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Streamline-Based Integral Modeling for Waterflooding Design Optimization, Surveillance and Monitoring

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Abstract

The Dynamic Numerical Simulation in Flowlines (DNSFL) is an alternative tool adapted to handle Dynamic Models in Fine Scale. This feature has been particularly relevant for studying the current case, a huge multilayered waterflooding process developed in a giant field of great extension reservoirs with considerable facial and stratigraphical variations.

The DNSLF develops these tasks suitably because uncouples reservoir geometry and heterogeneity from transport equations, solving the problems dominated by convective flows in a faster and computationally more efficient way. This allows to build models of greater space discretization and, therefore, to represent better the heterogeneity of the reservoirs.

The analyzed field is constituted by fluvio-lacustrine deposits, nine sand-clay cycles of normal grading (only eight of them were modeled), partially connected reservoirs; with 250 actives wells in commingled production and water injection; and with a long and detailed history of simultaneous primary and secondary events.

In a previous paper (SPE 94815) a Streamline-based Global History Matching of this field was presented. This process enabled to achieve the Geological Modeling Calibration, a clear conceptualization of the current primary and secondary production mechanisms, its productive behavior, and to evaluate the geostatistical and Upscaling procedures to apply for the definition of the Simulation Model.

This paper illustrates how the Integral Model achieved, with a detailed Streamline-based History Matching, is used for Waterflooding Design Optimization, Surveillance and Monitoring, showing that these principles are key factors to understanding reservoir performance and identifying opportunities that will improve the ultimate recovery.

During the detailed History Matching process CPU runtimes around 200 minutes were achieved using a 1225000 grid cells Model, with 190 timesteps, quarterly at the starting, and monthly after, based in a Pentium 4 PC, 3.2GHz CPU and 2GB RAM. It showed that it is possible to work with a big Streamline-based Model in relatively short processing time.

Introduction

The classical techniques of waterflooding surveillance, including methods like: mapping (gas-oil ratio, water cut, pressure, etc.) total liquid production vs. time, injected poral volumes vs. recovery factor, Hall plots, etc., jointly with the monitoring process have backed-up successful Exploitation Optimization processes[1]. Most of these techniques, as those mentioned above, are 0D; some recent practices made 1D or 2D spatial distribution of the relevant characteristics to the process, essentially productions and injections, but without integrating the pressure fields.

Streamline simulation goes further and incorporates pressure fields, which determine streamline as the most probable way of fluid movement. In this sense, and always in the pressure field, there are two well differentiated work levels in the waterflooding projects[2] (Fig. 1):

1. The first level, called "Production-injection surveillance" based on the historic analysis of the waterflooding, allows for the examination of injectors and producers, identifying well and poorly swept areas.
2. The second level, "Streamline-based simulation" based on a detailed geological model, fluid physics and history matching, which allows, in addition to the previous one, for an integral redesign and forecast of the waterflooding towards its optimization.

Both levels are sustained and fed by monitoring the field process; as it is clear, the development of the second level, as in the example of Puesto Hernández Rayoso Field– Block 4, implies achieving the first level.

As it is known, the classical surveillance techniques have been widely discussed in several well-known publications and experts have recommended some high-value principles to develop them. The following principles make up the minimum platform required by simulation techniques, especially by the streamlines, here considered:

- A key ingredient of any surveillance and simulation program is the planning, gathering and validation of "all" available information.
- To implement surveillance and simulation efforts it is essential to "understand" the reservoir expressed in their characteristics and fluid flow, while reducing the uncertainty of the interpretation. In the case of simulation, this understanding is reflected in reservoir models adjusted in the History Matching process.

- In general, one classical surveillance technique is not meaningful because different parameters (characteristics of reservoirs, production mechanisms, etc.) can produce similar answers. Instead, a well planned simulation model integrates the relevant analysis to the process under evaluation –waterflooding evaluation in this case- thereby avoiding this problem.
- Achieving a waterflooding surveillance controlled by fluid balance in the patterns requires important technical efforts (from engineering and geology) during the life of the project. Simulation also requires important technical efforts but specially concentrated on the initial phase –i.e. when models are developed.
- Surveillance techniques should always induce thorough deeper studies which include numeric simulation.

As mentioned above, streamline simulation in Puesto Hernández Rayoso – Block 4, and the related surveillance tasks, feed and depend from the monitoring process of the field to optimize the waterflooding presently in progress.

In all simulation process, including proposed optimizations, the methodological approach was based on blocks, sectors, well groups and wells resulting from the review of many cases of waterflooding. This type of work avoids implementing partial action plans or fast judgment, which is especially important in up to date situations where human and capital resources are critical.

Development

Puesto Hernández field is at the NW border of Neuquén Basin of Argentina (Fig. 2), extended along 147 km^2. It is developed in the Neuquén embayment, where the stratigraphical column is complete although thickness is reduced due to the proximity to the basin boundary (Fig. 3.)

Description and Main Characteristics of Reservoirs

The productive reservoirs of the field, Rayoso, Huitrín and Agrio belong to the Cretacic age. This work is developed in the Rayoso Fm, the main field producer.

Fm. Rayoso belongs to a clastic-evaporitic unit deposited in a predominantly continental environment of fluvio-lacustrine character[3]. The clastic section is interesting from the economic perspective; there are 11 sand-clay cycles, of normal grading out of which the most important 8 were modeled. The cycles are truncated towards the E-NE by the intercenomanian unconformity at the top of Fm Rayoso, with three different CAPOs (Original water-oil contacts); they consequently form three Hydraulic Units: inferior (IHU), medium (MHU) and superior (SHU). Fig. 4 shows the truncation of the various cycles of the Hydraulic Units, used to define the sectors of Block 4.

Structurally the reservoirs are a homoclinal of 5º average slope and dip to the SW. The 3D seismic registered in 1995, showed a main faulting that result in E-W vertical and sub-vertical faults, of few meters of throw. This paper analyzes the hydrodynamic connectivity of these faults, especially in Block 4 (Fig. 5).

Productive levels are relatively shallow, depth is below 600 mbgl (meters below ground level), show good petrophysical characteristics, low initial reservoir pressure and oil viscosities that vary laterally and with depth.

The main characteristics of these reservoirs, in the modeled area of Fm. Rayoso are:

- Average depth: 500 to 700 mbgl
- Average crude density: 25ºAPI
- Crude viscosity: 15 to 95 cp
- Initial static pressure ≈ 26 Kgf/cm^2
- Bubble pressure ≈ 15 Kgf/cm^2
- Gas in oil solubility ≈ 6 m^3/m^3
- Reservoir temperature: 33ºC

Development and Exploitation History

By mid 1976 the primary exploitation of Fm. Rayoso in Puesto Hernández Field started (Fig. 5). Production increased at the beginning of 1983 by perforating this formation in several wells that produced before the deepest levels. Water injection started at the beginning of 1994 in some peripheral wells; by mid of 2000 new wells drilling was intensified and changed to an irregular 9 spot injection pattern.

By the end of 2005, over 1500 wells were drilled in the Puesto Hernández area, 37 % from Fm. Rayoso.

The simulation area contains 265 wells (185 producers and 80 injectors) comprising Block 4, where the model is developed, and well strips from Block 3 and 5 (South and North from Block 4), as boundary conditions (Fig. 6).

Production or injection of most of these wells takes place in over one Formation. Only 240 wells perforated in Fm. Rayoso, produce this formation exclusively (38%), these are called *turnkey wells* and the remaining are *non-turkey wells.*

Most of injectors have valves to assure the selective injection among various formations but not among the various hydraulic units of Fm. Rayoso. To the Rayoso *non-turnkey* producers the oil production was allocated prioritizing the trends noted in Agrio and Huitrín formations.

Approximation in different levels

Model Definition and Adjustment

These tasks were performed by a work flow based on procedures issued by EIA (Estadística Integral Autocorrelada – Autocorrelated Integral Statistics[4]) for the simulator input model and its subsequent adjustment in the streamline simulation process (SFL). As expressed above, in the creation of the model, history matching and prediction process, and in the optimization proposals, the work methodology was based on block, sectors, well groups and well per well.

In the primary phase, the field produced due to monophasic fluid and rock expansion, while during the waterflooding convective flows are predominant. *SFL* is an appropriate choice for this type of flow[5 a 12].

To better map the behavior of fluids in the simulator the option of Little Compressible Black Oil was chosen. Considering the petrophysical conditions of reservoirs, the model chosen was of Simple Porosity and Permeability. Also, given the large field vertical extension, the presence of gravitating action was activated in the model.

The faults were represented in the model with their throw. The best adjustment was achieved considering them

like communicating ones, acting as boundary conditions with their natural throw.

The History Matching process included:

Global Adjustments at Reservoir levels: they were limited to the surroundings of the poorly adjusted wells (in the liquid production or static pressure) or to the correction of poorly informed situations, as in the case of aquifers.

Local Adjustments at Well level:

- Incorporating new well data as they were drilled.
- By adjustment of productivity rate to model fractures.
- By adjustment of transit profiles in the injectors.
- By adjustment of available RFT (*repeat formation tester*).
- By adjustment of dynamic pressure of producers.

The Goodness of the Model History Matching, in the various levels, as usual practice, was measured by comparing the results of the simulator with the available historic data.

For this process the Block 4 was divided in 4 areas, Fig. 4, limited by the "unconformities" lines in the indicated cycles.

Figs. 7, 8, 9 and 10 show the "goodness" of the fluid produced matching in the Block, Sectors, Well Groups (*turnkey wells*) and well per well.

Figs. 11, 12 and 13 show the "goodness" of the adjustment at well level as to injection profiles, static pressures, and water saturation at the time of well completion.

The achieve adjustments enables to consider that a "good" simulation streamline model was available (Block 4).

Analysis of the Actual Exploitation Scenario

The analysis of this Scenario comprised the sweep efficiencies, the well productivity index and the evolution of pressures, presently and to 10 years of exploitation.

The Sweep efficiencies were calculated and graphically conceptualized, in the different levels of the analysis, based on the streamline from injectors, from all the history and future projections, in connection with current oil saturation. The streamline density is proportional to the water injected by well-layer.

In the current waterflooding recovery process, the Middle Hydraulic Unit (MHU) is the best swept. As an example the Fig. 14 shows the streamlines. The Simulation lets us to observe:

- There are well swept oil areas as well as non-swept areas.
- Current oil saturations of swept areas do not exceed 50-55%
- Aquifer areas are unwillingly swept areas.

In Fig. 15, with the streamlines for the Inferior Hydraulic Unit (IHU), it is shown:

- The Oil areas are more poorly swept than MHU.
- The current oil saturations of swept areas are closer to those of MHU.
- The aquifer areas are swept more significantly than in MHU.

The conclusions for other HU are analogous, MHU records higher sweep than Inferior and Superior Hydraulic Units (SHU).

There is a preferential communication trend, West-East, in the injector-producer pairs. Given the higher density of lines, this distribution shows more clarity in MHU.

These characteristics of sweep efficiencies are related with the distribution of absolute reservoir permeabilities.

The sweep areal efficiency in different cycles is conditioned by the variation trend of absolute permeability (E-W) and the semi - parallel fault direction (Fig. 16). Although in the lower cycles this trend is washed out by the limited extension of reservoirs, the productive relevance of them is low.

Vertical sweep efficiency is ruled by the vertical distribution of permeability, the layers of higher admission are those from MHU, with average *K* (permeability) between 200 and 250 mD (mili Darcy), followed by the Superior Hydraulic Units, average *K* ranges between 150 and 200 mD; finally Inferior Hydraulic Units –average *K* between 100 and 150 mD.

Aquifer sweep, according to the simulation, is produced by some injectors located in the aquifers, but essentially by the flow orientation to the inner part of them due to the higher current static pressure of the oil areas, as a consequence of the water injection.

Poorly swept areas were also analyzed in well groups using streamlines. For example, Fig. 17 shows one of these areas in a N-S cross-section, which includes 3 injector-producer pairs with the corresponding permeability grid. Permeability shows relatively important variations (100 to 400 mD). It is also observed that injector wells, not totally perforated in the permeable thickness, result in a re-flow around the same well and even to some producers. Instead, injectors with perforated permeable thickness sweep better to the producers.

That is, sweeping is controlled by permeability, perforations and dynamic pressure of producers.

The Time variation of Productivity Index was finally a well-based analysis. Productivity was estimated by using dynamic pressures and fluid productions measured with the simulator estimation of static pressure (pseudo-stationary) around the well.

Several wells reduced its Productivity Index; some of them in an important way (Fig. 18) resulting from the damage in the hydraulic fracture together with a subsequent mild damage related to the productive process.

Simulation of the First Optimization Scenario

This scenario considered the improvement of the Areal Sweep Efficiency by an arrangement, agreeing injectors and producers with the absolute permeability distribution, and the closing of injectors in the aquifers.

Comparing the streamlines for MHU in this scenario, Fig. 19, with those of the *current exploitation scenario*, Fig. 14, it is possible to observe:

- The Increase of swept oil areas,
- The Increase of current oil saturation in some areas incorporated to the waterflooding.
- The Reduction of swept areas in the aquifers.

Analyzing the streamlines in this scenario it can be noted improved volume efficiency in all the field hydraulic units, Fig. 20.

Conclusions

- The analysis of the current waterflooding exploitation scenario, in different levels, using the streamline-based simulation made it possible to include the monitoring and surveillance injection/production aspects, indicated in the Fig.1, and closely related them to the characteristics of the reservoirs. From this standpoint, the most adequate recommendations to optimize the process are made:
  - A distribution of the injector-producer pairs that considers the permeability distribution of the area would improve the areal sweep efficiency.
  - Vertical efficiency of current waterflooding recovery, conditioned by K vertical distribution, would substantially increase by selective water injection per Hydraulic Unit.
  - The inclusion of "dynamic closings" with productive wells around the aquifers would reduce the sweep to the inner part of them.
  - The total or partial elimination of well damages would result in increased production.
  - The first optimization scenario, Fig.19, made sweep volume efficiencies grow dramatically. In the simulator it is evident that these efficiency improvements determine a substantial increase in the recovery factor of Block 4 to be reached in 10 years, Fig.20.

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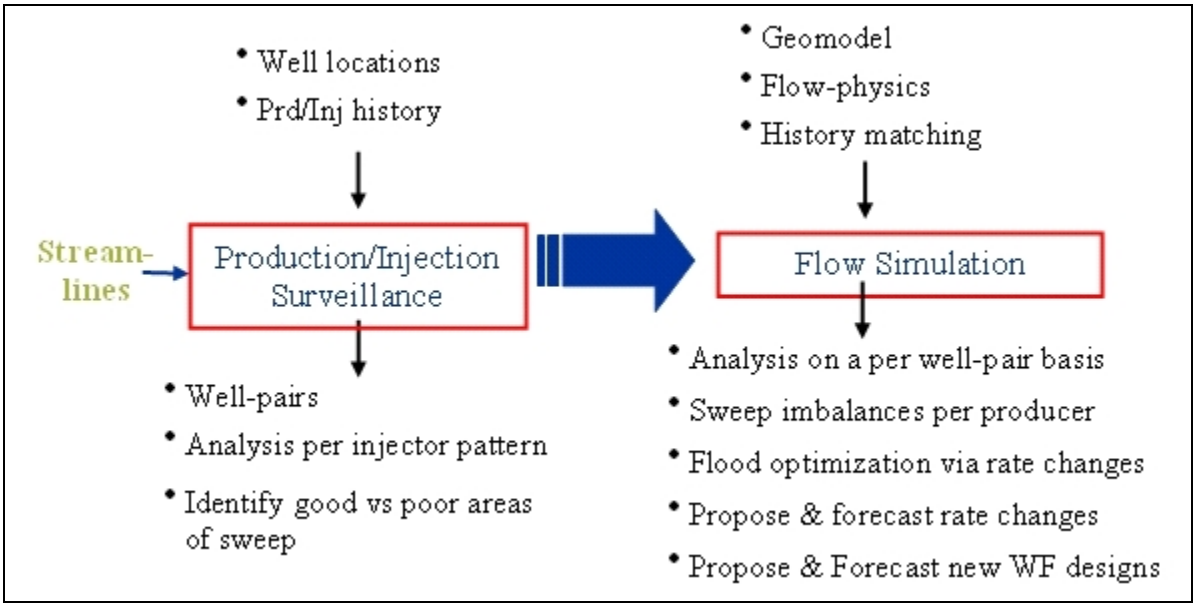

Fig.1 Two-Step Solution with Streamlines
Taken from: Using Streamline-Based Simulation to Proactively Manage Well-Pairs to Promote Improved Sweep and Reduce Fluid Cycling. Presented @ 2006 SPE ATW.

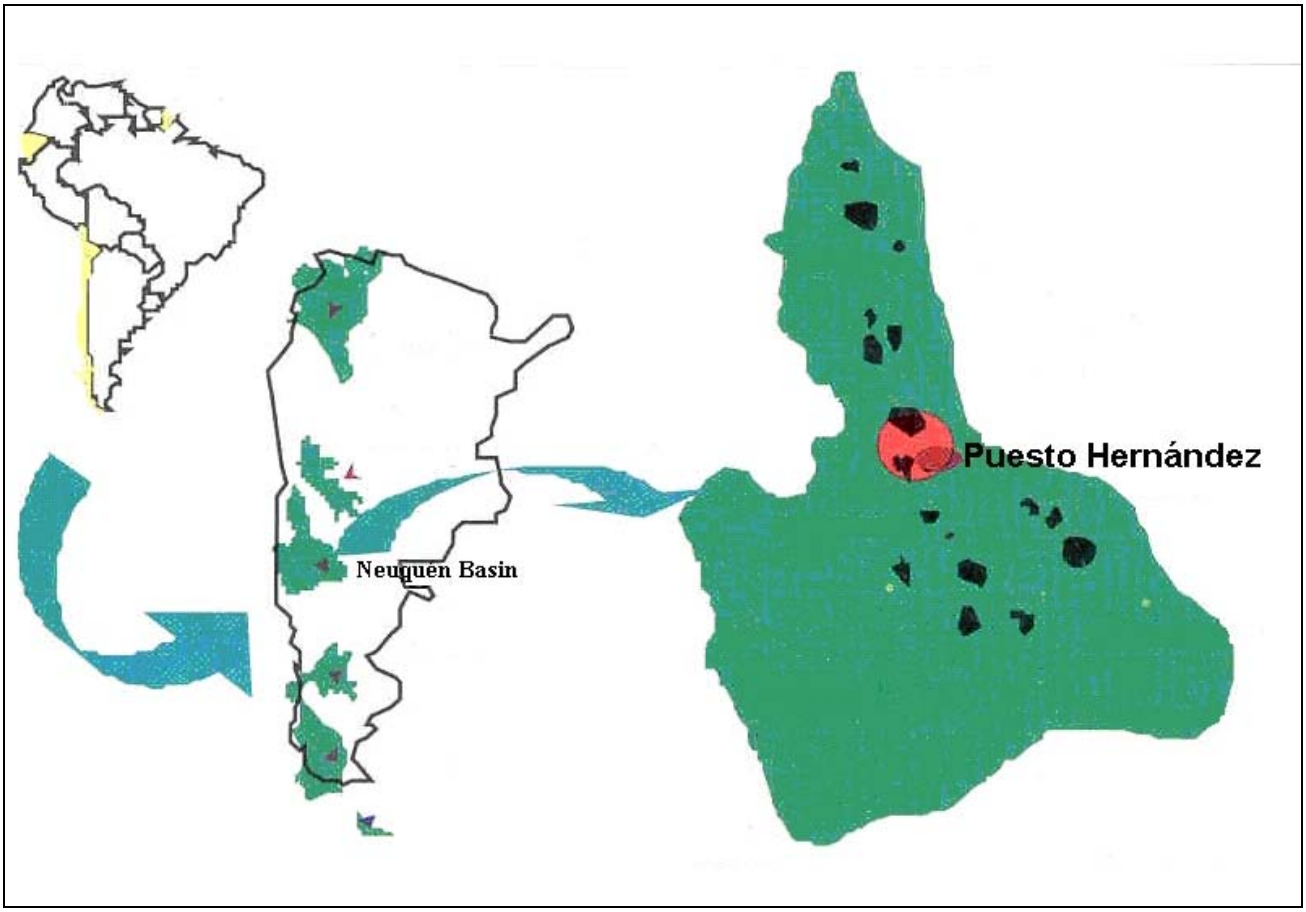

Fig. 2 Puesto Hernández Field Location, Argentina, Neuquén Basin
Taken from: Rocas Reservorio: Los Reservorios de la Formación Rayoso, IAPG Mar del Plata 2002

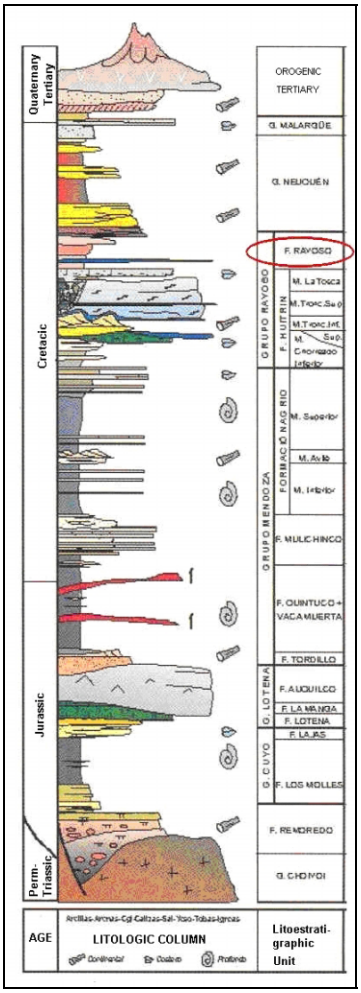

Fig. 3 Stratigraphic Column, Rincón de los Sauces Area, Neuquén Basin, Argentina.
Taken from: Rocas Reservorio: Los Reservorios de la Formación Rayoso, IAPG Mar del Plata 2002

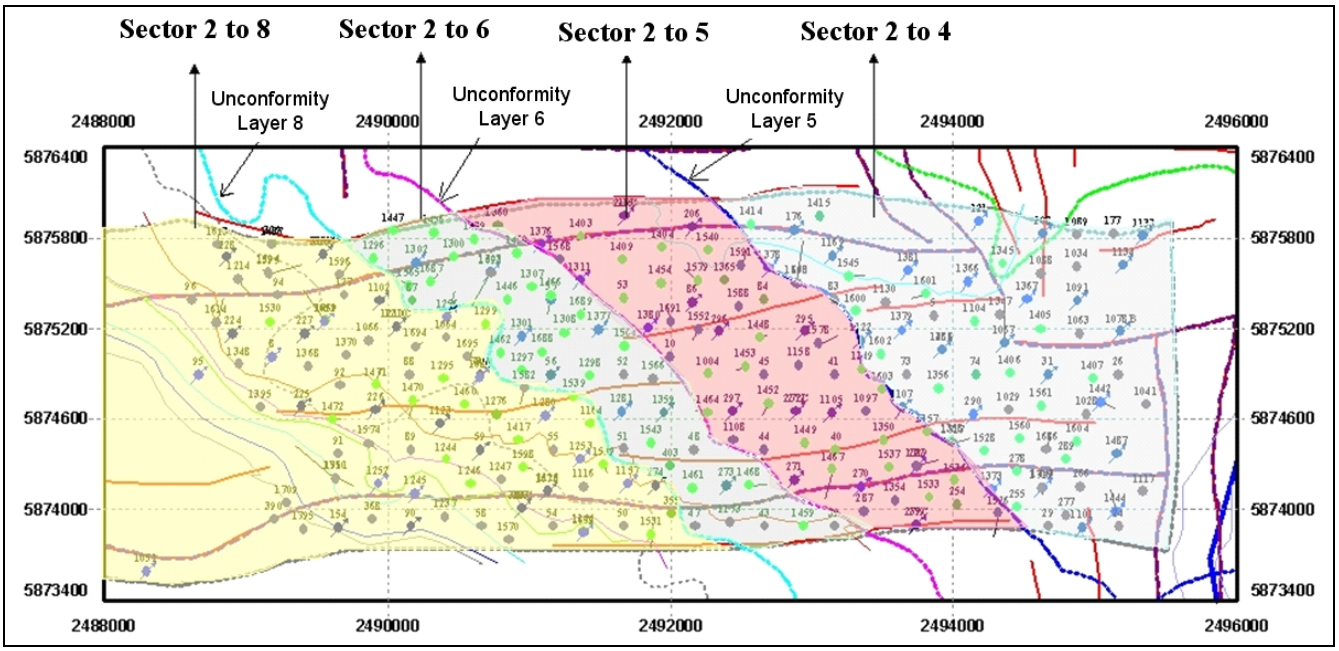

Fig. 4 Sectors of Block 4

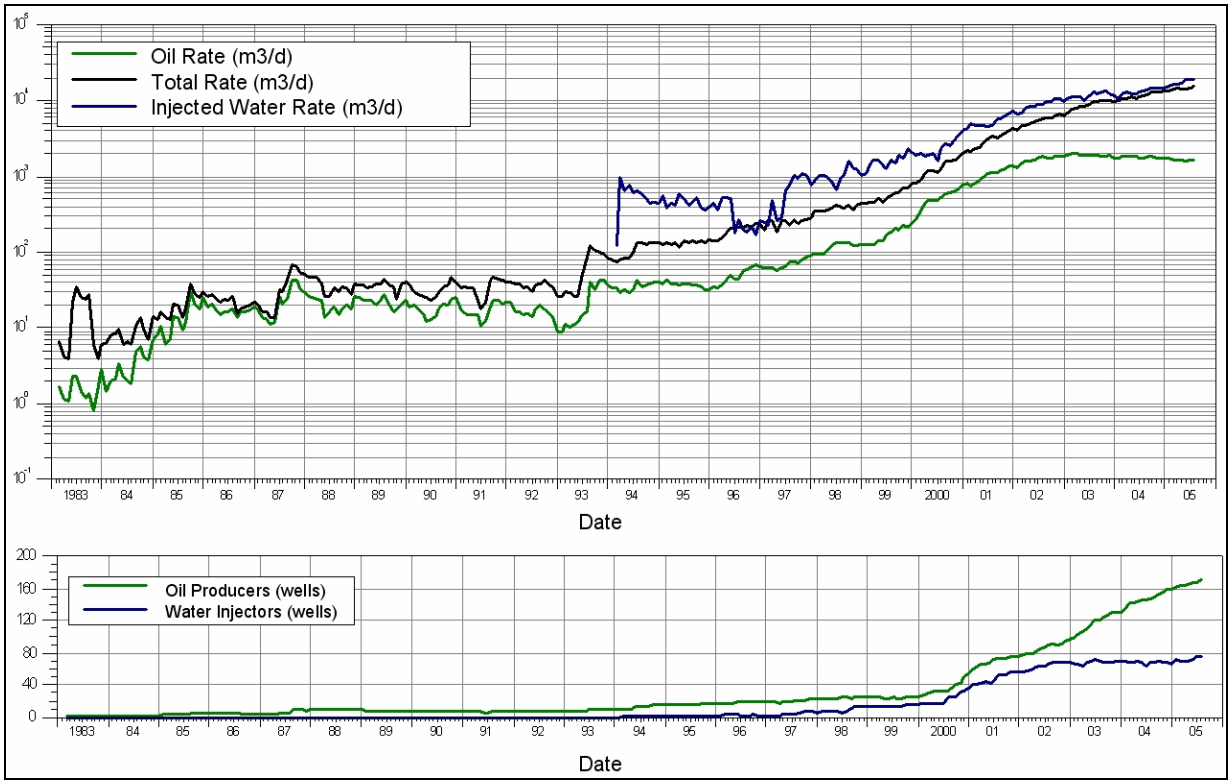

Fig. 5 Production and Injection History, Fm. Rayoso

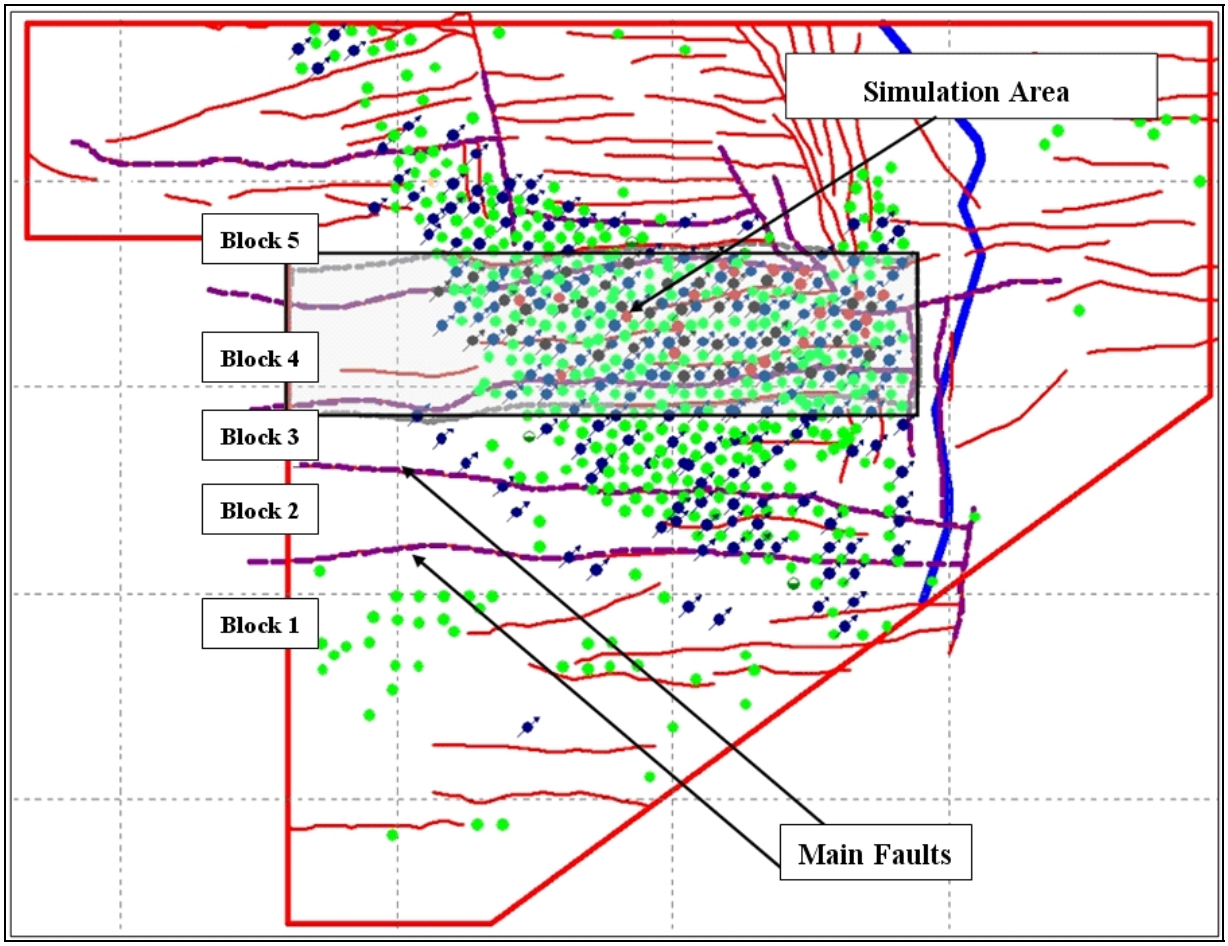

Fig. 6 Puesto Hernández Field and Simulation Area

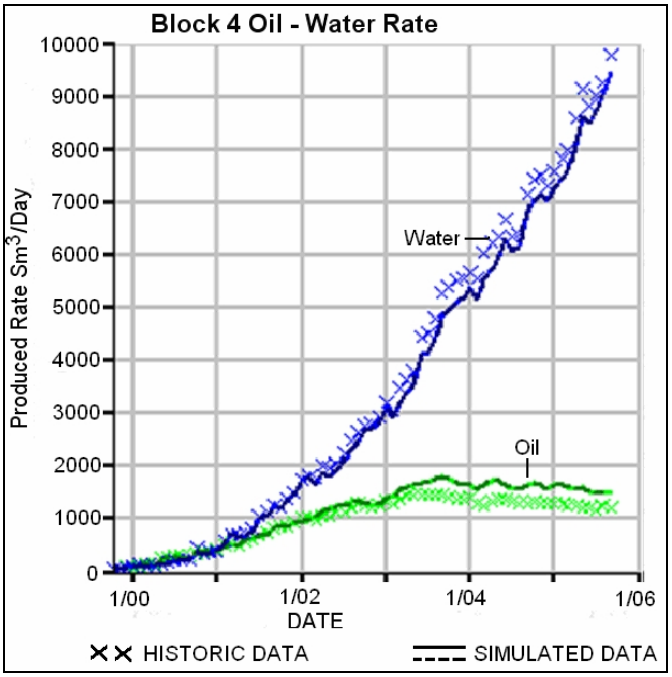

Fig. 7 Matching of Produced Fluids, Block 4

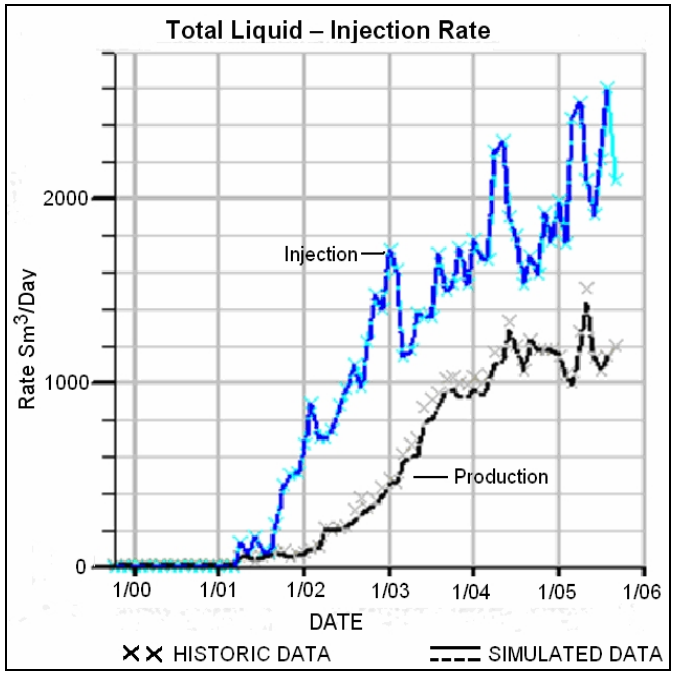

Fig. 8 Matching of Produced Fluids, Sector 2 to 4

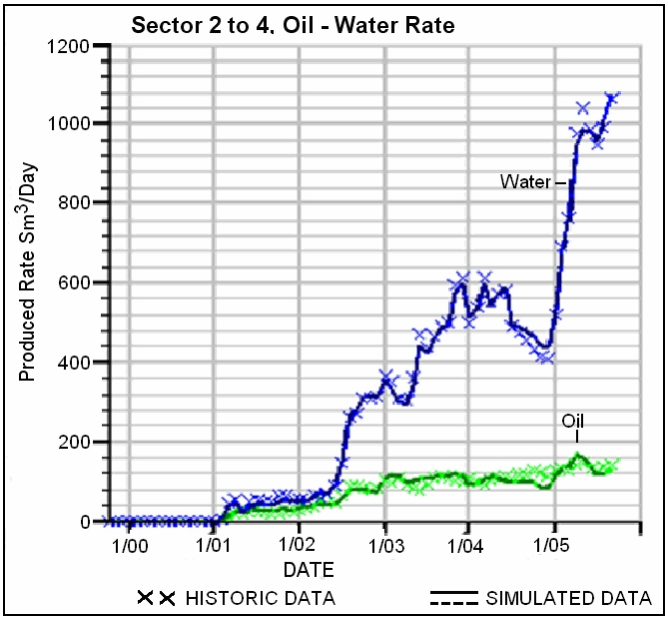

Fig. 9 Matching of Produced Fluids, Key Wells of Sector 2 to 4

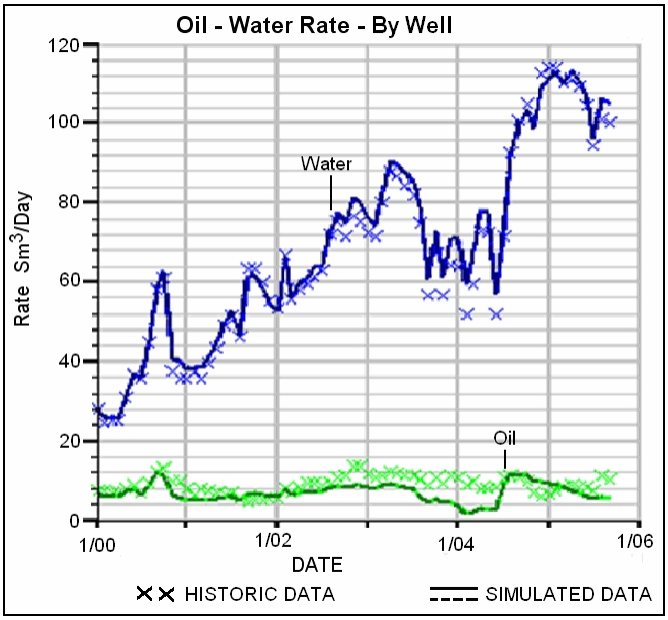

Fig. 10 Matching of Produced Fluids, by Well

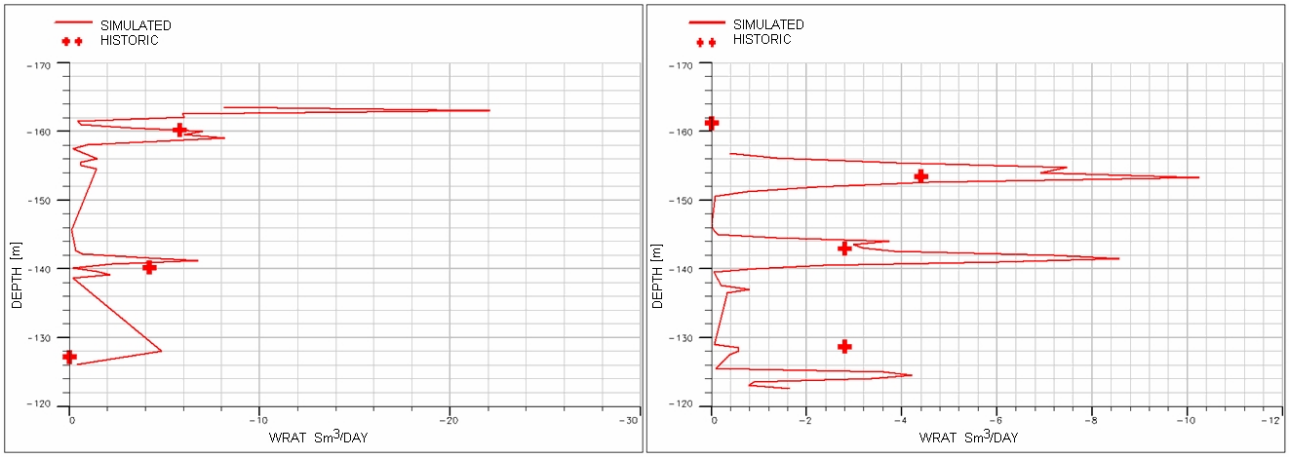

Fig. 11 Matching of Injectivity Logs

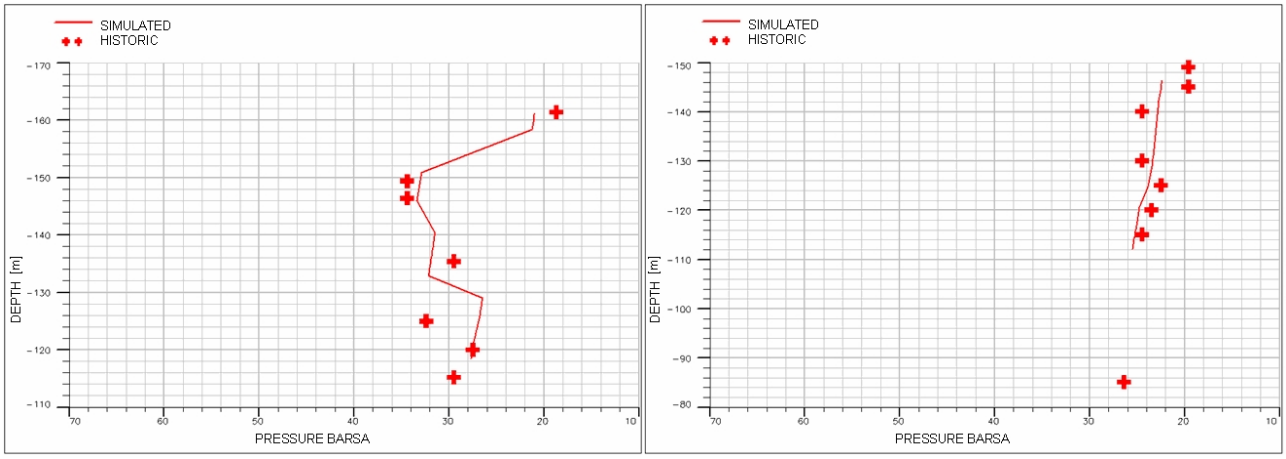

Fig. 12 Matching of Static Pressure

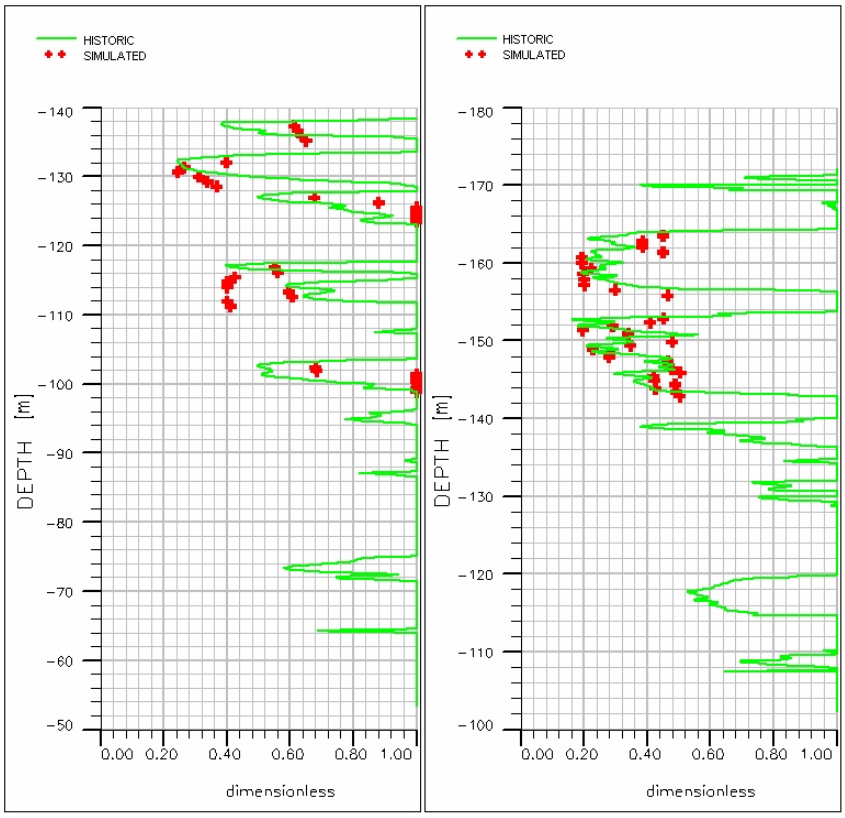

Fig. 13 Matching of Water Saturation to the Well Termination

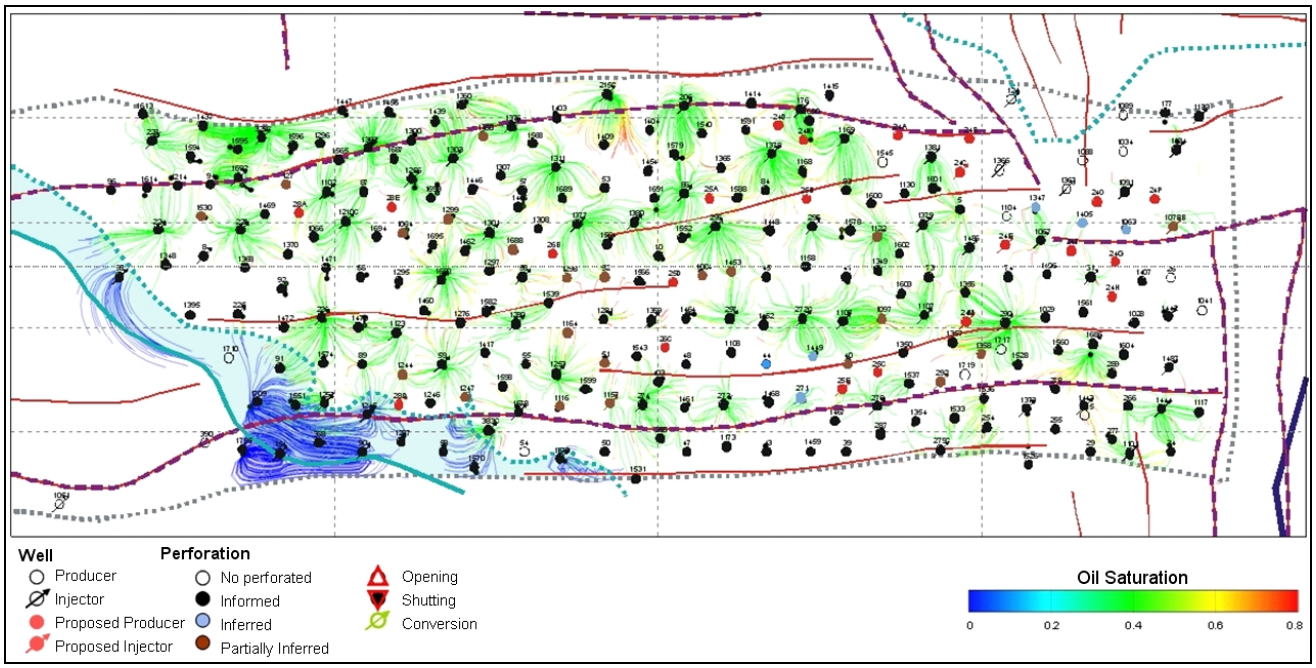

Fig. 14 Actual Scenario, IHU
Flowlines from Injectors, 10 years, with Actual Oil Saturation

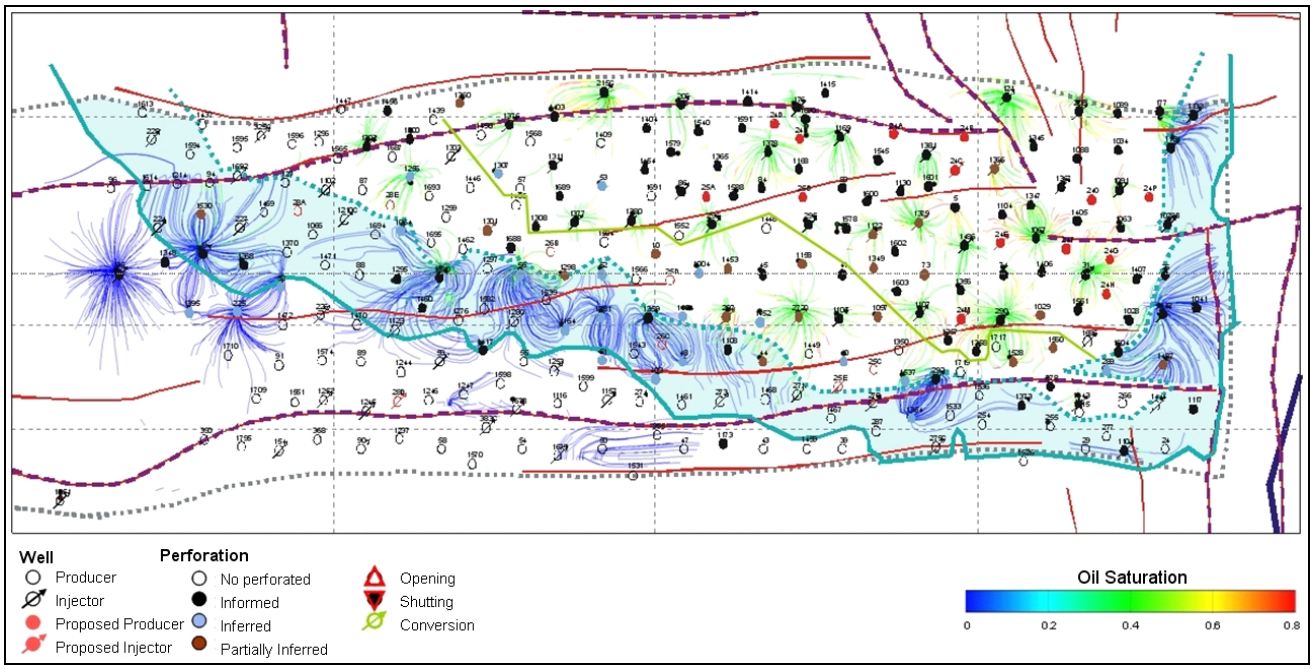

Fig. 15 Actual Scenario, MHU
Flowlines from Injectors, 10 years, with Actual Oil Saturation

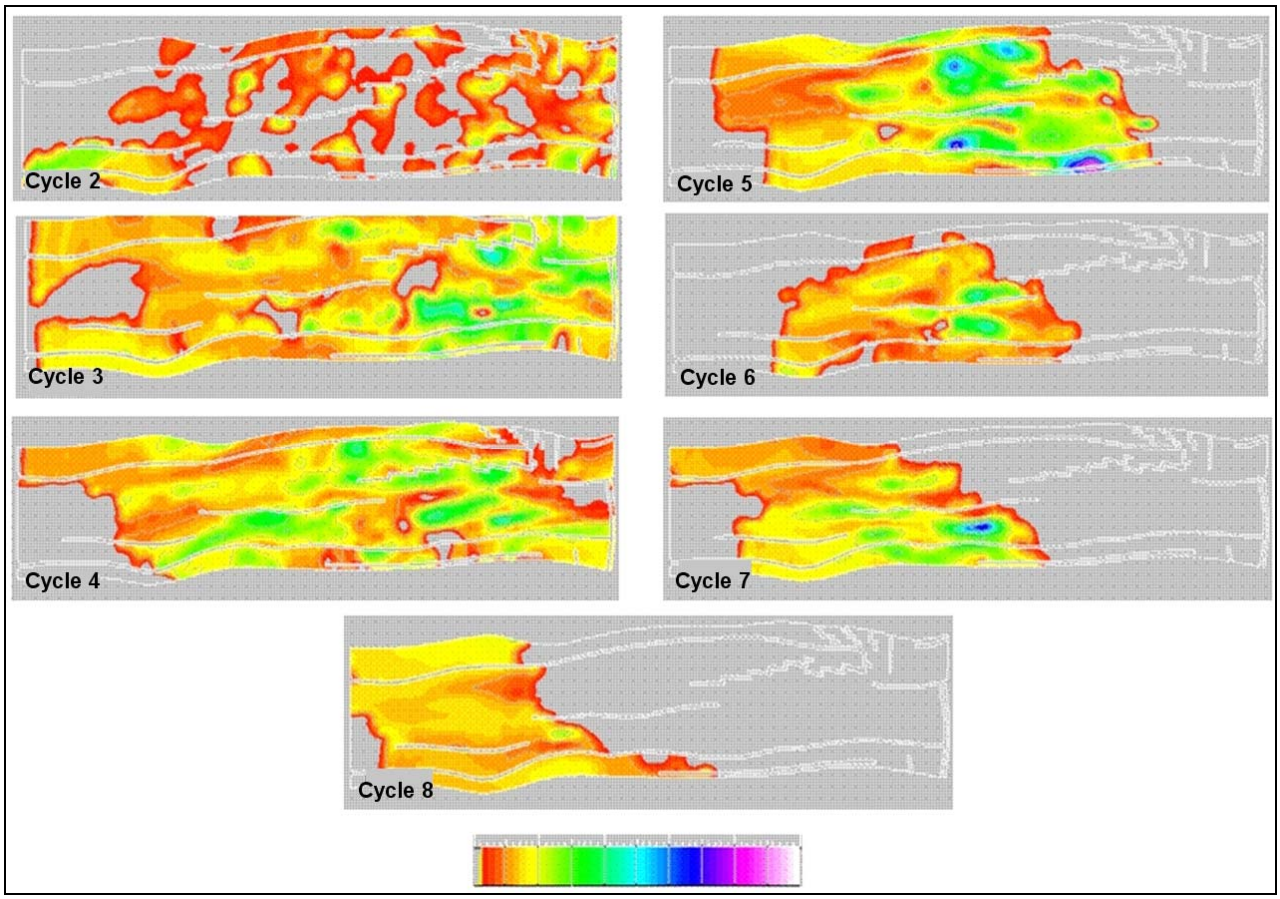

Fig. 16 Absolute Permeability Distribution per Cycle

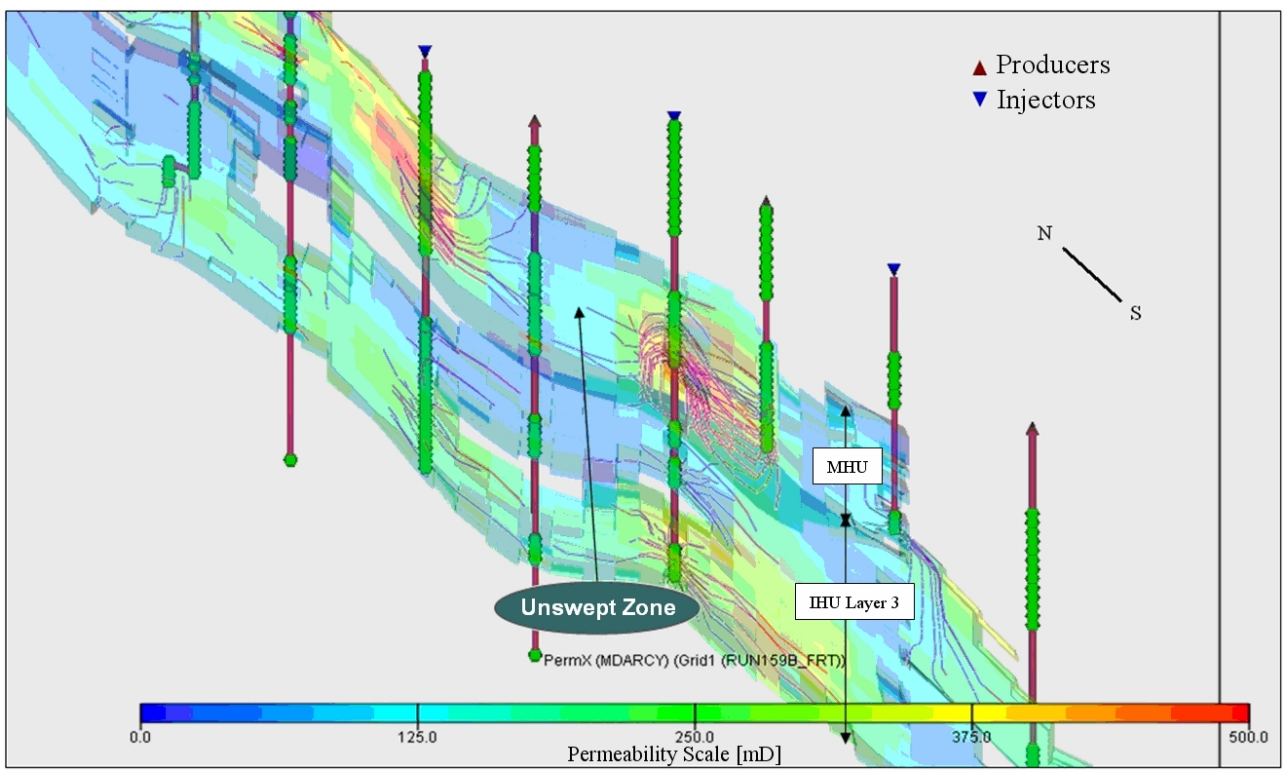

Fig. 17 Actual Scenario – Poor Swept Zones
K Variations and Perforation Amplitude

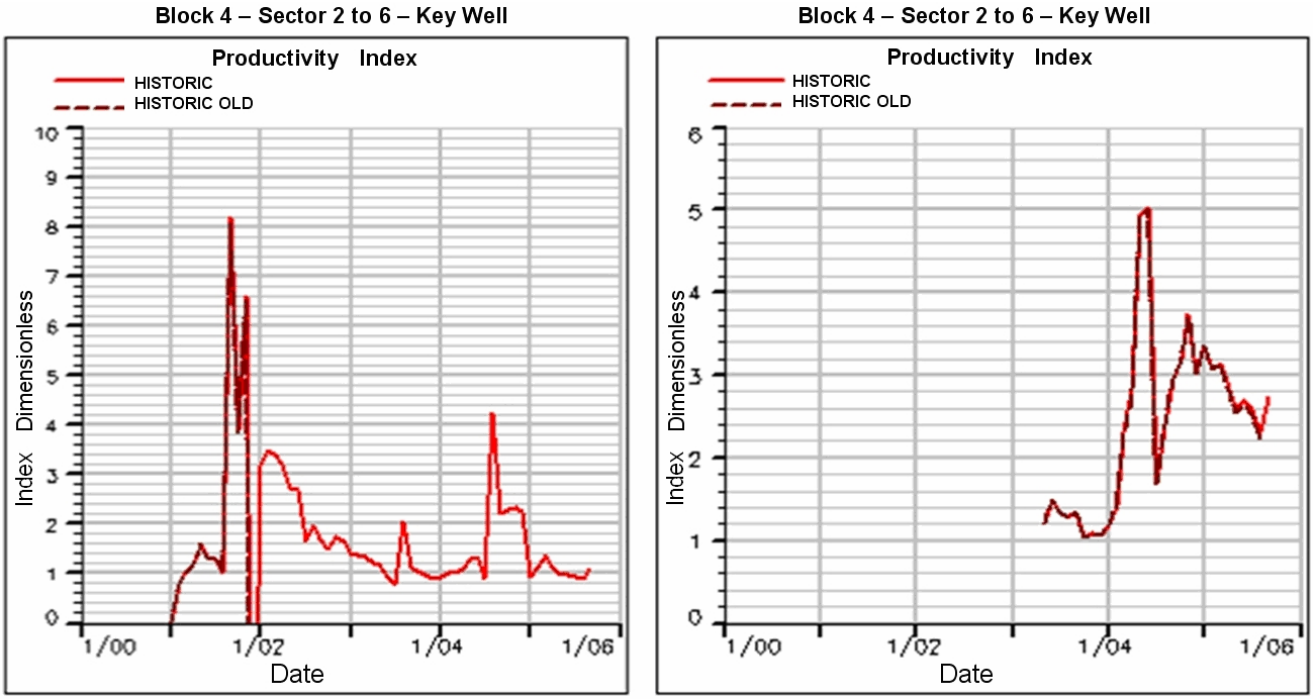

Fig. 18 Time Variation of Productivity Indexes

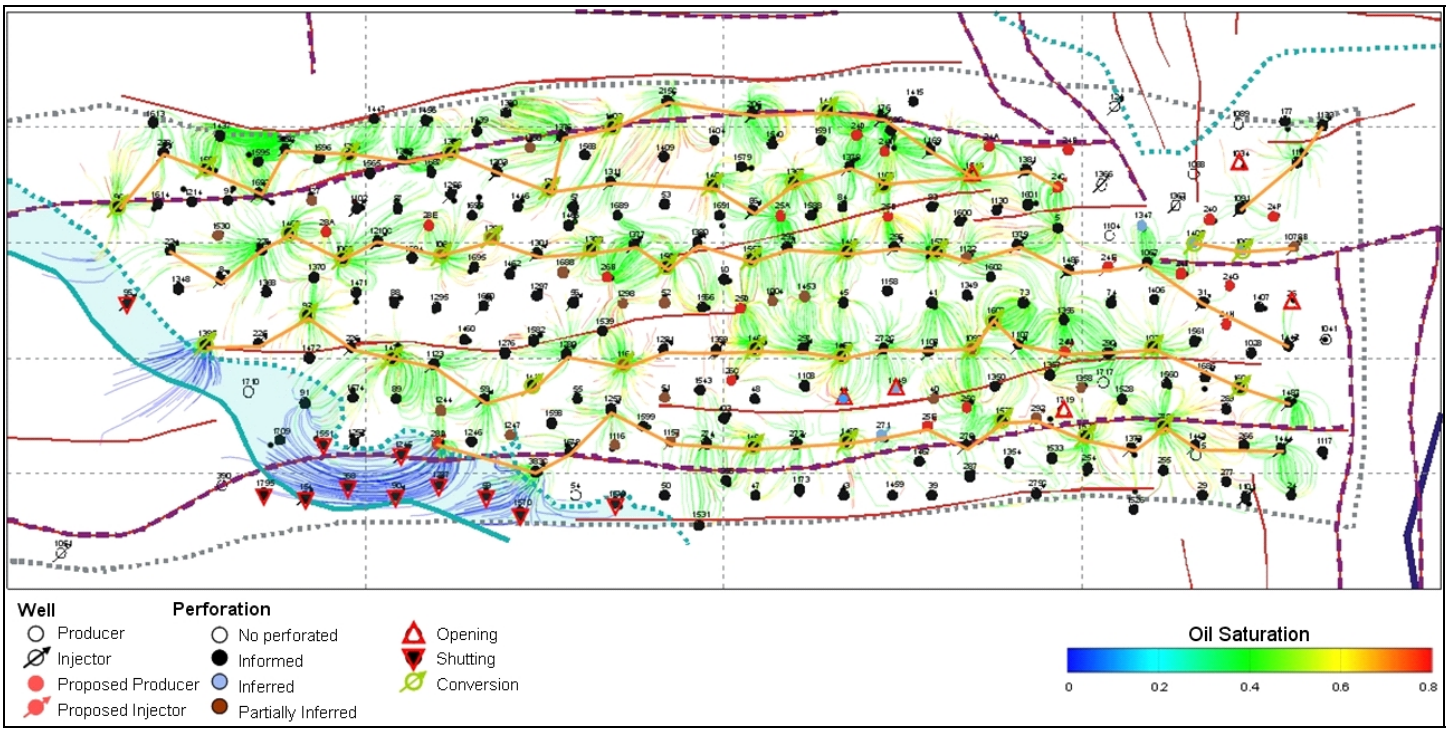

Fig. 19 First Optimization Scenario, MHU
Flowlines from Injectors, 10 years, with Actual Oil Saturation

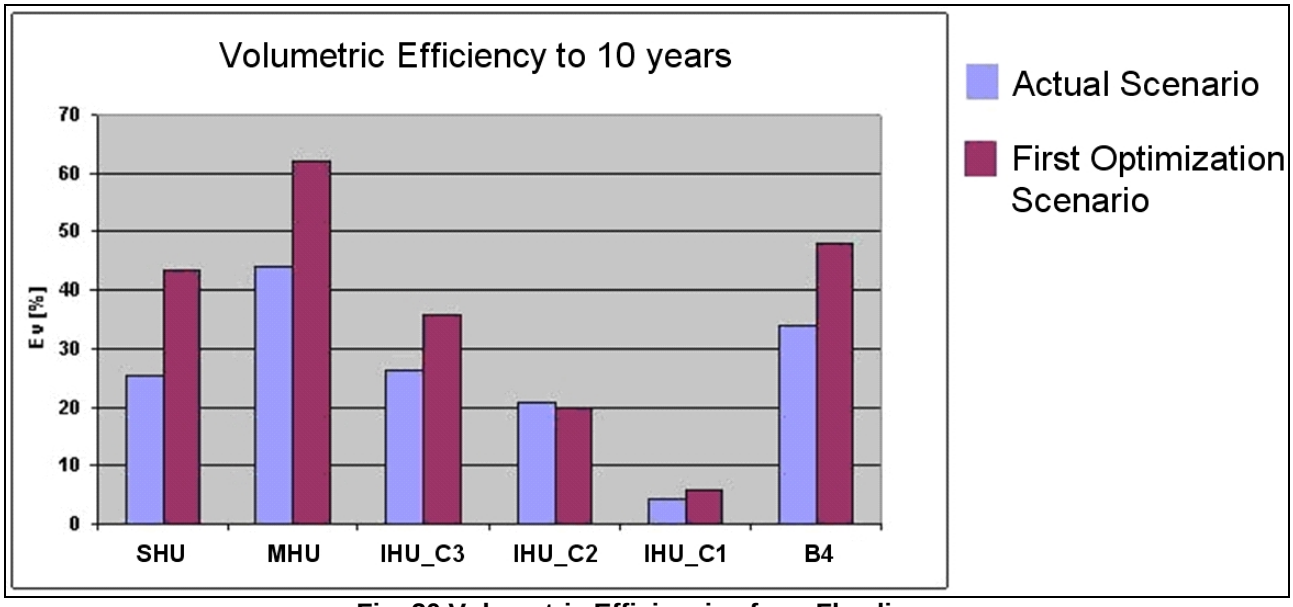

Fig. 20 Volumetric Efficiencies from Flowlines