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An integrated approach for understanding flow behavior to improve predictive capabilities of a reservoir model – a case study

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Abstract

Carbonate reservoirs, world over, are highly heterogeneous with varying degree of heterogeneities which causes variations in areal as well as vertical fluid movements within the reservoir. Understanding of the fluid movement is of prime importance for efficient reservoir management. Characterization of a carbonate reservoir with complex heterogeneity and building a reservoir model honoring both the static and dynamic data for the purposes of history matching and future prediction is a big challenge. The common practice to build a model, based on the static data and introduction of changes during history match, most often, has low predictive capabilities. Often in the brown fields, a large amount of static and dynamic data in terms of logs, core, production and pressure is available. Integration of this dynamic and static data for reservoir characterization at the initial stage help to identify and understand geological and geophysical uncertainties, vertical flow barriers, in-homogeneities, interlayer communication, nature of seismic picked faults and existence of flow barriers in the field. Similarly, in the brown fields under extensive and prolonged water flood, studying the varying level of interaction of producer-injector pairs in the field integrated with static properties gives very useful insight into the reservoir heterogeneity, fluid movement, identification of high permeable streaks and the likely pathways of water flood. This approach of integrated analysis of static and dynamic data in building reservoir model help minimizing the adhoc changes attempted during history match and thereby increasing the predictive capabilities of the model.

The paper describes the approach of understanding the complexities of a giant carbonate field by analysing the petrophysical, SCAL, pressure-production data and interaction of producer-injector pairs in an integrated way for reservoir characterisation and applying the findings for building the static models. This paper shows how this process was applied to a giant carbonate field, discussing the various processes and actions that had to be undertaken to reconcile the dynamic behaviour of wells in the simulation model, with the underlying uncertainties inherent in the construction of the geological model.

Introduction

The purpose of reservoir simulation model is to predict the future performance of the reservoir under different development and production strategies. For a reliable model, it is important to understand and describe the dynamic behavior of a hydrocarbon reservoir by properly integrating all the available geological, geophysical, petrophysical and engineering information generated over the period of time. Often a large amount of information is available in the mature fields in terms of logs, core, production-injection, pressure, level of interaction of producer-injector pairs, vertical flow barriers, in-homogeneities, interlayer communication, etc. The paper describes the building of reservoir modelfor Mumbai High South Field, one of the giant offshore fields of India, by integrating the static and dynamic data to represent the structural and petrophysical properties of the hydrocarbon-bearing formation and to describe the fluid dynamics taking place within the reservoir.

Mumbai High field is the largest producing oil field in Indian subcontinent. The reservoir is about 70km long and 25km wide, found at a water depth of about 75-80 m. It is a gentle westward dipping anticline bounded by a major fault trending NNW-SSE along the eastern margins of the field. A WSW-ENE trending graben divides Mumbai high Field into Mumbai high North and Mumbai High South two non-communicating fields. There are several hydrocarbon bearing reservoirs and among that the limestone layer L-III is the most prominent hydrocarbon bearing layer in both Mumbai High North and Mumbai High South fields. The L-III reservoir of Mumbai High South (MHS) was put on production in 1980 and water injection was initiated in 1987 as a measure for pressure maintenance and sweeping oil.

Since, it is a brown field and is under extensive and prolonged water flood, studying the varying level of interaction of producer-injector pairs in the field integrated with static properties gives very useful insight into the reservoir heterogeneity, fluid movement, identification of high permeable streaks and the likely pathways of water flood. The common practice to build a model, based on the static data and introduction of changes during history match, most often, has low predictive capabilities. However, this integrated approach in building reservoir model has resulted in minimizing the adhoc changes during history match and thereby increasing the predictive capabilities of the model. The paper describes the various processes and actions that had to be undertaken to reconcile the dynamic behaviour of wells in the simulation model, with the underlying uncertainties inherent in the construction of the geological model.

L-III reservoir

The L-III reservoir is a heterogeneous, multilayered carbonate reservoir interbeded by thin shale bands and argillaceous limestone. The layers have been designated as A1, A2-I, A2-II, A2-III, A2-IV, A2-V, A2-VI and A2-VII, B, C and D. The reservoir sub-layers, even though locally separated by intervening nonreservoir layers, are in communication with each other in some or other places, giving rise to a single hydrodynamic system. All these layers are having wide variations in properties resulting in highly heterogeneous reservoirs. The porosity ranges from 11% to 29% across the layers but there are wide variations in permeabilities. It is very difficult to draw a uniform direct correlation between porosity and permeability. The reservoir is characterized by intra-layer and inter-layer inhomogeneity. The level of inhomogeneity is reflected through the performance of the wells developed in different layers in different parts of the field. Such a high level of heterogeneity coupled with the areal extent of the field makes the L-III reservoir of Mumbai High South a very complex reservoir.

Static model

The static model was built in two main steps, structural modeling and property modeling. Initially, the structural modeling was performed to set up the 3D static model framework. The second step, the property modeling, includes the propagation of reservoir properties in the 3D static frame work including porosity, permeability and water saturation. The 3D seismic data was used for horizon and fault interpretations. The Electro-log correlation was carried out to identify the thin carbonate reservoir sub layers and intervening thin shale/ shaly limestone layers developed in reservoir. This was the basis for creating a consistent stratigraphic and structural framework of the field. Petrophysical properties of effective porosity and volume of clay, interpreted from well logs were populated in the 3D frame work using appropriate algorithm. The initial Saturation has been built using height function and permeability was calculated using Timur equation.

To understand depositional and diagenetic model, log character and role of fractures, a detailed core study was carried out. The study indicated that the producing units in the reservoir form extensive, laterally continuous deposits with minimal vertical relief within two meters. Dolomitization is rare. Moldic, intercrystalline, micro-moldic, and micro-crystalline types of porosity account for more than 90% of the total porosity. Lesser amounts of vuggy porosity were observed and very minor amounts of intraparticle porosity were also observed; fracture porosity was very rare. In all 0.06 fractures per meter were observed ruling out the reservoir as a fractured reservoir.

Integration with dynamic data

The basis of integrating the static properties with the numerous dynamic data acquired over the production period is to look into the field in totality. However, study is conducted to establish the fields within field. This is precisely known as compartmentalization with flow barriers.For this purpose, understanding lateral and vertical in-homogeneity is of utmost importance for which various analyses were carried out.

Property Variation Trend and Well Performance

Variations in properties across the reservoir were validated with actual well performance. Areal trend of various properties maps viz. porosity, effective thickness, permeability, facies, etc. were generated using the well level petrophysical and seismic inversion data and studied at individual sub-layer level. Based on overall analysis, four facies types (Fig.1) - one for non-reservoir and three for reservoir based on transmissibility (kh) were generated to assess the compartmentalization based on faults or otherwise. In case of compartmentalization, there should be sudden areal discontinuity, which is not observed in this reservoir. The variation in properties is found to be gradual in the field.

The layerwise facies variations were qualitatively validated with the well performance (Fig.2). To assess relation of facies to well performance the peak liquid rate of twelve months moving average values was considered. The twelve months moving average waschosen to avoid spikes of sharp decline in liquid production as observed in some of the horizontal wells especially thin layers. Prominent producing layers viz. A1, A2-IV, A2-VII, B and C, having good number of wells completed exclusively were selected for validation. The trends observed in facies variation were also reflected through well performances across the faults.

Faults Sealability and Tracer Surveys

Fault seal analysis was carried out to know the role of faults in the fluid dynamics. From a geological point of view the faults are characterized by low potential (membrane) seal properties, and should break down easily under production conditions. From a juxtaposition standpoint, the high net-to-gross reservoir series allow minimum opportunity for shale-on-limestone juxtaposition from the laterally extensive shale layers. Faults may be sealing mainlyeither due to juxtaposition of impermeable bed against the permeable bed across the fault and or formation of shale gouge smear in the fault plane. In L-III reservoir of MHS, the shale layers are very thin compared to the limestone layers. As the thin shale layer cannot effectively mask the thick limestone across the fault (Fig.3), the chances of sealing faults due to shale juxtaposition against limestone areminimal. Shale gouge smear, a fine clay material formed during faulting, can create an impermeable barrier along the fault plane. However, it requires about 50% clay in the adjacent beds to become an effective barrier. In MHS L-III reservoir the average clay volume is 16-17% only. According to the statistics it can make a smear of about 10-20 psi strength, which can easily be broken during production. This non sealing nature of faults was further validated by the results of tracer survey carried out in the field over the period of time wherein tracer breakthrough was observed across the faults (Fig.4). In addition, the shale gouge smear analysis along with the tracer surveys (though limited) indicates that the possibility of faults acting as areal barrier in L-III, MHS is negligible.

Producer-Injector Correlation and Waterflood Fairways

In the brown field under waterflood the liquid production data series of producers is often correlatable to the water injection data series of injectors. A set of correlation coefficient can be generated for the producers with respect to injection. A positive correlation coefficient indicates producers experiencing impact of water injection while a negative correlation indicates producers with no significant impact from water injection. A map generated based on these correlation coefficient can serve as a guiding tool for understanding the likely fairways of water flood and identifying the areas lacking water injection support. Availability of large amount of production – injection data over a long period in a brown field come very handy for carrying out such an analysis. A normalized correlation coefficient map thus generated for L-III, MHS (Fig.5) indicates the likely fairways (correlation between 0.5 - 1) and areas lacking water injection (correlation between 0 - 0.5). The findings have been validated with the subsequent recording of pressure data. Higher pressure values have been measured at the producers falling along the fairways (high correlation areas) while relatively lower values have been found at producers falling in low correlation areas.

The analysis indicates occurrence of fairways across the faults and non compartmentalization of water flood to a particular area rather water flood follows facies variation, indicating absence of dynamic compartmentalization.

These analyses clearly indicate the absence of any significant lateral compartmentalization and suggest that the lateral inhomogeneity in the field arises from facies variation which directly impacts the dynamics of the field both in terms of well productivity and flood movement (Fig.6). Therefore the understanding of layerwise heterogeneity in terms of facies variation is important for the success of field development and waterflood strategy.

Vertical Compartmentalization Analysis

The sublayers of L-III reservoir are separated by thin shale or shaly limestone layers, which act as vertical flow barrier. However, these flow barriers are discontinuous laterally and give way to vertical windows at various places. The analysis of the MDT / RFT pressure data recorded across the shale layers in a well can give a fair idea on the dynamic behavior of these shale barriers. A similar pressure dynamic must exist across the shale layers if it gives way to the vertical window while different pressure dynamic would exist across shale layer ifit is prominent enough. The large amount of MDT / RFT pressure data acquired over field history against the respective sublayers have been used for understanding dynamics across the intervening shale layers. The RFT / MDT pressure data of the individual layers are plotted as separate point series. Had the layers been in good communication throughout the field establishing a perfect single hydrodynamic system, all layers would have followed the uniform and parallel pressure depletion trend. Also the pressure of deeper layers must have been more than that of shallower layers at all times. However, it is seen that the depletion trend of various layers cross each other at different times. This indicates the presence of variability in vertical connectivity amongst the sublayers.

A closer examination of the MDT / RFT pressure variation alongwith the well log at well level further strengthens thisunderstanding on vertical connectivity. A comparison of the pressure depletion from initial field pressure in various sublayers indicates similar pressure depletion wherever poor intervening shale barrier exists and vice versa.Integration of the MDT / RFT pressure data of various wells with shale layer properties indicate the variation in inter-layer pressure dynamic across the field, though happening differently at different places. The analysis indicates that L-III reservoir of MHS acts as a single hydrodynamic system though with localized vertical baffles arising from inter-layer shale barrier. The understanding of these vertical baffles has been of great help in fine tuning the water injection in multilayers commingled water injection.

Dynamic model

The geological model, having fine grids (340x661x283), was upscaled to coarser grids for dynamic simulation purposes. Although the more detailed the model, the most accurate the description of fluid flow phenomena but to achieve a balancebetweenaccuracy andspeed of computation, a coarser model having166x192x14 cells with grid size of 250mx250m was constructed. Accordingly, all the properties were also upscaled to the coarse grids.With this model, simulation studies were carried out using reservoir simulator, Eclipse using three phase-3D fully implicit model. The reservoir was sub divided into several equilibrium regions representing each sub layer. It was defined in a fashion to facilitate different OWC but common GOC. It was represented by using different threshold water oil capillary pressure for each sub layer with commonfree water level (FWL). The analysis of dynamic data has indicated vertical communication between sub layers as the shale is missing at some place or other in the field. The GOC, common for all sub layers, as observed on logs, was defined at 1330m and a common FWL for these layers was considered at 1460m. There were wide variations in OWC. The deepest OWC was observed for the upper most layer A1 and shallowest for the deeper layers.

The upscaled model was having 14 layers representing the 11 sublayers (A1, A2-I, A2-II, A2-III, A2-IV, A2-V, A2-VI, A2VII, N, B and C layers. The model was tested for equilibration by allowing it to run for several years without opening any well for production. The model confirmed the capillary gravity equilibrium in different layers as there was no interlayer fluid flow. The model was run on reservoir volume mode to assess the level of aquifer support. The pressure variations with observed RFT pressures indicated partial edge water support from west and South. The movement of water from western edge has also been confirmed by the salinity of produced water from western peripheral wells which was close to formation water. All subsequent history match runs were carried out on oil rate control. The direction of injection water movement with time in the model was tied up with the observed injection-production wells interaction and where-ever there was noticeable difference flow properties were modified accordingly in static model and the same was again converted to dynamic model. This process of going back from dynamic to static and vice versa was repeated till the observed movement of fluid was reasonably captured in dynamic model. Beside, to capture the water cut trends as observed in the field, oil water pseudo relative permeability curves were also used along with conventional ones. Standard parameters like rate, pressure, GOR and Water cut were taken as history match parameters. Field level, Platform level and well level water cut and GOR match was attempted in history match by tuning layer wise transmissibility, interlayer communications and permeability as per the actual performance. This model is being used for management and development of the reservoir with increasing understanding of the flow behaviour in various parts of the field and predictions in terms of infill wells and other reservoir management measures are most often in close agreement withactual performance of the field.

Conclusions

The integrated approach of building static and dynamic models of a mature field under water flood and having large amount of data both static and dynamic available,helped not only in characterizing the carbonate reservoir in terms of static properties but also in understanding the fluid flow dynamics in the field. This has resulted in a dynamic model with comparatively better predictive capabilities for identifying inputs for better reservoir management and improving the recovery. The study indicated that

- Permeability modeling has been challenging for L-III reservoir. After various attempts to correlate with facies and SCAL data, Timur correlation was used for calculating the permeability and modified for each layer based on actual well behaviour. Later during history match minor modifications were again used in certain areas to capture well behavior.
- There are no discernible lateral or vertical compartments in L-III reservoir of MHS. The L-III constitute as a single dynamic system, though local baffles exist at places. The variation in the lateral and vertical connectivity exists due to variation of facies and interlayer shale properties respectively.
- The waterflood pathways are largely governed by the facies variation but no correlation could be drawn for generating permeability.
- Understanding these behaviour helped in incorporating the properties suitably to make the model fit for the purpose.
- The model was capable of identifying the areas for infill drilling and improves water injection with a good degree of confidence as proved by the performance of recent infill wells and side-tracking of poor producers.

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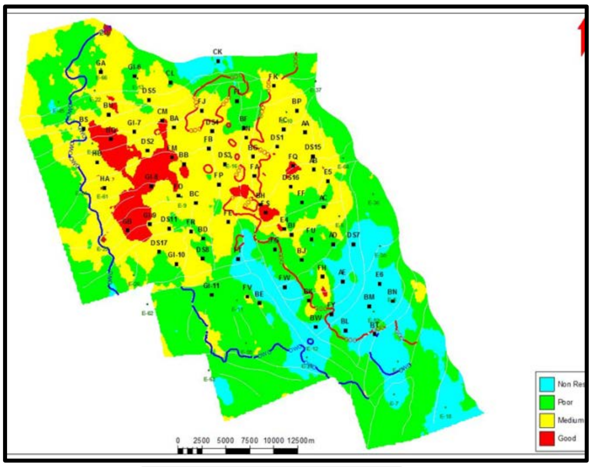

Fig.-1: Facies Map

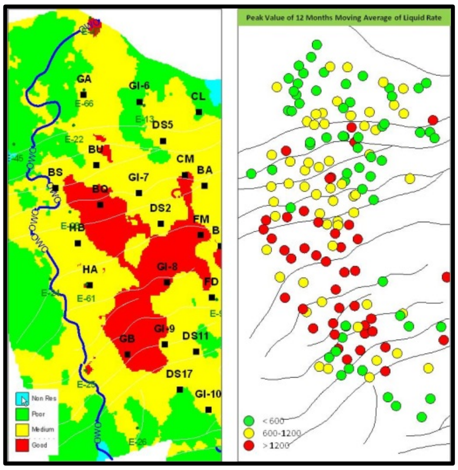

Fig.-2: Facies Map Validation with performance

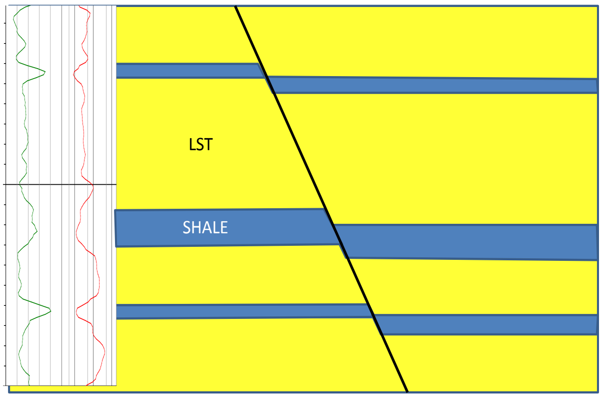

Fig.-3: Typical Shale Juxtaposition across fault

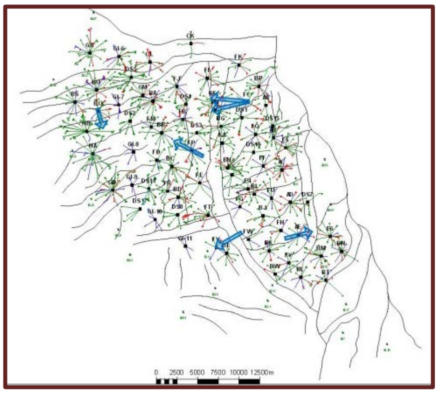

Fig.-4: Tracer Movement across Faults

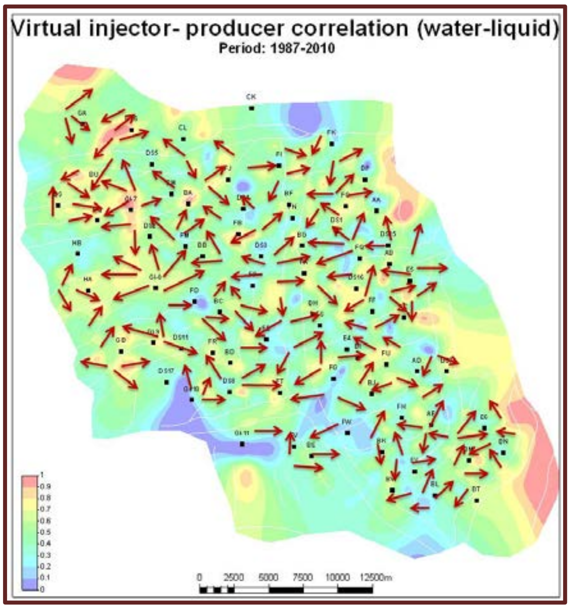

Fig.-5: Injection-Production Correlation Map

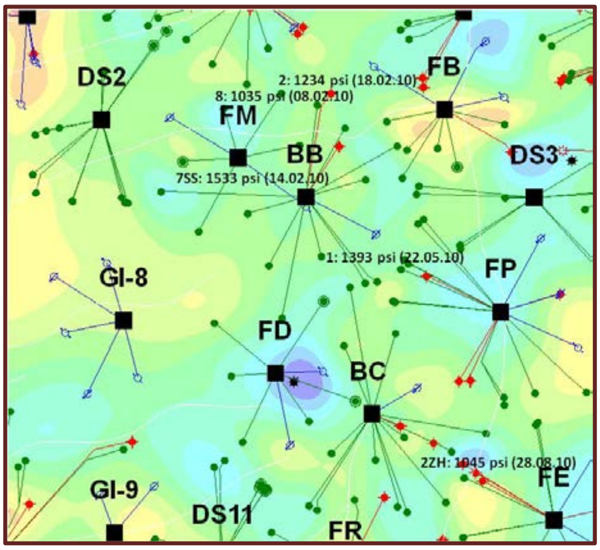

Fig.-6: Correlation Validation with recorded Pressure