

well has encountered two similar sand body interpreted from open hole log. The Fig 4 -5 represents two cases showing decision making challenge for horizontal well placement and perforation zone selection.

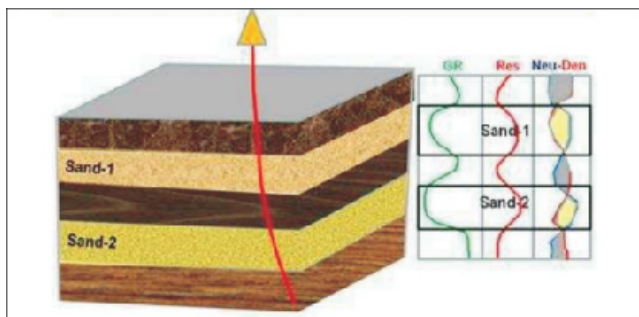


Fig.3: Analogue Model showing two sand bodies with similar petrophysical property.

Which is a better Candidate for Horizontal Well Placement; Sand-1 or Sand-2?

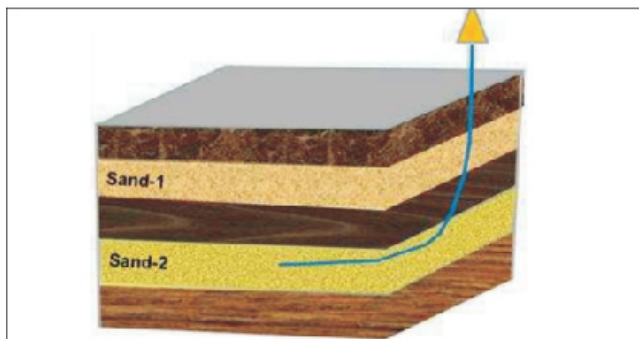
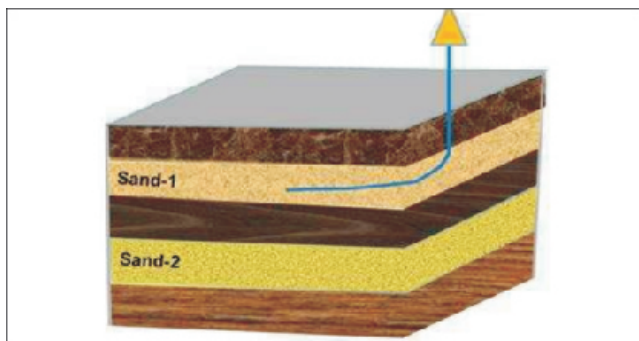


Fig. 4: Analogue Model showing challenge of proper candidate selection for horizontal well placement.

Which is a better sand for Perforation; Sand-1 or Sand-2?

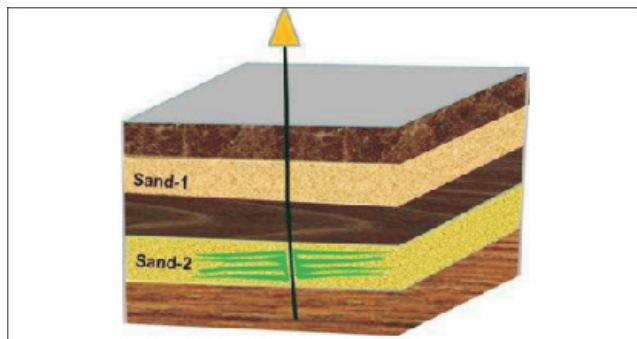
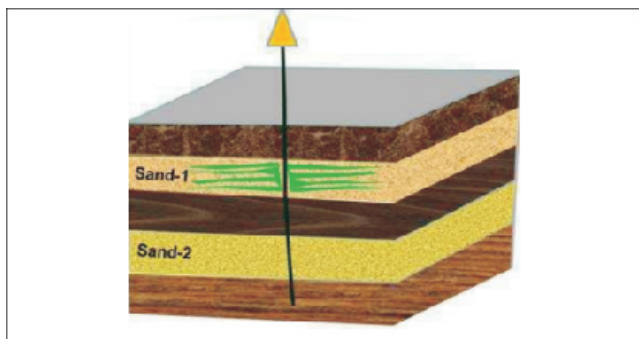


Fig.5: Analogue Model showing challenge of proper perforation zone selection.

Geological Control in Formation Evaluation

It is extremely important to have a clear idea about the geological framework of the area to understand about the reservoir quality. Predicting the fluid flow capabilities of different sand bodies need a robust understanding of the sand dispersal pattern and their genesis. In Fig-6, an example of fluvial depositional system and the different sub-environment has been shown. In Fig-7-10 outcrop of different deposits i.e. crevasse splay, channel cut, channel overbank levee and flood plain have been shown.

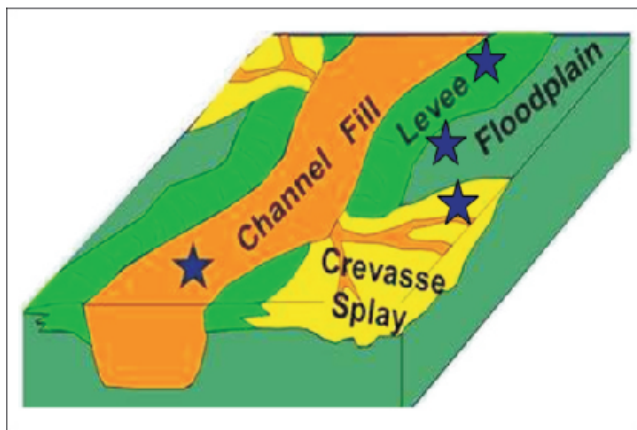


Fig. 6: Fluvial depositional framework (after Galloway and Hobde, 1983)

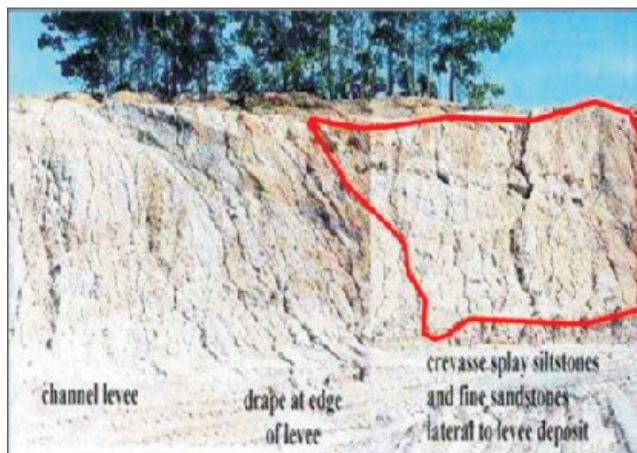


Fig. 7: Crevasse Splay Deposition (From Google Image gallery)

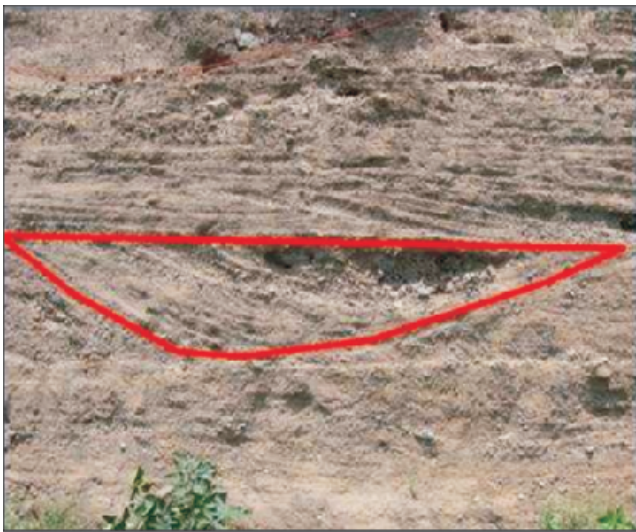


Fig. 8: Channel Cut (From Google Image gallery)



Fig. 9: Channel Overbank Levee (From Google Image gallery)

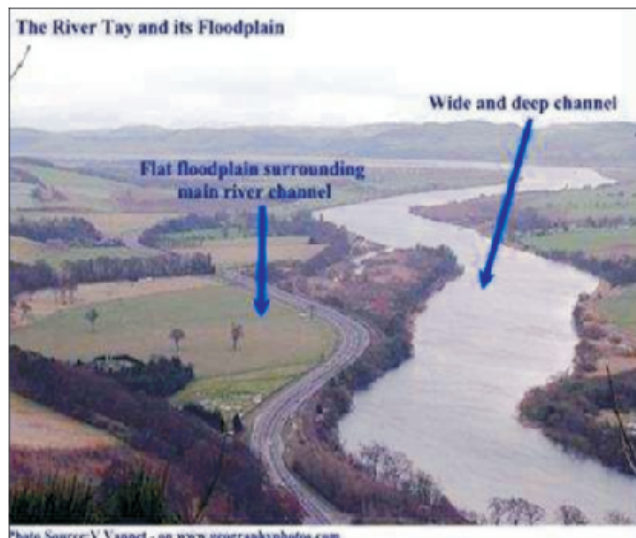


Fig. 10: Flood Plain (From Google Image Gallery)

Image Logging Application

The borehole microresistivity image log plays an extremely important role in heterogeneous clastic reservoir. The different high resolution output of Image log like bedding dip, image texture and the morphological pattern of cross bedding dip (Fig-11) gives an step by step procedure to identify the characteristics of sand body and its evolution within a sedimentary depositional setting.

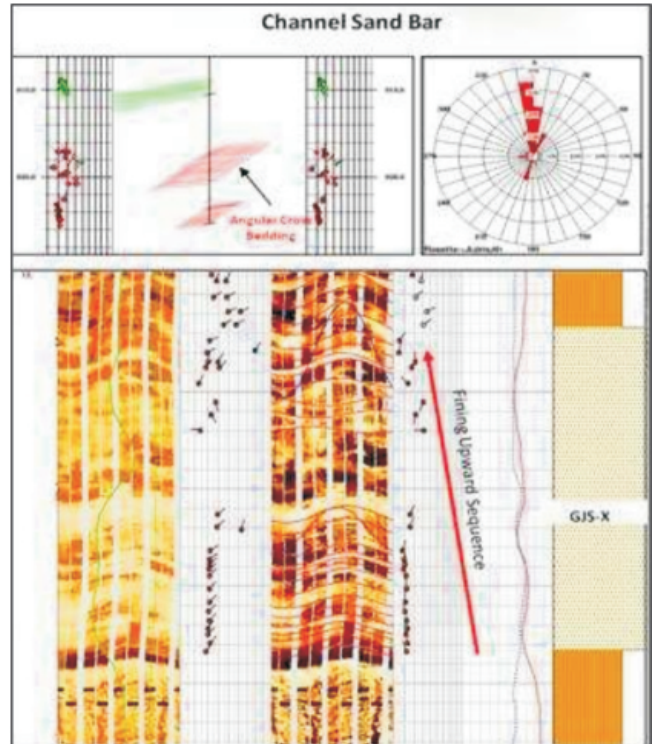


Fig. 11: Image log output to characterize sand body.

Workflow and Methodology

A workflow has been prepared (Fig-12) to characterize high resolution sedimentological facies and prediction of different flow unit from those facies. This workflow starts with the Image Processing and Manual Dip Interpretation followed by identifying different structural zones. From the different structural zones structural dip has been derived which has been used for structural dip removal. From removed structural dip data, detailed sedimentological analysis has been done which consists of identification of different sand body and first and second order paleocurrent analysis of cross bedding dip from each of the sand body. In the next step sedimentological modeling of cross bedding dip data has been done to understand the morphological variation between different cross bedding dipset and Image Core calibration was done to come up with a conclusive idea about the grain size variation along the image. Using all the out put from step by step analysis a robust high resolution sedimentary depositional facies have been created all along the borehole. Finally different flow units have been predicted using the existing permeability model in fluvial depositional environment and predicted flow units are compared with the petrophysical saturation model.

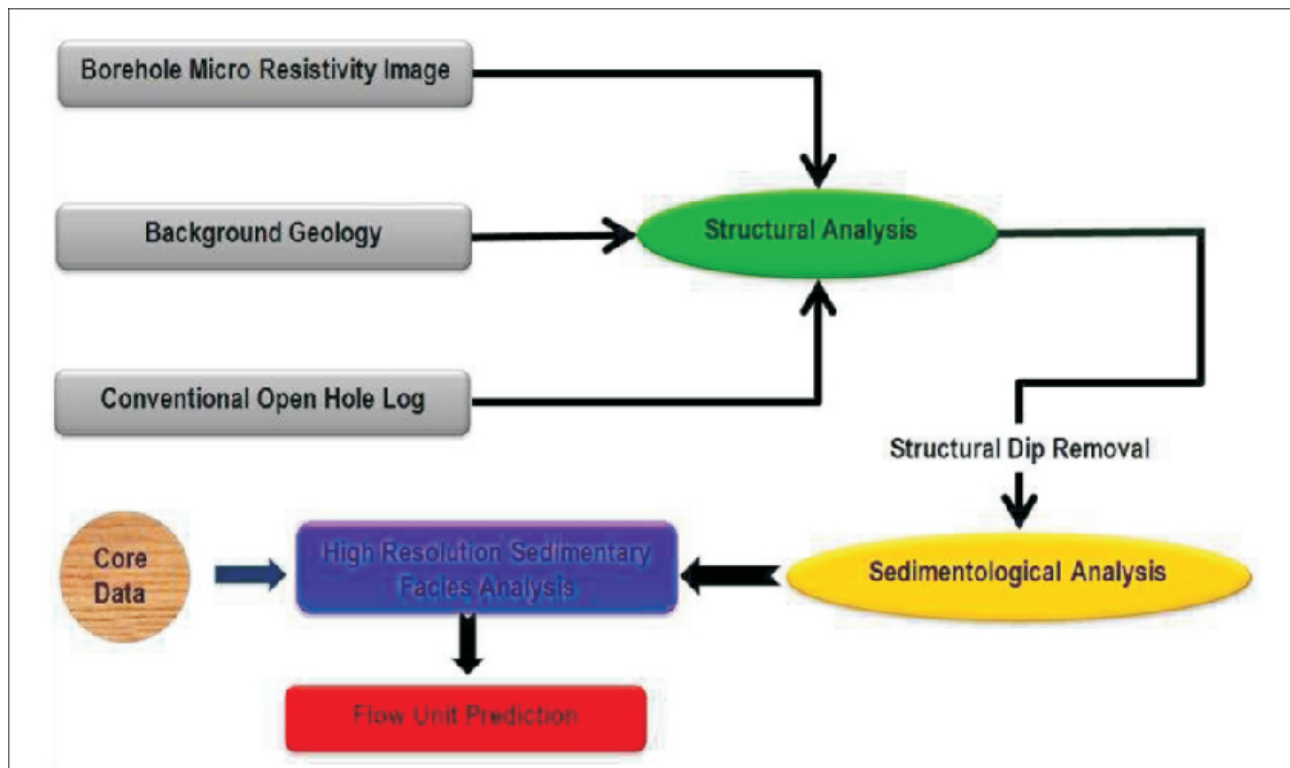


Fig. 12: Workflow

Structural Analysis

Structural dip is the overall regional tilt or the regional dip of a depositional basin, there may be structural deformations affecting the orientation of the paleo-sedimentary structure. It is therefore, necessary to determine the structural dip and remove its effect in order to obtain the original sedimentary structural orientation and paleo-current direction (Fig-13).

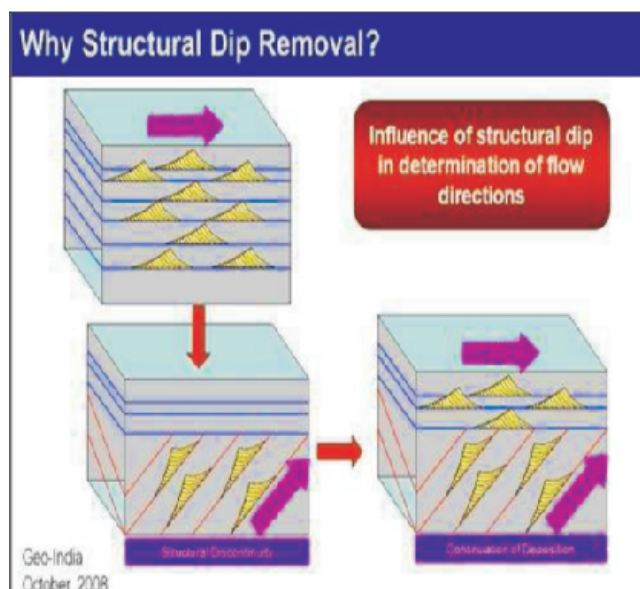


Fig.13: Importance of Structural Dip Removal (after, D.Roy et. al, 2008).

Structural Dip Removal

In the studied well initially from the shale and siltstone bedding/laminations dip different structural zones and their structural dip were determined. After determining the structural dip, structural dip removal process was carried out (Fig-14). In order to re-construct the sedimentary structure orientation, structural dips were, therefore, removed from the computed bedding dips. First, the regional South Eastward tilt from the whole section and then the North Eastward tilt from the lower zone were removed.

In the Fig-15-16, successively the effect of structural dip removal on the dip vector plot and different litho units has been shown.

Fig-15 shows that the orientation of dip vector plot changes from NE to NW after the structural dip removal whereas Fig-16 shows the disappearance of deformation effects after the structural dip removal.

Sedimentological Analysis

Paleo-current Analysis

The bedding dip orientation specially the cross bedding dip orientation gives very critical information about the paleo-current direction of the paleo-channel which deposited sandstone. The cross bedding dip angle and their distribution pattern gives an overall idea about the

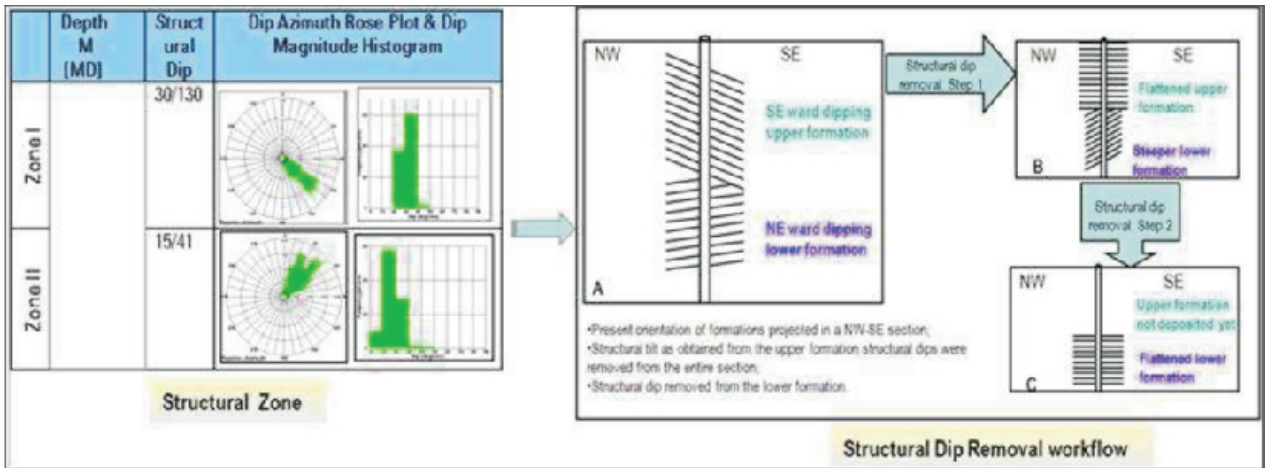


Fig.14 : Structural Dip Removal Process

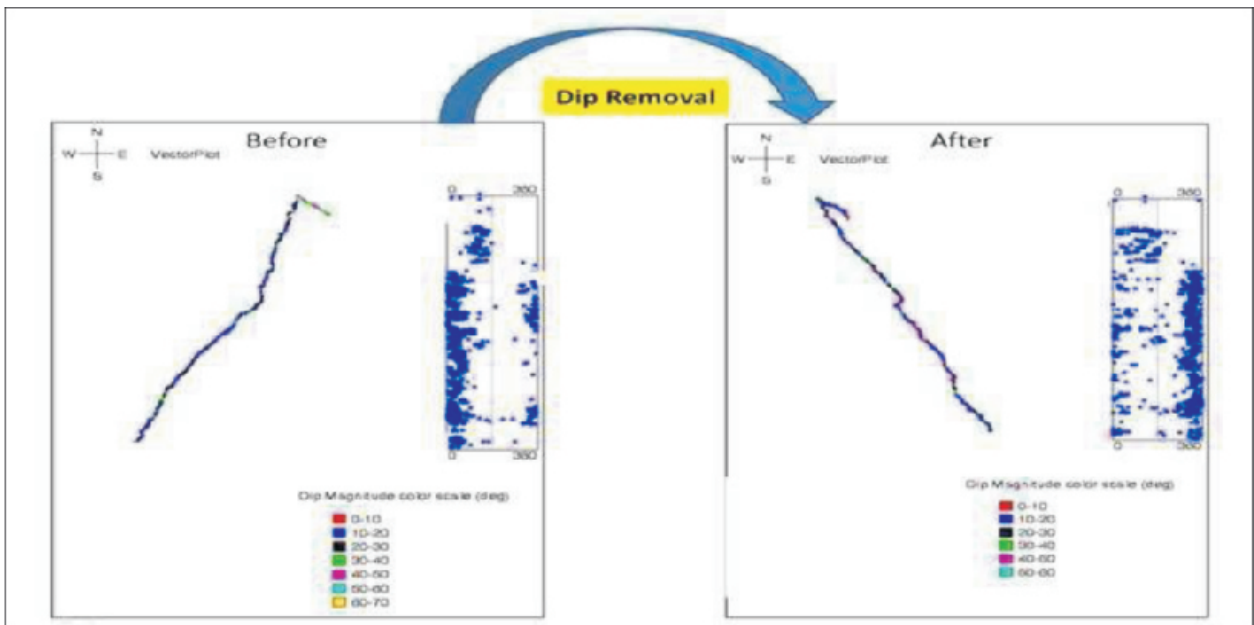


Fig.15 : Dip Vector Plot Trend before and after the dip removal process

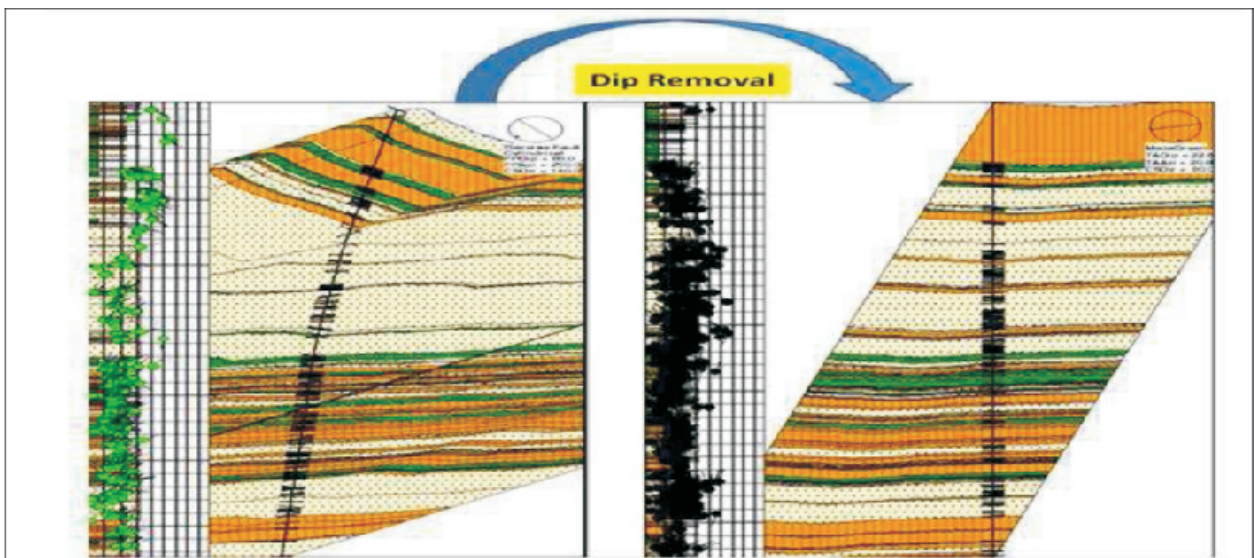


Fig.16 : Lithological Model before and after the dip removal process

Importance of Paleo-current analysis

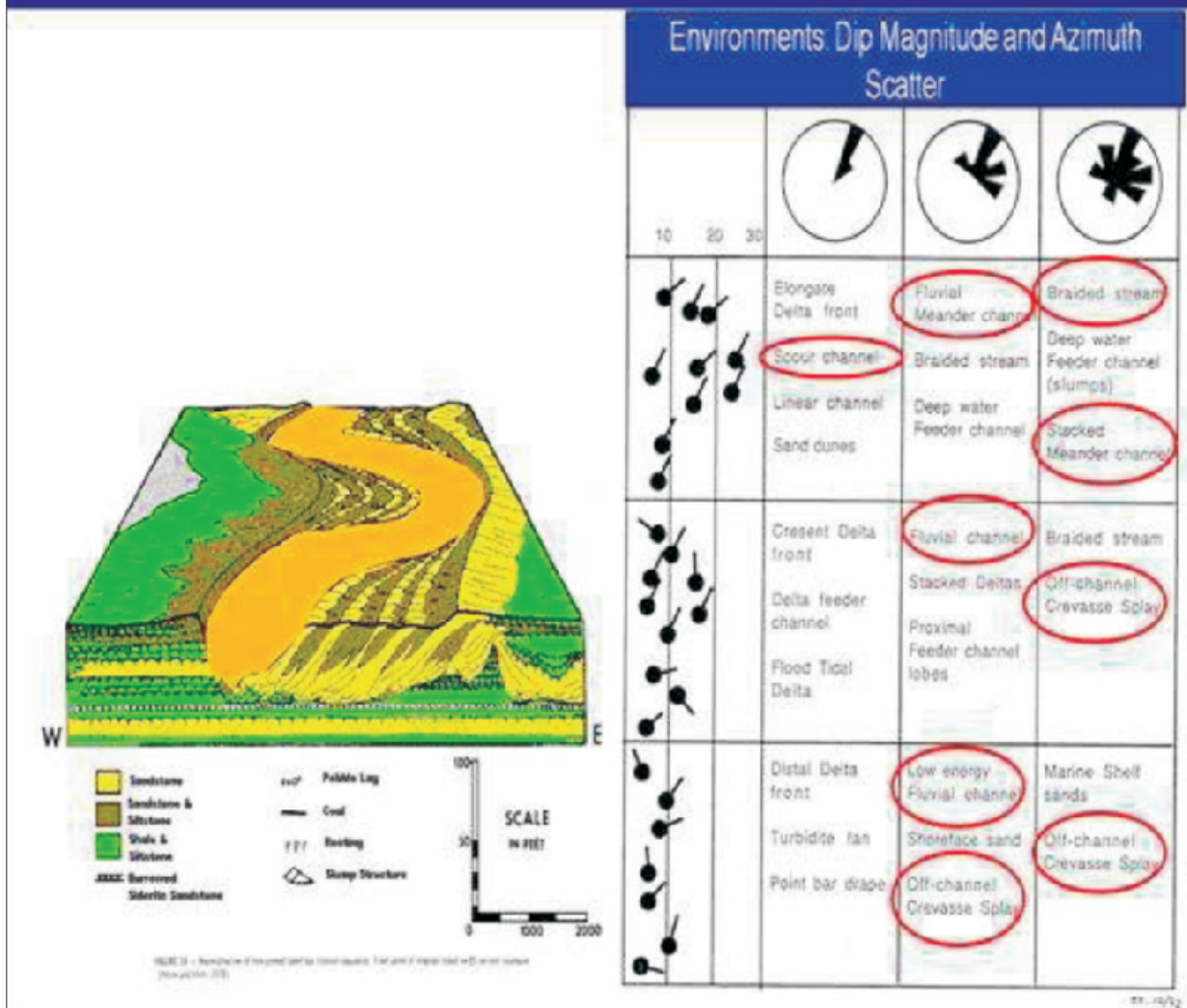


Fig. 17: Paleo channel model depends on the paleo-flow distribution pattern and the dip magnitude (after Horne and Fenn, 1978)

Paleo-channel morphology. In Fig-17, a schematic representation of the paleo-channel morphology identification technique has been described using the information of cross bedding dip magnitude and their paleo-flow pattern.

In this well, the association of bedding planes and cross-beds features were critically analyzed to understand the paleo-flow/sand transport direction. To carry out such an analysis in an extremely complex setting method of first order and second order segregation of cross-bed/lamination was done as mentioned below: First order paleo-current analysis of the cross-bed/lamination based on the different structural zones encountered in the well. Second order paleo-current analysis of cross-bed/lamination was completed based on major sand units identified in different structural zones.

Image Core calibration

Different geological facies identified in Image log from the well were critically compared and correlated with Core Image (Fig-18). From this calibration; a considerable amount of match has been found out in terms of the textural variation like grain size, bedding pattern etc. from both the Images.

Cross Bedding Modeling

Sedimentary Dip modeling carried out using the 2D sedimentary dip modeling software to visualize the cross bedding morphology throughout the interval. It is clearly seen from this study that the majority of the cross bedding are generally tangential and concave shaped (Fig-19) which are indicative of high energy current transportation.

Core-FMI* Image facies calibration

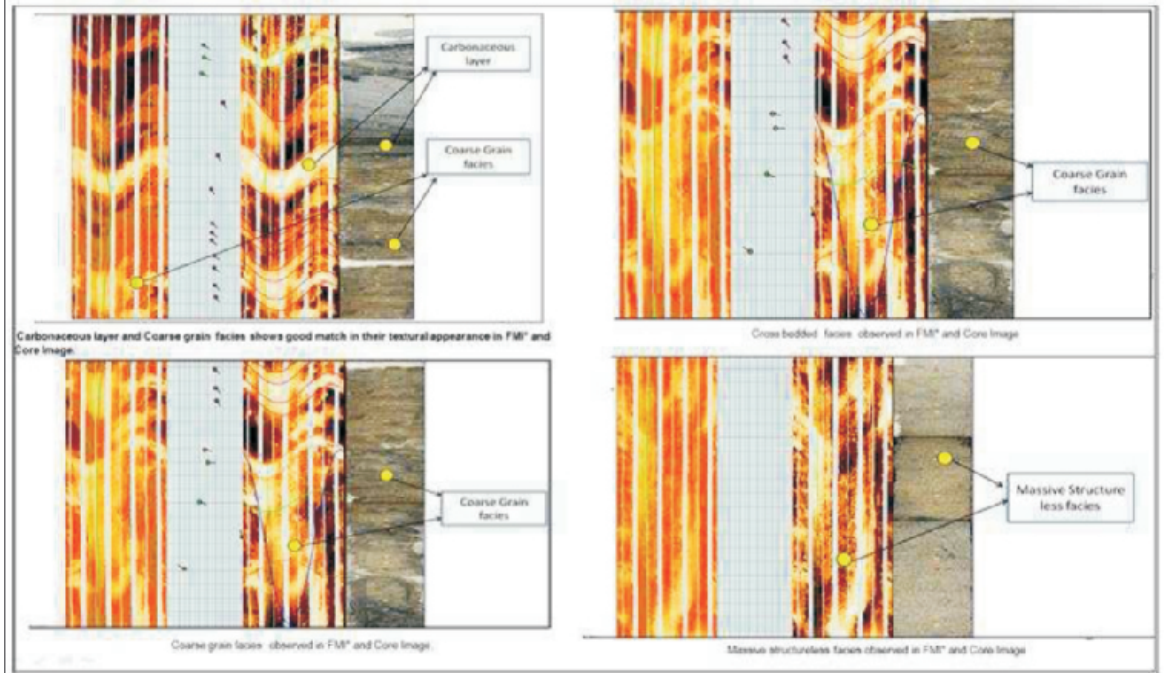


Fig. 18 : Core-Image calibration

Cross Bedding Morphological Modeling

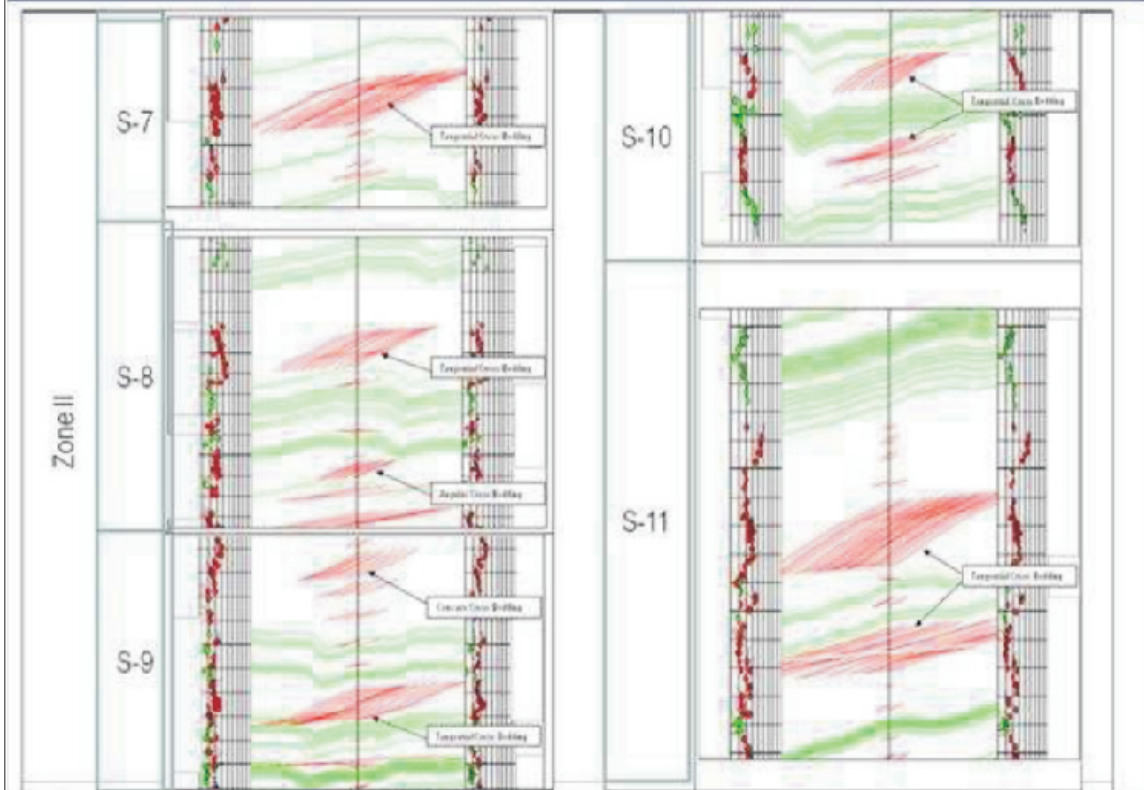


Fig. 19 : Cross bedding morphological modeling

High Resolution Sedimentary Facies Analysis

The formations were critically examined and all the major sand bodies in the formations that are identified and described are analyzed to understand and deduce the depositional setting for each sand body encountered. Also based on the different sandstone facies and their relationship with other facies in a vertical facies assemblage an effort was made to define different depositional distribution geometries like channel bar, channel overbank levee, stacking of channel bar and flood plain facies etc.

Predominantly silt deposits with sudden surges of sand body are observed. Silt units mostly exhibit planar bedded feature, whereas a few sand units show cross bedding. Syn-depositional deformation and bioturbation affected the internal structure of the rock. Higher angle dips are found in siltstone. Resistive calcareous nodule is observed in many places of the siltstone facies (Fig-20). From the facies association of low energy fine sediments; this interval can be interpreted as proximal levee deposits.

Cross bedded sandstone unit grades to the silty facies towards the top. Gamma Ray shows fining upwards sequence. The paleo-current analysis shows an unidirectional paleo-flow towards NW (Fig-21). From the facies association this sequence can be interpreted as channel sand bar deposit.

Predominantly cross bedded succession of stacked sand with some planar bedded intercalation is observed. An erosional base can be noticed at the base of each sand unit. Gamma Ray exhibits blocky nature. The paleo-current analysis shows an unidirectional paleo-flow towards NW (Fig-22). Individual sand unit shows decreasing dip amount with increase in depth. Core data shows cross bedding, coarse grained nature of sand and concentration of carbonaceous material, which is also identified in the images in the form of resistive beds. The facies association suggests that the sequence can be inferred as stacked channel bar deposit.

Predominantly shale litho-facies with variable siltstone content forming moderately defined planar beds is observed. Occasional sand surges are also observed in the facies. Syn-depositional deformation and bioturbation affected the internal structure of the rock. Higher angle dips are found in siltstone. Resistive calcareous nodule is

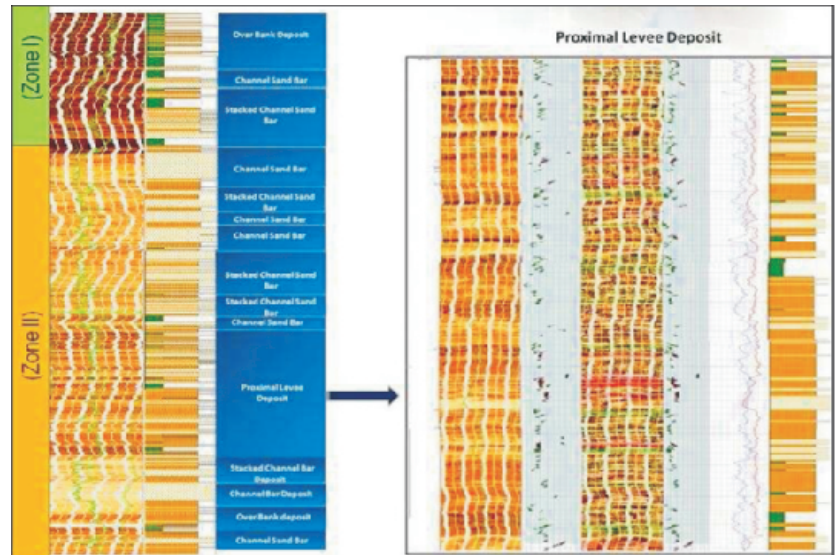


Fig. 20: Proximal Levee Deposit

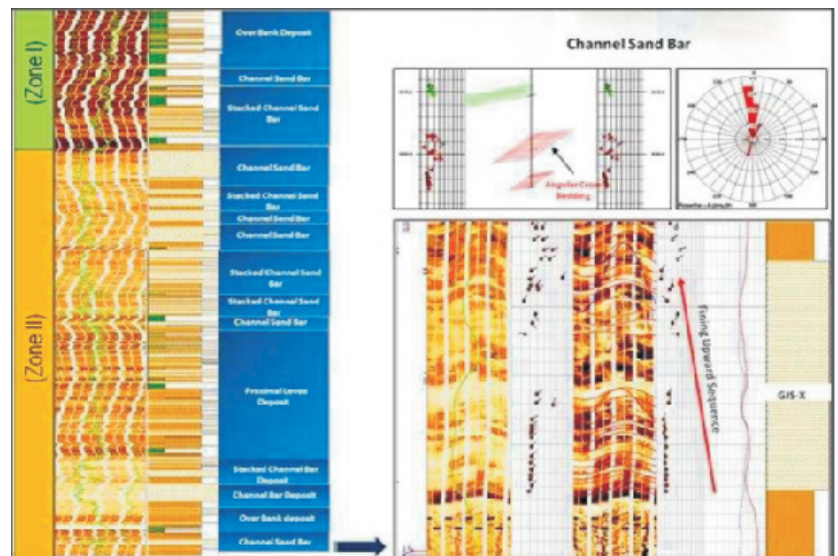


Fig. 21: Channel Sand Bar Deposit

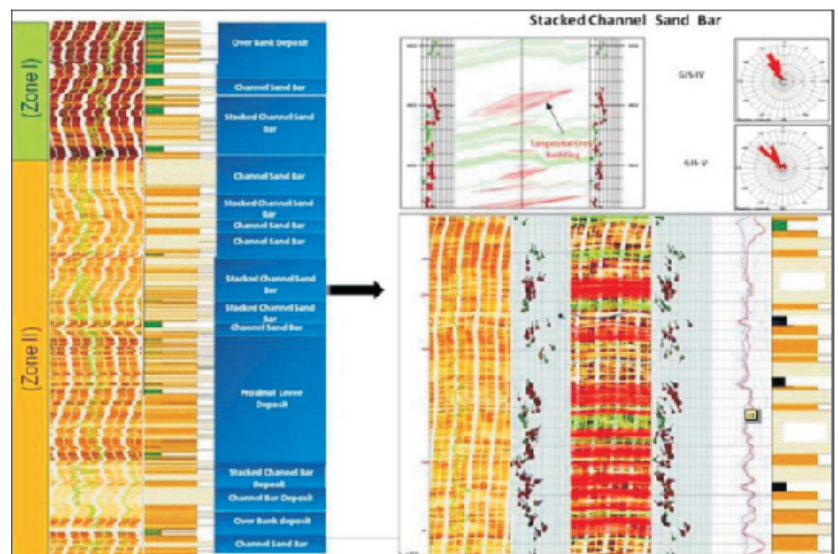


Fig. 22 : Stacked Channel Sand Bar Deposit

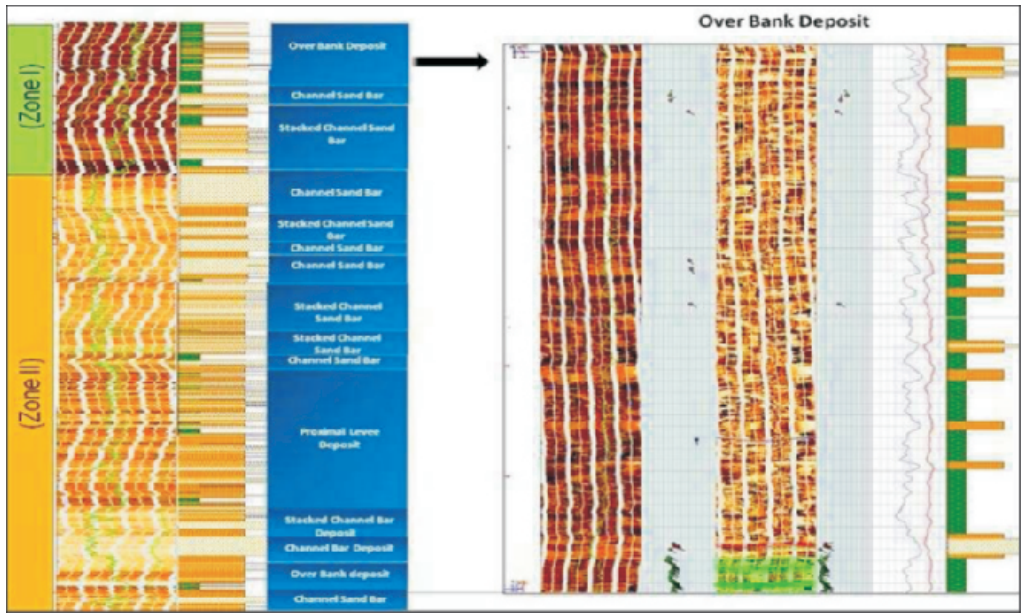


Fig. 23: Over-Bank Deposits

observed in many places. From the facies association of low energy fine sediments, the interval can be interpreted as over bank deposits (Fig-23).

Conceptual Depositional Analogue

In the studied well, overall four different depositional distribution geometries are interpreted; i.e, channel sand bar, stacked channel bar, proximal levee and over bank deposits (Fig-24). These facies are interpreted based on the sand-shale basal contact, nature of the sequence, i.e.coarsening up sequence or fining up sequence, image texture, bedding dip magnitude and their pattern.

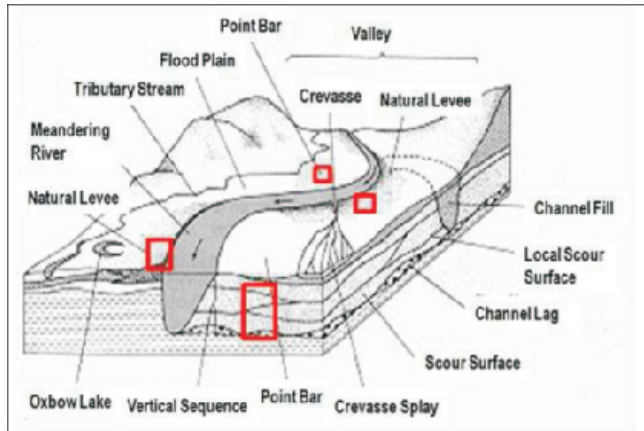


Fig. 24: Analogue Model of different depositional sub-environment observed in the studied well

Flow Unit Prediction

Permeability behavior of different formation depends upon the petrophysical property of rock. The distribution of shale or clay within sand and their proportion controls how easy a reservoir can flow fluid. Galloway and Hobday in 1983 (Fig-25) have proposed an empirical model which

shows the permeability within fluvial depositional system varies from channel sand to flood plain sand. The channel sand shows the best permeability whereas the flood plain shows the least permeability.

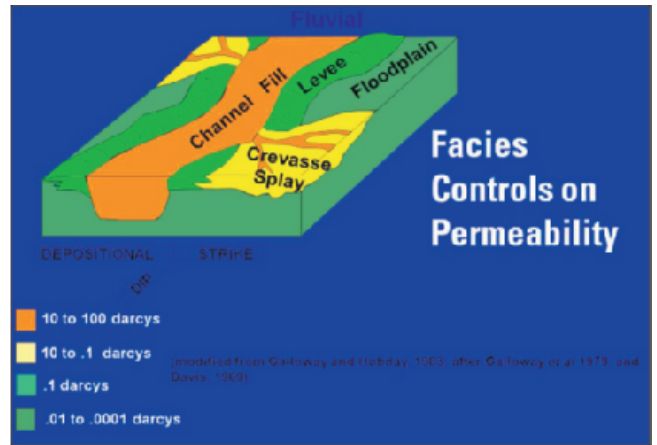


Fig. 25: Analogue model of facies controls on permeability.

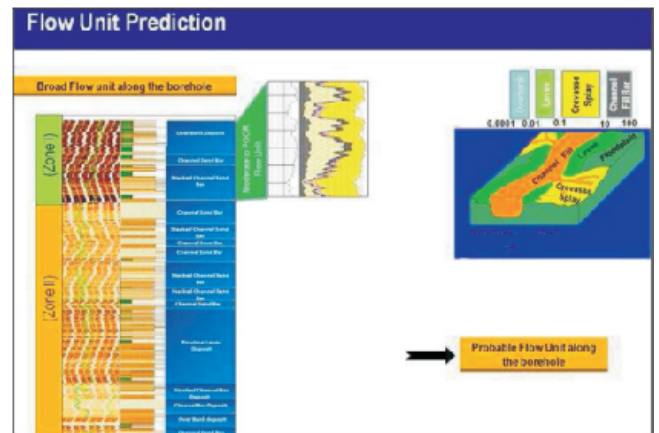


Fig. 26: Flowunit Prediction: Moderate to Poor Flow unit.

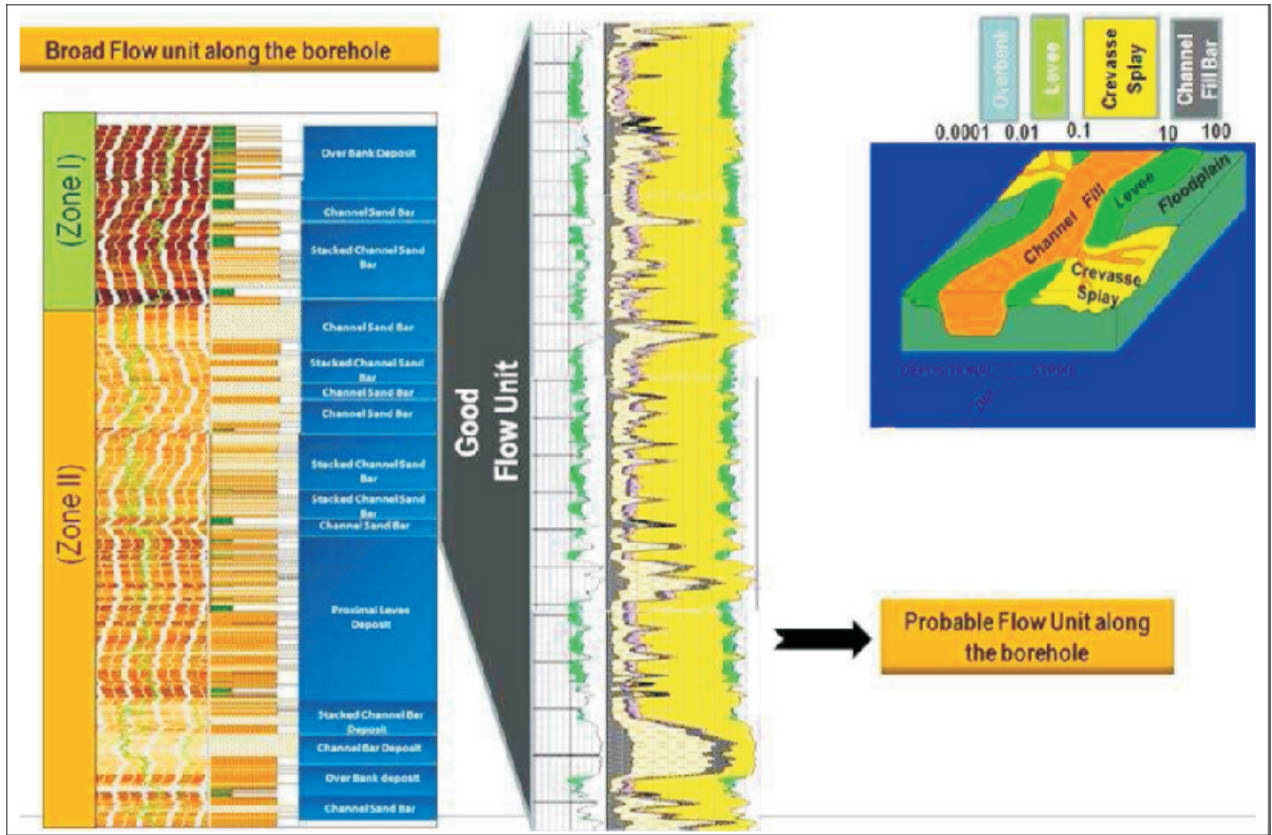


Fig. 27: Flow unit Prediction: Good Flow unit.

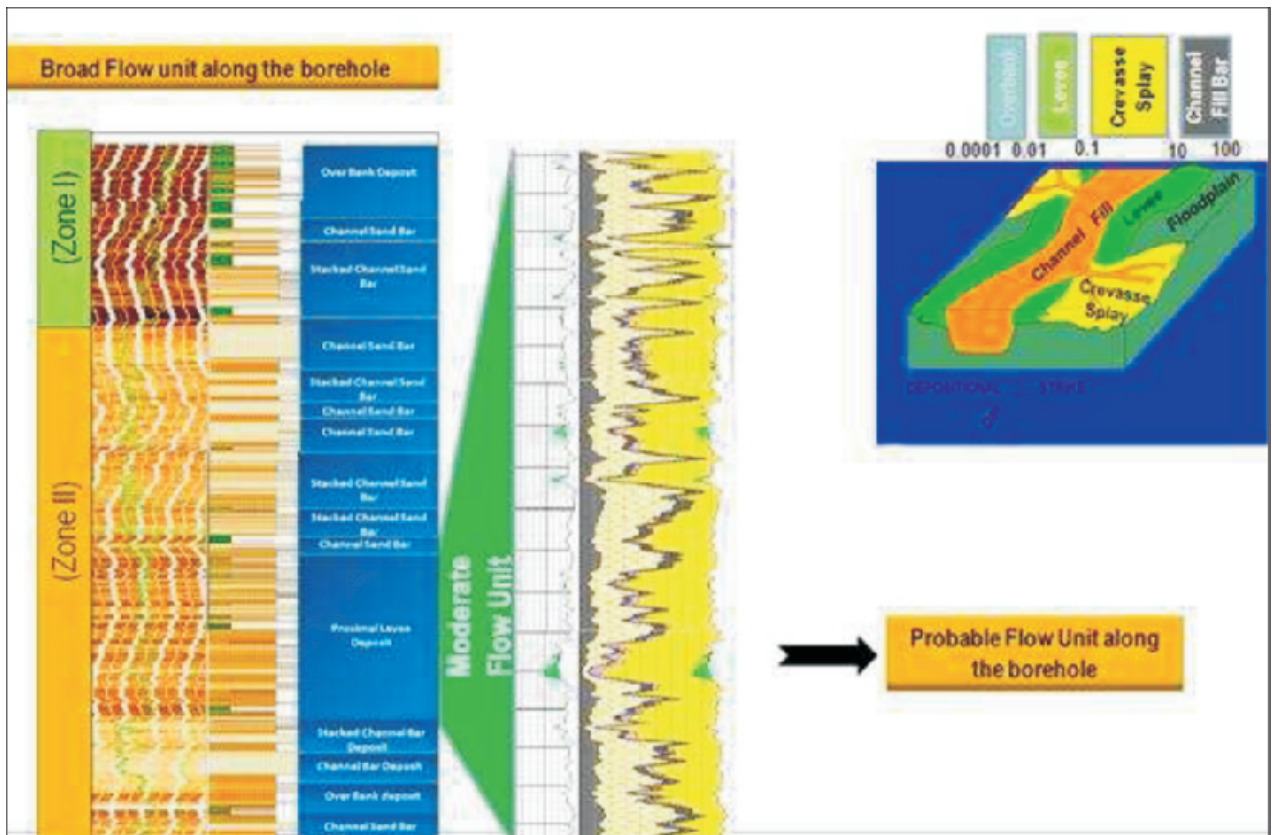


Fig. 28: Flow unit Prediction: Moderate Flow unit

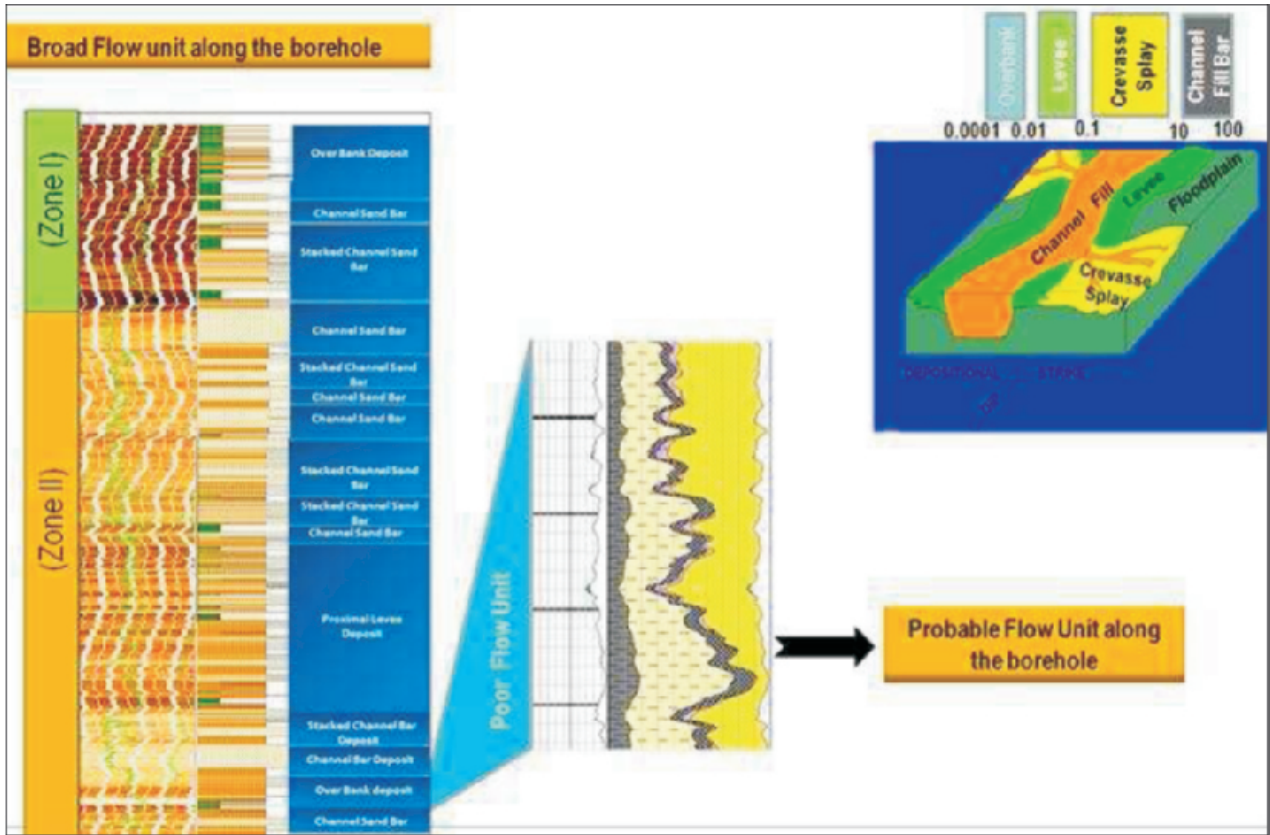


Fig. 29: Flow unit Prediction: Poor Flow unit.

In the Figure-26-29 different flow units starting from good flow unit to poor flow unit have been shown. Different flow units have been validated with volumetric result from petrophysical data.

Application

Understanding different depositional distribution geometries and facies using Image log combined with other advanced logs, help in selecting the best candidate sand for planning horizontal well for production optimization. Identification of paleo-flow direction of sand also helps in predicting the elongation direction of sand body which further helps in deciding the horizontal drilling direction.

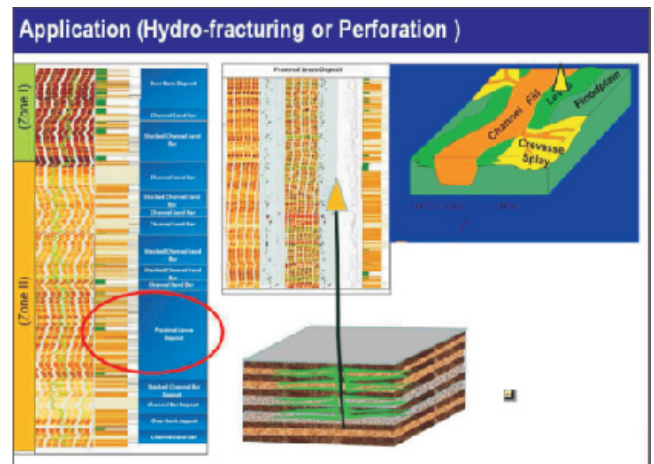


Fig. 31: Sedimentary facies analysis optimizing the hydrofracture designing

In the current well, channel levee sand is identified by the sand-silt alteration, image texture and dip pattern. Hydro fracturing is best technique compared to horizontal well to increase the vertical permeability of channel levee sand which ultimately helps in production enhancement.

Results and Discussion

This workflow depicts an interdisciplinary methodology to identify the sand dispersal pattern in fluvial environment. By identifying the sand dispersal pattern in a meandering system, reservoir quality of sand is understood and their flowing capacity has been estimated.

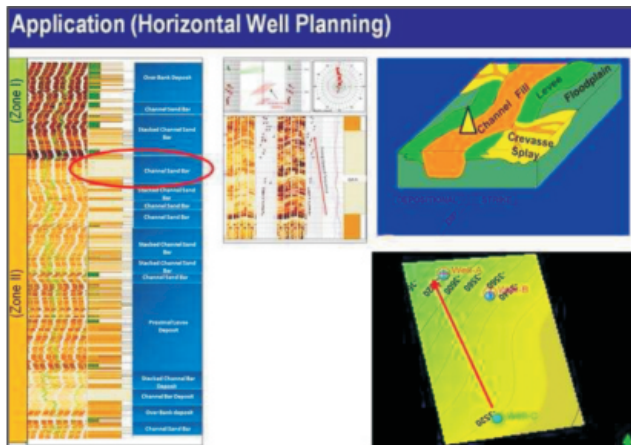


Fig. 30: Sedimentary facies analysis optimizing the planning of Horizontal well.

In the current study cross bedding modeling, Core-Image integrated data helped to understand the morphological pattern of cross bedding which are of mainly angular and tangential type. This angular and tangential cross bedding and the grain size information from core data indicates towards the high energy condition prevailed during deposition.

In the next step, the high resolution facies analysis is done which reveals the vertical succession of different sedimentary facies assemblage along the well. The facies assemblage varies from channel sand, point bar sand, and proximal channel levee sand to over bank sand. The relative distribution of sandy units across the different sub-environment within a meandering system gives a very good idea about the expected variation in reservoir quality.

Once the reservoir quality of different sand body is understood, a fair idea about the flowing capacity of different sand units can be established integrating with petrophysical analysis. In this approach the borehole section has been divided into good, moderate and poor flow units based on their facies assemblage within fluvial meandering system.

This flow unit characterization result can be immensely helpful for optimizing reservoir development strategy with integration of other petrophysical analysis.

This approach depicts an unique methodology to characterize different flow units according to their reservoir properties within a single well. Identified flow units based on the facies assemblage and sand body distribution will lead to best candidate selection for lateral well placement.

The established flow units can further be utilized for segmented completion and thus production enhancement from borehole.

Conclusion

- The enhanced workflow developed will convey significant impact on field development, providing a strong technical geological support for defining the accurate completion strategy.
- Identification of best flow unit in terms of reservoir quality will help in proper candidate selection for lateral well placement.

- Also, understanding the sand dispersal pattern will help in future well planning.
- This high resolution sedimentological and structural study will also help in upscaling the existing model with the help of available seismic and well data.

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