Facies Classification Based on Seismic waveform  
-A case study from Mumbai High North

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ABSTRACT: The recognition of reservoir facies variation based on seismic wave shape has become an increasingly important part of seismic interpretation. The seismic wave shape is a resultant effect of amplitude, frequency and phase and is sensitive parameters for changing lithology, porosity, bed thickness, and fluid content etc. In the present study, seismic facies analysis is based on pattern recognition of wave shape of seismic traces within a specified window from reservoir top i.e. LIII of Mumbai High North. Seismic facies analysis has been carried out in two ways i.e., supervised classification and unsupervised classification of seismic traces. The supervised classification is aimed to predict good or bad reservoir facies based on porosity, lithology and shale volume directly integrating petrophysical data with seismic. From the result of direct interpretation based on supervised classification of seismic facies, some aspect of depositional process and environment can be predicted indirectly. Unsupervised classification is carried out without considering the well data to assess the maximum variability or heterogeneity of the facies from reservoir to non-reservoir part and un-biased classification of seismic facies with some limitation. In this paper we have restricted our discussion mainly to direct prediction of reservoir facies of LIII layer of Mumbai High North based on supervised classification. The 3-D seismic data acquired with OBC technique was used for classification. Seismic facies maps prepared for Upper stack and Lower stack of LIII carbonate reservoir (Early Miocene) layers, in combination with other seismic attributes and petrophysical property maps, indicate lateral variation of facies. It can be used for sector wise analysis of seismic and reservoir data in future.

INTRODUCTION

In geology, many definition and classification of facies have been used, but the term ‘facies’ have been mainly used to denote differences in appearance, composition and biological content between different rocks or lithostratigraphy units or their parts (M M Rocksandic 1978). Similarly, one part of a sedimentary sequence or unit can be distinguished from others according to general seismic appearance. Therefore, a seismic facies can be defined as a lithostratigraphic or seismostratigraphic unit which has appropriate seismic characteristics distinguishable through seismic waveforms from those of other units. Always one to one relation between geological and seismic facies is not possible due to limitations of seismic especially in high pressure zone where high pressure affects the seismic wave shape. Seismic facies analysis is a powerful qualitative technique and a part of facies model analysis frequently used in stratigraphic analysis from seismic data. Seismic facies are group of seismic traces whose wave shape differs from those of adjacent groups. Since seismic attributes such as amplitude, frequency and phase are estimated from seismic waveform generated by reservoir and petrophysical properties, it is natural to use the waveforms directly to infer the reservoir quality by sorting the seismic traces into different groups or classes.

The three possible causes for variation in wavelet are:

1. Variation in source signature caused by variation in acquisition parameters
2. Vertical and lateral variations introduced by processing and
3. Variation introduced by vertical and lateral change in lithology

Assuming first two causes are taken care during processing the wave shape variation is related to change in facies.

The approach is based on the assumption that the waveform carries the target geological information and similar wavelet corresponds to similar stratigraphy. In the present case, seismic facies analysis is performed in two steps:

1. Seismic facies classification by delineation of lateral / vertical variation and,
2. Interpretation of lateral/vertical variation with the help of well calibration to produce a geological and depositional meaningful facies map.

The vertical sequence of facies can be interpreted in terms of changing environment of deposition through time.
In the same way lateral variation of facies can be interpreted for the same bio-stratigraphic or chrono-stratigraphic time window. Once the spatial variation in environment has been identified for discrete interval of sedimentary rock, the paleogeographical map or three dimensional block diagram can be constructed.

The main carbonate reservoir layer L-III (Early Miocene) is divided into ten sublayers namely A1, A2-I, A2-II, A2-III, A2-IV, A2-V, A2-VI, A2-II, B and C layer. These layers are separated by thin shale layers. In the present study, top of A1 layer and B layer have been taken as reference for analysis as these layers were mappable seismically with confidence throughout the area. Top of A2-IV and A2-VII have also been mapped for better confidence. Small time windows have been taken from top of A1 and B layer for the study of variation in facies.

An attempt has been made to produce a 3D facies classification with the help of Landmark™ “Waveform Classifier” software. This technique tracks the wavelet within two horizons or a constant window from a reference horizon and put them in different classes on the basis of similarity or dissimilarity.

The basic principle, involved with this technique, is statistical measurements using Manhattan Distance

$$M = \sum_{i=1}^{N} |A_i - B_i|$$

where M is Manhattan Distance, A is the reference wavelet, B is the target wavelet guided by horizon and N is number of time or depth samples in each wavelet.

Two identical wavelets will result in a value of zero and non identical will result in positive Manhattan Distance. The values between zero and one are used for classification. The maximum M (threshold) for a classification depends on data quality. Traces having less similarity to reference trace and falling below threshold value will be put in reject or null class. In the present study, 0.4 (in fraction) has been taken as threshold value. In other words, similarity value 0.6 (in fraction) or 60% and above has been taken for classification.

**STUDY AREA AND AVAILABLE DATA**

The target area taken for the study as shown in fig.1 attains significant importance in light of the ongoing redevelopment program for L-III reservoir of Mumbai High North particularly with reference to two new platforms P1 and P2. Oil water contact (OWC) as marked in figure1 with a black contour indicates the boundary of reservoir. Well no.W1, W2 and W3 fall in non reservoir area having bad facies. The core data available in wells W1, W2, W3, W11, W6, W8, W9 and W12 were studied. In most of the wells the cores are available from A1 layer to A2 layers only. In well W9 core is available from A1 to B layer and in well W11 and W12 core is available from A1 to E layer. Mineralogical study has been carried out in three wells i.e., W3, W11 and W9. The study indicates calcite as dominant mineral (71% to 95%) with dolomite (5% to 29%). Lower layers below B layer have more dolomite content up to 50%. Biostratigraphic data are available in four wells – W3, W11, W12 and W9. Due to limited availability of core in LIII sublayers, datum could not be marked in all wells. However one particular bio-event recorded from west to east direction in well W3 at 1444 m, (4 mt. below LIII top), well W11 at 1315 mt. in A2-III layer (15.45 mt. below LIII top) and well W12 at 1364 mt. in B layer (45 mt. below LIII top) indicates that sublayers of LIII do not have conformity to time correlation (chrono-stratigraphic correlation) which has been adopted during the seismic correlation. In such situation it becomes difficult to integrate seismic with core facies via electro-facies analysis.

**METHODOLOGY**

Within LIII reservoir, four horizons were mapped and calibrated with well data and Synthetic seismograms. Seismic facies analysis was carried out using “Waveform classifier” application of PAL software of Landmark. Two
approaches- unsupervised and supervised classification of seismic facies were adopted for the analysis of seismic facies. In the initial stage of the classification, over subdivision to obtain more variability is beneficial. Therefore, study was started randomly with more than ten classes. But it was found that variability becomes unnatural. Finally, ten classes were selected for the study on the basis of wells falling in different parts of area and preferably having core data and electro-facies logs.

Unsupervised Classification identifies the seismic facies, i.e., families of traces showing a similar character at the reservoir level. These different seismic facies can be related to major geological variations of the reservoir and it provides a qualitative interpretation of the seismic data. In the unsupervised approach, the geological interpretation of the area of the seismic facies is done afterwards by analyzing the correspondence of the seismic facies around the wells with reservoir characteristics, known at these wells. This interpretation can also be corroborated by seismic facies classification of synthetic traces associated with wells.

Supervised Classification uses estimation techniques to build a relationship between reservoir properties of the interest and wave shape of related seismic trace. For good quality seismic data, the seismic trace near well is representative of petro-physical property of the particular well. These traces are called super traces or trained traces or reference traces. Five traces were taken around the well and averaged out to remove noise, if any, and generate super trace. The clustering of seismic traces is done on the basis of these super traces. In the supervised approach geological interpretation is required from the very beginning and wells are selected on the basis of facies variation. Synthetic traces based on well data and geological model can also be used as training traces. Classification based on pattern recognition is then performed and traces were grouped in separate classes as per their similarity. Each class is assigned with a different color code. Discrete color (block color) was chosen for the study.

In general a spatial analysis window of 5 traces and 5 lines provide maximum lateral resolution as it has been taken in present case but it can be more susceptible to noise in case of acquisition footprints and processing artifacts. Temporal analysis window greater than 50 ms allow us to stack the discontinuity associated with vertical fault and deltaic regime, while window of 20 ms or less avoid blending or mixing of stratigraphic discontinuity from geological feature above and below zone of interest. It is advisable to have more than one window as per objective. In the present study window of 10 and 20 msec. have been tried and a negligible difference was observed. Finally window of 20 msec. was taken for the analysis.

This analysis is more quantitative but it requires more wells distributed in all type of facies present in the area. Ten wells were selected varying in facies from the study area and ten classes of super traces were initiated for classification of seismic facies map with optimum window from reservoir top. Out of ten wells or classes, six wells are having core and electrofacies log both. Other wells were taken on the basis of geographical distribution of the wells in the area. The core represents porosity and microfacies whereas seismic traces are resultant effect of pore, fluid, mineralogy, and bed thickness etc. and it represents macrofacies. Therefore, electrofacies logs, communication tool between seismic and core facies were also generated for few wells and an attempt was made to correlate with seismic facies.

CONFIDENCE MAPS

Since the study is based on the time window taken from reference horizons LIII top (top of A1 layer) and B top, question arises for confidence level of mapping of the horizon. Therefore confidence maps (Fig 3 and Fig 4) were generated for these reference horizons. Fig 2 indicates the horizon and well control in the study area. It has been observed that confidence factor varies from 65 to 98 percent which can be
considered as good for considering these horizons as reference for seismic facies analysis. Confidence factor is shown in color bar at the left side of figures. In the gas cap area and eastern boundary fault zone, the decrease in confidence factor is compensated by densely populated well control and it can be interpreted in terms of geology rather than data quality. Horizon A2-IV and A2-VII tops were also mapped and considered for the help in selection of reference horizon where ever confidence factor is low.

**OBSERVATION AND INTERPRETATION**

Synthetic seismograms indicate good correlation above 70% required for seismic facies analysis. Electrofacies logs (orange color) generated on the basis of neural networking is shown in right side of synthetic seismogram (yellow color) and petrophysical logs (sonic log with red and GR log with green color) are shown on left side of synthetic seismogram. Above LIII top, facies are shown bad as per electrofacies and petrophysical logs (Fig 2). Horizon names and well pick names are given in the figure. Seismic line passing through wells is shown in the base map with red color.

Based on the classification and color codification of each seismic facies, it can be interpreted in terms of depositional processes and heterogeneity of reservoir. In case of carbonate sediments, especially in shallow marine sequences, intensive diagenesis activity makes it difficult to look into environmental interpretation. However attempts have been made to correlate the seismic facies analysis with wells and picturise the complexity of facies and identify reservoir facies on the basis of porosity and hydrocarbon saturation.

It was observed that unsupervised classification gives better picture of classes in comparison to supervised classification due to limitation of wells as only three wells i.e. W1, W2 and W3 are available in the non reservoir part. Even in the non-reservoir part, unsupervised classification makes different clusters. But these clusters are not interpretable in the absence of wells. The main reservoir LIII was divided in LIII Upper (A1 to A2-III/A2-IV layer) and LIII Lower (A2-IV to B layer) as analyzed below.

**L-III (Upper)**

Facies number 6,7 and 8 (numbers written on the right side of the color bar) corresponding to well W1, W4 and W2 under supervised classification (Fig 6) is equivalent to class/ cluster 3 and 5 of unsupervised facies map (Fig 5) and have identical cluster for L-III (upper) layer. It indicates non-reservoir or poor facies developed in periphery of MHN area, part of permeability barrier and east of main boundary fault as these wells are representative of poor facies.

Non-reservoir area especially west of OWC (Oil Water Contact) shows clear-cut clustering of facies no. 8. Oil water contact is shown with black color contour in base map. Core analysis of well W2 indicates the facies is mainly dominated by shale and argillaceous packstone having low porosity.
Area east of main boundary fault, is showing bad facies similar to well W2. Seismically, the horizons are continuous and stronger than events of main reservoir area.

Other facies, especially in gas cap area and densely populated fault zone are influenced by mixed nature of petrophysical properties, fluid content from gas to oil and crisscross faults. Facies no. 1, 3 and 4 assigned to well W10, W11 and W9 are equivalent to cluster number 1 and 9 of unsupervised classification. Seismic events are deteriorated due to low reflection coefficient especially in gas cap area. This class predicts about good facies having porosity range from 20% to 25% and good hydrocarbon saturation approximately above 60%. The proposed platforms P1 and P2, falls within these good facies zone. Both anisotropy change (lateral and vertical) in gas cap area and surrounding areas is faster than non-reservoir rocks due to faster variation in velocity, caused by porosity and fluid content. It affects the facies clusters and mixed nature of facies is observed. These clusters can be utilized for sector-wise seismic inversion and attribute analysis of seismic data for prediction of petrophysical properties in detail.

Facies no. 9 and 10 allotted to well W13 and W5 during the training of neural networking is equivalent to cluster no. 1 and 4 in unsupervised facies map with invasion of other class. It is only dominant in southern part of permeability barrier and around W14 and W15 platforms. Porosity range is moderate from 17 to 22%

Facies no.2 and 5 corresponding to well W8 and W6 in supervised classification is not identifiable and it is in scattered way as these facies and corresponding wells fall in transition zone of good and bad reservoir facies.

**L-III (Lower)**

Classification method is same as used for generation of supervised facies map of L-III (Upper) and same wells were taken. Supervised facies map of L-III (Lower) is mostly affected by gas cap area due to absorption of dominant frequency and discontinuous horizons. Facies variation is very sharp from MHN main field to permeability barrier and the presence of barrier is clearly seen in maps, which could not be seen in the seismic facies map of L-III (Upper).

Facies no. 6, 7 and 8 are assigned to well W1, W4 and W2 in supervised facies map (Fig 8) corresponds to cluster 5, 3 and 1 of unsupervised facies map (Fig 7) and it indicates poor facies in L-III lower also. From seismic point of view, reflectors within these facies are stronger and continuous. It indicates compactness of limestone and decrease in porosity.

Facies no. 10 corresponding to well no W5 is dominant near W15 platform, surroundings of permeability barrier and in the northernmost part of MHN area. Facies no.1, 2 and 3 corresponding to well numbers W10, W8 and W11 are observed in clusters and dominant in gas cap area having good porosity range from 18 to 22% and good hydrocarbon saturation from 50 to 60%. One to one correlation between supervised and unsupervised cluster is not possible. Facies number 4&5 are not identifiable in the map.

Seismic facies map is more sensitive to lithofacies variation and it corresponds to depositional environment. In
VALIDATION

Well W7 was not taken purposefully so that it can be validated with seismic facies analysis. As per seismic facies map, W7 falls in transition zone of poor to good reservoir facies area. The core analysis also indicates that L-III pay in W7 is poorly represented and available samples give an indication of poor reservoir facies. Specially, in lower part, out of 38 samples, only 5 samples shows better reservoir quality. Poor permeability (less than 1 millidarcy) is found in some intervals of the core data.

COMPARISON WITH OTHER SEISMIC ATTRIBUTES AND ITS USE

Seismic attribute maps generated for LIII upper and LIII lower stacks were compared with seismic facies maps. It was observed that facies maps provide more detail than attribute maps and supervised facies maps directly demarcate the non reservoir rocks. Even in the reservoir part it indicates the cluster of different facies whereas the other attribute maps usually indicates same color or facies.

REMARKS AND CONCLUSION

The seismic facies classification using pattern recognition technique highly improves the efficiency of seismic interpretation. The out put classification volume is not the final product. This requires transformation of 3D seismic volume into different seismic facies classes and then a geological and depositional model. This stage of analysis still requires some more study with other seismic attributes.

In interpreting seismic cluster or facies one must account for the fact that seismic response is smeared across overlying and underlying sequences and gas cap area. Response from some unit such as shale and gas cap may interfere the target level. In such case window selection is critical.

Analysis of seismic facies and geometries provide an initial framework to constrain stratigraphic correlation based on well data (log and core data). Instead of assuming a continuous facies between two wells, far away from each other during stratigraphic correlation, seismic facies map can be utilized as a tool to identify the changes in facies inter wells.

The study has brought out a clear cut picture of non-reservoir facies, eastern boundary fault and permeability barrier dividing north and south Mumbai High field.
In view of present study it is observed that pattern recognition of seismic wave shape based on neural network can be very powerful approach to characterize reservoir properties, its accurate boundaries and predict areal distribution of reservoir quality for planning and drilling horizontal wells with acceptable degree of confidence.

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