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Integrated Facies Modeling of fluvio-deltaic environment using seismic attributes and analogue training image

Abstract

The Saurashtra-Dahanu block is situated to the north of Bombay Platform, south west of Tapti-Daman area and east of Saurashtra depression. It has an area of 2500 sq. km. with B-9 field in the north-western part with drilled wells. The sedimentary fill in the drilled wells range from 3000 to 4400m. The basin consists of sediments from Palaeocene to Recent and overpressures have been encountered within Eocene, Early Oligocene, Late Oligocene and Early Miocene respectively (Nambiar et. al., 2010).

The B-9 structure is a north east-southwest trending inversion structure formed due to reactivation of north east- south west trending fault. However, the intensity of the structural strain is more pronounced in the eastern part, where wells A, B & C are drilled, as compared to western part.

The Panna formation of Palaeocene to Early Eocene with mainly Type- III and Type-II organic matter is the dominant source rock unit. Hydrocarbon accumulation is proved within sands of Daman Formation of Late Oligocene age and Mahuva carbonates of Early Oligocene age. The migration is through deep seated faults whereas shales provide effective top seals.

A 3D geological model for this field was built by integrating geophysical, geological, petrophysical and reservoir engineering data and interpretation. The 3D framework of this model was built using the domain converted seismic marker horizons tied up with well markers and the faults interpreted from seismic and well data. A vertical zonation of the model was made after studying the upscaled logs vertical resolution for the target Daman and Mahuva reservoirs.

A hierarchical approach of property modeling was followed in which facies was populated using MPS algorithm and modern-day tide dominated delta systems as analogues. Effective porosity was populated with trend from seismic attributes and conditioned to facies model. After population of porosity, water saturation was modeled using a height based function derived for gas.

Introduction

Tapti-Daman fields lie within the Surat Depression, a broad depocenter of Tertiary age clastic sedimentation in the North-eastern portion of the Bombay Offshore Basin. The Tapti-Daman block (Figure 1a) is a predominantly clastic sub-basin of the Bombay Offshore basin. The basin is moderately well explored up to the Oligocene level with most of the discoveries being predominantly gas. The Tapti – Daman block consists of Tertiary clastics from Palaeocene to Recent.

Hydrocarbon accumulations have been found in the Daman and Mahuva sands of Oligocene which form the equivalent to Heera and Mukta formations in the nearby Mumbai High Block and Dadar sandstones in the South Cambay Basin. The major challenge in terms of reservoir characterisation is the definition of a feasible Field Development Plan in the face of scarce well data availability. Thus, a combination of trend maps from seismic conditioned with regional geological understanding and present-day analogues were used to create a viable model in which multiple uncertainty scenarios could be explored.

General Geology and Stratigraphy

The wells of the B9 block encounter sediments from Late Oligocene (Mahuva Formation) to Late Pleistocene (Chinchini Formation) with the major reservoir sands being the Daman and Mahuva formations in the Oligocene. These form equivalents to the Heera and Mukta formations in the nearby Mumbai High Block and Dadar sandstones in the South Cambay basin as shown in Figure 1b. The tectonic history of Saurashtra Block suggests a shift from the shallow marine limestone deposits (Panna equivalent) to fluvio-deltaic environment in the Late Cretaceous. Daman and Mahuva formations in detail were discussed next as they form the main reservoir pay sands in this basin.

Figure 1: a) Structural Elements of the Mumbai Offshore Basin (from Pandey and others,2013) b) Generalized stratigraphy of the Bombay-Cambay-Kutch area (modified from Mishra and others, 1997; ONGC, 1983; Biswas and others, 1982)

The Lower Oligocene Mahuva Formation unconformably overlies the Diu Formation and is subdivided into two units; the lower unit is represented mainly by thick, monotonous shale with occasional development of limestone. The upper unit is represented by thick shale with interbedded sandstone, siltstone and limestones. The Mahuva Formation is unconformably overlain by Daman Formation of Upper Oligocene age (Zutshi et al. 1993). The Mahuva formation is marked by episodes of marine transgressive and regressive phases leading to alternation of limestone carbonate facies with fluvio-deltaic clastic environment. The Upper Oligocene Daman Formation is characterized by a rapid decrease in the sea level wherein the Surat Depression witnessed reduced subsidence resulting in a regressive coastline. A package consisting of sand bodies deposited in distributary channels, coastal bars, tidal deltas and other transitional environments encased in marginal marine normally pressured silty and carbonaceous shale overlying prodelta clay stone of Early Oligocene. The primary sediment flow direction in the basin being in the NE-SW, the Surat Depression especially the Daman low where the B9 field is located, experienced heavy clastic influx characterized by sub-aqueous prodelta sand packages and shales in the distal part transitioning into off shelf carbonates formed in shallow marine conditions towards further SW, away from the influence of the delta deposits

Conceptual Sand Distribution Model

As a part of understanding the sand continuity to be expected in this case, a study of the different tide dominated delta systems currently in the world was done by superimposing the scaled field boundary on the current delta front/prodelta sediments with the direction of the river flow oriented towards the expected flow of the Tapti river in late Oligocene. The Tapti river system is still active today with a prominent sub-aqueous prodelta deposit visible from Landsat Imagery (Figure 2). The actual field boundary and an estimated field location in late Oligocene based on the conceptual geological information is shown at the transition between the sand and shale facies.

Figure 2: Landsat imagery of Present day Tapti Daman Delta with approximate sand limit shown

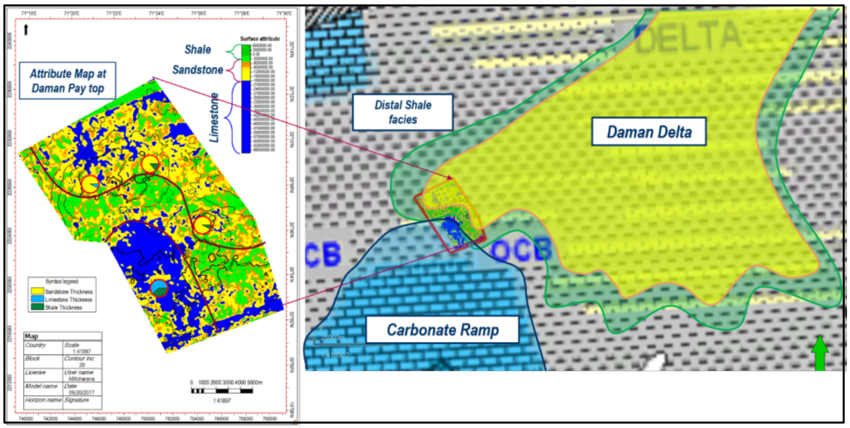

Figure 3: Conceptual Training image model created on the basis of well data, regional geology and seismic attribute study (modified from DGH, NDR archives)

Available literature studies provide us with some sand distribution maps based on other well information in the region. Also, Vp Vs and S Impedance RMS maps were made available from existing literature (Singh, B.K et al., 2013). These maps were georeferenced in the project with the available wells and conceptual model was validated with the geometry in these maps. A combination of the available seismic attributes and the conceptual model was used to create a conceptual training image model shown in Figure 3. This sand distribution model forms the base for our 3D training image model used as an input for the Facies Modeling Process.

Methodology

The aim of static geocellular model is to integrate multi-scale data and interpretations available from different disciplines. The model captures necessary structural complexity, associated sedimentary fill sequences, and evaluation of lateral and vertical continuity of hydrocarbon bearing reservoirs. This section describes the methodology and results of static reservoir modeling for the reservoir section only i.e. Daman Reservoir. The 3D geological modeling process involves structural modeling, 3D stratigraphic grid modeling, reservoir facies and property modeling.

The main pay zones in Daman and Mahuva are all less than 5m thick and thus below the seismic resolution. As we have 3 wells with prominent pay markers equidistant from each other (~5 km apart) an isochore was built honouring the well data as well as the conceptual model which dictates that towards the South-West there is a pinch out of the sands transitioning into shallow marine limestone facies as shown in Figure 3. Thus, keeping this in mind, the seismic interpretation was executed with the nearest correlatable reflector near the well based Daman Pay Sand 1. The bottom of the pay zone was marked in the wells and an isochore was computed with the well data.

Property Modeling

The objective of the study is to build a comprehensive 3D reservoir model that truly simulates the heterogeneities that are encountered in the wells. In this respect, the aim of static reservoir modeling is to integrate the relevant data spanning from core to conceptual geological model, into a coherent and meaningful reservoir description for the Daman reservoir & upside prospective Mahuva reservoirs. This reservoir description will serve as a deterministic basis for volumetric estimation and history matching.

The key inputs to property modeling include stratigraphic well correlation, core information, scaled up petrophysical interpretation, review of reservoir engineering and production/flow data. To integrate and optimize the multi-scaled input data, property modeling workflow is devised within a framework of geological conceptual model guided by a geostatistical modeling scheme.

By nature, geology is essentially hierarchical in its distribution of properties and heterogeneities. To capture the hierarchy of heterogeneities, a hierarchical workflow was adopted for building the reservoir model of B-9 area. The reservoir container facies are mainly sandstone, Limestone & shale. This was modeled using multi-point simulation algorithm which uses present day analogues as a training image to generate the geological objects in the facies model. Following the facies modeling, the effective porosity was populated. The output effective porosity was used to calculate permeability and water saturation using the equations provided by petrophysics and basic reservoir engineering study.

The workflow of property modeling can be divided in the following steps (Figure 4):
Step 1: Facies modeling with modern day analogue.
Step 2: Population of effective porosity
Step 3: Calculation of Permeability and water saturation using transform and SHF respectively.
Step 4: Definition of NTG and volume calculation after defining the contacts.

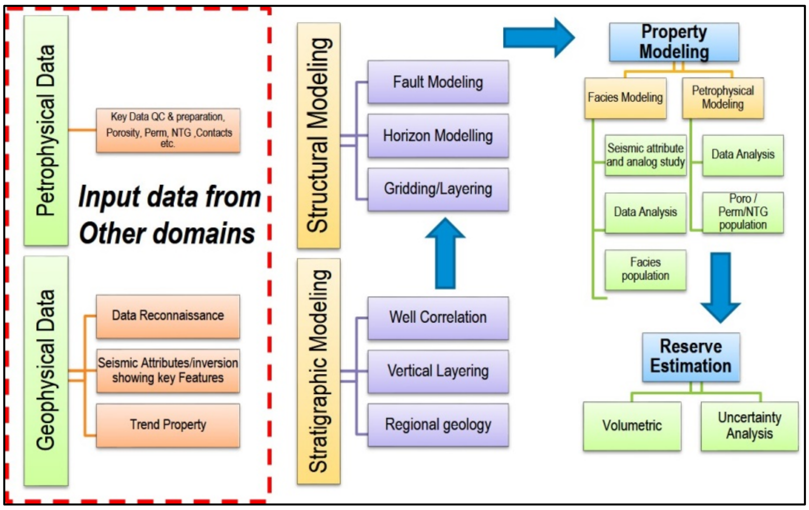

Figure 4: Static Modeling Workflow used in the Model showing data flow from Geophysics & Petrophysics into Static Modeling and Volumetrics

Trend Analysis

To achieve the basic goal of property modeling below crucial information is required,
1. The deterministic information gives the main framework (structural-stratigraphical model)
2. The statistical information such as histograms, variograms, correlation and trends give the property variation on the model
3. The conceptual information provides the connectivity of the reservoirs (e.g. object orientation, size, shape, correlation lengths and so on).

Due to good quality of seismic available for this study, trend for property modeling is mainly derived from seismic attributes and sand proportion analysis aligned with conceptual models. An attempt has been made for trend analysis keeping in mind the conceptual geology of the region to get some meaningful results as shown in Fig. 3. Existing publications from nearby fields and the basin were referred to arrive at a final trend map for the Daman Pay Sand 1 which is usable in the model and explains the conceptual depositional setting well. However, the same could not be successfully replicated for the Mahuva Pay Sands which are laminated to an extent where hydrocarbon bearing pay sands approach <2 m of thickness. Different methods are available and applied for modeling different reservoirs which is discussed in the following sections.

As shale is the predominant background facies in the area, a change of facies from shale to limestone (lower to higher acoustic impedance) will give rise to a higher amplitude contrast. Similarly, a change of facies from shale to sandstone (lower to moderate acoustic impedance) will give rise to a moderate amplitude contrast. Hence it can be interpreted that the lower amplitude will signify higher proportions of shales whereas the higher amplitude will signify limestone facies. The moderate amplitude values signify higher proportions of sandstone. This analysis is qualitative in nature.

Following steps are involved in generating 2D trend map from seismic attribute:

- Seismic Attribute (minimum amplitude) was correlated qualitatively with the facies proportion shown as pie charts representing the various facies as shown in Figure 3
- Additional maps obtained from literature in the form of manual sand isoliths, Vp/Vs, S Impedance maps were georeferenced and converted into normalized probability surfaces using the Petrel Surface Imaging algorithm.
- The conceptual model is compared with the seismic attributes and any sand limit polygons or contours from the conceptual image is incorporated.

- The single seismic attribute is differentiated into separate probability maps for each facies by normalization of values & removing the attribute values for the other facies.

The resultant facies probability maps for each facies are shown in Figure 5.

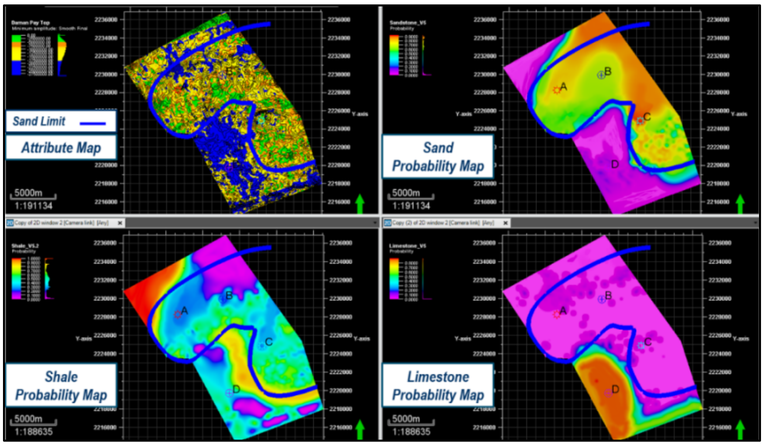

Figure 5: Probability maps for the different facies derived from the single seismic attribute surface shown with the conceptual sand limit boundary. Manual editing and smoothening was done to the maps as output from seismic was noisy and could have led to isolated disjointed facies bodies

Facies Modeling

Multi Point Simulation (MPS) relies on the concept of training images. Training images are essentially a database of geological patterns, from which MPS, including the variogram parameters, can be borrowed. Once the required patterns are extracted from the training image, they need to be anchored to subsurface data (e.g. well-log, seismic and production data). The training image replaces the variogram in multiple-point geostatistics as a measure for geological heterogeneity, it contains multiple-point information and, more importantly, is much more intuitive since one can observe, prior to any geostatistical estimation/simulation, what patterns will be reproduced in a set of multiple reservoir models (Caers and Zhang, 2002).

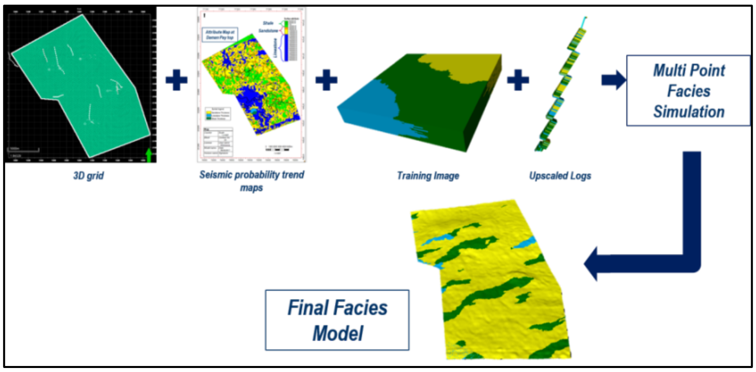

Figure 6: Facies modeling Workflow followed in the model

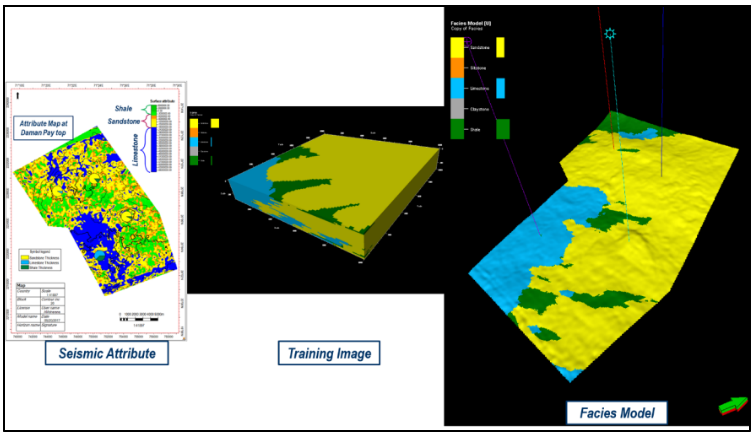

Figure 7: Facies inputs and 3D Facies model for Daman Pay Sand 1

In addition to a training image to describe the inter-facies relationships, probability maps from the seismic attribute trend analysis were used for the model to laterally restrict the distribution of the facies (Figure 6 & Figure 7). In addition to this, different simulation constraints are imposed on the MPS model to account for spatial variations of facies proportions (horizontal and vertical trends), and body geometry (orientation and size):

1. Target facies proportion is also imposed on the model using the upscaled facies proportion in different zones
2. The vertical proportion curve (VPC) of each zone is also imposed.
3. Facies probability cubes (soft probability) obtained through pre-stack inversion and well data is accounted for in MPS models.

The average sand thickness map from the model is shown in Figure 8.

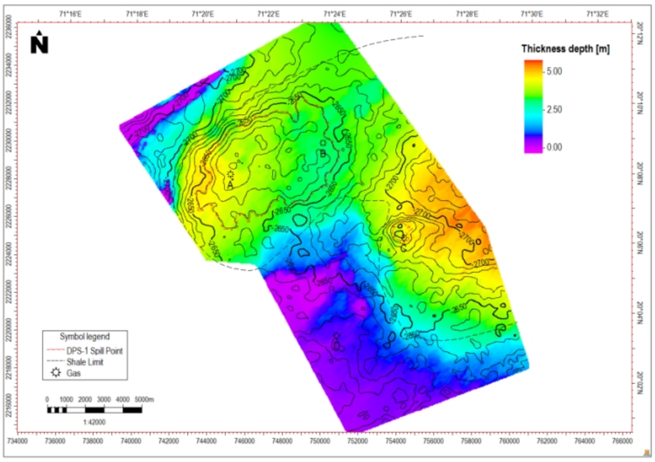

Figure 8: Sand Thickness Map from the model for Daman Pay Sand 1

Conclusions

With the sparse data availability in the area, conceptual geological understanding as used to fill in the data gaps with help of seismic generated trends as well as present day understanding of the Tapti Daman prodelta region morphology. The use of Multi Point Facies Simulation algorithm provided a better connectivity proxy for the simulation model than traditional variogram based facies model which is crucial in the case of thin sands like the Daman Pay Sands. This helped us to build a feasible facies model incorporating both clastic and carbonate elements which formed the foundation for further volumetrics and uncertainty calculations and development of a viable Field Development Plan.

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