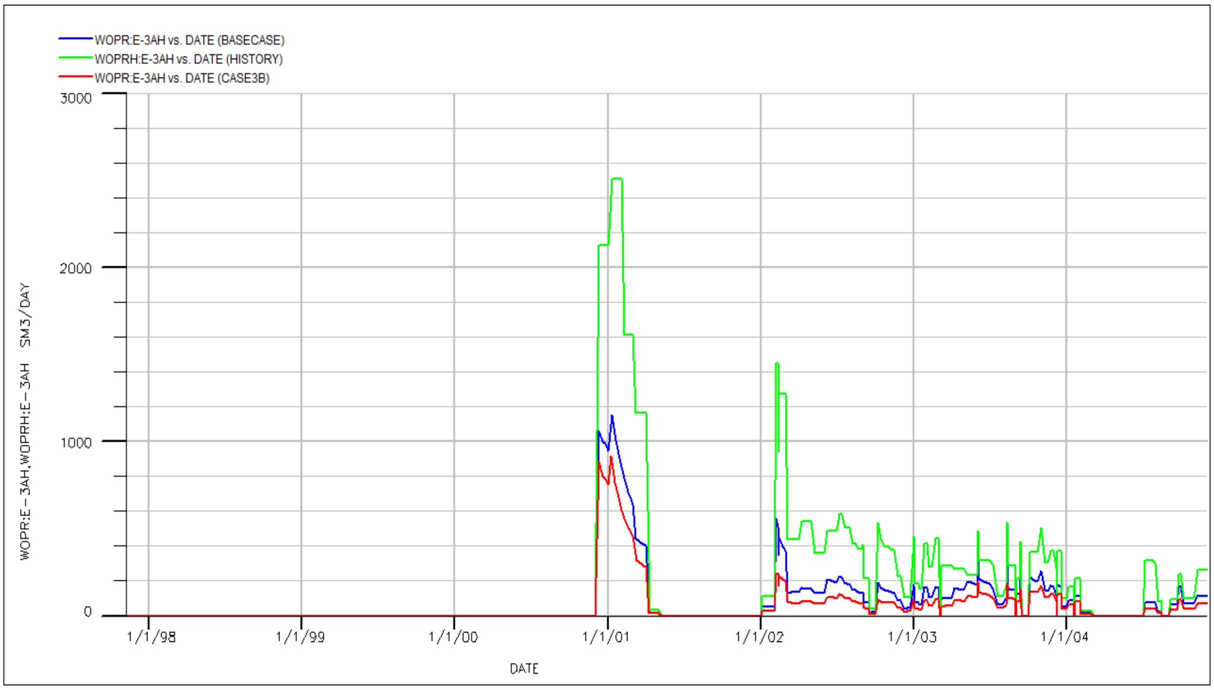


Figure 5.2.3.33 E-3H Oil production rate, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

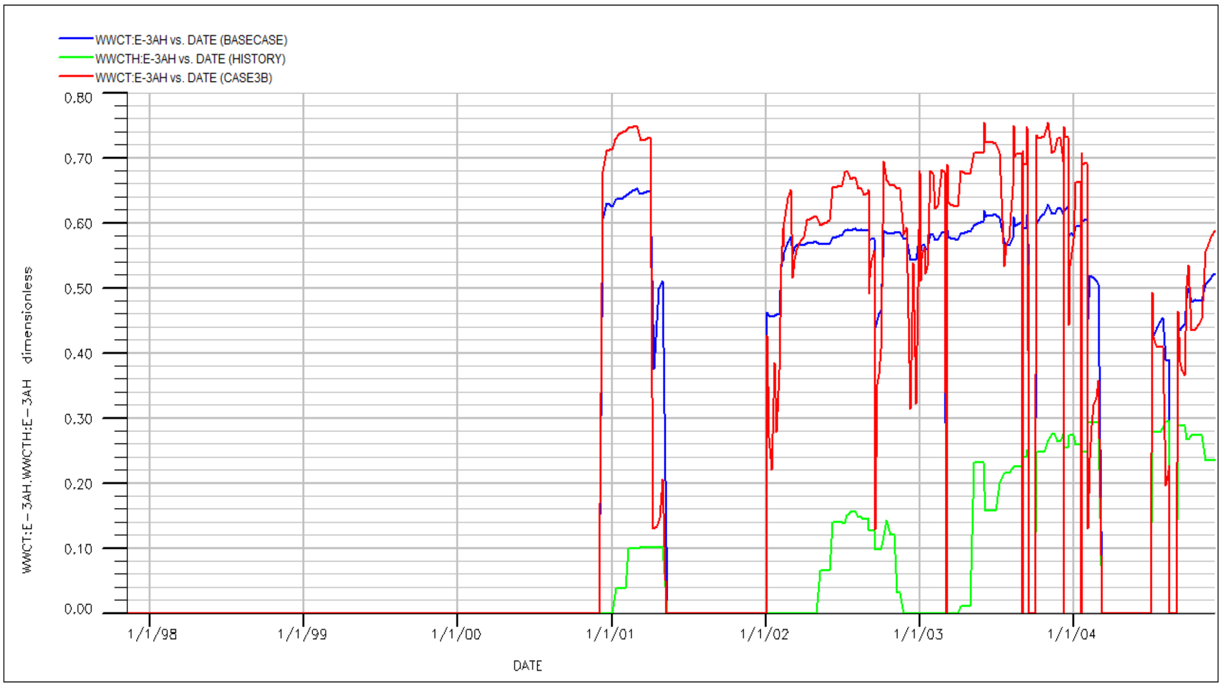


Figure 5.2.3.34 E-3H water cut, Green=History Data, Blue=Basecase Model Data, Red= History Matched data

5.3 Observation and Result

5.3.1 Case1: Adjustment of PERMZ

The parameter PERMZ affects the field oil production rate and water cut, but has little influence on GOR. After PERMZ adjustment, a better match is achieved as shown in figure 5.2.1.7 to 5.2.1.15. There is a slightly change compare to base case especially for well E-2H and E-3H. Oil production rate curve of well E-2H is increased and the water cut is reduced. Fluid flow in z direction is changed by modifying PERMZ, more oil in area close to wellbore is trapped. However, oil production rate performance from year 2000 to 2001 is much higher than the history performance.

5.3.1.1 Case2a: Adjustment of PERMX

The parameter PERMX affects the field oil production rate and water cut. In detail level, performance of E-2H is the most sensitive of the three production wells. E-2H is the main production well and oil production is significant higher than other production wells on E-segment, which means improvement of E-2H may leads to a better match for the whole field. Field production rates, GOR and WCT curves get better matched after adjust PERMX values around wellbores, cells between production and injection wells far from the wellbores is also taken into consideration in order to control the water flow from injection wells (figure 5.2.2.7 to 5.2.2.15). Oil production rate performance improved more than the first modification case.

5.3.1.2 Case2b: Combination of PERMX and PERMZ

Overall the analysis shows alter PERMX and PERMZ at the same time for individual wells can give a better match (Figure 5.2.2.17 to 5.2.2.25). Oil near the production wellbore is trapped and underlying aquifer and water from injection wells is better controlled. Field oil production rate performance and water cut have significant improvement especially after year 2002. This is the best modified case so far in this thesis.

5.3.1.3 Case3a: Adjustment of fault transmissibility

Fault transmissibility has an influence on flow direction in reservoir model. Faults generally increase the overall vertical connectivity of a reservoir and decrease the overall horizontal connectivity. The field oil production and water cut are sensitive on fault properties. By adjusting fault transmissibility, field production, water cut and gas oil ratio are better matched (figure 5.2.3.17 to 5.2.3.15). Production profiles of well E-2H and E-3H are improved. However, water production for well E-3AH is higher than the base case which leads to lower oil production. Fairly good match for well E-2H OPR is achieved between year 1999 to 2000 and after year 2003. WCT for E-2H got an early Water Break Through and high WCT at start of water production.

5.3.1.4 Case3b: Combination of PERMX, PERMZ and Faults

By adjusting fault transmissibility together with permeability in x- and z direction, change of performance is more noticeable. The biggest change in the global production data is the WCT. The model has lower water cut except year around 2001. Oil production is higher than history performance for E-segment.

Case 2b, combination of PERMZ and PERMX is chosen as the best case and will be discussed further in this thesis. Regarding to the field oil production, better much is located on two distinct periods as from production start to year 2000 and from April to the end of simulation. Water cut is reduced and better matched during the production period. GOR is not sensitive. The basecase GOR is good matched except data around year 2000.

5.4 Discussion

The earliest oil and gas production on E-segment was well E-3H in September 1998, while the main production well E-2H started in November 1999. The well E-3H is shut in October 2000 due to high water production. E-3AH is drilled as a side track well to well E-3H and started oil and gas production in December 2000. However, water production started shortly after year 2001 and the well has to be shut in at the same year and re-opened in February 2002. Water issue came up again after several months' production. There is no water production to well E-2H until January 2002. From then till December 2003 where the history production ended, well E-2H and E-3AH produce oil gas and water.

The above observation proved that exist huge amount of underlying aquifer on Norne E-segment which has the potential of water encroachment into the production wells immediately oil and gas production starts. It is clear that water production has been a great issue. Simulation results shows that reducing the vertical permeability between the oil water contact and horizontal permeability between the production and injection wells could reduce the quick flow of water towards the production wells and therefore prevent the early water breakthrough in to the production wells. The model is responding positively to the adjustment of vertical and horizontal communication.

Due to the fact that the pressure data is lacking, the main priority was to alter the flow of fluids. Prior to consulting with Statoil in Harstad the focus was more on the faults of reservoir which have different transmissibility values affects the horizontal flow. Fault zonation and fault transmissibility are used to control flooding from the injectors. Faults generally increase the overall vertical connectivity of a reservoir and decrease the overall horizontal connectivity.The fault E_01 and DE_2 are highly sensitive. Altering these values leads to better match, however, the model oil production is much higher than history performance when we combine altering faults transmissibility with modification of permeability in x- and z-direction.

Observation of results of 3 Cases indicate that the process of manual history matching is a complex procedure, however, for the accurate historical data and small field, manual history matching is still a good method.

5.5 Quality control of Norne E-segment model

The model used in this thesis is the Norne E-segment model which is separated from the Norne whole field model on the assumption of a constant flux boundary. A checking is done after modification. The referred match is illustrated in table 5.5.1 and 5.5.2

At start of simulation, year 1997, a good match was obtained when a section was sliced from isolated segment after modification and compared with the same section in attached segment after modification. During the production, a different of saturation is observed near the fault.

The quality testing was also done to the main production well E-2H.In the figure 5.5.2. The red line represents the full field model and the black line represents the separated E-segment

The differences mean that property parameters of this segment must be related to the other segments. Communications between segments must be considered in order to improve the accuracy of the Norne full flied model. For instant, alter water flood in E-segment may alter fluid behavior in C-segment as well. This thesis focus on improvement of E-segment reservoir model and not represent the Norne full field model.

Table 5.5.1 Oil saturation match at different times

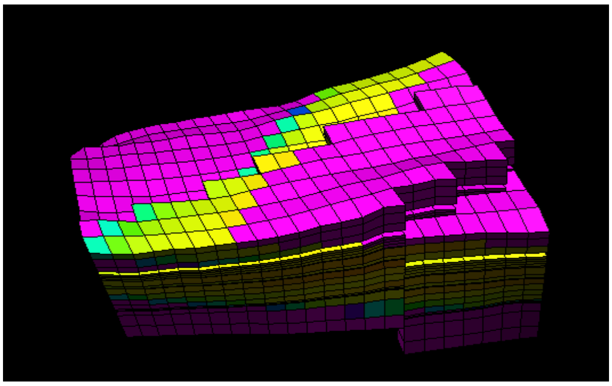
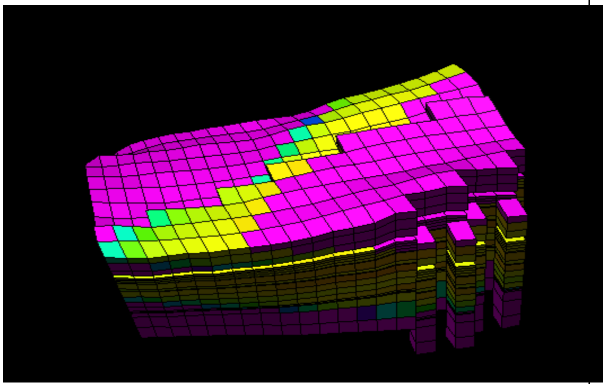
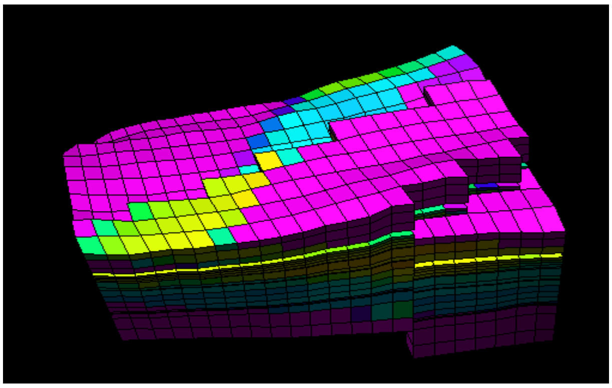
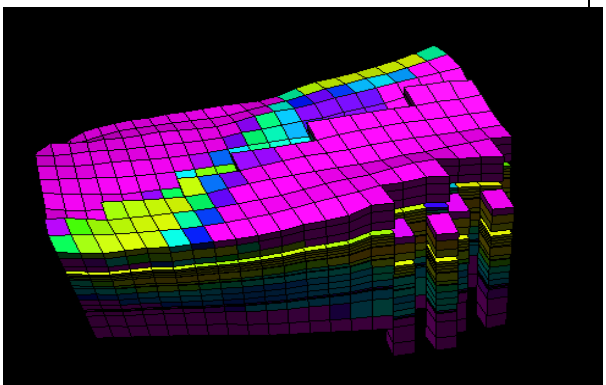
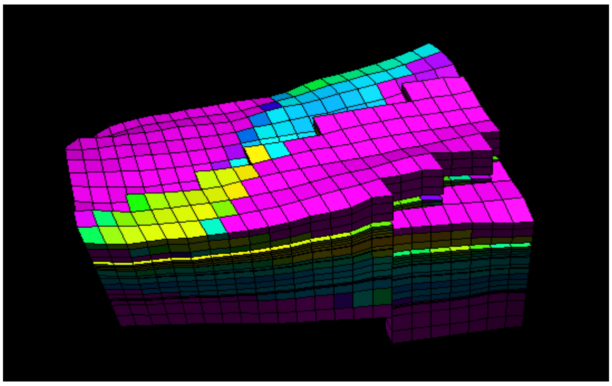
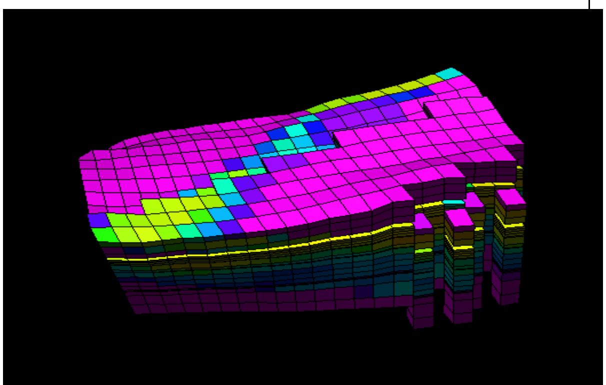
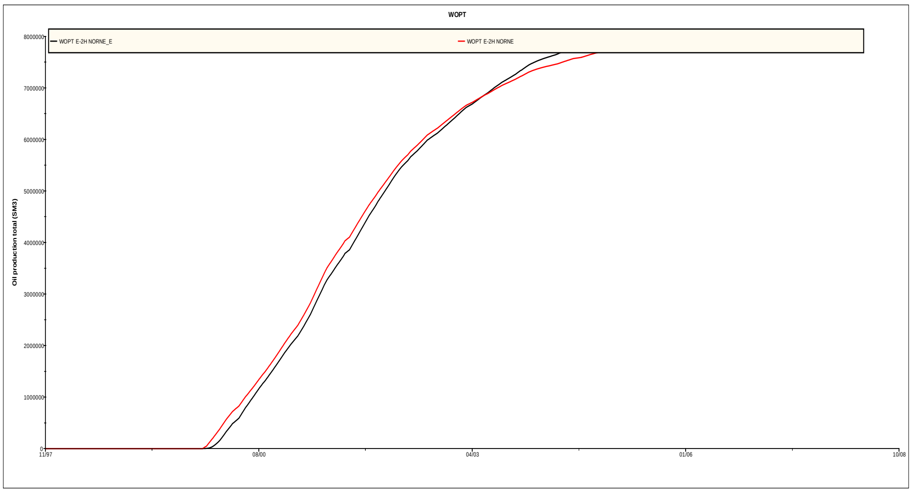
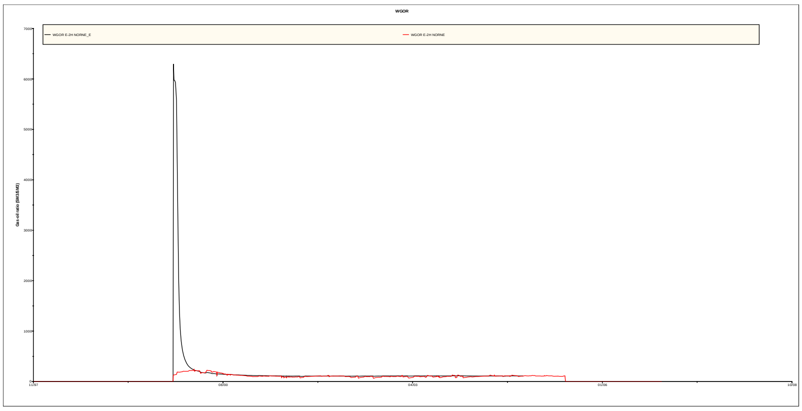
A Section from E-segment run in Full Field Model	A Section from E segment run in Separated E-segment Model
 06 November 1997	 06 November 1997
 02 January 2003	 02 January 2003
 19 January 2004	 19 January 2004

Table 5.5.2 Well E-2H matching between the separated E-segment and attached E – segment.



Total Oil Production



Well gas-oil ratio: E-2H

6. History matching using 4D seismic

The main objective of 4D seismic history matching in this thesis is using 4D seismic qualitatively to study the behavior of the reservoir at different times in order to improve eclipse model.

6.1 Processing and strategy of 4D seismic interpretation

The seismic processing is done before interpretation start. It is used to adjust the seismic shots which represent geological structure of the sub-surface. The steps include typically: analysis of velocities and frequencies, static corrections, de-convolution, normal move-out, dip move-out, stacking and migration [31].

The OWC movement at Norne can most effectively be interpreted by using the 4D difference data. Seismic modeling of rise of the OWC from 0 to 70 meter is shown in figure 6.1a. The new OWC (blue) is almost impossible to locate on these stacks. However, using of 4D differences could cancel the geology, as shown in figure 6.1b. Seismic differences modeling of OWC rise with the first base trace is in the left. The 2003 line through a water injector is shown in figure 6.1c. The OWC cannot be interpreted on this line. However, the 2003 OWC is interpretable on the 2001–2003 difference line (shown in figure 6.1d). Some synthetic modeled difference data in the injector based on repeated saturation logging in 2000 and 2002 are shown in figure 6.1e. The relative change in acoustic impedance between base and 2000 (blue) and base and 2002 (black) surveys are shown in the left figure 6.1e. A complete flushing of the oil with water causes an acoustic impedance change of 7–8%.Figures 6.1 c–e are plotted at the same depth scale.

Norne history matching could use 4D reservoir simulation modeling approach. Seismic modeling of the simulation model is performed and compared with the 4D data. In areas where the simulation model does not coincide with the 4D data and production data, simulation model update could be done. Both seismic reflection amplitudes and acoustic impedance could be compared. Seismic parameters are calculated using Norne rock model and the Gassmann equation. Seismic modeling is important for history matching and is also a guide to how the 4D difference data can be interpreted and understood. Seismic modeling in pilot wells and in wells with repeated saturation logging (as in Figure 6.1 e) is also very important as an interpretation guide and to validate the 4D interpretation.

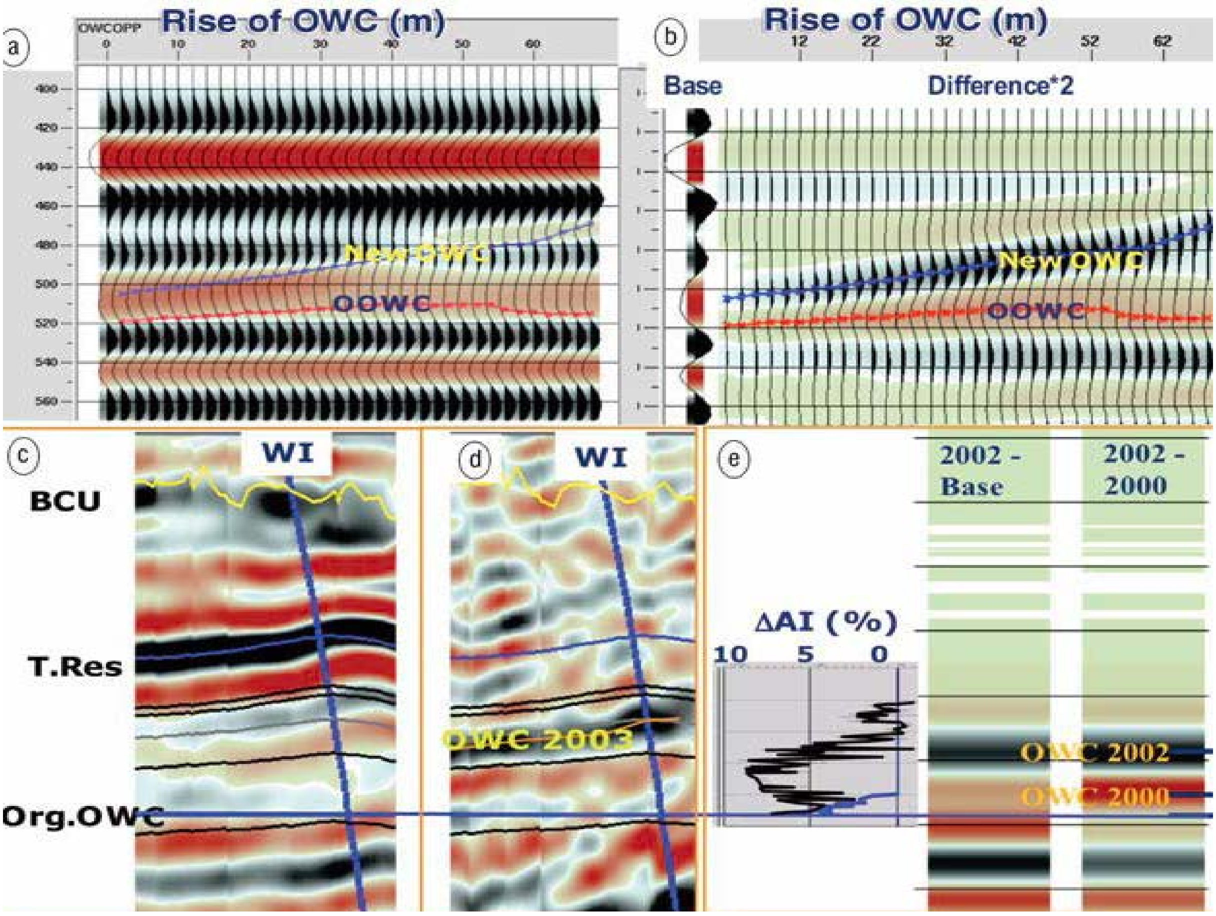


Figure 6.1 (a) Seismic modeling for varying OWC rise from 0–70 m. (b) Seismic differences for varying OWC riseand the first base trace. (c) 2003 4D data around an injector. (d) 2001–2003 4D difference around same injector. The 2003 OWC can clearly be interpreted here. (e) Left curves show change in acoustic impedance in % from base to 2000 (blue curve) and base to 2002 (black curve). Seismic modeling on the right shows differences between base and 2002 and 2000–2002. [32]

6.2 Statoil Case Study

Based on 4D data from 2003[30], an infill production Well E-3CH is drilled on April 2005 perforated on Ile formation (layer5). The well location was confirmed to be good on the 2004 data. The location of the well is shown in figure 6.2.1. The comparison of a line through well E-3CH from the simulation model and seismic data is shown in figure 6.2.2 to 6.2.5. By analyzing the 2003 data, a significant difference can be seen between the 4D data and the reservoir simulation model. Figure 6.2.2 shows water saturation from the simulation model in mid-2003. Figure 6.2.3 shows the amplitude difference between year 2001 and 2003 of simulation model. Figure 6.2.4 shows the AI difference between year 2001 and 2003 of 4D seismic. Figure 6.2.5 shows the amplitude difference between year 2001 and 2003 of 4D seismic model. From the last two figures, it is clearly that the OWC from 4D (blue line) can be interpreted deeper than in the simulation model (yellow line).

From figure 6.2.1 the reservoir map shows fault E_01 was open at the simulation time and the water flowed easily from the water injector F-1H through fault E_01. The 4D data indicated that fault E_01 was partly sealing and most water from F-1H therefore flowed along fault E_01 instead of through it. This is confirmed by tracer data in the area and agrees with the point in manual history matching fault transmissibility part in Chapter 5. By decreasing the fault transmissibility of fault E_01 could improve the water cut and pressure match in the area which is already shown in Chapter 5(Figure5.2.3.17 to figure5.2.3.25) and a series of modifications could be done to improve the accuracy of the simulation model.

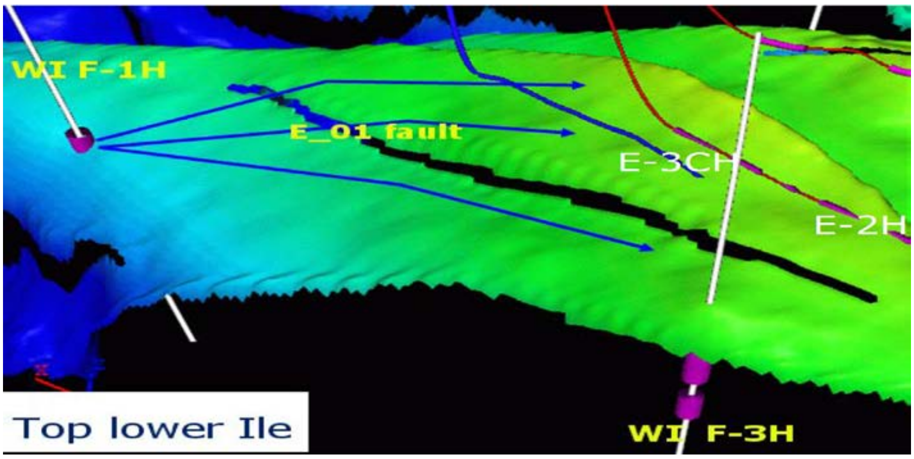


Figure 6.2.1 the reservoir map [33]

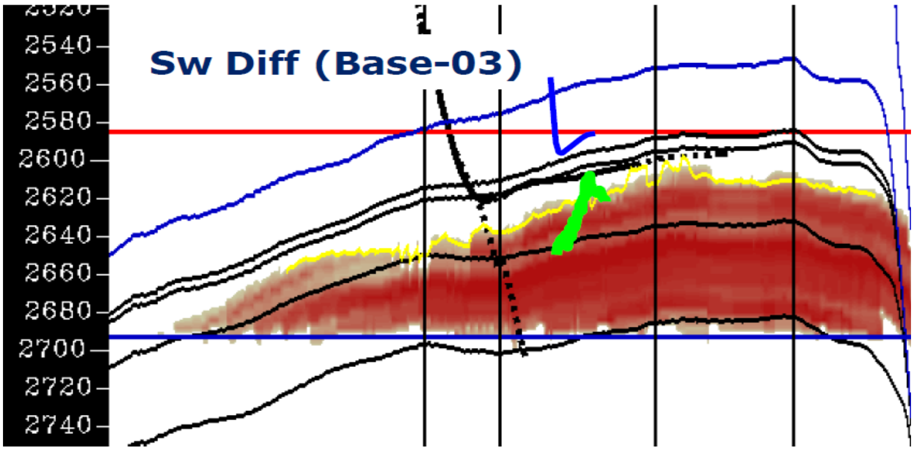


Figure 6.2.2 Water saturation (red is high saturation) of simulation model base case, yellow =OWC from simulation model [33]

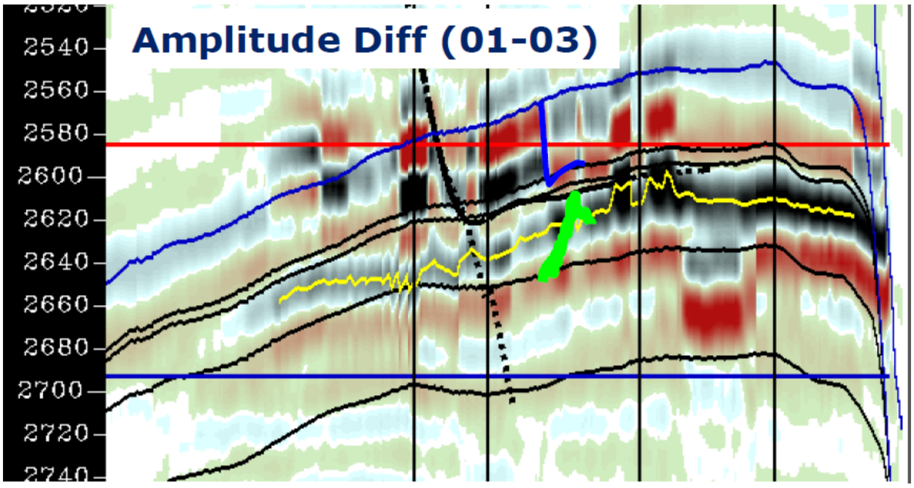


Figure 6.2.3 Amplitude difference of simulation model basecase. yellow =OWC from simulation model [33]

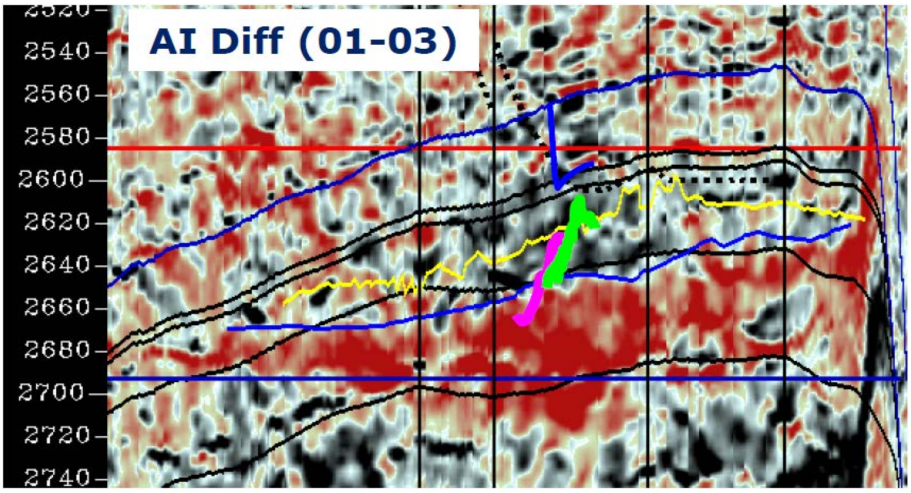


Figure 6.2.4 AI difference 4D of seismic model, yellow =OWC of simulation model, blue= OWC of seismic model[33]

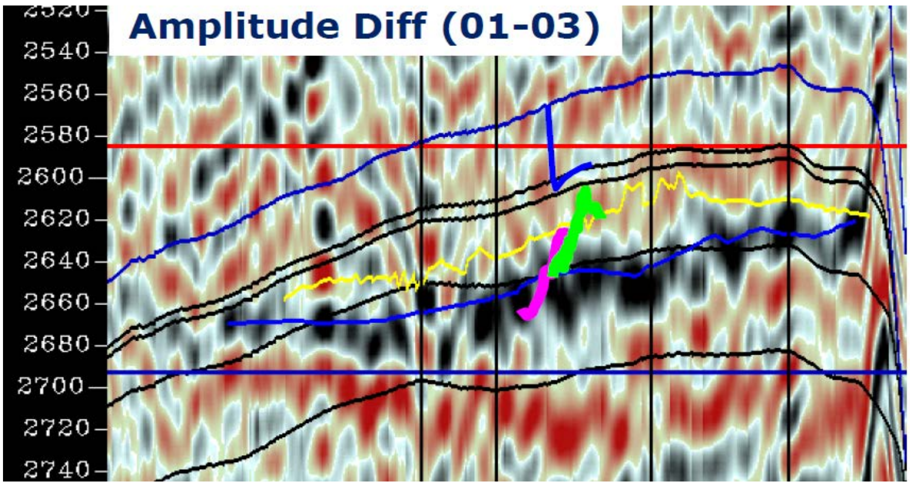


Figure 6.2.5 Amplitude difference of seismic model, yellow = OWC of simulation model, blue= OWC of seismic model[33]

Figure 6.2.6 to 6.2.9 shows the model created after modification of faults which is much better match with the 4D data. The green line represents the OWC on the new simulation model, the line in pink color represents the time-lapse seismic OWC. WOC of simulation model decline and the difference between simulation and seismic curves is reduced. The location of E-3CH is also good in the simulation model. Water cut is improved as well. Figure 6.2.10 shows the WCT of neighbor well E-2H.

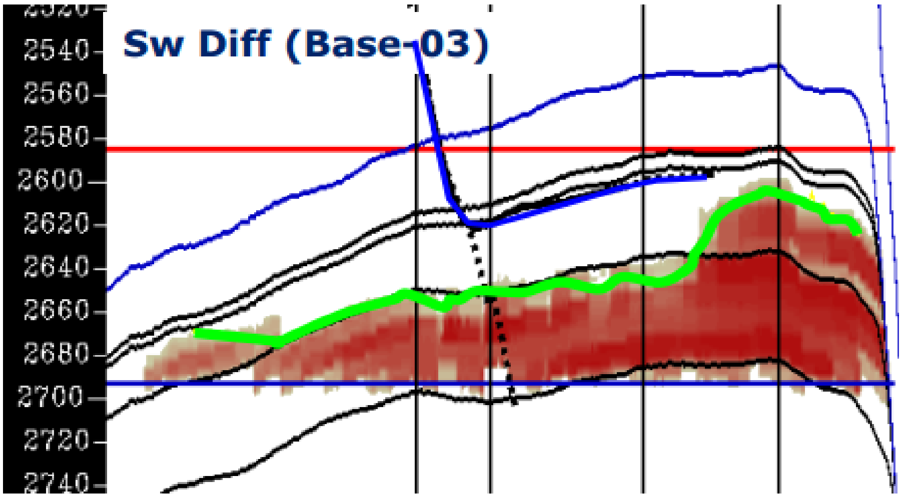


Figure 6.2.6 Water saturation (red is high saturation) of simulation model after modified fault, green =OWC from simulation model [33]

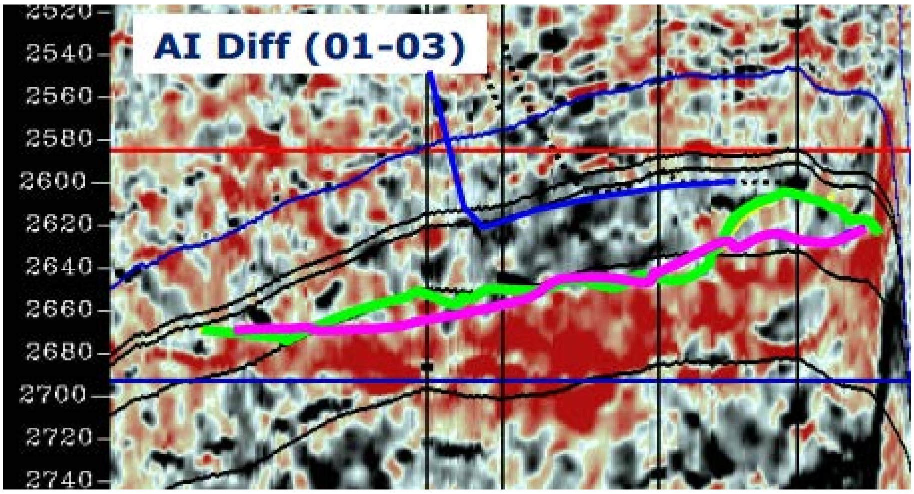


Figure 6.2.7 AI difference 4D of seismic model, green =OWC of simulation model, pink= OWC of seismic model[33]

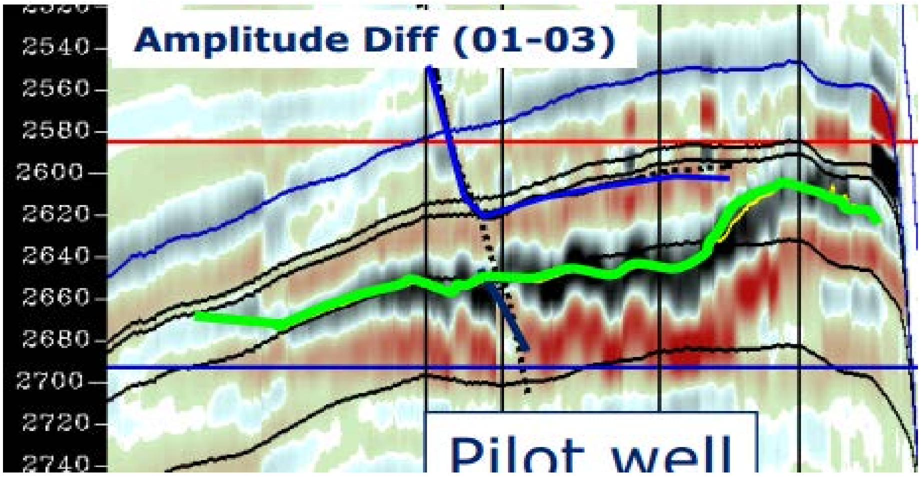


Figure 6.2.8 Amplitude difference of simulation model after modification. Green =OWC from simulation model[33]

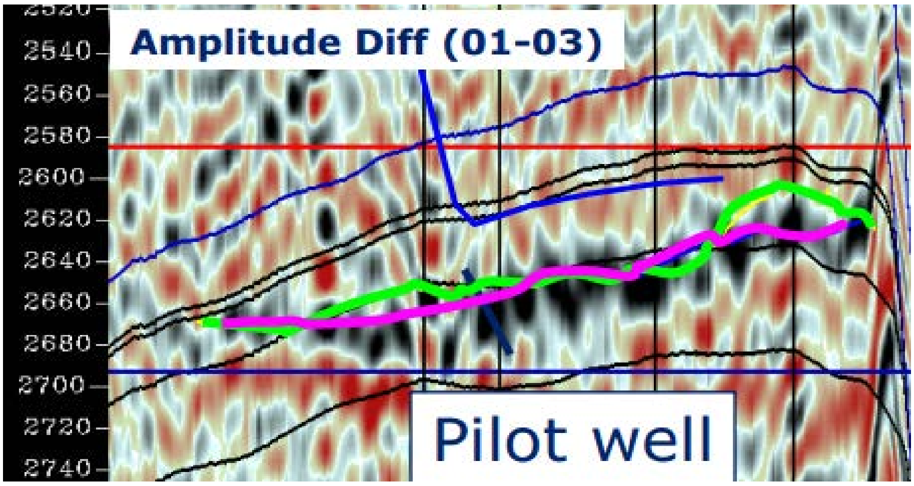


Figure 6.2.9 Amplitude difference of seismic model, green = OWC of simulation model, pink= OWC of seismic model[33]

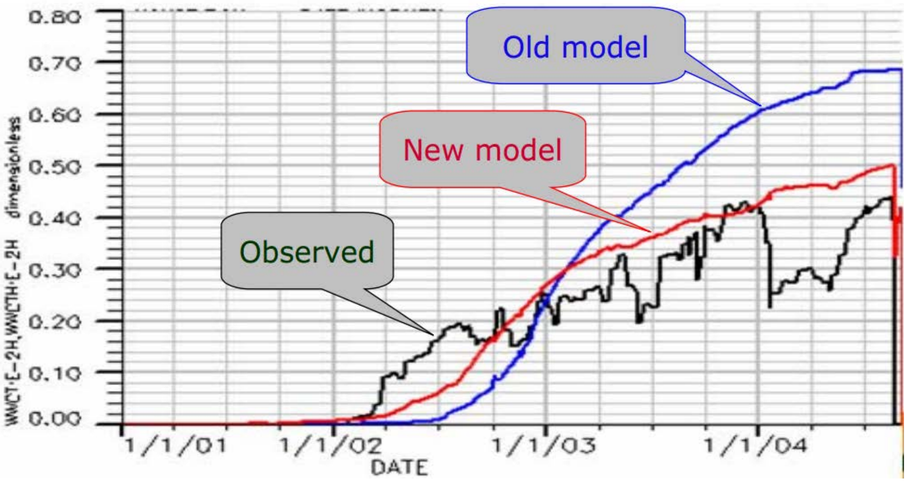
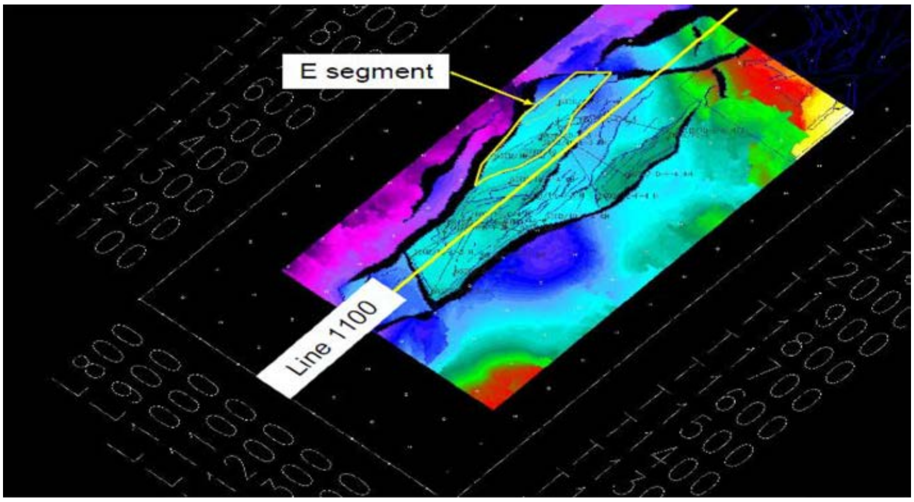


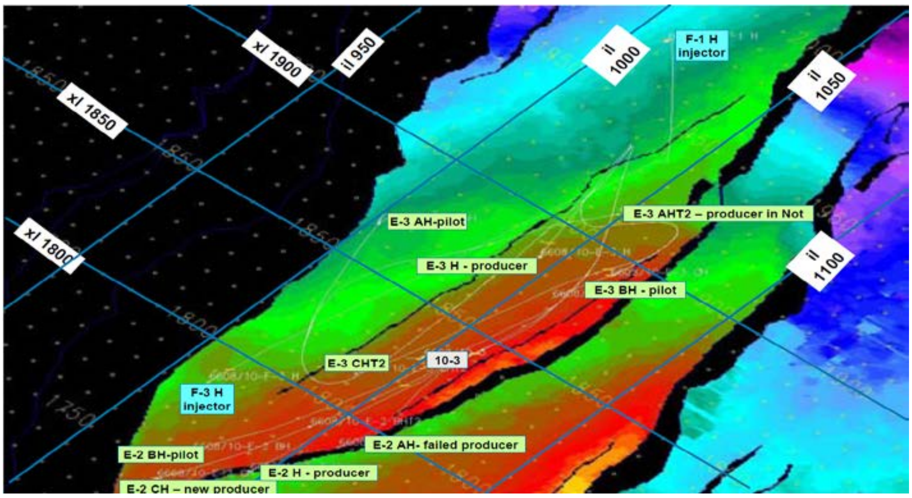
Figure 6.2.10 WCT of neighbor well E-2H, blue =old model, red=modified model, black= history model[33]

6.3 Qualitative comparison of OWC

The interpretation was done in seismic line from 2001 and 2004, in order to compare the OWC difference. The line 1050 is chosen in the map because it goes through the Norne E-segment and may be representable for major detail of the subsurface in Norne E-segment (Figure 6.3.1 and 6.3.2). The seismic survey result provided is shown in figure 6.3.3.



6.3.1 Map view of Norne E-segment[33]



6.3.2 Seismic line selected through the segment [33]

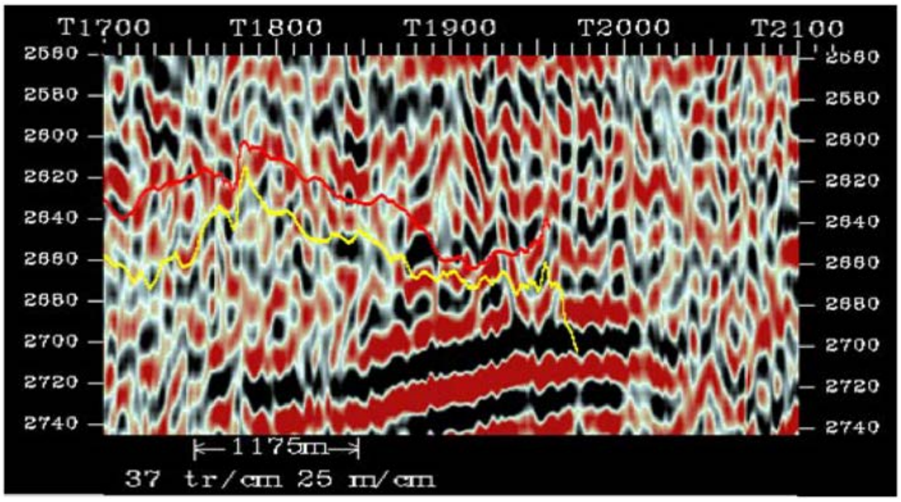


Figure 6.3.3 Interpretation of OWC, line 1050 seismic difference 2001 and 2004 at Norne Field [33].

6.3.1 Procedure

- Locate the seismic line path on simulation model. Sever the cross section on E-segment, which seismic line crosses through (xl 1770 to xl 1970 near location il 1050) as shown in figure 6.3.4
- Determine OWC in both seismic and simulation model. OWC in seismic model is given in Figure 6.3.3. Simulation model OWC should be decided after consideration of monthly water saturation profile.
- Qualitative comparison of OWC. Both depth and water migration is taken into consideration.

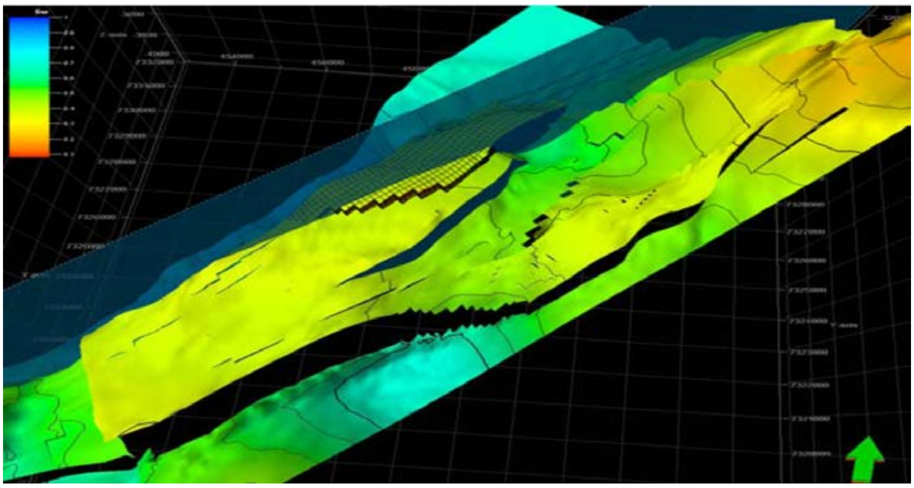


Figure 6.3.4 Relocation seismic line

6.3.2 Observations and Results

6.3.2.1 The Base Case

In order to decide the OWC of simulation model, the following assumption is made: 100% water saturated formation is in dark blue. The interphase between 100% water saturated and lighter blue is assumed to be the free OWC, or initial OWC before production started. The green color is used as boarder line for oil and water. It is approximately 50% water saturation and may due to residual oil saturation.

The qualitative comparison of OWC in basecase is shown in figure 6.3.5

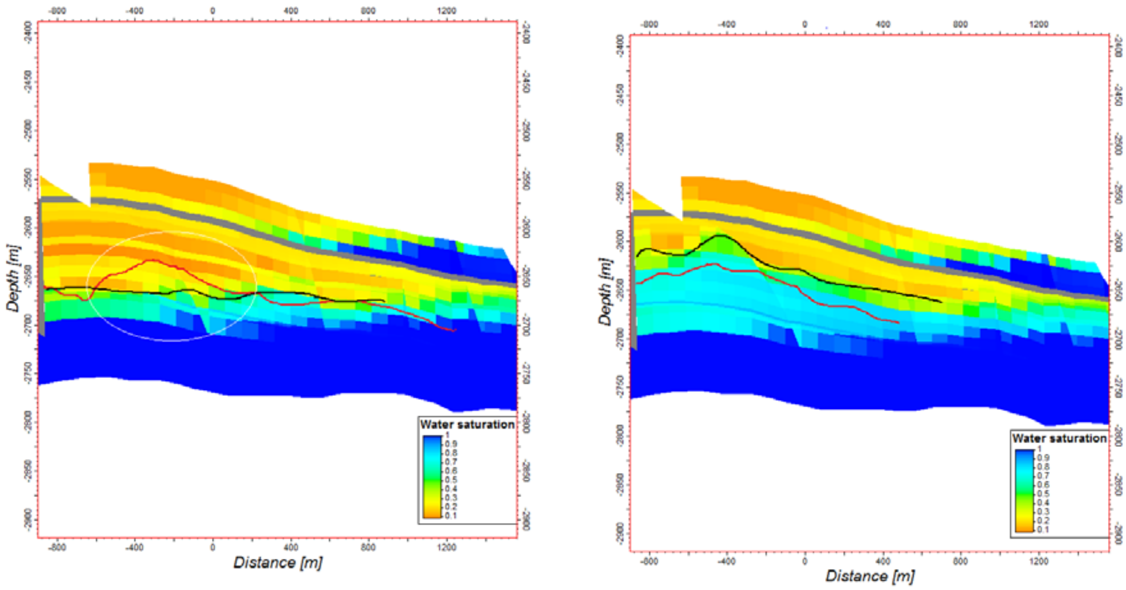


Figure 6.3.5 Comparison between obtained OWC in 2001(left) and 2004(right) the base case, black=reservoir model red=simulation model, the horizontal axis is a scalar for distance.

At year 2001, it is interesting to focus on area inside the white circle where performs significant difference between two curves. The reason can be the placement of the well E-2H, which indicates that properties such as permeability and transmissibility of drainage area near production wellbore is important to be considered in order to improve the accuracy of the simulation model. The OWC have a great impact on production and water cut. At year 2004, OWC from 4D is interpreted deeper than in the simulation model which in accord with the Statoil study in Chapter 6.2.

6.3.2.2 The History matched case

Further, accuracy of modified simulation model Case 2b in Chapter 5 is investigated by qualitative comparison with seismic data. The result is illustrated in figure 6.3.6

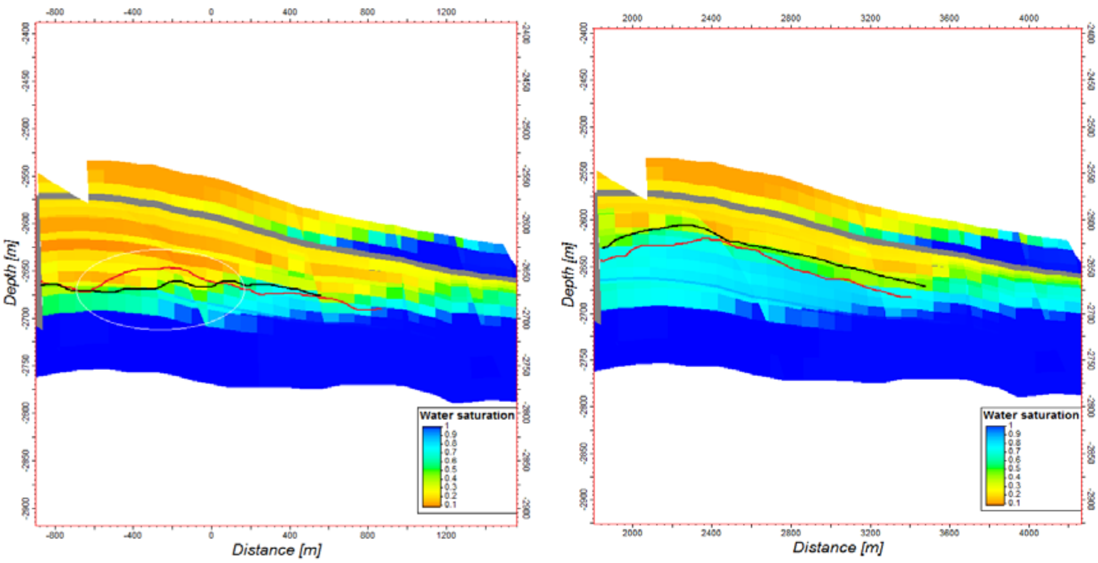


Figure 6.3.5 Comparison between obtained OWC in 2001(left) and 2004(right) after modification black=reservoir model red=simulation model, the horizontal axis is a scalar for distance.

At year 2001, difference between simulation and seismic curves is decrease inside the white circle. At year 2004, OWC from simulation model decline and the difference between simulation model with 4D data performance is reduced.

6.3.3 Conclusion and discussion

The first issue for inaccuracy during the process is to relocate the seismic line on the model. The intersection plan is supposed to sever a cross section as close as possible to the location of the seismic line 1050 in seismic interpretation figure which is used in further comparison. However, in this thesis the following assumptions has to be made, the saturation property in the same layer in location nearby is assume to be similar and the trend of OWC interacted between 2001 and 2004 is almost the same.

The second issue for inaccuracy is to decide the OWC of simulation and seismic data interpretation model. The OWC of seismic model is supposed to be as similar as possible to the given seismic interpretation figure 6.3.3. For simulation model, the green color is used as boarder line for oil and water.

However, the comparison of water saturation images shows that, OWC was rising during production period from 2001 to year 2004 and 4D is interpreted deeper than in the simulation model in 2004 model which is considered to be reasonable. After modification by controlling the permeability in horizontal and vertical direction, OWC of simulation model is declined and difference between simulation and seismic model is reduced which means that the accuracy of simulation model is improved.

7. Conclusions and recommendations

According to the analysis and results performed in manual history matching and seismic interpratation, the following conclusions can be obtained:

1. The sensitivity analysis results proved that the horizontal permeability, vertical permeability and fault transmissibility are key factors which have significant effect on oil and gas productivity and shaping the nature of Norne E-segment.

2. PERMZ has impact on fluid flow in z direction. It is proved huge amount of underlying aquifer on Norne E-segment. To reduce PERMZ around the wellbore especially near OWC could control the OWC rise in order to reduce the water flood into production well and more oil in area close to wellbore is trapped.

3. PERMX values around wellbores is modified, cells between production and injection wells far from the wellbores is also taken into consideration in order to control the water flow from injection wells.

4. Faults transmissibility which is important for vertical water movement is adjusted. Reduction of local fault transmissibility is used to guide the water flooding. F-1H is guided west of E-segment's main fault E_01 and communicates across the northern part of E_01.

5. Better match is achieved after each modified case above. History matching is not a unique procedure.

6. Time-lapse seismic data is incorporated in order to reduce the degree of non-uniqueness. Qualitative comparison of oil-water contact movement give a better understanding of flooding patterns and water rise. By comparing OWC of modified simulation model and 4D data, proved that adjustment of fault transmissibility could guide the water flooding and adjustment of PERMX together with PERMZ could control the water rise. OWC of simulation model is declined after each modification and difference between simulation model and seismic data is reduced which proves that accuracy of simulation model is improved after modification.

There are several recommendations for future work on the history matching of Norne field E-segment. Adjustments of relative permeability curves can be done in order to improve the GOR and water cut profiles. Vertical barriers transmissibility which is used to control the water rise should be considered in order to improve the accuracy of reservoir model. Communications between different segments should be take into consideration in order to improve the reservoir model accuracy for the entire Norne field. There are several issues on seismic interpretation part of thesis work which leads to inaccuracy. The precision of qualitative use of 4D seismic can be improved by creating synthetic seismic model from the simulation model which requires skilled knowledge of petro-physics and then compare it visually with the observed seismic data. OWC development can be observed and studied from seismic and then improve the accuracy of simulation model.

References

[1] Dadashpour, M. (2009). Reservoir characterization using production data and time-lapse seismic data (Doctoral dissertation, Norwegian University of Science and Technology).

[2] Norne Reservoir Simulation Model Updated Reference Case 2005.pdf

[3] Eirik Morell (2010) History matching of the Norne Field

[4] Fahimuddin, A. (2010). 4D seismic history matching using the ensemble Kalman filter (EnKF): possibilities and challenges. The University of Bergen.

[5] Calvert R, Insights and methods for 4D reservoir monitoring and characterization society of exploration geophysicists. SEG/EAGE Distinguished Instructor Short Course, 2005.

[6] Nur A and Simmons G, The effect of saturation on velocity in low porosity rocks, Earth and Planetary Sciences Letters, 7, (1967).

[7] Wang Z and Nur A, Effect of temperature on wave velocities in sands and sandstones with heavy hydrocarbons, SPE 15646, SPE Reservoir Engineering, (1988).

[8] Rwechungura, R., Dadashpour, M., & Kleppe, J. (2011, September). Advanced History Matching Techniques Reviewed. In SPE Middle East Oil and Gas Show and Conference.

[9] Kabir C S and Young N J 2001 Handling production-data uncertainty in history matching: The Meren reservoir case study, SPE 71621, SPE

[10] Landrø M 2005 Seismic Reservoir Monitoring, Lecture notes, Norwegian University of science and technology, NTNU, Norway.

[11] Gruenwalder, M., Poellitzer, S., & Clemens, T. (2007, June). Assisted and Manual History Matching of a Reservoir with 120 Wells, 58 Years Production History and Multiple Well Re-Completions. In EUROPEC/EAGE Conference and Exhibition.

[12] Chen, W.H et al.: “A new algoritm for Automatic History Matching”, SPEJ, Dec 1974

[13] Bissell, R.C.: “Calculating Optimal Parameters for History-Matching,”paper presented at the 1994 European Conference on the Mathematics of Oil Recovery, Roros, Norway, 7–10

June.

[14] Bissell, R.C., Sharma, Y., and Killough, J.E.: “History Matching Using the Method of Gradients: Two Case Studies,” paper SPE 28590 presented at the 1994 SPE Annual Technical Conference and Exhibition, New Orleans, 25–28 September.

[15] Tan, T.B. and Kalogerakis, N.: “A Fully Implicit, Three-Dimensional, Three-Phase Simulator With Automatic History-Matching Capability,”paper SPE 21205 presented at the 1991 Symposium on Reservoir Simulation, Anaheim, California, 17–20 February.

[16] http://infohost.nmt.edu/~petro/faculty/Engler571/HistoryMatching.pdf

[17] Principles of Applied Reservoir Simulation John R. Fanchi

[18] Master thesis Jideofor Odinukwe and Celia Correia History Matching and Uncertainty Assessment of the Norne Field E-Segment Using Petrel RE

[19] Saleri, N.G.(1993) Reservoir Performance Forecasting: Acceleration by Parallel Planning

[20] Annual Technical Conference and Exhibition, Louisiana

[21] http://www.statoil.com/en/ouroperations/explorationprod/ncs/norne/pages/default.aspx

[22] http://www.ipt.ntnu.no/~norne/wiki/data/media/english/gfi/introduction-to-the-norne-field.pdf

[23] http://www.offshore-technology.com/projects/statoil/

[24] Statoil, 2001. PL128 - Norne Field Reservoir Management Plan

[25] Verlo, S. B. and Hetland, M. 2008. Development of a field case with real production and 4D data from the Norne Field as a benchmark case for future reservoir simulation models testing. Masters Thesis, NTNU, Norway.

[26] Statoil, "Annual reservoir development plan for Norne and Urd," 2006

[27] Statoil Plan for Development and Operation-Norne-Reservoir engineering 1994

[28] http://www.npd.no/no/System/Sok/?quicksearchquery=norne

[29] Oddvar Husby, Hans A. Aronsen, Nan Cheng, Trine Alsos Bård Osdal, "Mapping the fluid front and pressure buildup using 4D data on Norne Field," The Leading Edge, 2006

[30] http://www.sintef.no/Projectweb/MRST/Gallery/Faults/http://acdl.mit.edu/mdo/mdo_06/Multi-variable.pdf

[31] David H. Johnston Partial Applications of Time-lapse Seismic Data

[32] https://www.slb.com/~/media/Files/westerngeco/resources/articles/2006/mapping_the_fluid.pdf

[33] Updating the Norne Reservoir Model Using 4D Seismic Data, Nan Cheng, Bård Osdal, IO Workshop, 12 February 2008, Trondheim

Appendix

(A).Group input file

```
GRUPTREE
'INJE'          'FIELD' /
'PROD'          'FIELD' /
'ESEG'          'PROD'  /
'MANI-B2'       'PROD'  /
'MANI-B1'       'PROD'  /
'MANI-D1'       'PROD'  /
'MANI-D2'       'PROD'  /
'MANI-E1'       'PROD'  /
'MANI-E2'       'PROD'  /
'MANI-K1'       'MANI-B1'   /
'MANI-K2'       'MANI-D2'   /
'MANI-C'        'INJE'    /
'MANI-F'        'INJE'    /
'WI-GSEG'       'INJE'    /
'B1-DUMMY'      'MANI-B1'   /
'D2-DUMMY'      'MANI-D2'   /
'MANI-E1ESEG'   'ESEG'/
'MANI-E2ESEG'   'ESEG'/

GRUPNET
'FIELD'         20.000      5*   /
'PROD'          20.000      5*   /
'ESEG'          1* 9999     5*   /
'MANI-B2'       1*   8      1*          'NO'     2*   /
'MANI-B1'       1*   8      1*          'NO'     2*   /
'MANI-K1'       1* 9999     4*   /
'B1-DUMMY'      1* 9999     4*   /
'MANI-D1'       1*   8      1*          'NO'     2*   /
```

```
'MANI-D2'         1*   8      1*          'NO'    2*   /
'MANI-K2'         1* 9999     4*   /
'D2-DUMMY'        1* 9999     4*   /
'MANI-E1'         1*   9      1*          'NO'    2*   /
'MANI-E2'         1*   9      4*   /
'MANI-E1ESEG'     1*   9      1*          'NO'    2*   /
'MANI-E2ESEG'     1*   9      4*   /
/
```

(B).PERMZ modification input file

```
-- Permz reduction is based on input from PSK
-- based on same kv/kh factor
-- ******************************************
-- CHECK! (esp. Ile & Tofte)
-- ******************************************
MULTIPLY
    'PERMZ'   0.25    1   46   1   112 3    3    /   Garn 1
    'PERMZ'   0.0     1   46   1   112 4    4    /   Not (inactive anyway)
    'PERMZ'   0.13    1   46   1   112 5    5    /   Ile 2.2
    'PERMZ'   0.13    1   46   1   112 6    6    /   Ile 2.1.3
    'PERMZ'   0.13    1   46   1   112 7    7    /   Ile 2.1.2
    'PERMZ'   0.07    1   46   1   112 10   10   /   Ile 1.2
    'PERMZ'   0.19    1   46   1   112 11   11   /   Ile 1.1
    'PERMZ'   0.13    1   46   1   112 12   12   /   Tofte 2.2
    'PERMZ'   0.64    1   46   1   112 13   13   /   Tofte 2.1.3
    'PERMZ'   0.64    1   46   1   112 14   14   /   Tofte 2.1.2
    'PERMZ'   0.64    1   46   1   112 15   15   /   Tofte 2.1.1
    'PERMZ'   0.64    1   46   1   112 16   16   /   Tofte 1.2.2
    'PERMZ'   0.64    1   46   1   112 17   17   /   Tofte 1.2.1
    'PERMZ'   0.016   1   46   1   112 18   18   /   Tofte 1.1
    'PERMZ'   0.004   1   46   1   112 19   19   /   Tilje 4
    'PERMZ'   0.004   1   46   1   112 20   20   /   Tilje 3
    'PERMZ'   1.0     1   46   1   112 21   21   /   Tilje 2
    'PERMZ'   1.0     1   46   1   112 22   22   /   Tilje 1
/
--E-3H
MULTIPLY
    'PERMZ'   0.5     9    9    70   74   2    22   /
    'PERMZ'   0.5     10   10   70   76   2    22   /
    'PERMZ'   0.5     11   11   72   80   2    22   /
    'PERMZ'   0.5     12   12   71   80   2    22   /
    'PERMZ'   0.5     13   13   73   78   2    22   /
    'PERMZ'   0.5     14   14   73   80   2    22   /
    'PERMZ'   0.5     15   15   74   81   2    22   /
```

```
    'PERMZ'   0.5     16  16  75  82  2   22  /
/
--E-2H
MULTIPLY
    'PERMZ'   0.001   7   7   55  58  8   9   /
    'PERMZ'   0.001   8   8   54  58  8   9   /
    'PERMZ'   0.001   8   8   66  69  8   9   /
    'PERMZ'   0.001   9   9   54  56  8   9   /
    'PERMZ'   0.001   9   9   59  69  8   9   /
    'PERMZ'   0.001   10  10  52  58  8   9   /
    'PERMZ'   0.001   10  10  66  69  8   9   /
    'PERMZ'   0.001   11  11  52  58  8   9   /
    'PERMZ'   0.001   12  12  52  58  8   9   /
    'PERMZ'   0.001   12  12  61  64  8   9   /
    'PERMZ'   0.001   13  13  60  70  8   9   /
    'PERMZ'   0.001   14  14  63  70  8   9   /
/
--E-3AH
MULTIPLY
    'PERMZ'   3   6   6   45  50  1   2/
    'PERMZ'   3   6   6   60  70  1   2/
    'PERMZ'   3   7   7   45  58  1   2/
    'PERMZ'   3   7   7   66  72  1   2/
    'PERMZ'   3   8   8   46  58  1   2/
    'PERMZ'   3   8   8   66  72  1   2/
    'PERMZ'   3   9   9   50  60  1   2/
    'PERMZ'   3   9   9   66  75  1   2/
    'PERMZ'   3   10  10  58  65  1   2/
    'PERMZ'   3   10  10  66  78  1   2/
    'PERMZ'   3   11  11  60  66  1   2/
    'PERMZ'   3   11  11  70  76  1   2/
    'PERMZ'   3   12  12  62  68  1   2/
    'PERMZ'   3   12  12  75  80  1   2/
    'PERMZ'   3   13  13  62  68  1   2/
    'PERMZ'   3   13  13  76  82  1   2/
    'PERMZ'   3   14  14  66  70  1   2/
    'PERMZ'   3   14  14  80  82  1   2/
    'PERMZ'   3   15  15  66  70  1   2/
    'PERMZ'   3   15  15  80  84  1   2/
    'PERMZ'   3   16  16  70  72  1   2/
    'PERMZ'   3   16  16  80  86  1   2/
/
--F-1H
MULTIPLY
    'PERMZ'   0.005   10  14  83  88  1   22/
/
--F-3H
MULTIPLY
    'PERMZ'   0.005   6   6   55  58  1   1/
```

```
        'PERMZ'    0.005   6   6   51  58  2   2/
        'PERMZ'    0.005   6   8   56  58  3   7/
        'PERMZ'    0.005   6   8   56  58  10  22/
/
```

(C). PERMX modification input file

```
--E-3H
MULTIPLY
    'PERMX'   1.25    9   9   70  74  2   22/
    'PERMX'   1.25    10  10  70  76  2   22/
    'PERMX'   1.25    11  11  72  80  2   22/
    'PERMX'   1.25    12  12  71  80  2   22/
    'PERMX'   1.25    13  13  73  78  2   22/
    'PERMX'   1.25    14  14  73  80  2   22/
    'PERMX'   1.25    15  15  74  81  2   22/
    'PERMX'   1.25    16  16  75  82  2   22/
    /
--E-2H
MULTIPLY
    'PERMX'   15  7   7   55  58  8   9/
    'PERMX'   15  8   8   54  58  8   9/
    'PERMX'   15  8   8   66  69  8   9/
    'PERMX'   15  9   9   54  56  8   9/
    'PERMX'   15  9   9   59  69  8   9/
    'PERMX'   15  10  10  52  58  8   9/
    'PERMX'   15  10  10  66  69  8   9/
    'PERMX'   15  11  11  52  58  8   9/
    'PERMX'   15  12  12  52  58  8   9/
    'PERMX'   15  12  12  61  64  8   9/
    'PERMX'   15  13  13  60  70  8   9/
    'PERMX'   15  14  14  63  70  8   9/
    /
--E-3AH
MULTIPLY
    'PERMX'   0.03    6   6   45  50  1   2/
    'PERMX'   0.03    6   6   60  70  1   2/
    'PERMX'   0.03    7   7   45  58  1   2/
    'PERMX'   0.03    7   7   66  72  1   2/
    'PERMX'   0.03    8   8   46  58  1   2/
    'PERMX'   0.03    8   8   66  72  1   2/
    'PERMX'   0.03    9   9   50  60  1   2/
    'PERMX'   0.03    9   9   66  75  1   2/
    'PERMX'   0.03    10  10  58  65  1   2/
    'PERMX'   0.03    10  10  66  78  1   2/
    'PERMX'   0.03    11  11  60  66  1   2/
```

```
     'PERMX'    0.03      11   11   70   76   1     2/
     'PERMX'    0.03      12   12   62   68   1     2/
     'PERMX'    0.03      12   12   75   80   1     2/
     'PERMX'    0.03      13   13   62   68   1     2/
     'PERMX'    0.03      13   13   76   82   1     2/
     'PERMX'    0.03      14   14   66   70   1     2/
     'PERMX'    0.03      14   14   80   82   1     2/
     'PERMX'    0.03      15   15   66   70   1     2/
     'PERMX'    0.03      15   15   80   84   1     2/
     'PERMX'    0.03      16   16   70   72   1     2/
     'PERMX'    0.03      16   16   80   86   1     2/
     /
--F-1H
MULTIPLY
     'PERMX'    0.3  10   14   83   88   1     22/
     /
--F-3H
MULTIPLY
     'PERMX'    0.3  6    6    55   58   1     1/
     'PERMX'    0.3  6    6    51   58   2     2/
     'PERMX'    0.3  6    8    56   58   3     7/
     'PERMX'    0.3  6    8    56   58   10    22/
     /
```

(D). Faults modification input file

```
     ------------------------------------------------------
     --
     --          Grid and faults
     --
     ------------------------------------------------------
'./INCLUDE/FAULT/FAULTMULT_AUG-2006.INC'/

MULTFLT
     'm_west'       1.0  /
     'm_north'      1.0  /
     'DE_2'         0.01/
     'E_01'         0.015/
     'DE_1'         69   /
     'EF'           1.0  /
     'E_01_F3'           0.3  /
     'DE_B3'             0.0015/
     'DE_0'              30   /
/
```