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Simulation While Drilling: Utopia or Reality?

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Abstract

Numerical Reservoir Simulation has been used in the industry as a powerful production planning tool over the last 20 years, and its efficiency for reservoir production forecasts is very well known. Nevertheless, simulation models are the final result of multiple data sources representing considerable time efforts in model building and updating. This restricts the technique to processes and decisions that can only be held inside level of days, weeks and even months; and depending on the resolution of the geological description and the complexity of the fluid behavior, simulation runs could be very time consuming.

This paper address the possibility to use reservoir simulation while drilling to simulate the reservoir conditions in real-time and dynamically improve the well trajectory and completion strategy based on the well performance predictions. During this study a critical review of the techniques that can improve the reservoir simulation speed and the real-time model updates is presented.

To better quantify the impact of this technique, a synthetic model based on real information from a North Sea Field was used and the reservoir model was continuously updated by assuming new information from well logs and structural markers. Advanced simulation techniques, as boundary conditions and grid refinement, were combined to improve the speed of the simulation runs while preserving an acceptable level of accuracy in the well performance predictions. Multiple wells deviations and configurations can be planned using this methodology while drilling a well.

Introduction

On the last few years there has been an increasing adoption of advanced wells (wells with arbitrary trajectory and/or multiple branches) for many field development programs. These wells are designed to increase productivity by intercepting multiple targets and contacting greatest portions of the reservoir.

With the introduction of the Geosteering technique, real-time data acquisition from Logging While Drilling / Measurement While Drilling (LWD/MWD) tools has been used to make a correlation of the subsurface model and keep a continuous monitoring of the well position. While this technique results valuable to continuously correlate the initial well targets with the actual position, the optimization of the well trajectory based only in geological criteria may not lead to optimal results. The productivity of an advanced well is a very complex problem involving geometrical and structural considerations, anisotropy of near wellbore heterogeneities, multiphase flow phenomena like friction and phase slipping (non darcy effects), among others, which can only be treated rigorously by building a representative simulation model.

Reservoir Simulation has been traditionally used as a tool for field development planning, partly because model updates have only been considered within level of months and years, when an extensive amount of new information has become available. But today, this misleading conception may be coming to an end. Next generation reservoir simulators are becoming faster and more stable. The evolution of high performance parallel clusters dramatically increases the computational speed needed to solve complex flow problems and modern reservoir simulator architectures has been adapted to show scalable performance on these platforms. Novel software tools allow you to integrate real-time information and perform automatic geological and property updates on the reservoir description. The convergence of all of these state-of-the-art technologies clearly shows that today is feasible to perform fast and accurate performance predictions and introduce the reservoir simulation technique within the context of real-time optimization.

During this work a general framework for the introduction of Simulation While Drilling (SiWD) for the optimization of the well construction process in real-time will be presented. A detailed summary of the techniques that enable the process of SiWD are described and the existing challenges that still needs to be addressed for the success of this technique will be explained. Finally, a synthetic model is presented with its results to evaluate the potential benefits and pitfalls that might be expected from a SiWD exercise.

Background

One of the processes of greatest impact and that has evolved significantly over the last years is the accurate estimation of the optimal positioning, configuration and completion strategy of a new well. A common task during field development is the definition of the optimal well positioning. One of the key parameters in the success of a new well is their physical location into the reservoir.

With the increasing development and adoption of new technologies the adoption of advanced wells and real-time data acquisition processes has become economically feasible for many field development programs. However, during the design of an advanced well, there is a great source of uncertainty in the initial reservoir and fluid description. The value of these wells depends critically on these parameters and, in consequence, reducing the uncertainty in real-time and optimizing the decision making process while drilling results critical for the success of any new well. Depending on the case considered, many models or philosophies has been applied to optimize the well construction in real-time:

- Experience with drilling analogs/neighbor wells
- Analytics models
- Geosteering

The experience of drilling similar wells in the same field provides valuable information. An example is the location of a horizontal well in a position close to the water-oil contact (or even below, as in reverse coning) would be the optimal location. In such situation, the global strategy could be to locate all wells at a fixed distance relative to the water oil contact[1]

When it comes to well modeling, analytical techniques are fast and easy to use, however these analytical models are restricted to homogeneous reservoirs, stratified, without faults and dip, horizontal initial fluid contacts and well aligned in a single direction.

Geosteering is a widely used technique today, which consists in the interactive placement of a wellbore based on geologic criteria[2]. This technique only considers the assessment of the static model in real-time and does not take into account the inherent small scale heterogeneities which can greatly affect the inflow performance of the well. In some occasions, this technique is employed with the purpose of optimizing the initial productivity index of the well, which simply means locating the well into the target formation as much as possible and contacting the highest possible quality of the reservoir. This might work for some cases, for example in a single phase case or in a fluvial system where the goal is to penetrate as much sand as possible. However, in the presence of multiphase flow, if the water and gas inflow changes over time are not considered, and if some layers are in direct communication with the water or gas zones, the well could not be optimally located.

A significant number of cases can be found in the literature which demonstrates how to integrate the subsurface model in a closed loop with the drilling system[2-7]. In all these cases, decisions have been made in real-time to modify the well trajectory based on information collected during the drilling process. However, all these cases are based on the geological information acquired while drilling and do not consider that the well performance can be greatly affected by the heterogeneities in the near wellbore region, the influence of neighbor wells, water and/or gas influx among many other important factors.

Real-Time Simulation While Drilling (SiWD)

What is SiWD?

In designing and optimizing the configuration of advanced wells in real-time, it is necessary to have an element that allows predicting or modeling the expected performance of the system as new changes are found, hence optimizing the decision making process based on the given results.

Simulation while drilling (SiWD) can be defined as a real-time optimization process to dynamically improve the design of the trajectory (i.e., navigation, length of horizontal section), configuration (i.e., number of branches), and completion strategy (i.e., intelligent completion settings) of a well while it's being drilled.

The process is based on a closed loop as shown in **Fig. 1**, in which new information is measured and interpreted; the system model is updated based on the new information, the well parameters are changed and simulated until an optimal solution is obtained and the actions implemented. The cycle is conducted at a timescale dictated by the frequency of the measurements and the efficiency of the optimization process.

Useful Models for SiWD[1,9,10]

Generally speaking, the term simulation refers to the representation of a process by means of a physical or theoretical model[8]. Although we might intuitively consider the numerical reservoir simulation as the most adequate tool for a SiWD process, in relatively simple cases, analytic or semi-analytic expressions can provide adequate results with the added advantage of its high speed of calculation and ease of use.

Analytic models, in a broad sense, provide exact solutions to problems that have been sufficiently simplified. The simplest well models are based on analytical solutions of the pressure equation for single-phase flow derived for specific boundary conditions, well and reservoir geometry. The reservoir is also modeled as continuous and with uniform properties. A quantitative comparison of some of the analytic approximations can be found in Ref 11.

Through discretization of the well trajectory into segments, superposition and other numerical techniques, these basic analytical forms can be recombined to give more flexible semi-analytical models. The application of semi-analytic methods allows considering approximately reservoir anisotropy and well hydraulics. In cases where the reservoir heterogeneity, particularly the permeability distribution in the near wellbore region, is considered to be the dominant effect, semi-analytical approximations like the S-K method proposed by Wolfsteiner et al[9], is claimed to provide fast and accurate results and might be particularly useful when different well scenarios and/or geostatistical realizations are available, as is the case in SiWD, where many possible well trajectories and multiple realizations of the permeability field must be evaluated to determine the optimal length and well configuration in real-time.

As a final conclusion, for simple scenarios, of reservoirs with low heterogeneity, wells aligned in a single direction, no significant dip and faulting, analytical solutions may provide valuable insight with optimal calculation efficiency. At a higher degree of accuracy, semi-analytical solution techniques provide an approximation to model the productivity of advanced wells, particularly for reservoirs systems under primary production and if the permeability distribution along the well trajectory is considered the dominant factor. However, in cases of strong heterogeneities, multiphase fluid flow of multicomponent mixtures, reservoirs with irregular geometry, etc. then only numerical reservoir simulation can provide accurate results.

The Impact of SiWD for Real-Time Decision Making

The significance of optimizing the well construction process in real-time, using reservoir simulation during the decision making process, is that it is possible to consider the most critical factors that plays a role in the productivity of advanced wells and that are completely ignored with other traditional models (i.e. geosteering). Some examples are:

- More realistic and accurate well description (profile, completion details and the internal condition of the well)
- Model the artificial lift system used in the field
- Model multiphase, multicomponent flows in heterogeneous porous rocks
- Adequately characterize reservoir fluids, and mixtures of reservoir fluids and any fluids that are injected into the reservoir
- Model changes in fluid properties with changes in pressure and temperature (PVT models)
- Model the influx of fluids into wells as a result of drawdown along the well bore
- Model multiphase, multicomponent flow in wells (wellbore hydraulics)
- Specify the initial state (saturations and pressures) and the boundary conditions (water influx from aquifers) of each reservoir.

Opportunities and Benefits of SiWD

SiWD, as any real-time optimization process, can provide significant benefits in the different aspects of the field management. Within the more relevant operational benefits we might include:

- Minimize the risk of not reaching the economic targets.
- Maximize the well productivity based on well performance predictions.
- Consider all the factors that affect advanced wells productivity.
- Maximize ultimate well recovery.
- Reduce Operational Costs.

Apart from these general considerations, the creation of a near wellbore model with frequent updates as new information becomes available represents another significant advantage. Once the model is ready, the continuous well monitoring can be combined with techniques that allow quick and accurate updates of the near well model based on measurements[12, 13]. This makes possible to predict the performance of smart completions and optimize its configuration and also focus the reservoir characterization as a continuous process, beginning in the exploration phase, refining during development with the ultimate goal of optimizing the field production strategy and to continue during production to optimize ultimate recovery.

Another key benefit of integrating reservoir simulation to the drilling process is the ability to take decisions in quantitative terms by defining an objective function instead of qualitative criteria (for example geologic criteria as in geosteering). This will allow optimizing the process in terms of profit by coupling an economic model to the simulation results. The concept of the objective function for the decision making process will allow, in the future, the inclusion of optimization techniques for the automation of the drilling process.

Why SiWD is so uncommon?

SiWD is still a technique in its early stage of conception. As any new technique, SiWD will need more application on real scenarios before gaining complete acceptance. However, some other reasons have also contributed to this low acceptance, in particular:

- The information acquired while drilling is used insufficiently for reservoir engineering / simulation purposes.
- Lack of integration between technology and software tools.
- Lack of integration across different disciplines. The directional drilling and well planning team are not used to work in an integrated environment with geoscientists and reservoir engineers.
- The progress in the advanced wells modeling techniques is not well known.
- It is believed that model updates and predictions in time intervals of minutes and even second are not possible.
- Existing technology must be very well understood to model properly the physics of the problem.
- The evaluation of multiple well trajectories / configurations in a real-time framework might not be feasible without the implementation of an automated optimization algorithm and this has not been sufficiently explored in a SiWD scenario.

Existing Technologies for Simulation While Drilling

Recent improvements in Reservoir Simulation and Characterization techniques provide the basis for a successful SiWD process. It is crucial to know which technologies are available, that when put together can enable a SiWD process.

Advances in Numerical Reservoir Simulation

In recent years, new techniques has appeared in the different domains of reservoir simulation, including gridding, fluid modeling, numerical approximations, linear solvers, geologic and reservoir modeling, among many others, all of which makes the reservoir simulation a more realistic and accurate tool and the simulator more robust, fast, stable and easy to use.

First of all, advances in software and hardware technologies, parallel computing and modern software engineering techniques has created new opportunities and motivated the development of next generation reservoir simulators, like the recently introduced Intersect project (IX)[14]. Its specific design to take advantage of distributed-memory computational platforms promises an improved efficiency in computations and extended parallel scalability. This, in combination with enhancements in the formulation of the non linear equations, linear solvers and unified well model will result in a significant speed-up of run times and will enable timely decisions in real-time optimization scenarios.

In terms of accuracy, the prediction performance of advanced wells and "smart" completions has improved significantly with the introduction of sophisticate well models like the Multisegment wells[15]. This, in combination with the use of fully unstructured grid, allows an accurate representation of advanced wells geometries in the reservoir model and an explicit estimation of the "so important" well connection factors[16-19](see **Fig. 2**). In consequence, the combined use of complex trajectories and advanced gridding techniques introduces a significant progress in the accurate simulation of the well performance.

Other valuable technique to aid in the optimal design of the simulation model is the use of flow-based upscaling or the so called "intelligent grid coarsening" technique. The idea behind flow-based upscaling methods is to design an "optimal" simulation model in terms of cell resolution. Each cell will be upscaled to a given resolution, the level of coarsening as function of the local geologic heterogeneities, the degree of flow activity and the distance from the well of interest. Algorithms have been implemented in commercial modeling packages that successfully perform intelligent grid coarsening on simulation grids, thus ensuring and optimal performance of the simulation runs[20].

The use of flux boundary conditions allows running simulations on small sectors of the field using boundary conditions established from a previous full field run. The flow through the boundary (specified in the full field run) of the sector field is written to a flux file at each time step in the full field run. The flux file is read during the sector run to generate the appropriate boundary conditions. Practical examples can be found in the literature that illustrate the efficient use of flux boundaries for increasing full field simulation efficiency[21] and in the context of simulation while drilling[22].

To speed-up simulation times, preserve a high scale resolution of the reservoir heterogeneities and include multiple geostatistical realizations, it is necessary to make an efficient use of intelligent grid coarsening and flux boundary conditions. The refined scale of realistic geostatistical models, particularly the high number of thin layers, makes impractical to perform full field simulations at the same scale. However, not all the regions of the reservoir are equally important when evaluating the performance of a well. The saturation changes at greatest distances from the well might not be relevant; the main importance of the flowing reservoir regions more distant from the well concentrates in the pressure support provided and the flow quantities entering and exiting from the wells.

Advances in Reservoir Characterization and Interpretation

Many different examples can be found in the literature that illustrates the evolution of real-time characterization and interpretation techniques in different environments and conditions.

Measurement While Drilling (MWD) is a key technology for the transmission and monitoring of a number of borehole conditions such as downhole pressure, temperature and directional drilling information required to correlate the well location with the subsurface model. Logging While Drilling (LWD) allows acquiring logs and performing frequent formation evaluations in positions near the bit. From these measurements, is then possible to provide a robust real-time petrophysical interpretation, in different geologic environments, containing at least porosity, fluid saturations and permeability[23, 24].

Information measured at the rig can also be useful for the characterization (location and permeability) of the conductive fractures intercepted by the bit while drilling naturally fractured reservoirs. Those fractures are detected by a continuous monitoring of the fluid losses in the mud tanks using flow meters in the inlet and outlet of the tanks[24, 25]. Similarly, the possibility to characterize reservoir formations during under balanced drilling makes possible to estimate the permeability and pressure along the wellbore using the information measured, usually available during the drilling operations[26].

With the use of Magnetic Nuclear Resonance Logs while drilling it is possible to obtain information about porosity, pore size distribution, producible fluid fractions, and allow formation permeability predictions. The confidence of these techniques has been successfully proven in difficult environments[27, 28].

Table No 1 presents a summary of the main variables influencing the productivity of a proposed well and some of the measurement principles available which can be used for real-time estimations of each variable while drilling.

Practical Methodology for Simulation While Drilling

Once a general methodology for SiWD was identified, it was necessary to apply those principles using commercial software in order to prove the potential benefits of the dynamic reservoir evaluation while drilling. In **Fig. 3** are illustrated all the phases that contribute to the implementation of the SiWD, each process is described below.

Pre-Operational Planning

One of the primary aspects in the SiWD process is the multidisciplinary integration in a team work with geoscientist, reservoir engineers, drilling engineers, etc. Depending of the considered case and the available tools, the preparation could have different visions for each discipline.

High Performance Simulation Model

An appropriate machine or set of processors has to be selected for an adequate simulation time. Single processing in conventional machines are usually useful for small models (less than 100,000 cells), although parallel processing based on the domain decomposition of the reservoir can be used with different processors, the best performance occurs when each domain runs on its own cpu.

Drilling process could vary in terms of time depending of the different variables and complexity of the well. The selection of an appropriate set of tools is a very important step to assure a short time in interpretation, updating and simulation processes in order to have well path estimation in a feasible time frame. The following characteristics must be recognized in the selected application(s):

- Avoid Export and Import steps
- Model Structure Updating
- New data interpretation
- Property Modeling
- Well Design
- New Completion Definition

The cost of simulation in terms of time, better grid resolution, improved well models, are key factors that have to be considered from the point of view of numerical simulation; to address most of these challenges issues of SiWD the following simulation techniques could be selected:

- Streamline Reservoir Simulation
- Flux Boundary Conditions
- Parallel Processing
- Restart or Enumeration techniques
- Local Grid Refinement (LGR)
- Multi-Segment Wells

Well & Completion

In a numerical reservoir simulation the well modeling requires to couple the geometry and well configuration with the reservoir allowing the quantification of the borehole pressure with the block pressure of the model. Due to the multiple influences of the near wellbore region in the well performance like, high non-linear pressure gradients, heterogeneities, flooding patterns orientation, multiphase flow, etc., it is necessary to represent these effects with the appropriate tool in order to have accurate predictions and realistic descriptions of the process encountered in the reservoir around the well. From the point of view of well configuration it is also necessary to consider the effects of the pressure drop along the well and the completion caused by friction, slipping and acceleration of the phases, flow regimes and the incorporation of smart devices.

Optimization with SiWD

Once the planning of the required operations and a properly simulation and well modeling is established, the SiWD can be performed as a near real time process to optimize the well construction with the data acquire while drilling. The workflow proposed for SiWD is shown in **Fig. 4** and the most important steps are described below.

Input and Interpretation

Real time data has to be imported and interpreted into the modeling application to update the geological and reservoir simulation models, in order to have a quick interpretation of the logs based on the previous petrophysical understanding artificial intelligence could be used. **Table 1** shows the relation of log data measurement principle and properties of the reservoir.

Property Upscaling

Due to possible change in reservoir model resolution and the use of the LGR technique the upscaling of geological, dynamic and other special properties in the reservoir simulation model became of compulsory use.

Decision Making

An optimization plan must be represented using a quality indicator for the obtained results; mainly the problem could be addressed with an objective function. The objective function must involve any well performance parameter, usually the combination of a variety of production data are used. The Net Present Value of the proposed wells is a good indicator that includes production performance information and economics in the decisions.

Case Study

A reservoir Simulation Model was prepared for the application of the practical methodology based on real data from a reservoir of North Sea of fluvial environment (see **Fig. 5**) , the integration between different processes was a key factor in order to select the appropriate tool or set of tools, the problem of interaction between disciplines in terms of software has been addressed by Petrel®**,** which covers geological modeling, simulation management, economic analysis, neural network analysis and the possibility to used automated workflows.

The simulation model of approximately 600,000 cells was populated of facies with Object Modeling and the Porosity was conditioned with Sequential Gaussian Simulation, additionally a relationship between porosity and horizontal permeability is identify in the area, the vertical permeability ratio was adjusted to 0.13 based on the knowledge of the field. The amount of cells was reduced to 30,000 cells using the Flux Boundary Condition technique and including Local Grid Refinement, and to prove the success of the process a single processor machine was selected, the accuracy near wellbore run (reduced run) against a full field model is shown in Fig. 6.

For the purpose of this study the objective function was the analysis of the production profile, multiple production profiles of the field are shown in the Fig. 7, for this particular step of the SiWD process, a proposed trajectory 1-1 was selected as the most profitable between three different wells.

Future Research Directions for SiWD

A SiWD process is based on a complex interaction of numerous technologies and modeling components. In consequence, the accuracy and the efficiency of the optimization process will depend in the convergence of these technologies and the accuracy on the modeling response of each component. Some of the tools or techniques that will need further development or its application within a SiWD framework have not been sufficiently explored are:

- The implementation of optimization algorithms for the automatic selection of the trajectory, configuration and completion strategy of the well.

- The inclusion of defensive and reactive control strategies for intelligent completions during the prediction runs. A ¨real¨ optimum is not be determined without considering the future actions that will be implemented on the down-hole valves and other devices to control the inflow performance of the well.
- Parallel processing efficiency and its compatibility with other simulation techniques. The combination of parallel processing with intelligent grid coarsening, flux boundary conditions, local grid refinements, unstructured gridding technology etc., and the performance of the parallel runs in combination with these techniques.
- The application of Artificial Intelligence (AI) techniques; for example Neural Nets for automatic property estimation from well logs or fuzzy logic for automated steering of the well.
- Coupled fluid flow and geomechanics in the reservoir simulation calculations. Real-time measurements of the mechanical properties of the reservoir rocks are common during drilling operations due to their importance on well stability, however a real-time assessment of the geomechanics response has never been considered before. Mainly because of the computational costs involved.
- Integrated Surface-Subsurface Simulation. The coupling of a surface network model with the near-wellbore reservoir model increases the accuracy of the predictions runs but also increases significantly the processing time of the simulation runs.
- The inclusion of an uncertainty model in the closed-loop optimization process.
- The application of SiWD in fractured reservoirs. Accurate reservoir characterization and reservoir simulation is particularly difficult to achieve in naturally fractured reservoirs due to the inherent complexity in the fracture system description and the matrix-fracture interaction.

Conclusions

The productivity of advanced wells is strongly influenced by complex multiphase flow in heterogeneous porous rocks and many other factors which can not be considered by the geosteering technique when optimizing the well construction in real-time. Simulation while drilling has been introduced and a general framework has been established.

Reservoir simulation is becoming increasingly fast and stable and today is possible to perform practical reservoir simulations at a reasonable scale in time intervals of minutes and even seconds. However, for a successful Simulation while drilling exercise, it is necessary to consider multiple scenarios of trajectories and well configurations in real-time and this might become a time consuming task if a trial and error solution is considered. Hence, the introduction of an automated optimization algorithm to select the optimal well trajectory and configuration will make a significant progress in the feasibility of implementing the SiWD technique in real-scenarios. Even more important, is to consider the optimization of the well trajectory and configuration under uncertainty, especially because of the complexity in the predictions performance of advanced wells.

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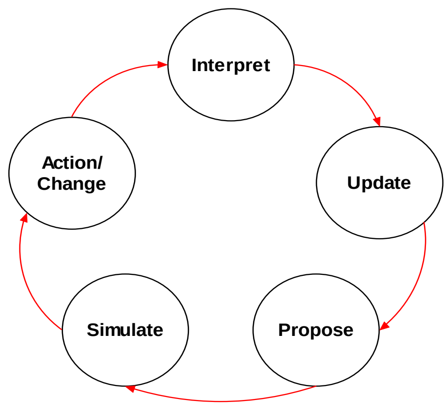

Fig. 1: Close loop in the Simulation While Drilling

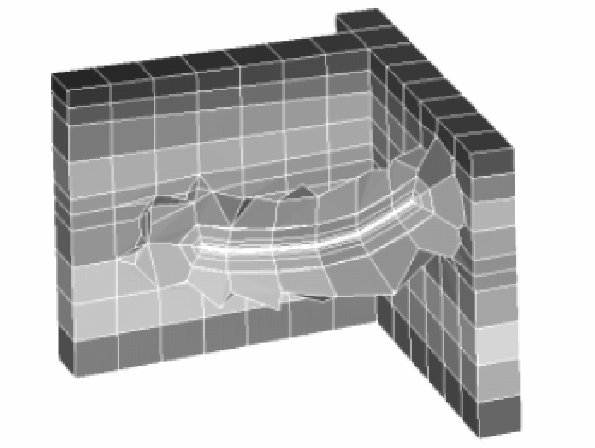

Fig.2: Unstructured 3D deviated grid

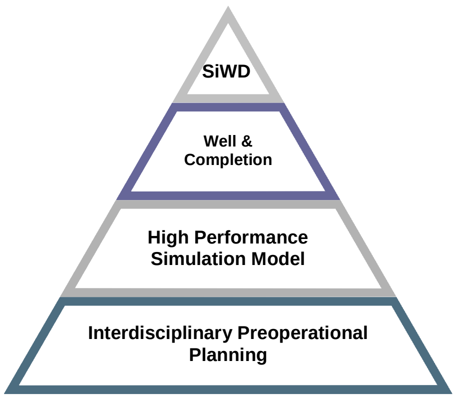

Fig.3: Phases involved in Simulation While Drilling

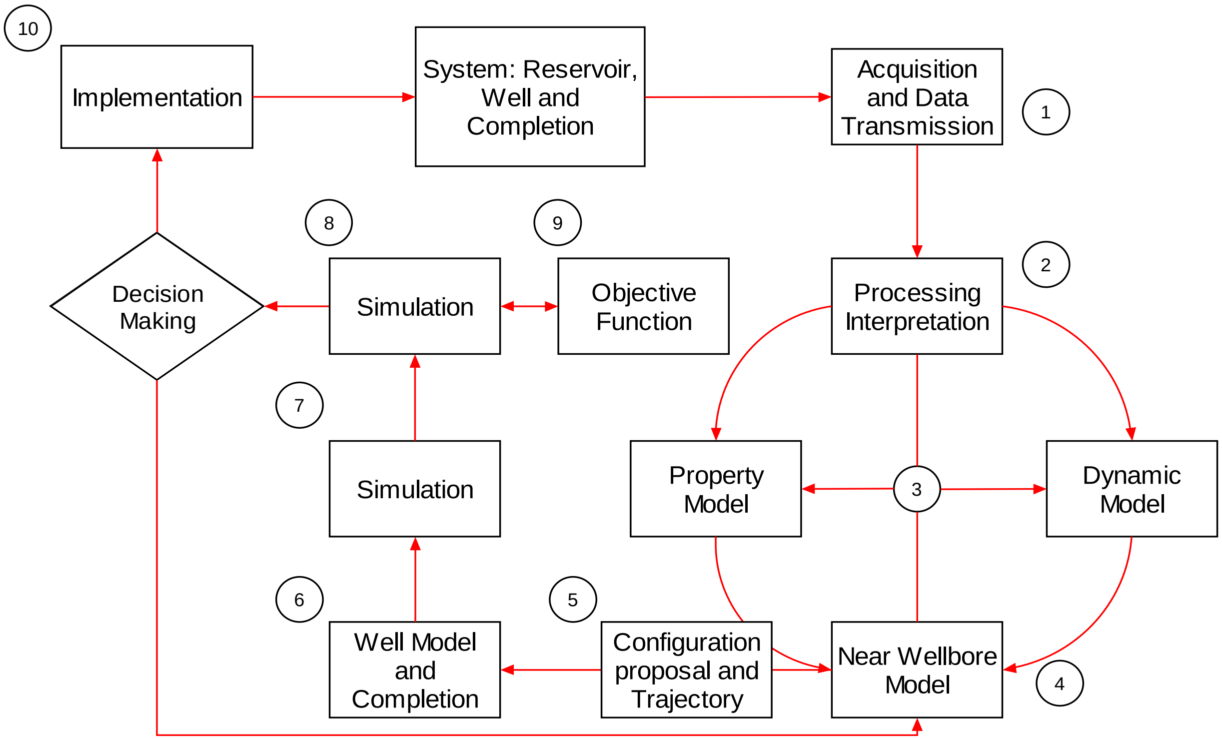

Fig.4: Workflow for SiWD.

Table 1: Reservoir variables vs Measurement Principles

Variables	***Sensitivity***	***Measurement Principle***	***Simplicity***
Matrix Permeability	High	NMR, Spectroscopy, Neural Nets.	Medium
Fractures Permeability	High	Mud weight losses Measurements	Simple
Porosity	High	Density, Neutron, Sonic	Simple
Saturations/ Fluids Distribution	High	Resistivity, NMR, Seismic	Complex
Pore Pressure	Low	Pressure Sensors, Sonic[29]	Simple
Formation Temperature	Low	Temperature Sensors	Simple
Composition	Low	Conductance and Capacitance Sensors, Ultrasonics	Medium
PVT Properties	Low	Differential pressure and temperature[30], NMR[31]	Complex
Lithology	Medium	Ionic, density, gamma ray, resisitivity	Medium
Stratigraphy	Medium	Azhimutal Gamma Ray	Simple
Structure	Low	Seismic, Gamma Ray.	Simple

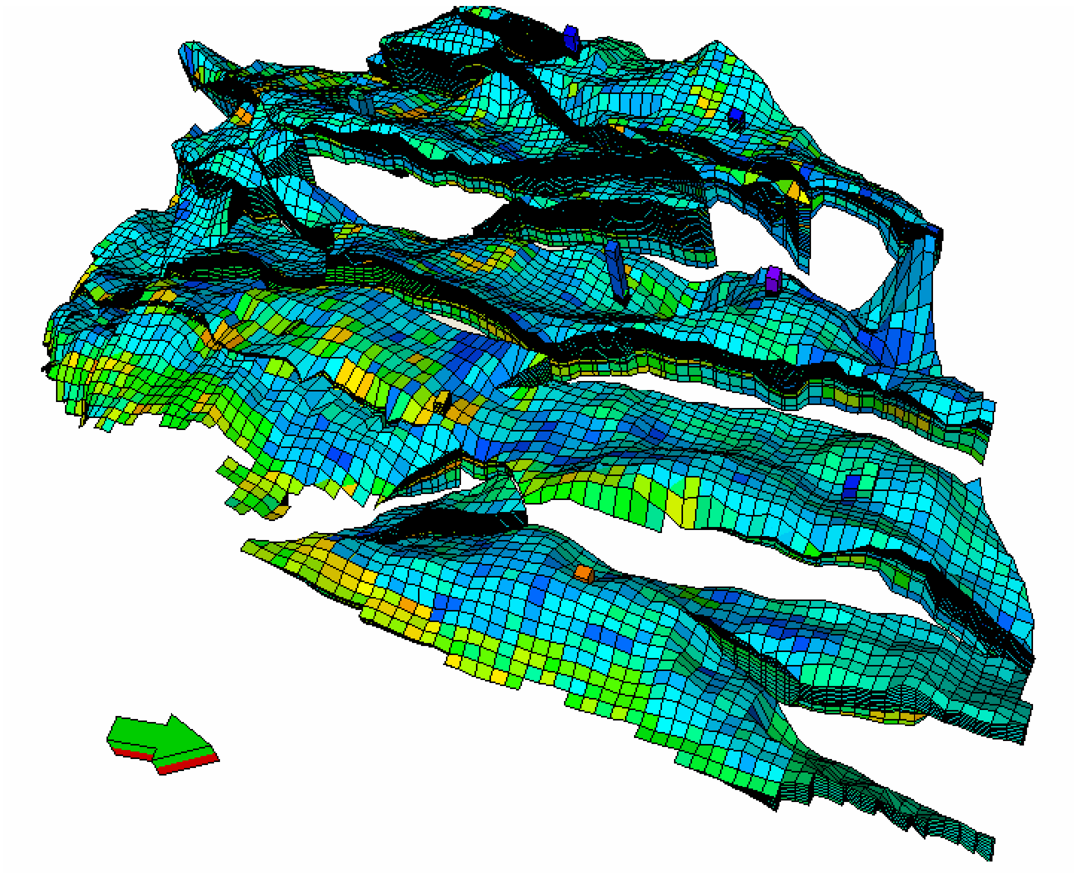

Fig.5: Reservoir Simulation Model

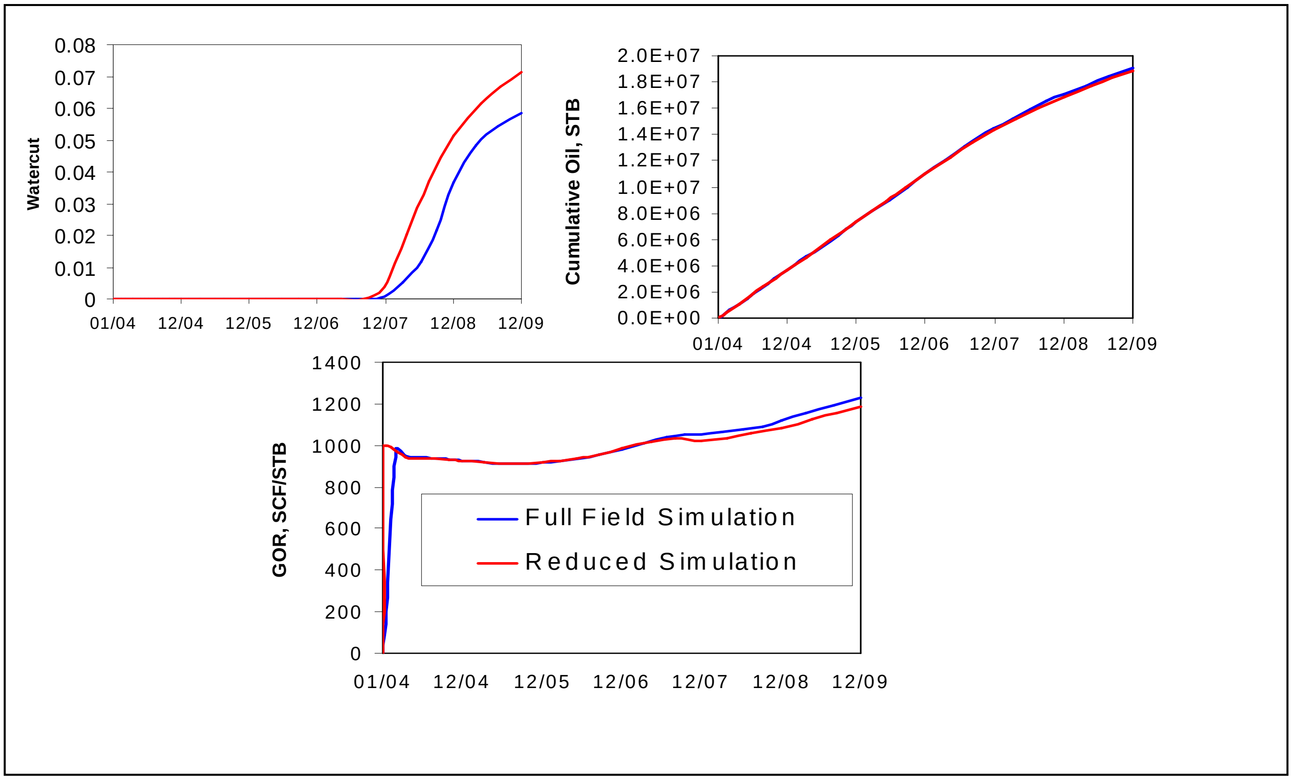

Fig.6: Plots of Comparison between Full Field and Reduced Simulation

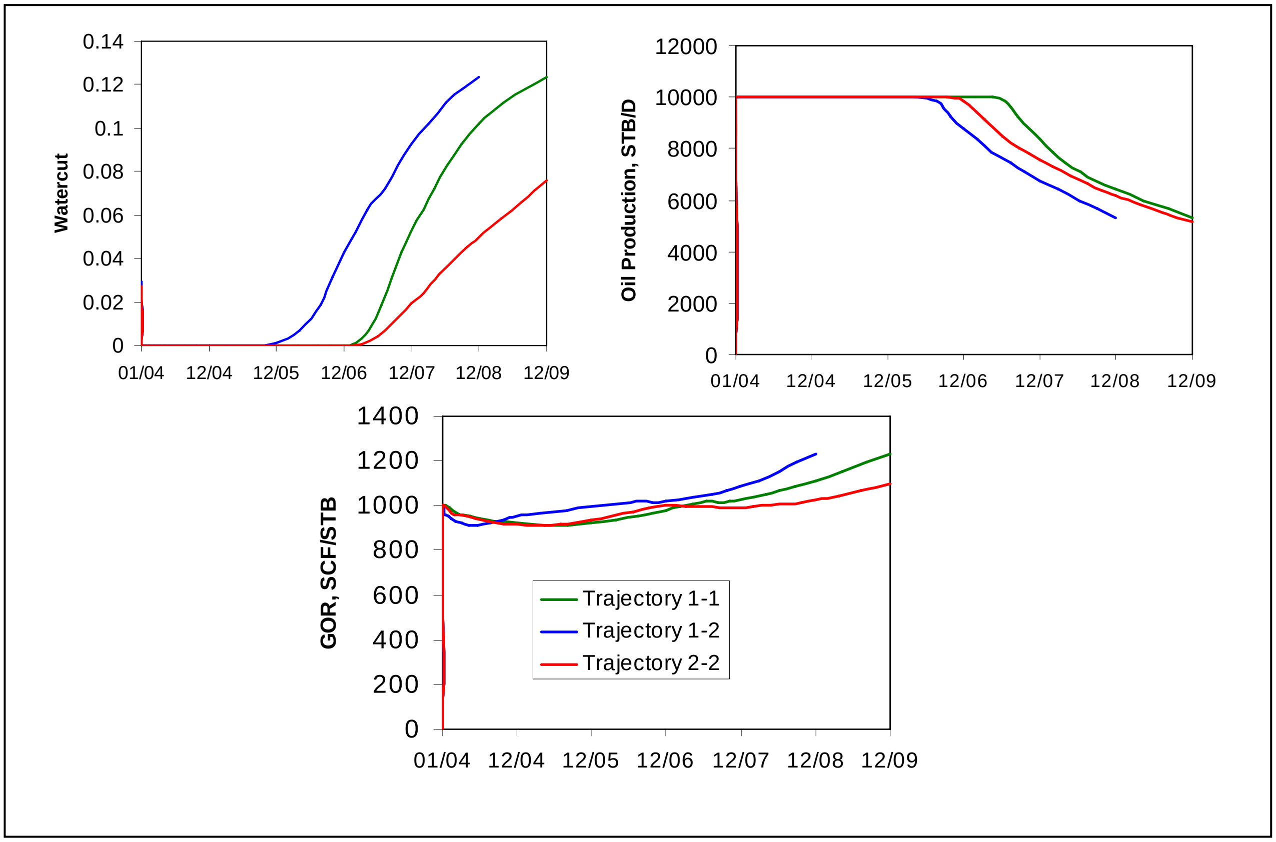

Fig.7: Plots for Decision Making based on Production Profile