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High Resolution Sequence Stratigraphy constrained reservoir prediction and characterization of Early Eocene pay sand of Kutch Offshore Basin, India.

Abstract

Fine characterization of clastic reservoir has always been a key challenge in oil and gas exploration and exploitation which also holds true for the Early Eocene pay sand of Kutch offshore Basin. Using seismic data, combined with the analysis of cores and well logs, a detailed high resolution sequence stratigraphic framework was evolved and correlated the individual cycles/pay units, to bring out plausible reservoir distribution of Early Eocene pay sand within Jakhau Formation and its upside potential in Kutch Offshore Basin of India. Higher order sequence stratigraphic framework (2nd and 3rd Order sequences) was established for the whole sediment package of Tertiary, starting from Deccan Trap Top to Chasra Fm.Top, using classical depositional sequence stratigraphic approach. The entire sedimentary fill of the Tertiary section of the basin was divided into Eight 3rd Order Sequences which were further subdivided into forty eight 4th Order depositional sequences. It is observed that the entire Tertiary sediments were deposited in TST-HST cycles punctuated by subaerial unconformity on the top of HST cycle. From High resolution sequence stratigraphic interpretation using seismic Horizon cube and Wheeler transformation, it is observed that the main pay of Early Eocene sequence (S-II pay Sand) was deposited in transgressive regime and sparsely distributed in the study area. Analysis of Wheeler Similarity cube has brought out the channel like feature close to Early Eocene pay level. Integrated analysis of different post stack attribute studies (Energy Half time), RGB Blending, and Prestack inversion has helped in understanding and identifying geological features which are paleo coast parallel along with the associated sub-environments, influenced by tidal regime. Isolith map of S-II pay sand also depict a similar pattern indicating sand bars cut by tidal channels. X-plot of P-impedance vs inverted Vp/Vs also helped in extracting geobodies representing reservoir facies corresponding to Early Eocene pay sand and likely to be hydrocarbon bearing is in sync with the Isolith map of pay sand which demonstrate the areal extent of this pay sand within the study area.

Introduction

Complex structural and stratigraphic conditions as well as the restriction of seismic resolution, reservoir prediction has become one of the major challenge in the exploration stage of Kutch Offshore Basin. For areas with complicated geological conditions, the ambiguity of geological methods and uncertainty of geophysical methods (especially seismic attributes) have always been the key factors restricting reservoir prediction. The combination of high resolution sequence stratigraphic analysis and seismic reservoir prediction methods are the effective means solving the above-mentioned problem. Well-seismic unified isochronal stratigraphic framework and sedimentary model of the whole study area was constructed through well log based stratigraphic sequence division and Horizon Cube based high resolution seismic sequence stratigraphic analysis, provide better understandings on the spatial distribution of reservoirs, and constraining the seismic reservoir prediction methods.

Kutch Offshore basin forms the northern part of Western Offshore basin of India and is located in a divergent margin setup (Biswas, 1982) (Fig.1). The Kutch Offshore basin covers an area of about 28,000 Sq.Km upto 200m bathymetry and is bounded by Saurashtra arch to the south and Indus basin of Pakistan to the north, the Arabian Sea to the west and Kutch onland to the east. It is a pericratonic rift basin which came into existence during the breakup of India from Africa. The Kutch Offshore is characterized by dominantly NNW-SSE striking faults, corresponding to Dharwarian grain. The rift evolution and synrift sedimentation continued through the Jurassic and Cretaceous time. The rift extended from north to south by successive reactivation of faults. The movement of Indian plate during the rift stage induced horizontal stress and the faults bounding the half graben became wrench faults with divergent strike slip movements. The blanketing sediments drape over the major faults and marginal flexures are seen. The sense of movement was thus oblique slip along the reactivated faults. In Cretaceous, the Kutch basin experienced regression of sea and intense tectonic activity accompanied by Deccan Trap volcanism.

Sedimentation started in Late Paleocene in Kutch Offshore (carbonate and claystone with sandstone) and these marine Cenozoic sediments are encountered in almost all the near and far offshore wells. The thickness of Pre-Cretaceous (Jurassic), Early Cretaceous sediments and Trap is increasing towards the coast in the east, whereas the Tertiary sediments are thickening towards west. Hydrocarbon discovery in commercial quantity had already been established both in Tertiary sediments in Kutch and Saurashtra Basins. The generalized stratigraphy of the area is shown in Fig2.

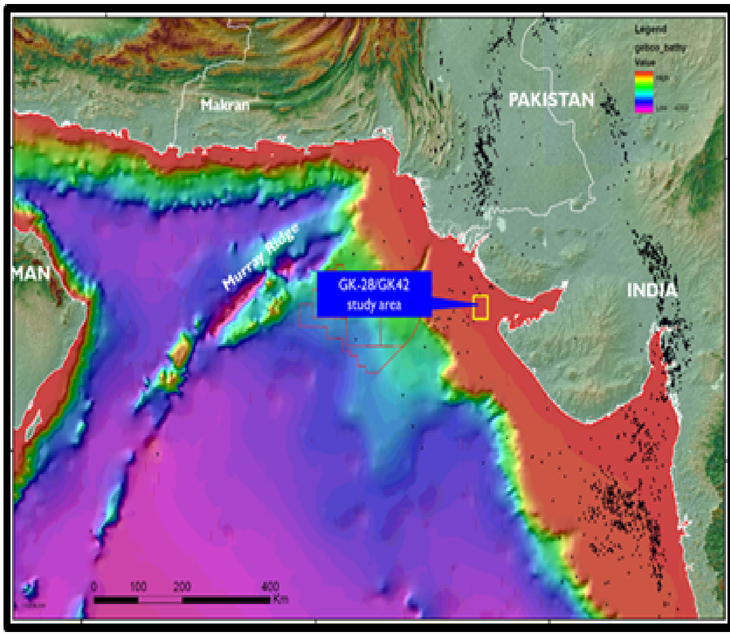

Fig1: Location map and area of study in Kutch Offshore Basin

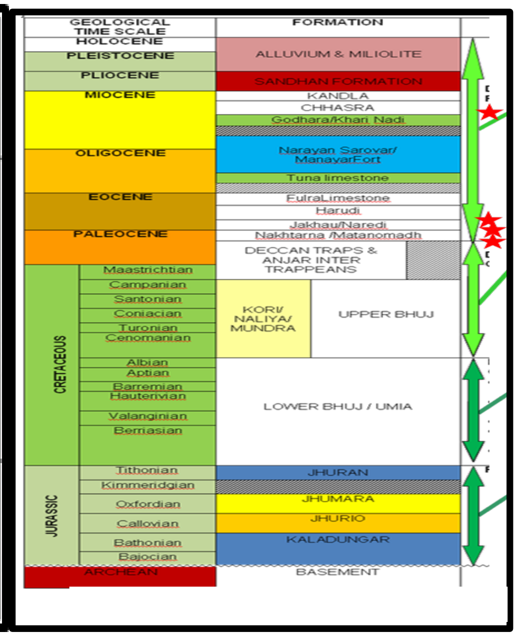

Fig2: Generalised Stratigraphy of Basin

Seismic data:

The offshore part of Kutch Basin is covered with 2D/3D seismic data with varying fold through different campaigns. Among those merged PSTM data of two 3D seismic volumes with combined area of around 1200 SKM is considered for the present Study. The data is of 36 fold with sampling interval 2ms and record length of 5sec. Quality of seismic data is fair to good and band width of 5-71Hz in the shallow zone of interest and 5-30Hz in the deeper zone within Mesozoic section.

Well data:

The present study covered the Tertiary section and in particular E. Eocene pay sand. Total twenty two wells were used in this study. Conventional logs (GR, RT, RHOB, NPHI, DT) were available for all the wells. All the well logs were conditioned before using for the interpretation and all the producing wells were processed for PIGN, Vshale and SUWI. Synthetic seismogram was prepared for tying seismic with well data in the study area.

Present Study:

This study was carried out with synergistic use of different subsurface dataset. PSTM data of Merged and reprocessed 3D volume was used to a large extent to understand the subsurface disposition and stratal pattern. Some of the 2D seismic lines were also used to establish the sub basinal sequence stratigraphic framework. All the available data derived from the laboratory studies, Well logs, cutting and core data were used to construct the Lithofacies, to understand their stacking pattern through the basin fill history, biostratigraphic data was integrated for age and environmental interpretation wherever available. Lithologies of the total drilled section of all the wells were plotted. Well logs were carefully tied to the seismic data and different sequence stratigraphic surfaces (Unconformities, Maximum Flooding Surfaces etc.) were picked up and correlated.

In the present study, based on the understanding of the tectonic evolution of the Kutch Basin, nature and type of sedimentary fills, biostratigraphic data, span and duration of hiatuses, identification of 1st, 2nd, 3rd and 4th order sequences were attempted. In the Mesozoic-Cenozoic sedimentary succession of Kutch Basin, the 1st order sequence is represented by the major tectonic event of the breakup of the Gondwana and separation of Madagascar-Antartica-India- Australia (Eastern Gondwana) from Africa and initiation of the Kutch Basin formation. There are two 2nd order sequences observed in the Basin. First 2nd order sequence is represented by Upper Gondwana Synrift, Post rift sag and Breakup of Madagascar from India (Late Jurassic to Late Cretaceous) and the second 2nd order sequence is represented by separation of Seychelles and formation of Western India Passive Margin setup (Early Late Paleocene to Recent). For the Tertiary sequences, eight 3rd order sequence boundaries are identified which are major formation boundaries. Additional 4th Order sequences are also identified of which few correspond to established pay zones.

Sequence stratigraphic framework based on well logs

Detailed high frequency sequence stratigraphic interpretation was carried out in GK-28/ 42 area for the Tertiary interval between Deccan Trap top and Late Miocene hiatus that falls within Kandla Fm. in the offshore part. However, the main focus remains within the sequences between Chhasra Fm. Top (Mid Miocene Top) and Deccan Trap top (Late Cretaceous Top). Among all the established pays, E. Eocene S-II pay, which is the main producing pay in the study area is confined within Jakhau Fm. and falls within the interval of consideration for sequence stratigraphic interpretation. Higher order sequence stratigraphic framework (2nd and 3rd Order sequences) was established for the whole sediment package from the Deccan Trap top to Chhasra Fm.Top, using classical depositional sequence stratigraphic approach on logs. Whole sedimentary fill of the Tertiary section of the basin is divisible into Eight 3rd Order Sequences. Each top of these sequences corresponds to a Sequence Boundary. In this approach the Maximum Flooding Surface (MFS) and Flooding Surface (FS) are identified on the top of the retrograding stacking pattern on top of the shale/ Coal/ Claystone within the clastic sequence and the MFS+FS were picked up within the carbonate sequence based on the electrolog pattern of fining upward trend. Within this broader framework detailed sequence stratigraphic study **(4th Order sequences)** was carried out in the entire Tertiary sequence using the **Depositional sequence Model-IV of Catanuanue (2006),** where each subaerial unconformity (SU) and their correlative conformity surfaces are taken as sequence boundaries. The designation of depositional sequences assumes that the observed cyclicity is the product of changes in relative sea level, with stages of rise and fall along with change in accommodation or sediment supply. These surfaces (SU) make the important reference level (markers) and allow us to generate detailed chronostratigraphic framework for Tertiary interval in GK-28/42 area. The earlier mentioned eight 3rd order sequences were further subdivided into fortyeight numbers of 4th Order Depositional Sequences for the entire Tertiary sequences.

The Jakhau Fm.(E. Eocene sequence) was further subdivided into 10 numbers of 4th Order sequences (depositional sequences) (Fig.3). The formation is dominated by sandstone in the lower (S-I pay sand) and upper part (S-II pay sand) with shale or claystone or limestone layers in between these two sand layers. These limestones are Foraminiferal Wackestone/ packstone with isolated vuggy/ moldic porosity. There are also some rare occurrences of coal bands. The upper pay sand (S-II) is Quartz arenite with subrounded, moderately sorted, non-calcareous quartz grains with moderate porosity (15-20%). It is the main hydrocarbon bearing layer in Early Eocene sequence. Overall this sand is transgressive in nature in all the wells as indicated by fining upward Gamma Ray log (GR) trend. This sand is capped by a

Highstand System Tract (HST) Shale or Claystone layer. The pay sand thickness varies from 5-15m. The lower pay sand (S-I) is Quartz wacke with fine to medium grained (predominantly fine grained), well sorted quartz grains with good porosity, however it is devoid of hydrocarbon. It is much thicker and cleaner than S-II sand. Like S-II sand, this sand is also dominantly transgressive in nature. There is a thin Coal/ Carbonaceous shale/ Claystone layer within this lower sand which divides it into two parts. Overall this sequence was deposited under transgressive regime as indicated by fining upward GR trend.

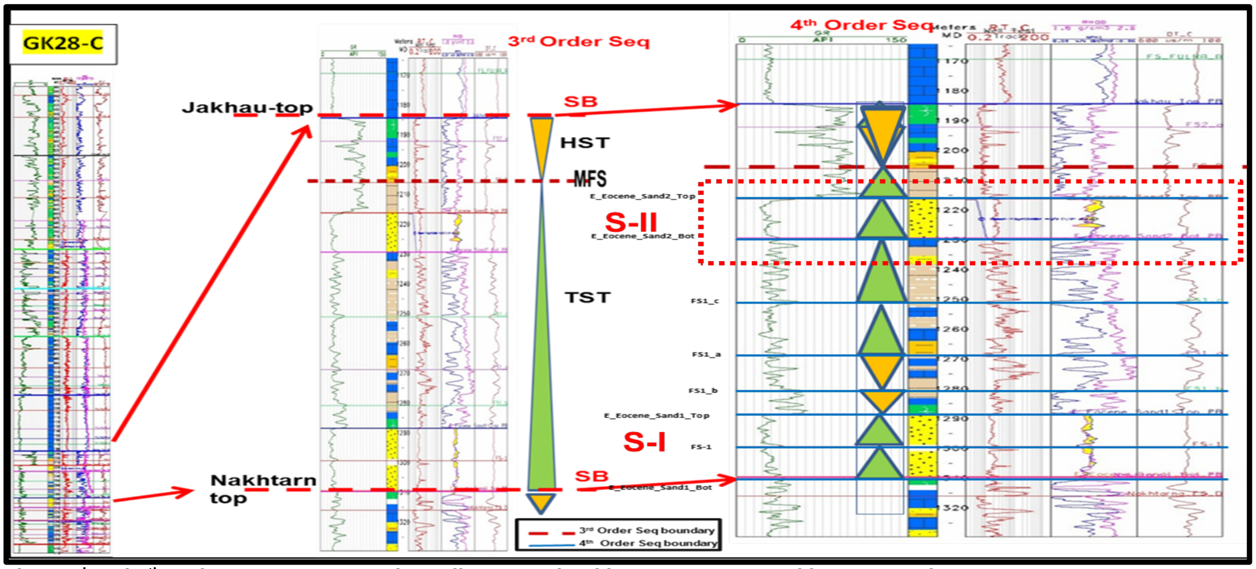

Fig3: 3rd and 4th Order Systems Tracts in Well GK28-C (Nakhtarna Fm. Top- Jakhau Fm.Top)

High-resolution seismic sequence stratigraphic interpretation:

The purpose of sequence stratigraphic study is to establish well-seismic unified isochronous stratigraphic framework on the basis of high resolution sequence stratigraphic division, thus revealing the spatial distribution regularities of reservoirs. The high resolution/frequency sequence stratigraphy tackles scales of observation that typically fall below the resolution of seismic data, within the realm of 4th order or lower rank stratigraphic frameworks. The use of high frequency sequences eliminates the need to employ the concepts of “parasequence or small scale cycle”.

The relevance of high frequency sequence stratigraphy to reservoir characterization is evident, as heterogeneities at the scale of 4th order control fluid migration pathways, which are fundamental for hydrocarbon production development. The features that can be recognized at the scale of high frequency sequences include the distribution of coarse grained and muddy deposits as well as the framework of sequence stratigraphic surfaces and facies contacts, which are essential to reconstruct the architecture of clastic reservoirs. In addition, diagenetic processes at this scale of observation may profoundly alter the primary porosity, fluid migration pathways and the volume of reservoirs, with important implications to the evaluation of prospects.

During the study, first the higher order sequences (2nd and 3rd order) are calibrated with seismic reflectors on 2D seismic data (Long regional 2D lines connecting 3D survey area and deeper basinal part). The identified sequence boundaries are then extrapolated into the seismic 3D area. This provided the broad subdivision of the whole basin fill. These seismically bounded stratigraphic units are further progressively subdivided into finer and finer units as allowed by the given data set. All the 2nd and 3rd order sequence boundaries are mapable on the seismic data. However, among the fortyeight 4th order Depositional Sequences identified on well logs, four 4th order sequence boundaries corresponding to different established pays including S-II pay top, was correlated on seismic data and mapped.

Horizon Cube and Wheeler domain Interpretation

Manual mapping of all seismic events using a conventional interpretation method is almost impossible, thus, we need an automated method. One such is the HorizonCube approach, which helps in creating a set of seismic events automatically that are chronostratigraphically sorted. Coloured lines are the automated events of a data driven HorizonCube. The method not only reveals that the mapped horizons are chronostratigraphically significant but also extracts key geologic elements (e.g. stratigraphic units, depositional trends, base level changes etc.), which are building blocks for constructing a sequence stratigraphic framework. The horizons could be treated as time (chronostratigraphic) events representing a relative geologic time scale (RGT) of a rock unit based on the principle of superposition, older at the base and younger at the top. **There are two types of Horizon cubes viz. Continuous Horizon cube and Truncated Horizon Cube.** In case of "**Truncated horizon cube"**, the events will terminate against other events. With this advantage, the horizons can be used to carry out a 2D/3D **Wheeler (chronostratigraphic) transformation** and sequence stratigraphy interpretation. In the Wheeler diagram the **Y-axis represents the relative geological time (RGT), while the X-axis represents spatial distance**. In the Wheeler domain, a surface is generally flat because of the Y-axis, which magnifies to understand the time gap between two surfaces. Once the data are transformed into a Wheeler domain, it is ready for sequence stratigraphic interpretation and the integration of results with the well data (logs, core, cuttings, etc.). The Systems Tracts analysis was carried out simultaneously along with the Wheeler Transform. Here Depositional Systems Tracts (FSST, LST, TST and HST) are considered for the analysis part. Once the Systems Tracts analysis was carried out the same was overlaid on seismic to understand how the seismic packages are behaving under the assigned Systems Tracts.

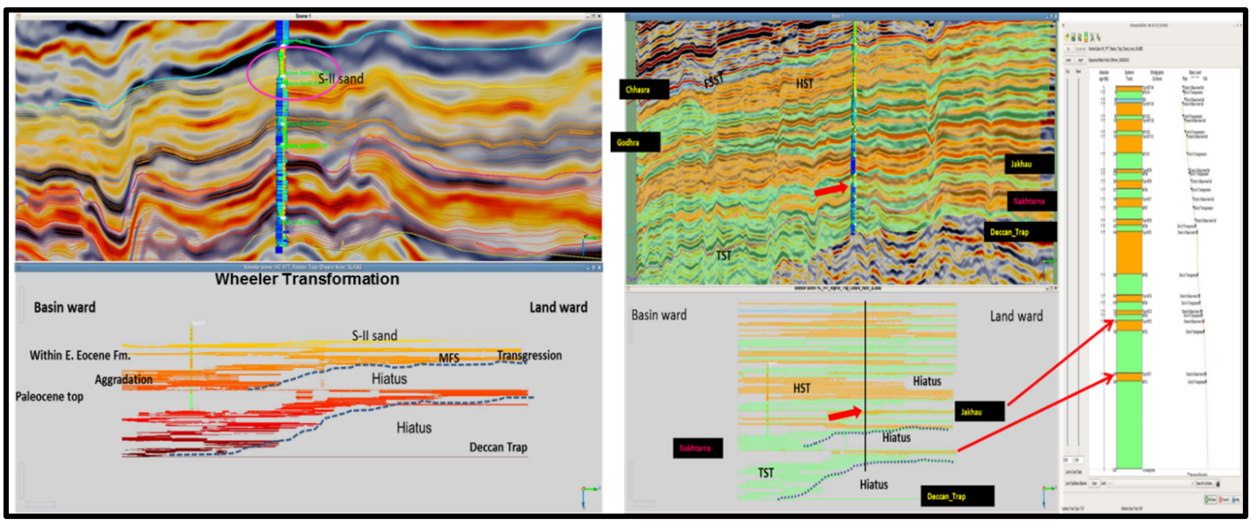

Fig. 4a&4b: E-W Seismic section passing through a well in GK28 area showing E. Eocene S-II pay sand falling in the early phase of transgression (TST), both in depositional and Wheeler domain.

Interpretation of the Wheeler Transformation diagram on the seismic line (Fig. 4a & 4b) clearly shows that there is a hiatus after Deccan Volcanism followed by marine transgression in the early part of Paleocene age and aggradation of HST in the Late Paleocene followed by a hiatus of regional scale. This corresponds to the hiatus present at the top of Nakhtarna Fm. After the hiatus again there was a marine transgression in the early part to middle part of the Early Eocene age followed by aggradation belonging to HST phase, followed by hiatus and subaerial unconformity. The Jakhau Fm. was deposited during this time and as per Systems tracts analysis, the S-I pay sand and S-II pay sand are part of Transgressive phase (TST) while the finer clastics (Shale / Claystone) and Streaks of Limestone present above the S-II pay sand is part of HST phase. These finer clastics might have act as cap for these S-II reservoir leading to the entrapment of the hydrocarbon. Further, it was observed in Wheeler domain, that the different fault blocks were inundated at a different time during the transgressive phase, leading to the spatio-temporal facies variation with time and depth. Also, rapid sea level fluctuation towards landward side resulting into 4th order scale hiatus was observed in Wheeler domain, which has a bearing on sedimentation pattern on the shelfal part and in controlling the reservoir quality and its distribution. Similarly, horizon slice of

Wheeler Similarity cube brought out the tidal channel like feature in the area indicating of tidal flat environment (Fig.5a).

An attribute known as Energy half-time which acts like a measure of average amplitude change within a window was considered to bring out the spatial distribution of S-II pay sands. In principle, Energy half-time can track the extent of a highly reflective unit juxtaposed against a weakly reflective unit, which could represent a sand-shale lateral facies variation. It is observed that this attribute has helped in bringing out better picture for S-II pay sand distribution (Fig.5b). Also, RGB blending of different mono frequency volumes were also carried out at S-II pay level, which shows tidal channel feature and facies variation of 4th order level (Fig.5c).

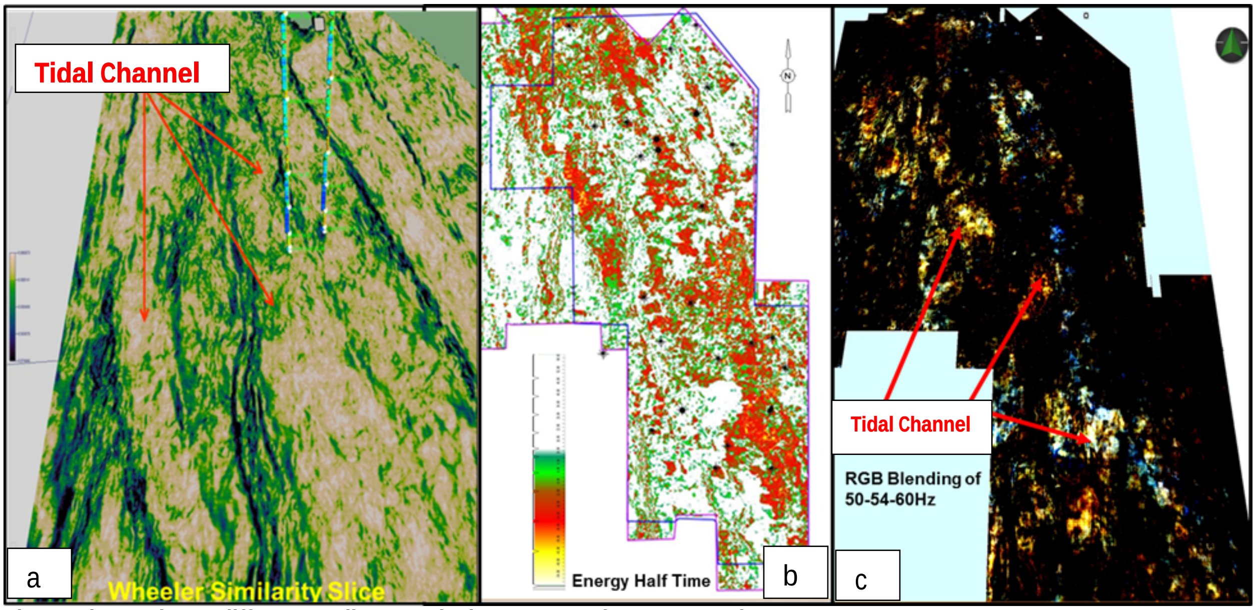

Fig.5a, 5b&5c shows different attribute analysis outcome of S-II pay sand.

Prestack inversion within Jakhau Fm. was carried out corresponding to the window of S-II pay sand for better understanding of the reservoir facies distribution based on the leads obtained from high resolution seismic sequence stratigraphic interpretation. Identification of probable hydrocarbon bearing pay sand polygon was carried out using crossplots between inverted P-impedance vs. inverted Vp/Vs, predicted NPHI and predicted VCL extracted at well locations colored with Litho logs, which separates the pay zone within Jakhau Fm. The same most probable pay sand polygon was used to extract geobodies from inverted volumes for S-II pay which may be indicative of hydrocarbon bearing. Subsequently the geobodies were overlaid with S-II sand Isolith map (Fig.6).

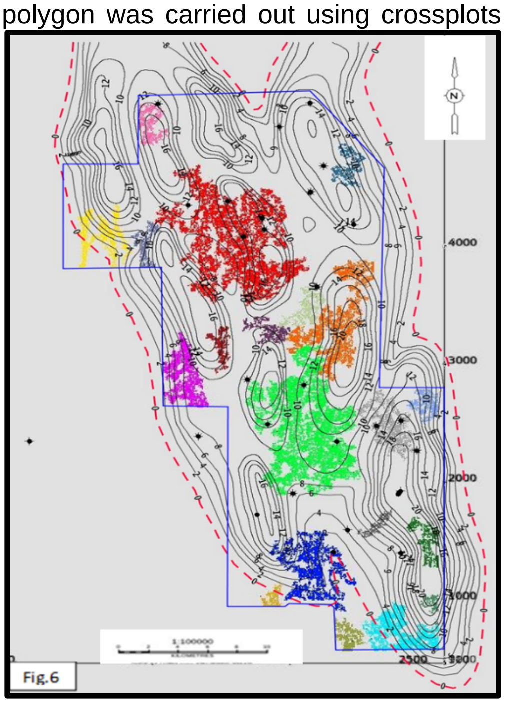

Fig.6

The Isolith map was generated based on the well data which clearly suggest that these sands are paleo coast parallel sand bodies that might have been deposited by tidal /distributary channels. These sand bodies within the area are oriented N-S, suggesting an input from the North. The most likely input is through the Kori Creek through which the paleo river(s) (Proto Indus River?) was flowing and dumping their sediments into the sea. These sediments were subsequently oriented by the tidal effect to form tidal bars that are cut by tidal channels. The different lab and core reports also support the same hypothesis.

Geobodies extracted from the pre-stack studies shows number of geobodies present at S-II pay level, which get oriented with sand isolith map of the same pay level.

Fig.6: Geobodies of S-II pay sand overlaid on Sand Isolith

Conclusions:

Well-seismic unified isochronous stratigraphic framework is established through high resolution sequence stratigraphic analysis. It is observed that in this study area the whole Tertiary sediments were deposited in TST-HST cycle punctuated by subaerial unconformity on the top of HST surface. The main pay of Early Eocene sequence (S-II pay Sand) was deposited in transgressive regime capped by HST shale. Different attribute analysis like Energy half time, RGB blending, etc. helped in understanding and identifying geological features which are paleo coast parallel and most likely depicting a tidal environment. Isolith map of S-II pay sand also depict a similar pattern indicating tidal sand bars cut by tidal channels. Most probable hydrocarbon bearing sand polygon identified from crossplots of inverted P-impedance vs inverted Vp/Vs, predicted NPHI and predicted VCL helped to extract Geobodies for S-II pay sand. These geobodies may be indicative of most probable hydrocarbon bearing sands in the area.
High frequency Sequence Stratigraphic study carried out here aptly demonstrated the capability of this methodology in pay scale reservoir characterization and helped in improving the geological model of the area, which will effectively reduce the uncertainty of seismic methods and improve the accuracy of reservoir prediction and characterization.
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The views expressed in this paper are solely those of the authors and not necessarily be that of ONGC.

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