# Play based exploration of Mandhali pay in Linch & Sobhasan Complex field (Cambay Basin) – A Petrophysical perspective

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**Keywords**

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**Abstract**

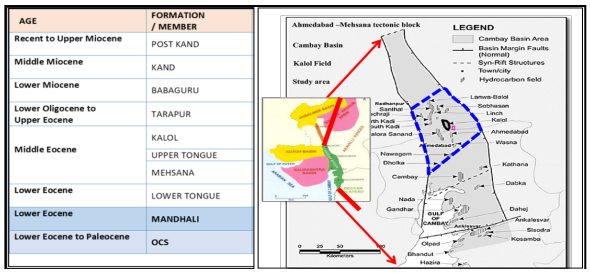
Every formation is different due to its depositional condition and time, thus complexities associated with their identification, evaluation and production are also unique. Development and consolidation of each pay requires thorough attention for maximizing exploitation. Some of the established pays, need revisit through advanced technologies for identifying new zones that may have been missed out previously (missed opportunities). Play based exploration can give success in exploration and exploitation of such complex reservoirs.

Kalol and Mehsana sands are prolific producers in Cambay Basin, but Mandhali pays sands developed above Older Cambay shale (OCS) section are also potential hydrocarbon reservoirs. Pay sands are characterized by low effective porosity & high shaliness from conventional petrophysical analysis. They have also been observed to have low free fluid porosity and low to moderate permeability from the analysis of Nuclear magnetic resonance logs. Due to their poor to fair petro-physical properties, limited success has been achieved in production.

Identification, proper evaluation and optimum production are challenging for Mandhali formation. To overcome these complexities, comprehensive evaluation of these pays has been carried out. Facies analysis (both electro and reservoir) indicates moderate reservoir facies in abundance. Depositional environment give understating of reservoir extension and prospective area for exploration and exploitation. Saturation height modelling provides realistic saturation estimation in low resistivity sands. Rock physics modelling is developed for the prediction of Compressional and Shear velocity along with density logs. Predicted compressional and shear velocity from rock physics modelling can be directly used for effective HF design through Geomechanical study to improve productivity of low permeability and tight reservoirs of Mandhali formation in Linch and Sobhasan complex area of Cambay Basin. These approaches together brought out true potential of complex pay sands and consolidation of pays effectively.

## Introduction

Kalol and Mehsana sands are prolific producers in Cambay Basin, but Mandhali pays sands developed above Older Cambay shale (OCS) section are also potential hydrocarbon reservoirs. Pay sands are characterized by low effective porosity & high shaliness from conventional petrophysical analysis. They have also been observed to have low free fluid porosity and low to moderate permeability from the analysis of Nuclear magnetic resonance logs. Due to their poor to fair petro-physical properties, limited success has been achieved in production. These reservoirs require proper characterization and hydro-fracturing for optimum production. Play based exploration can give success in exploration and exploitation of such complex reservoirs. The generalized stratigraphy of Ahmedabad-Mehsana tectonic block of Cambay Basin is appended below:



| AGE | FORMATION / MEMBER |
|---|---|
| Recent to Upper Miocene | POST KAND |
| Middle Miocene | KAND |
| Lower Miocene | BABAGURU |
| Lower Oligocene to Upper Eocene | TARAPUR |
| Middle Eocene | KALOL |
| | UPPER TONGUE |
| | MEHSANA |
| Lower Eocene | LOWER TONGUE |
| Lower Eocene | MANDHALI |
| Lower Eocene to Paleocene | OCS |



Figure-1: Generalized stratigraphy of Cambay Basin And location of study area

We generally carried out the projects broadly for integrated Petrophysical Reservoir characterization utilizing lab and high-tech log data along with all vintage data, Developing work flows/methodologies for Unconventional Reservoir Evaluation, Geomechanical modelling. It also takes up projects for bringing out depositional environment components, reservoir geometry, facies distribution, rock physics modelling based reservoir, fluid characterization by integrating all the Geological and Petrophysical inputs. Petrophysics perceives its role in PBE processes as Play developer, play consolidation and play opener as follows (Fig-2):

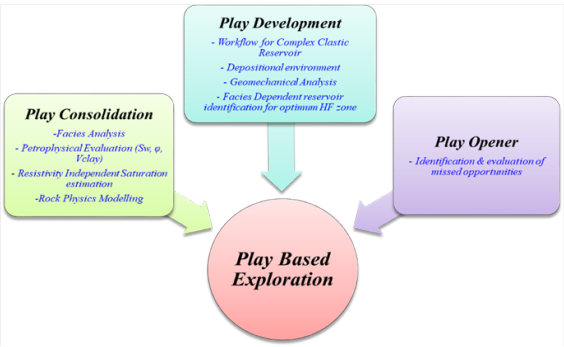



Figure-1: Play Based Exploration for Mandhali Formation (Petrophysical perspective)

**Play developer**:
Identifying the required technology for evaluation, Depositional Environment, developing new work flows for interpretation of complex clastic carbonate reservoirs, thin bed reservoirs, Geomechanical interpretation for facilitating smooth drilling and completion.

**Play consolidation**:
Micro Depositional environment, Higher order Sequence stratigraphy, Reservoir characterization with advanced methodologies (facies, image, RPM), carrying out required lab studies and standardizations, developing facies-based interpretation models, data analytics for reservoir property mapping and prediction, Reservoir monitoring, procuring and establishing new lab hardware and software resources.

**Play opener**:
Evaluating subtle Petrophysical responses, re-looking for missed opportunities, interpreting vintage data, data analytics for predictions.

**Study approach and Discussions:**

The present study focusses on Play based exploration of Mandhali pays of Linch field and Sobhasan complex area, which are members of Younger Cambay shale (YCS). For this study, facies classification (rock type) is identified using 86 core samples from 16 wells. Saturation height modelling (SHM) and Rock physics modelling (RPM) were carried out in 35 and 32 wells of Linch and Sobhasan complex area. Depositional environment and Geomechanical study were attempted in 7 and 5 wells respectively. After studying several evaluation approaches for complex reservoirs, play base exploration proved effective in Mandhali formation of Linch and Sobhasan complex area.

Different Methodologies are briefly discussed below, which are the petrophysics solution for the evaluation of complex Mandhali formation of Linch and Sobhasan complex area.

**1. Reservoir extension and Prospective area-Depositional environment**

Sand Geometry and Depositional Environment of Mandhali member of Linch Field with advance log (Resistivity image data) study have been carried out to understand depositional channel system, sand dispersal pattern (deciphering the paleo-current/sand transport direction/ channel axis etc.) and sand extension regimes within fault block. Dip pattern from processed data & Image patterns from FMI data are used for inferring structural and textural details of the sand units calibrating with available cores & FMI logs.

The paleo-environment of deposition for Mandhali sands in Deltaic set-up, were have been mostly inferred as Distributary Channel fills, Distributary Front deposits/Mouth bars and at times Distributary Mouth bars cut by Scour Channel/Distributary Channels (Fig-3).; of course, at most levels it is stacked or amalgamated micro-environments in succession.

The consistent blue pattern towards south east observed in the Mandhali section indicates the sediment transport due SE. At bottom of Mandhali (mostly in MP-IV and below), paleo-current is seen to be towards ENE or NE (which agrees more with that in OCS).

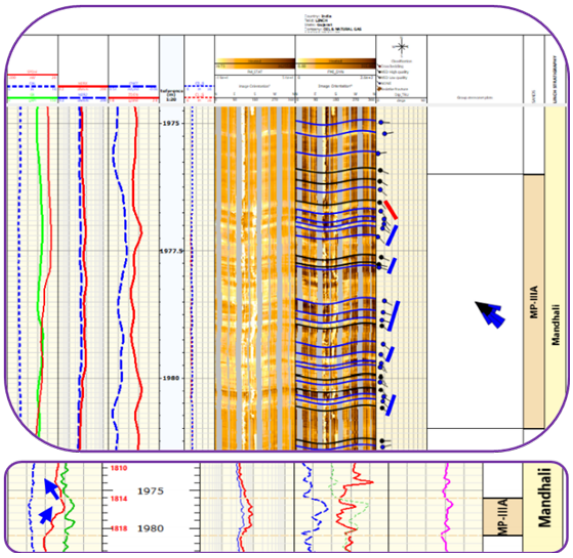



Figure-3: Dip pattern from FMI log

Depositional features such as cross bedding, herringbone structures, yellow dips and sediment transport direction due NE observed towards the bottom of the Mandhali is inferred to be transition of depositional environment from deltaic to shallow marine.

Integrating the sand geometry patterns of the sand units with Seismic data will help in better identification of prospective areas for exploration / exploitation and thereby reserve accretion.

**2.Porosity/permeability/mineralogical complexity-Core study**

Cores studies were carried out in 16 wells of Sobhasan Complex by RGL Vadodara for determination of Petrophysical parameters Porosity, Permeability, Grain density & XRD mineralogy. XRD study is showing the presence of Quartz, feldspar, Siderite and Mica in Mandhali formation. Dominant clay minerals are Kaolinite and Chlorite. Which is used for the establishing the petrophysical model. Core Porosity, permeability and Saturation data have been used for calibration of Petrophysical model derived porosity, Permeability and saturation.

**3. Reservoir quality- varying k and phi- Reservoir facies analysis**

Facies classification is identified using 86 core sample of Mandhali formation from 16 wells. Based on plot of PORO-PERM, RQI vs PHIZ & DRT- FZI, it is observed that there are 10 trends in porosity, permeability plot which indicate 10 types of facies variation (reservoir and non-reservoir) in clastic rock facies in the Sobhasan complex area (Fig-4).

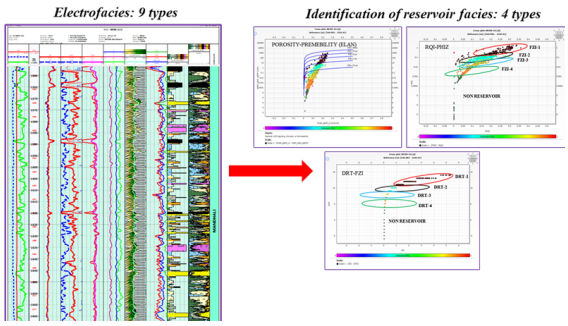



Figure-4: Electro facies and reservoir facies analysis

Based on log-log cross plotting of RQI {Reservoir Quality Index = 0.0314sqrt (KINT/PIGN)} vs NPI {Normalized Porosity Index = PIGN/(1-PIGN)} for the wells of Sobhasan complex, total four types of reservoir rock facies and rest of other non-reservoir facies have been differentiated (Fig-4). Reservoir facies brought out by facies modelling can lead to identify suitable hydro-fracturing zones.

**4. Lithology and fluid identification-Rock physics modelling**

A workflow of rock physics modelling is developed for the prediction of Compressional and Shear velocity along with density logs. Inclusion theory-based Xu-White rock physics model has been applied successfully for prediction of elastic properties (Vp, Vs, density, Vp/Vs, P-imp) in the wells across Sobhasan complex area. Predicted compressional and

shear velocity from rock physics modelling can be directly used for effective HF design through Geomechanical study to improve productivity of low permeability and tight reservoirs of Mandhali formation.

Rock Physics Modelling is able to differentiate different litho-facies as well as fluid type (hydrocarbon-bearing reservoir, water, coal and shale) on rock physics templates (Fig-5).

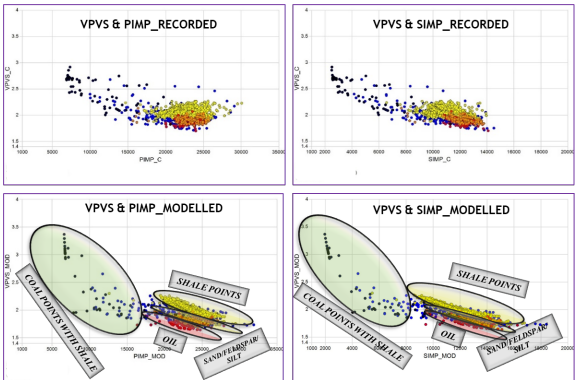



Figure-5: Rock physics modelling template

As recorded compressional and shear slowness data is only sparsely available in the study area and that too available data is prone to be affected by the near borehole environment; estimation/prediction of compressional and shear velocities in all the wells is critically important for Seismic modelling as well as effective designing of hydro-fracturing. Thus, the study of rock physics modelling aids in taking measures to improve the productivity of low permeability and tight reservoirs of Mandhali formation.

**5. Saturation estimation- Saturation height modelling (Resistivity independent saturation)**

A workflow is developed integrating conventional logs and lab studies on core plugs for realistic estimation of net pay & water saturation with resistivity independent saturation method. Saturation height modelling workflow as follows:

1-Generation of Electro-facies with advanced statistical algorithms viz. Self-organizing Map (SOM) and mapping them with corresponding core derived reservoir facies with specific poro-perm relationship are the initial components of the methodology.

2. The continuous permeability curve was generated using individual poro-perm relationships for the identified facies and is correlated with NMR derived permeability and core measured permeability.

3. The advanced capillary measurements on cores are further modelled and regressed for deriving the constants in the selected facies and absorbed them in the considered saturation height function.

4. Finally, resistivity independent water saturation was estimated using saturation height modelling workflow (Fig-6).

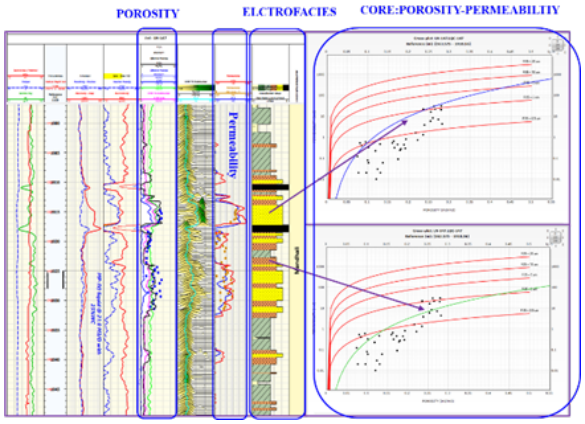



Figure-6: Poro-perm relationships for Res facies

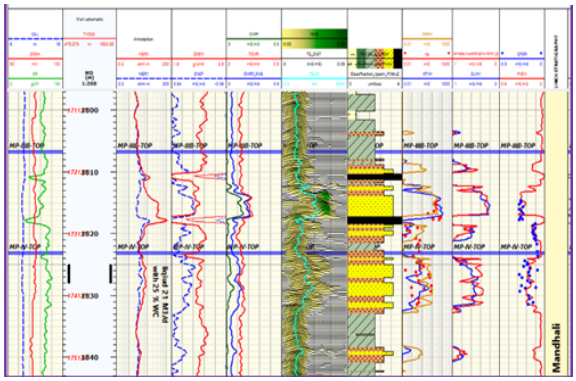



Figure-7: Saturation estimation using Saturation height modelling

Saturation height modelling appears to provide more representative reservoir parameters where probabilistic multi-mineral evaluation does not provide solutions due to affected resistivity measurement especially in MP-III & MP-IV pays agreement with that of conventional methods against the clean HC bearing layers validating the adopted work flow (Fig-7).

**6. Production improvement- H.F design input from Geomechanics**

Low permeability tight reservoirs developed in Mandhali member have limited production success. These tight reservoirs need extra input for hydro fracturing because of low porosity, permeability and silty nature. For this we estimated effective hydro-fracturing parameter from Geomechanical studies. From Geomechanical studies we estimated HF parameter for well-X. In Mandhali Pay, pore pressure ranges in 2460-3000 psi (gradient 0.44-0.49 psi/ft). The closure pressure in Mandhali section is approximately 3500-4150 psi (0.66-0.74 psi/ft). Rock compressive strength in Mandhali pay is around 2300-2800 psi & Young's modulus ranges from 0.5-1.0 Mpsi and Direction of Maximum Horizontal Stress is 170-180o N.

These HF parameters will help in improve production from low permeable tight Mandhali sands.

**Conclusion:**

After studying several evaluation approaches for complex reservoirs, play base exploration proved effective in Mandhali formation, thus an integrated study that involves petrophysical evaluation, core study, Saturation height modelling, depositional environment, Rock physics modelling, geomechanical study and facies analysis can provide better understanding of reservoir complexities and enhance producibility of Mandhali sands in Linch and Sobhasan complex area of Cambay Basin.

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