Optimizing the Reservoir Model of a Tight Oil Field Through Pore Structure Characterization: A Case Study from KG-Onland Basin, India

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Summary
The scarcity of conventional, easy to find oil & gas reserves along with the concern of global energy shortage has forced the industry to explore and develop geologically complex and more challenging tight oil reservoirs. The Nandigama Formation of Malleswaram Field, located in KG-Onland basin in eastern India, represents such a scenario.

Conventional reservoir characterization approach is based on identification of depositional facies and their propagation through various seismic attributes. The inherent limitation of these attributes in the study area has resulted in the adoption of novel analysis procedure, which include identification of different mappable geological units; integration of well, sedimentological, FMI & core data to determine their deposition environment. Present study attempted to establish the presence & absence of hydrocarbon within Nandigama Formation by classifying the Synrift sequence into five different geological units and mapping their disposition in the subject field.

Non-parametric regression-based approach for permeability modeling instead of linear regression of core porosity-core permeability data resulted in establishing a proper porosity-permeability relationship within each depositional facies. Reservoir rock typing and incorporation of hydraulic flow units resulted in characterization of complex pore networks, which in turn are by-product of frequent vertical and horizontal facies changes and diagenetic processes within reservoir. Mapping results of rock typing lead to presence and continuity of high-quality speed zones, baffles and seals throughout the field. Integration of all these studies through hierarchical modeling-based approach resulted in manifestation of a highly detailed 9-million cell Geo-Cellular model. This model was history matched and can be used to determine a range of feasible scenarios to consider for field development.

Introduction
The Krishna Godavari Basin is a Continental Passive Margin Basin comprising of a number of North East - South West trending horsts and graben.

The basin has a polycyclic (dual-rift) evolution history in the eastern continental margin of Indian Plate. Tectonically, the basin can be divided into three sub-basins, namely the Krishna, West Godavari & East Godavari Sub-basin, which are separated by the Bapatla and Tanuku Horsts respectively. The West Godavari Sub basin is further separated by Kaza – Kaikalur Horst into the Bantumilli Graben and Gudivada Graben (Figure-1).

Malleswaram Field (Figure-2) was discovered in March-2011 and is located over the SW plunge of Bantumilli high in the West Godavari sub-basin of KG Basin.

Figure-1: Tectonic set-up of KG Basin.

Figure-2: Base map of Malleswaram Field.
In the study area, the oldest sediment belongs to Nandigama Formation, which overlies the gneissic basement. This Nandigama Formation is envisaged to be the result of synrift deposition during Late Jurassic to Early Cretaceous in a marginal marine setting. This formation is overlain by the transgressive shale called Raghavapuram Formation (Early Cretaceous) which is the regional seal and prominent source rock.

Field Overview

The Malleswaram structure was perceived to be a single sedimentary fan, deposited on the rising slopes of Bantumilli high, delimited by faults (Figure-3). A net oil column of about 100 m was encountered near top part of the Synrift section (at depth of ~3500m) in discovery well, which produced Oil @ 47 m3/day.

Pay zones of Malleswaram Field belong to Nandigama Formation and are having a high degree of heterogeneity with porosity ranging from 0.01 to 20% (Average φ - 12.3%) and permeability ranges in 0.01-10 mD. The reservoir is under-saturated oil reservoir having initial reservoir pressure of around 560-590 KSc in different wells. API gravity of produced oil varies from 38 to 42 API. Produced GOR in most of the wells is around 110-150 m3/m3. The gas is composed of methane with higher hydrocarbons along with little fraction of Carbon dioxide and Nitrogen.

Primary hurdle in these reservoirs is poor permeability of the formation, which deters the commercial production and these reservoirs fall in the category of tight reservoirs. Out of 15 drilled wells in Malleswaram Field, production could be taken from only 8 wells. Although the initial HC flow rates were good but the production rates declined steeply in all the wells. With a view to enhance production, as being done globally for the tight reservoir exploitation, hydro-fracturing was carried out in number of wells. However, no improvement in terms of production, was seen.

Production Performance

Production from Malleswaram Field started in the year of 2011 and most of the development wells have a production history of less than 3 years. Another challenge in the wells of Malleswaram Field is limited number of representative reservoir pressure data points. Low permeability of the reservoirs requires very high shut-in time for proper stabilization of pressure, which is not always feasible. In order to have a better understanding of reservoir behavior, performance analysis has been attempted at sand level, sector level and well levels (Figure-4).

Integrated Workflow

As per the initial models, Malleswaram Field was perceived to be a single sedimentary fan structure delimited by faults. However, two development locations (Well-K & L) drilled at structurally favorable position were met with negative surprises. Inferior performance of some of the wells (Well- C, D, E, I, J and N) in terms of well productivity as compare to other wells (Well- A, B, F and G) also indicates that the current geological model needs to
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be reviewed and model which can explain the fluid distribution need to be developed.

In the present study, integrating all processed logs, drill cutting analysis, core analysis, reservoir study reports, FMI logs & Lab data; a unique scheme of geological classification has been brought out, where entire Malleswaram Field is divided into five vertical units and a number of fault bound sectors (Figure-5). It is observed that every unit in each sector behaves distinctly and presence of multiple pools (sector wise, unit wise) is brought out.

Figure-5: Geological model of Malleswaram Field

Limited production history and sparse pressure data points limits the reservoir continuity analysis. Since, conventional performance analysis does not facilitate in reservoir compartmentalization analysis, an unconventional workflow (non-parametric statistical algorithm) was adopted for the present study. The workflow adopted for present study is based on five stages of analysis (Figure-6), which is summarized below-

- Pressure Behavior Analysis
- Production Behavior Analysis
- Cluster Analysis
- Vector Analysis
- Fluid Composition Analysis

The Pressure Behavior Analysis part of the workflow is based on analysis of the available information for wellhead pressure (THP), Bottom-hole pressures (\(P_{ws}\) & \(P_{wf}\)) and pressure transient test interpretations, to determine degree of reservoir compartmentalization (Null, partial or complete).

Analysis of Production Behavior at well level was carried out with an objective of identifying patterns or groups of wells with similar behavior of historical production. Various techniques to find out similarity among the well-wise performance were attempted.

Figure-6: Workflow adopted for Reservoir Compartmentalization analysis

Cluster Analysis is an exploratory data analysis tool which aims at sorting different objects into groups (called as clusters) in a way that the degree of association between two objects is maximal if they belong to same group and minimal otherwise. For the purpose of this study, cluster analysis was performed over various components of well performance viz. normalized reservoir pressure, oil production rate, GOR and water-cut to identify and classify the wells into different clusters based on likelihood of wells falling in same group.

Vector Analysis is based on the novel concept of Interference test, where characteristics of response as a function of time reflect the reservoir properties between the active and observation wells. Even in the absence of artificially generated event/disturbance, same concept should work if we analyze intrinsic events of one well with its neighboring wells. For vector analysis, oil rate was converted into vector and pattern match of wells was carried out for reservoir compartmentalization.

Fluid composition and Thermodynamic behavior of the produced fluid can be used to predict the dynamic behavior of the reservoir and identify the degree of compartmentalization. This analysis used PVT studies, variation in field GOR and oil gravity measurements to identify degree of reservoir compartmentalization.

Integrating all these five stages of analysis with Seismo-Geological model brings out that Nandigama reservoir of Malleswaram Field is having a number of reservoir compartments. In and around areas of Malleswaram Field can be divided
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into 9 fault bound sectors which in turn is taken as input for generation of Fluid distribution model.

**Reservoir Characterization**

Reservoir characterization techniques are quite valuable as they provide a better description of the storage and flow properties of a petroleum reservoir and thus provide the basis for developing its simulation model. Permeability and porosity of the reservoir rock have always been considered as two of the most important parameters for formation evaluation, reservoir description, and characterization. Beyond evaluating permeability and porosity, accurate determination of pore-body/throat attributes and fluid distribution are central elements in enhanced reservoir description.

In the study area, seismic data has bandwidth of upto 30 Hz, but peak frequency of seismic data is around 12 Hz and similarly the peak seismic velocity lies in the range of 3800-4000 m/s, which pose a serious limitation towards seismic based reservoir characterization. Although rock physics analysis indicated discrimination of hydrocarbon bearing zones on log scale but due to lack of frequency in the data, it is not possible to discriminate hydrocarbon bearing zones from the rest. Pre-stack inversion has been carried out to generate P-impedance as well as Vp/Vs volumes of CRAM processed scaled to time PSDM data. Integrating the results of Inversion study with well based geological model brought out sand dispersal pattern and geological trend of deposition in the study area.

In this scenario, where seismic based reservoir characterization is having a lot of uncertainty, a fit-for-purpose workflow was developed to capture the heterogeneity of Malleswaram reservoirs, which is enumerated below:

- Effective Porosity Mapping
- Permeability Modeling
- Hydraulic Unit Approach / Rock Typing

Reliable modeling of Effective Porosity is essential for accurate determination of storage capacity of the reservoir. An integrated analysis of Core derived porosity and log data was carried out to generate continuous Effective porosity (EPOR) log for all wells of Malleswaram Field. To generate core calibrated effective porosity logs, Multi Attribute Non-Linear Regression Analysis employing Alternating Conditional Expectancy Analysis employing Alternating Conditional Expectancy (ACE) have been used. Generated EPOR curves were calibrated with NMR computed porosity.

Classically Permeability modeling is carried out from porosity using:

\[ \ln(k) = a\phi + b \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \quad \text{Eq-1} \]

Where \( k \) is permeability, \( \phi \) is the porosity, \( a \) and \( b \) are the arbitrary constants.

However, this equation is often based on statistically insignificant data sets and lacks theoretical background. Therefore, Non-parametric regression-based approach for permeability modeling instead of classical method using core porosity-core permeability data, was adopted for the purpose of the study (Figure-7).

Figure-7: Workflow adopted for Permeability Modeling

Pore geometry is the prime influencer of fluid flow through porous media. Pore throat attribute is dependent on mineralogy (type, abundance, location) and texture (grain size, grain shape, sorting and packing). Various permutation and combination of these petrophysical and geological properties could lead to determination of distinct hydraulic units that will have similar fluid transport properties.

Hydraulic Unit is the representative portion of the reservoir facies within which the petrophysical and geological properties that governs the fluid movement are internally consistent but different from the other rock facies while comparing on similar properties. HU’s are related to geological facies distribution; but do not necessarily coincide to facies boundaries.

The Rock Typing of reservoir rocks was carried out based on the established methods of reservoir rock
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typing. The prime objective of Rock Typing was to build a simple and robust model that responds to flow and captures both vertical as well as areal reservoir heterogeneity. To achieve this objective, the Winland (R35) method, Capillary Pressure method and Flow Zone Indicator method were used to classify rocks based on their Porosity-Permeability and pore throat radius. Through these methods, four distinct reservoir rock types could be identified in the study area. For enhanced reservoir characterization and identification of the more prospective areas within Nandigama Formation, Reservoir Rock Quality map was prepared (Figure-8).

Figure-8: Reservoir Rock Quality map of Malleswaram Field

Subsurface Modeling

Geo-cellular model is the 3D digital representation of the geology through replicating the structural disposition of the reservoir, reservoir architecture/facies distribution and petrophysical properties. In the study area, the biggest challenge is to build a GCM model which can capture the spatio-temporal facies variation and properly represent field behavior. Workflow adopted to capture uncertainties in reservoir properties and build a robust subsurface model is discussed below (Figure-9) -

Figure-9: Subsurface Modeling Workflow

1. Static Reservoir Modeling:

Integration of geological, geophysical, petrophysical, production and reservoir analyses were carried out to replicate the Seismo-Geological model and build a static geo-cellular model. Zonation and Layering was optimized to balance the tradeoff between capturing reservoir heterogeneity and minimizing dynamic simulation run times.

Facies Modeling: Manually interpreted geological facies were upscaled and used for Facies modeling. As the number of wells were not evenly distributed across the sectors identified. Neither the geological distribution of facies was evenly represented by the wells. Hence, an approach of hierarchical modeling via the sequential indicator simulations (SIS) algorithm was adopted to introduce maximum certainty in the facies modeling as far as possible. Probability density function and Connected volume calculation was used to determine the best model among twenty equi-probable facies models.

Petrophysical Modeling: Porosity, Permeability and V-Clay have been populated throughout the reservoir/model, based on the input data, knowledge of their trends & distributions and the same was performed through Gaussian Random Function Simulation (GRFS) and biased through Facies.

For Saturation modeling, a Core Build Model was generated using core porosity, permeability and stress corrected and re-sampled Pc data through Skelt-Harrison model (This model appears to be having better fit result as compared to Leverett J function and Brooks-Corey model). A best fit Capillary curve was generated for each hydraulic unit. Now using Permeability volume, Effective
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Porosity volume and parameters of Skelt Harrison model, Saturation model was generated using HAFWL as the secondary trend.

Net-to-Gross (NTG) was computed from facies properties by discriminating reservoir versus non-reservoir facies.

II. Dynamic Reservoir Modeling:

The geo-cellular model was used for dynamic reservoir simulation purpose. No upscaling of the static model was carried out, as the GCM was built considering optimization of reservoir simulation run time. Dynamic properties including PVT data, relative permeabilities and capillary pressure curves were used to represent realistic hydrocarbon flow in the reservoir. Additional properties such as active cells, equilibration etc. were generated.

For different reservoir compartments, modified black oil PVT tables were generated from lab analysis of bottom hole fluid samples. With a low-permeability system and gross thickness of ~300 m, variation in PVT properties was expected laterally and vertically. Lab derived relative permeabilities curve were used for determination of Corey exponent for gas, oil and water systems. Capillary pressure curve for each reservoir rock type was assigned, fluid contacts for each compartment was fixed and model was initialized using monthly oil rate as base.

The initialized reservoir simulation model was calibrated by matching more than seven years of historical production. Shut-in bottom hole pressure, flowing bottom hole pressure, Gas Oil Ratio and Water cut were used to calibrate the simulation model. Some global changes were made in the model, to achieve a representative Field level & Well level history match.

Conclusions

In the present study, an attempt has been made to understand the finer scale geological variation within the arenaceous pack of Nandigama Formation. Integrating all Geological, Geophysical, Petrophysical data with Reservoir data and employing 5 stages of analysis, a new Geological Model is brought out where entire Synrift pack of Malleswaram Field is divided into five vertical units and nine fault bound sectors. Each unit represents a distinct geological setup and each sector is characterized by its distinct reservoir behavior. Non-parametric regression-based approach for permeability modeling, Reservoir rock typing and incorporation of hydraulic flow units using FZI approach resulted in enhanced reservoir characterization. Mapping results of rock typing in form of Reservoir Rock Quality Map, lead to establishment of presence & continuity of high-quality speed zones, baffles and seals throughout the field.

Integration of all these studies through hierarchical modeling-based approach resulted in manifestation of a high resolution, robust Geo-Cellular model which is able to capture log scale heterogeneity. History matched reservoir simulation model demonstrated significant upside potential for the field which needs to be tapped with phase wise development plan. This model would be helpful in taking strategic decisions like course, spacing & placement of future wells; HF design; deployment of different technologies for sustainable and economically viable oil production.

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