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Well Log Simulation- A new vista in Formation Evaluation

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Summary

The approach of Formation Evaluation through log simulation, which is relatively new to the E&P industry includes modeling the reservoirs with given mineralogical and fluid components (fixed proportions of saturated aliphatic hydrocarbon components) apart from the borehole, geological and petro physical environments. The log interpretation is based on pre-defined earth model with radial and petrophysical zonation of the Formations and putting in place a static reservoir petrophysical model initially. The bore hole fluid invasion is separately modeled through fluid simulator for knowing the dynamic behavior of the reservoirs and the results could be imported into static model to compute the invasion accounted petrophysical results. The simulations are to be carried out with a good match between simulated logs and the Field logs. The results obtained for the three wells which were interpreted with this new interpretation methodology indicated correlativity with the results obtained with conventional interpretation methods. The sand layers interpreted to have lesser drilling fluid invasion from the simulation results with relatively better porosity and permeability have been observed to have good producing characters, which were supported from initial testing data. MDT sampling results are also supportive of the invasion based simulation results and this methodology can be utilized further to infer about the flow characters of the reservoirs. Improvised fluid saturation and permeability after importing dynamic simulation results to static earth model as observed could contribute to the overall understanding of the reservoirs qualitatively and quantitatively.

Keywords: *Formation Evaluation, Log Simulation.*

Introduction

The inversion based interpretation methodologies for log analysis to evaluate the reservoirs for their static properties are in vogue for more than two decades. These methods involve different tool responses for different lithological and fluid components of the reservoirs, log measurements and estimated volumetric components with error minimizing techniques and result in providing static reservoir properties. These methods also focus to provide accurate petrophysical analysis for more complex reservoirs which can be integrated with other G&G data viz. seismic and geology and put for reservoir simulation for providing E&P Portfolio management. These methodologies do not give much information on the dynamic behavior of the reservoirs for identifying sampling/testing intervals and stimulation requirements.

Normally bore hole environment along with geological and petro physical environments affect the log responses and the correction charts/algorithms provided by different vendors does the bore hole corrections to a greater extent. However, modeling for invasion radially along with side bed corrections in a given geological and petro physical environment offer more representative physical parameters of the strata. The approach of Formation Evaluation through log simulation includes modeling the reservoirs with given mineralogical and fluid components apart from the borehole, geological and petro physical environments. The geological and petro physical environments are introduced with the help of bed boundaries and radial boundaries. The logs thus simulated are compared with the original logs until a good match is found between the recorded and original logs. This process is completed through Static and Dynamic simulation.

The products resulted from these simulations are static reservoir parameters such as porosity, fluid saturation, hydrocarbon column thickness and the dynamic simulation resulting the invasion profile and radial saturation profile which will help in understanding the dynamic reservoir behavior.

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Method

The Modeling Platform named as Integrated Petrophysics and Well-Log Modeling Platform (UTAPWeLS) under MS Windows environment (1 GB RAM, Graphics Card with 1GB Memory, Hard Disk space of 2.8 GB) includes User-friendly, Matlab-based simulation modules and is provided by **FE Consortium at University of Texas at Austin**. The platform constructs multi-layer static and dynamic petrophysical models that can be subjected to reservoir and geophysical up scaling and that lend themselves to multiple-hypotheses testing, rock classification, and cross-validation and numerical prediction of measurements. It also includes basic and advanced well-logging calculations, layer-boundary detection algorithms, basic digital processing routines, simulation of the process of mud-filtrate invasion in vertical wells with water- and oil-base muds, and numerical modeling/inversion of well logs for the estimation of layer-by-layer petrophysical properties.

The wells undertaken in the present study are from Krishna Godavari Offshore and Onland area. These wells are HPHT wells and the objective Formation is Syn-rift sediment section (Gollapalli sandstone) which is characterized by low porosity and low permeability in general. As invasion plays a dominant rule in these types of reservoirs and the potential of these reservoirs can be judged by studying the properly modeled invasion phenomena, a total number of four wells have been taken up for study where conventional testing has been carried out.

Resistivity Log Simulation

The purpose of resistivity modeling and inversion is to estimate the invaded zone (Rxo) and virgin zone (Rt) resistivity's and the radius of invasion (rinv) from raw array-induction conductivity measurements. Initially, it assumed a single-layer case and a piston like radial profile of invasion. The system is bounded at the top and bottom by shale beds (shoulders) with resistivity Rshtop and Rshbot, respectively. Also, the model is bounded by a borehole with fluid resistivity equal to Rm and the virgin zone whose resistivity is one of the main inputs necessary to estimate water saturation. An induction tool measures formation resistivity by inducing low-frequency electric currents into the formation surrounding the borehole. The simulation of induction measurements assumes a 2D axial-symmetric model where current loop sources are located at the center of the borehole. A Numerical-Mode Matching Method (NMM) is assumed to perform the corresponding simulations.

Numerical Mode Matching method

The Numerical-Mode Matching Method (NMM) is used to solve the above 2D simulation problem (Chew et al., 1984; Zhang et al., 1999). This algorithm combines a 1D finite element solution in the radial direction with an analytical solution in the vertical direction. When augmented by the new type of basis functions (Zhang et al., 1999), the NMM is several times more computer efficient than 2D finite element and finite-difference methods.

Inversion: Minimizing the quadratic cost function given by

$$C(\bar{\mathbf{x}}) = \frac{1}{2}\left\{\left\|\bar{\mathbf{e}}(\bar{\mathbf{x}})\right\|^2 + \lambda^2 \left\|\bar{\mathbf{x}}\right\|^2\right\},$$

where x is the unknown model parameters (layer-by layer values of Rxo, Rt, and rinv), λ2 is a regularization (stabilization) parameter, and e is the vector of data residuals given by

$$\bar{\mathbf{e}}(\bar{\mathbf{x}}) = \bar{\mathbf{d}}_o(\bar{\mathbf{x}}) - \bar{\mathbf{d}}^o.$$

In the above expressions, do (x) contains the simulated measurements and do contains the field measurements (raw AIT conductivities).

On the other hand, the inverse problem of raw array-induction measurements is approached with the distorted Born iterative method (DBIM).

Nuclear Logs Simulation

As a result of its high numerical accuracy and versatility to include complex tool configurations and arbitrary spatial distributions of material properties, the Monte Carlo method is the foremost numerical technique used to simulate borehole nuclear measurements. Although recent advances in computer technology have considerably reduced the computer time required by Monte Carlo simulations of borehole nuclear measurements, the efficiency of the method is still not sufficient for estimation of layer-by-layer properties or combined quantitative interpretation with other borehole measurements. A new linear iterative refinement method to simulate nuclear borehole measurements accurately and rapidly was developed and successfully tested.

The approximation stems from Monte Carlo-derived geometric response factors, referred to as flux sensitivity functions (FSFs), for specific density and neutron-tool configurations. The procedure first invokes the integral representation of Boltzmann's transport equation to describe the detector response from the flux of particles emitted by the radioactive source. Subsequently, the Monte Carlo N-particle (MCNP) code was used to calculate the associated detector response function and the particle flux included in the integral form of Boltzmann's equation. The linear iterative refinement method accounts for variations of the response functions attributable to local perturbations when numerically simulating neutron and density porosity logs. Variations in the FSFs of neutron and density measurements from borehole environmental effects and spatial variations of formation properties were quantified. Simulations performed with the new approximations yield errors in the simulated value of density of less than with respect to Monte Carlo-simulated logs. Moreover, for the case of radial geometric factor of density, a maximum shift of at 90% of the total sensitivity as a result of realistic variations of formation density is observed. Neutron porosity values simulated with the new approximation differ by less than 10% from Monte Carlo simulations. The approximations enable the simulation of borehole nuclear measurements in seconds of CPU time compared to several hours with MCNP.

Simulation for Mud Filtrate Invasion

Invasion of mud filtrate into the formation is modeled as a two-dimensional (2D) axisymmetric chemical flood process. Filtrate invasion is simulated to obtain cross-sections of water saturation as a function of depth and radial distance away from the borehole wall. Mud-filtrate invasion is treated in an equivalent manner to the process of water injection into a gas reservoir. Accordingly, two-phase immiscible fluid flow is assumed in the simulations of mud-filtrate invasion. Rate of invasion of mud filtrate across the borehole wall is calculated as a flow rate function resulting from mudcake buildup. The flow of mud filtrate through mudcake can be described by Darcy’s law, i.e.,

$$Q_f = \frac{kA}{\mu}\frac{\Delta P}{h_{mc}}, \qquad (1)$$

Where Qf is the flow rate of mud filtrate across the borehole wall, k is the mud cake permeability, A is the cross-sectional area through which the filtrate flows, μ is the viscosity of filtrate, hmc is the thickness of mud cake, and ΔP is the pressure drop across the mud cake. The flow of mud filtrate across the mudcake is modeled using an axisymmetric version of the 3D multi-phase, multi-component compositional simulator developed. Both dynamic growth of mudcake thickness and dynamic decrease of mudcake permeability are coupled to formation properties. This process results in a dynamic monotonic decrease of flow rate across the borehole wall.

After a short initial spurt of mud-filtrate invasion, the rate of flow is found to reach a steady-state value specific to a particular layer. In the present work, the layer-dependent rate of mud-filtrate invasion is assumed to be the steady-state value yielded by the simulations of invasion. The simulation of mud-filtrate invasion can also take into account several cycles of mudcake rub-off and buildup. Assumptions made by the reservoir simulation model are those of multi-component immiscible fluid displacement governed by Darcy’s law and mass balance. The general form of the mass balance equation for the k-th component can be written as

$$\frac{\partial}{\partial t}(\phi C_k \rho_k) + \nabla\cdot\left[\sum_{l=1}^{n_p}\rho_k\left(C_{kl}u_l - \widetilde{D}_{kl}\right)\right] = R_k\,, \qquad (2)$$

where Φ is porosity, Ck is the overall concentration of component k per unit pore volume, Ckl is the concentration of component k in phase l, ρk is fluid density, ul is the Darcy flux for phase l, Rk is the total source/sink term for component, k and Dkl the dispersive flux, defined as

$$\widetilde{D}_{kl} = \phi S_l K_{kl}\cdot\nabla C_{kl}\,, \qquad (3)$$

where Sl is the saturation for phase l, and Kkl is a dispersion tensor. The latter tensor includes contributions from molecular diffusion and hydrodynamic dispersion (Bear, 1979). A more detailed discussion of both model formulation and solution algorithm used is available in Saad (1989) and Delshad et al. (1996).

Two-dimensional cylindrical flow is assumed for the numerical simulation of mud-filtrate invasion near the borehole (i.e. 3D flow with no spatial variations in the azimuthal direction). A finite-difference scheme is used to discretize and numerically solve equations (2) and (3).

Discussion of Results

The interpreted static model with all Petrophysical boundaries is compared with conventional interpretation results (Fig 1) in relatively better porous and permeable layers in well A. Suitable Petrophysical boundaries are introduced along with radial zones.

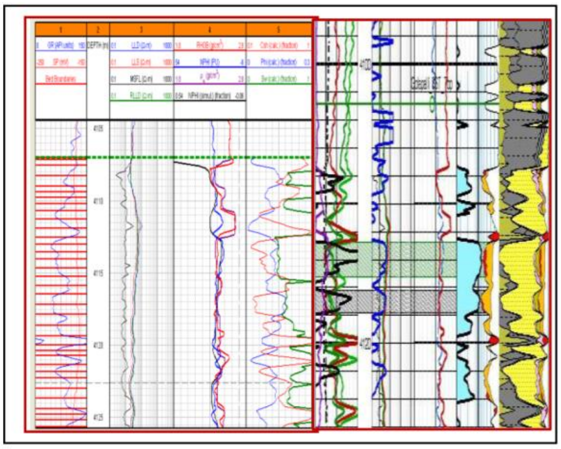

Fig 1: A good match between static interpretation model with many petrophysical boundaries and conventional interpretation (well A).

The mud filtrate invasion was simulated after the completion of static model varying the time of invasion (Fig 2).

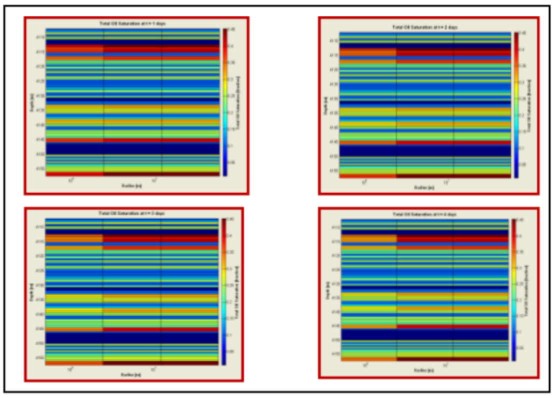

Fig 2: Dynamic simulation results for four days of invasion in well A. X axis denotes the hydrocarbon saturation variation. Invasion affected the reservoirs to a lesser extent in this well as minimum variation along x-axis is noticed with time.

MDT sampling at 4113.5m yielded 2.72cu.ft of gas and 120cc mud filtrate and 80cc of light oil while sampling at 4140.5 m yielded little gas with 200 cc mud filtrate. The radial hydrocarbon saturation brought out by dynamic simulation is able to distinguish these zones with varying invasion affected hydrocarbon saturation.

In Well B, the invasion simulation results from dynamic simulation are imported to the interpreted model and all the logs are re simulated and the porosity and water saturation are recomputed. A good fit between neutron-density and Resistivity logs is seen between re simulated and Field logs with minor variations in water saturation (Fig 3).

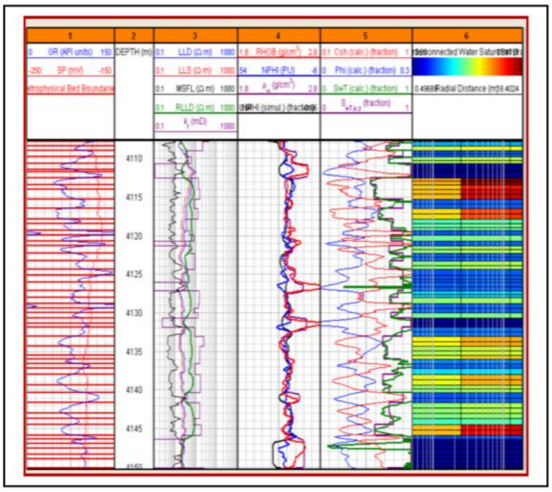

Fig 3. Radial water Saturation distribution and computed results for Well B where reservoirs are of moderate porosity and permeability.

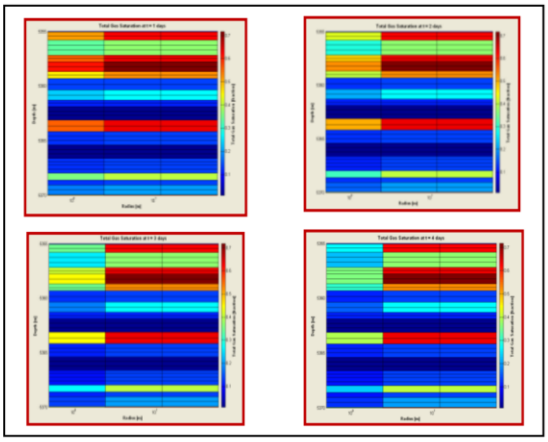

Fig .4 Dynamic simulation results for four days of invasion in well C. The reservoirs are highly affected by invasion in this well as a variation in hydrocarbon saturation is on X-axis seen.

The dynamic simulation carried out for 1, 2, 3 and 4 days in this Well C indicates that the invasion has affected the layers to varying extent and the relatively better porous layers are less affected (Fig 4). A comparison of invasion diameter and dynamic simulation results indicates (Fig 5) that deeper invasion characterized by higher invasion diameter resulted in estimation of higher water saturation.

Rock typing can also be attempted using these invasion profiles (Fig 6) and selection of better sampling points can be taken up after simulation results.

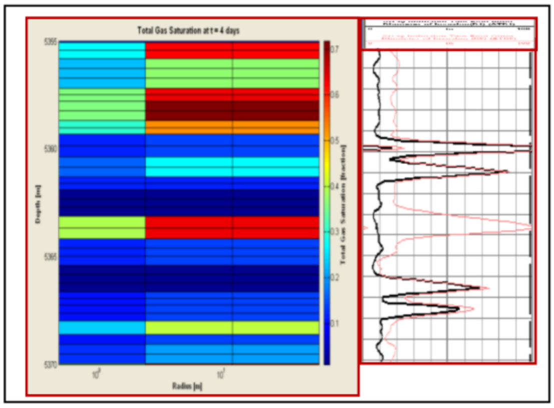

Fig 5. The invasion diameter estimated from conventional resistivity logs in this well corroborates with the invasion simulated results(High caving sections are having low hydrocarbon saturations).

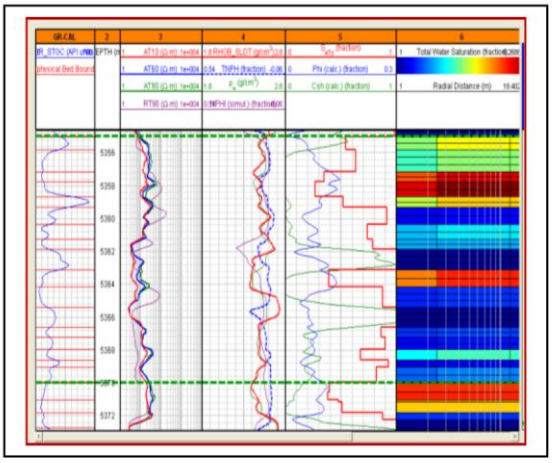

Fig 6. The recomputed resistivity and reservoir parameters In well C indicate that the layers in the intervals 5357-58.5m and 5363-64m are having better hydrocarbon saturation with lesser invasion and are better sampling points.

Conclusions

Usage of log simulations facilitated better understanding of the reservoirs. The present study is carried out with the help of log simulation package UTAPWeLS in reservoirs with low porosity and low permeability. This package provides resistivity, nuclear log simulations for the log data recorded by various vendors.

The present study clearly brings out the lesser susceptibility of the reservoirs in two wells viz. well #A and Well # B for invasion compared to other well Well # C under study. The testing results in these wells also indicate the same. While Well#A produced oil, gas and water together and Well #B gave good amount of gas with traces of oil. The invasion inferences are well supported from Wire line Formation testing data in well#A. A comparison of invasion diameter and dynamic simulation results indicates that deeper invasion as characterized by simulation corresponds to higher invasion diameter as estimated from conventional logs.

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