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An Integrated Approach to Characterize Karstified Eocene Carbonate Reservoir - A Case Study From Western Offshore Basin, India

Abstract

This paper deals with the characterization of highly karstified monotonous carbonate reservoir of Late Eocene age spreaded over an area of ~400 sq km in Neelam field on the western continental margin of India. Severe mud loss, unstable borehole condition, early water breakthrough/coning, gas coning owing to intense karstification, are the hurdles in the field development. Major challenges in reservoir characterization process were of four fold, to demarcate the karstification window, establishing hydrodynamic continuity within the fault blocks, electrofacies identification and its relation with karstification. In the present study an attempt has been made to model the zone of karstification by integrating well and sedimentological core data with the seismic attributes, electrofacies determination based on Principle Component Analysis and Cluster Analysis was carried out to bring out the sweet spots. Different hydrodynamic compartments were demarcated based on the analysis of Pressure-Production, Tracer study data. It explicitly established that the extent of karstification was the main factor for mud loss and water/gas coning problem. Integrating the heterogeneity from micro (Core level) to mega scale (Seismic) a static model was prepared which would be helpful in planning future well course, completion and identification of infill development locations.

Introduction

Neelam field was discovered in January 1987 and is located about 45 km west of the Mumbai coast, at about 55 m water depth and is the third largest field after Mumbai High and Heera fields of the Western Offshore basin of India. The field is about 28 km long and 14 km wide. The field is crescent shaped with two culminations in north & south, a gentle saddle in between bounded by N-S trending fault in the eastern side and defined by oil water contact at 1477m (MSL) at the western periphery. There are two structures Neelam-South & Neelam-North, on which 15 exploratory wells have been drilled. The first exploratory well was drilled in the southern culmination in 1986 and proved to be oil & gas bearing in Bassein Limestone. The second exploratory well was drilled in northern culmination in May 1987 and also proved to be hydrocarbon bearing in Bassein Limestone. Southern culmination was comparatively large in size and has a NNW-SSE trend while northern culmination has a NNE-SSW trend. In the eastern part, there is an N-S trending structural low. Both the culminations are connected with a common OWC of 1477m but different GOCs viz., 1402 m, 1450 m and 1454 m. (**Fig.1**). The field was put on production in March 1990 with 4 wells from platform ‘A’. At present there are 11 production platforms, 2 water injection platforms and total 216 wells including development, sidetracks and water injectors in the field. The field is divided in three sectors based on the production monitoring purpose viz., Sector A, Sector B and Sector C. While OWC is common to all the three sectors at 1477 m but depth of GOC is different for all three sectors. In Sector ‘A’ GOC is at 1402 m, in Sector ‘B’ it is 1450 m while in Sector ‘C’ it is at 1454 m. The field is currently producing oil @ 95000 BOPD with average 90% water cut.

The Bassein Formation is highly karstified/ fractured with connected vugs/caverns system. While drilling within the pay zone, severe mud loss and high permeability conductive bodies have been encountered. Water and gas coning and high water cut are the prime hindrance to implementation of development plan.

Geological Setup

Mumbai Offshore Basin came into existence on a divergent continental margin set-up. The basin was evolved through two stages, an early rift phase comprising narrow rift valley and proto-oceanic stage from Late Cretaceous to Early Paleocene, a post rift phase comprising shallow marine platform and open marine stage from Middle Eocene onwards. The basin depicted a horst-graben topography with NW-SE trends. Neelam Field falls in Heera-Panna-Bassein Block, which is a part of horst-graben complex and is flanked by Deccan Trap outcrops in the East, Bombay High East Fault in the West, Ratna North Fault in the South and Diu Fault in the North.

Bassein Formation is the main oil and gas producer in this field, deposited during Middle to Late Eocene period and it has thickness is about 550 based on electrolog correlation. Green House/Ice House periods and Milankovich Cycles impart variable sequence architecture on carbonate depositional cycle. It is globally established that carbonates deposited during Paleocene Eocene Thermal Maxima (PETM) and Eocene Thermal Optima (ETO) exhibit relatively thick low frequency cycles owing to low oscillation in sea level fluctuation. These carbonates often contain very low clay volume (<20%) with diagenetic enhancement of porosity at the top of the cycles due to exposure and destruction of porosity at the lower part. Bassein Formation also shows same kind of porosity architecture. At the top part it is intensely karstified due to a major unconformity at H3B level with comparatively tight middle and lower part.

Karst is described as diagenetic facies, an overprint in sub aerially exposed carbonate bodies, produced and controlled by dissolution and migration of calcium carbonates in meteoric waters. Karst is a 3-D drainage system, including integrated turbulent flow and involving waters of meteoric origin that 1) enhance pre-existing permeability networks by dissolution and mechanical erosion, and/or 2) reduce permeability by sedimentation and carbonate cementation (Satyanarayana, K., 1999). The main conditions for the karst formation are presence of paleohigh; presence of unconformity; decrease of sea level that create sub aerial conditions for carbonate dissolution. During Late Eocene period, Neelam field represents an emergent platform beneath the regional unconformity. With the metastable suite of carbonate rocks comprising of low magnesium carbonate and with the creation of permeable pathways it is most susceptible to karst development. All the processes and resultant products have been active in some stage or the other on the exposed Bassein Formation of Neelam field (**Fig.2**). This has resulted intensely karstified top level in Bassein Formation.

Hydrodynamic Compartment Identification

Initial OWC of the whole field was considered to be 1477m MSL and GOC were taken to be 1401, 1450 and 1455m MSL for sectors A, B and C respectively. But well by well analysis yielded that both OWC and GOC varied considerably from previous estimation. At places OWC was found to be as shallow as 1461m MSL and as deep as 1485m MSL. Wells NLM-C#E, NLM-D#D, NLM-C#C and NLM-C#F conspicuously showed initial OWC at 1485m MSL (**Fig.3**). Oil Rate (Qo) vs Cumulative Oil (Np) plot of wells NLM-C#E, NLM-D#D, NLM-C#C and NLM-C#F shows (**Fig.4**) very good correlation between themselves. Peaks and troughs in the oil rate curve in this plot showed in sync appearance. Pressure data also showed identical depletion pattern for the wells within same compartment but limited amount of pressure data in some wells is serious road block for this study. Therefore based on the initial fluid contact identified in the wells whole modelled area has been divided into 21 segments (**Fig.5**). For this purpose only the wells drilled prior to 1993 were considered since accelerated production started after 1993 and it was assumed that the initial fluid level was more or less maintained until 1993. Tracer study was conducted in this field during May 1996. Radioactive tracer was injected in the well WN-B#C and NLM-G#D and monitored in wells NLM-B#B, NLM-B#C, NLM-B#D, NLM-B#E, NLM-B#I, NLM-C#C, NLM-C#D, NLM-C#E, NLM-C#F, NLM-D#E, NLM-G#A, NLM-G#B, NLM-G#G, NLM-G#H, NLM-G#I, NLM-I#F and NLM-I#G. Start of Water injection, breakthrough of water and tracer is tabulated in Table 1. It was found that water and tracer breakthrough time for the wells within same sector takes less time than the wells in different sectors irrespective of the flow path length. In this figure the first number is the water injection breakthrough time and second one is tracer breakthrough time. It is to be noted that where water breakthrough had already occurred prior to tracer injection, tracer took less time to travel to monitor wells irrespective of sector since water had already made the flow path high permeable.

Electrofacies Modelling

Facies prediction in terms of petrophysical and flow parameter is the integral part of the reservoir modelling. To capture the uncertainty and explain fluid distribution and movement multivariate statistical analysis of well logs was adopted (Baveja and Ghosh, 2015). To identify similarities among rock types on different well log suits in multivariate log spaces and group into classes are the principal aim of multivariate statistical analysis. Different groups generated from this approach are also called electrofacies (Euzen et al, 2010). "Electrofacies symbolize a distinctive set of log responses which portrays properties of the rocks and fluids based on depositional, diagenetic and rock fluid interrelation characteristics" (Serra and Abott, 1982).

In the present study well log suite GR, DT, NPHI, RHOB and SUWI along with depth track on the wells drilled prior to 1993 have been considered. Log responses of pertaining to 130 m of Bassein section were screened out from the log suites on the basis of already identified seismogeological markers. Principle Component Analysis on the recorded log suites followed by K-Means Cluster analysis to identify and distinguish different electrofacies was adopted in this study. This is a two-step procedure and is discussed below.

Step 1: Principle Component Analysis (PCA) is a tool for the identification of patterns in the data. PCA summarizes the data effectively with the reduction of dimensionality without loss of information. In order to minimize the effect of scale and environmental effect, the entire log suite data was normalized by subtracting each value of recorded log suite from its corresponding mean and dividing by standard deviation (Lee and Dutta-Gupta, 1999). PCA was carried out on the normalized data to determine the optimum number of principle components.

Step 2: Cluster analysis was performed with the target to classify the data set in to groups in such a way that objects within the same group are internally similar to each other and externally desolated from the other groups in terms of measurement of similarity. In the present study, K-Means clustering technique was undertaken to identify the distinct groups based on the well log measurement. K-Means clustering algorithm was chosen because of its robustness, easy to apply and it works without any priori information (Kuroda et al., 2012). Each cluster treated as electrofacies, represents unique hydrological, lithological, depositional and diagenetic characteristics.

PCA followed by cluster analysis yielded 4 facies types (**Fig.6**) viz., High-Porosity-HydroCarbon (HPHC), Low-Porosity- HydroCarbon (LPHC), High-Porosity-Water (HPW) and Tight (Tg). Crossplot of Effective Porosity and Acoustic Impedance coloured with electrofacies showed HPHC was having high porosity and low impedance while Tg was having low porosity and high impedance. HPW superimposed on HPHC also showing high porosity and low impedance but when we restricted the plot up to 1477m MSL, HPW facies vanished. Since below 1477 m only water was present within the pores and the rock was equally porous.

For the modelling of electrofacies first Posterior Probability Distribution Function (PDF) of the 3 electrofacies given P-Impedance was generated (**Fig.7**) and facies was populated in the model using this probabilistic approach. Flow chart for facies modelling is placed at **Fig.8**. Electrofacies model thus generated served as the bias for the petrophysical property population.

Karst Facies Modelling

The different karst facies viz., highly karstified, moderately karstified, chalky alteration and massive country rock in the studied cores were standardized with the Caliper, Gamma Ray, Density, Porosity logs. Facies were identified based on core and cutting analysis as per the sedimentological studies. An upper intensely karstified zones comprising predominantly of cave collapse and filled breccia which grade downward to a zone of unaltered but fractured country rock. This zone is followed by a chalky karst zone, comprising predominantly of altered chalky/marly country rock with minor proportions of breccia. This zone is followed downward by massive rock with minor fractures and finally underlain by unaltered massive country rock. This sequence forms an idealized karst profile in the upper part of Bassein Formation in Neelam field. A perspective view of Bassein structure with karstification zonation is shown in **Fig. 9**.

For the propagation of karst facies four karst facies i.e. highly karstified, moderately karstified, chalky and massive country rock has been clubbed into two facies viz., Highly Karstified and Non-Highly Karstified as on the impedance domain the other three facies was not discernible. Posterior Probability Distribution Function (PDF) of the karst facies given P-Impedance was generated for the model section (**Fig.7**).

Karstified zones are the zones of high porosity and permeability. During drilling these are the zones where excessive mud loss occurs and if the well is completed in these section gas/water coning happens at very early life of well. This karst volume it will serve as the guide to steer the future wells to avoid highly karstified zones .

Petrophysical Modelling

Porosity model was conditioned to seismic data using collocated co-krigging since P-impedance shows linear and inverse relationship with effective porosity (PHIE) in clean limestone. Gaussian Random Function Simulation (GRFS) using collocated co-krigging was performed taking P-Impedance as the secondary variable. For saturation modelling first height above contact volume was prepared for each zone (segment wise) by taking log based fluid contacts for each zone (segment wise). Saturation modeling was done through xyz krigging algorithm taking the height above contact as the secondary trend (**Fig.10**). In the blind wells saturation at the top parts shows good match but at the lower part match deteriorates. This is due to the fact that most of the blind wells drilled much after the production started therefore the poor match at the bottom is the effect of depletion.

Conclusion

In this paper an effective workflow is discussed for the characterization karstified carbonate system. This approach is suitable for the characterization of Green House Carbonates. Carbonates deposited during Green House episode are massive in nature and clay contain is also very low clay. Therefore the compositional heterogeneity is very low in Green House Carbonates. This kind of carbonates exhibit heterogeneity in terms of porosity architecture as their original porous framework is often altered/obliterated due to secondary processes such as diagenesis. Identification of the diagenetic imprint in normal log interpretation is extremely difficult job and often it remains undetected. Electrofacies approach helps to identify the sweet spots as this brings out the fluid-rock, rock-rock interrelationship by the multivariate analysis. Generally karst system corresponds to the best electrofacies. Karst facies modelling approach presented in the present study increases the confidence.

In the present model karst facies model serves as the guide to steer the future well course for better placement, suitable completion, reduce the mudloss effect and gas/water coning phenomenon. Electrofacies model coupled with porosity and saturation would be immensely helpful to identify infill development location and side track locations of sick wells.

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References

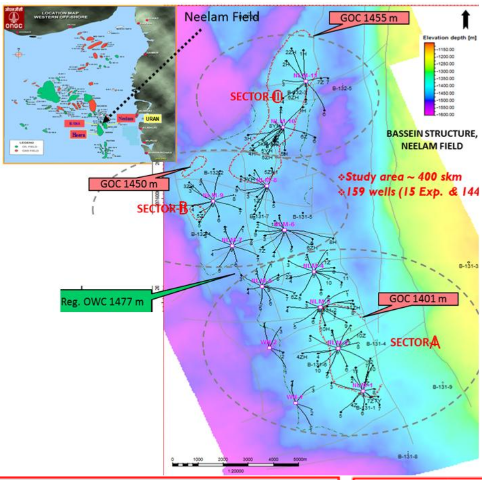
Baveja, A. K. & Ghosh, Aninda. (2015). Smart way to finalize Development Drilling Locations by Electrofacies Analysis and validation by Reciprocal Productivity Index Method- Case study from heterogeneous clastic reservoir from Gas field of Tripura. *In GeoIndia 2015. 3rd South Asian Geosciences Conference and Exhibition. New Delhi India*, Paper Id – 1995647.

Euzen, T., Delamaide, E., Feuchtwanger, T., & Kingsmith, K.D. (2010). *Well Log Cluster Analysis: An Innovative Tool for Unconventional Exploration*. *Society of Petroleum Engineers*. doi:10.2118/137822-MS

Lee, S. H., & Datta-Gupta, A. (1999). *Electrofacies Characterization and Permeability Predictions in Carbonate Reservoirs: Role of Multivariate Analysis and Nonparametric Regression*. Society of Petroleum Engineers. doi:10.2118/56658-MS

Kuroda, M. C., Vidal, A. C., Leite, E. P., & Drummond, R. D. (2012). *Electrofacies characterization using self-organizing maps*. *Revista Brasileira de Geofísica*, *30*(3).

K. Satyanarayana (1999). Paleokarst Process Response Model of Bassein Formation B-zone Upper, Neelam Field. *ONGC Unpublished Report Integrated Geological Lab. Study, RGL Mumbai*.



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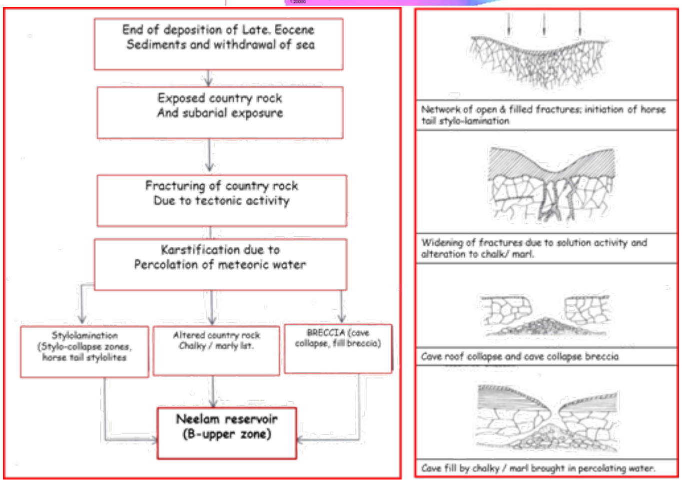


Fig.2: Schematic representation of Karst Process

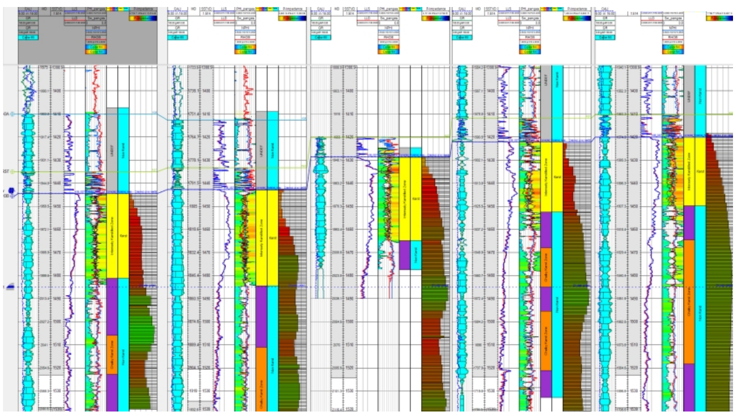


Fig.3: Hydrodynamic Compartment identification based on initial fluid contact

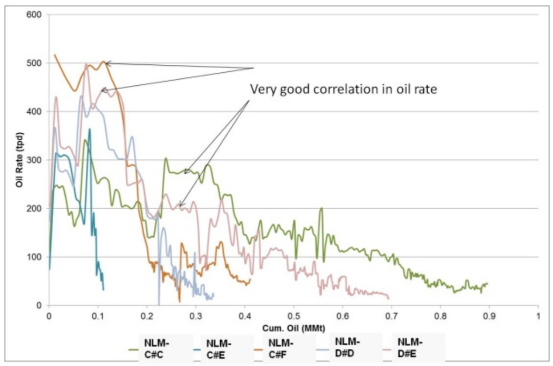


Fig.4: Hydrodynamic Compartment identification based on Production analysis

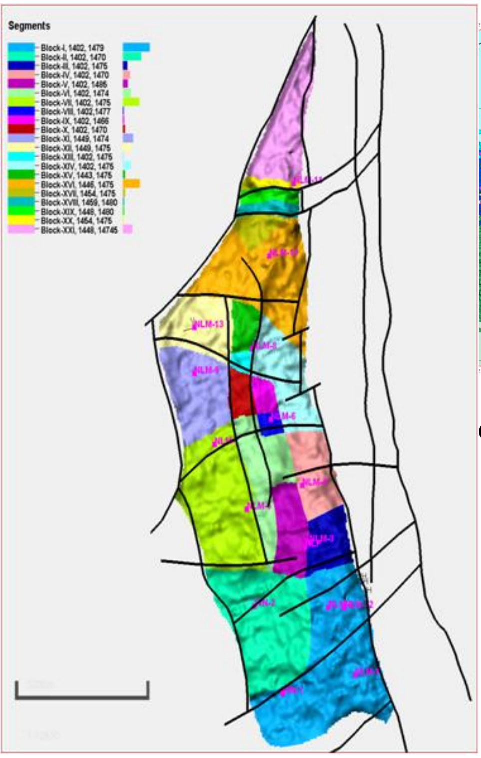
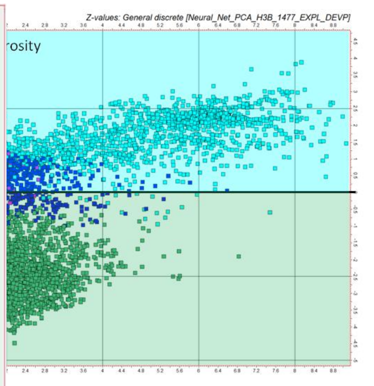


Fig.5: Identified Hydrodynamic Compartment in Neelam Field



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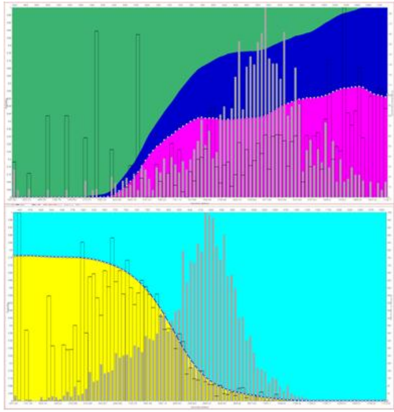

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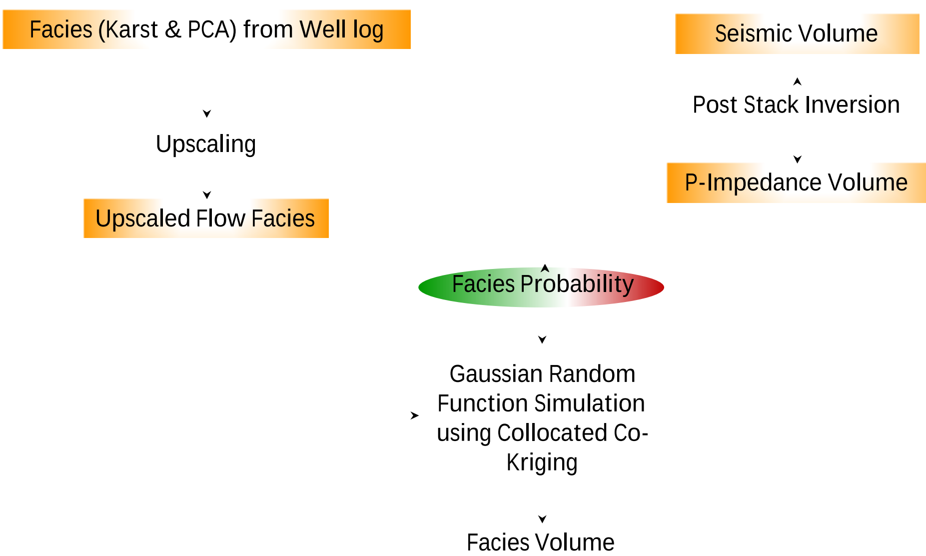

Fig.8: Flow Chart for facies modelling

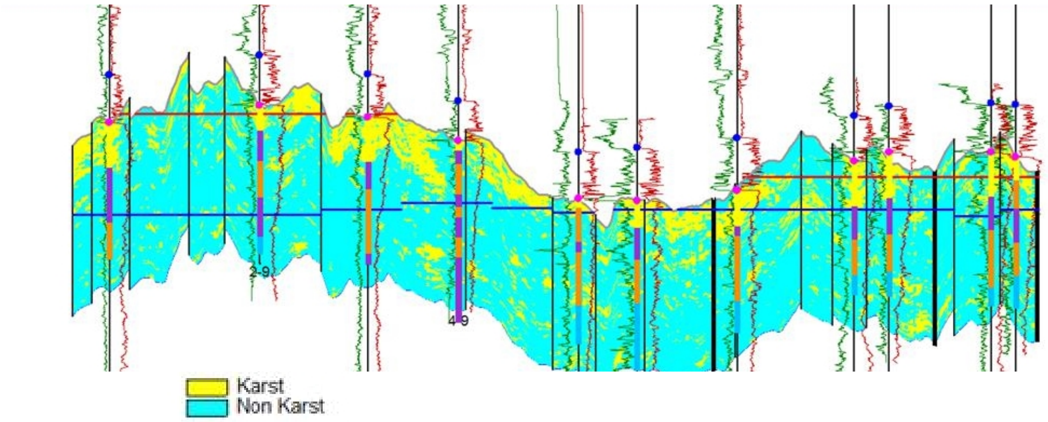

Fig.9: Perspective view of karst facies model

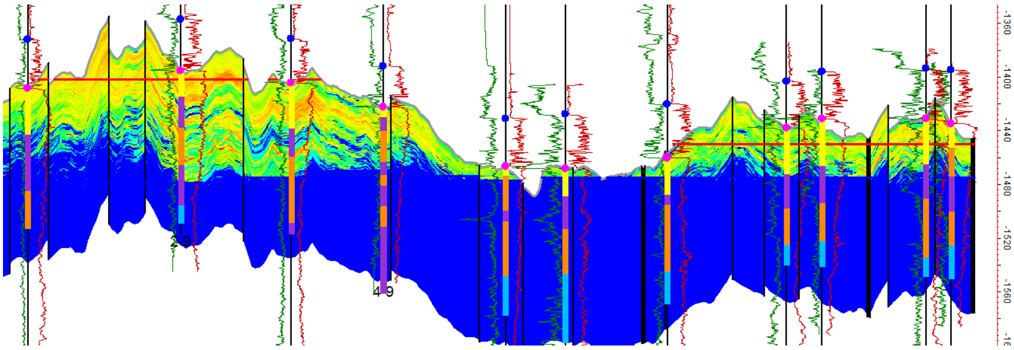

Fig10: Perspective view of Saturation model