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Effect of Clay Mineralogy on Velocity trends and Its Implication on Pore Pressure Prediction: A case study from Deep-water Offshore Cauvery Basin, India.

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Abstract

In deep-water Cauvery offshore basin, the compressional sonic logs from the drilled wells shows significant lowering of velocities in Paleocene stratigraphic sequence in comparison to the overlying Eocene section. Since the dominant lithological facies in the Paleocene were of claystone, the general reason for such velocity lowering was earlier assumed to be compaction disequilibrium. This assumption invariably led to prediction of moderate to high pore pressures in low velocity Paleocene section during predrill analysis, which in turn demands extra casing and higher mud weights for safe drilling practices. However, real time well events and well behavior of drilled wells do not support the presence of such moderate to high pore pressures within the Paleocene stratigraphy.

In the present study, attempt has been made to bring out the cause behind this substantial velocity lowering observed in Paleocene stratigraphy through establishing velocity relationship with the change of dominant clay mineralogy. Analysis of Spectral gamma ray (SGR) log and X-ray diffraction data (XRD) data shows direct evidences of change in dominant clay mineralogy from Kaolinitic rich in Eocene section to Smectite-Mixed type in the Paleocene section. Experimental compactions studies have already shown that smectite rich clays are less compressible and tend to have lower velocities and permeability than the kaolinitic rich clays. By attributing the low velocity nature of Paleocene stratigraphy to the change in dominant clay mineralogy rather than to compaction disequilibrium related overpressure, the results of this study has helped in reducing the uncertainty in pore pressure estimation for Paleocene sequence. Additionally the study has also helped in optiminsing the well design for future planned wells, which resulted in significant saving in terms of well cost and rig time.

Introduction and Purpose of Study

Compaction of claystone is strongly influenced by their clay mineralogy, effective stress, and the time-temperature history (Bjorlykke.K, 1998, Marcussen et.al. 2009). It has been shown that argillaceous sediments change their physical properties such as velocity, density and porosity during burial in response to both changes in clay mineralogy as well as change in compaction processes i.e. from mechanical compaction to chemical compaction (Bjorlykkr, 1998; Mondol et.al., 2007). Experimental mechanical compaction studies have shown that Smectite rich clays are less compressible and have lower velocities and permeability than the Kaolinitic rich clays (Mondol et al., 2007). Since changes in clay mineralogy can affect the compaction processes, it effectively deviate the compaction indicators like velocity and porosity curves from their Normal Compaction Curve (NCC). Any such deviation from NCC will results in the estimation of either overpressure or subnormal pressure using standard velocity based pore pressure prediction techniques. Therefore awareness and causes for such deviations from NCC must be thoroughly understood to reduce the uncertainty in pore pressure prediction.

Within the study area (**Figure.1**) of Cauvery offshore basin, the seismic and compressional sonic logs from drilled wells show substantial lowering of velocities in the Paleocene stratigraphic unit from its NCC (**Figure.2**). Furthermore seismic signature of Paleocene sequence shows relatively blank to very low amplitude facies. This is visibly different in comparison to shallow Tertiary and deeper Cretaceous sequences (**Figure.3**). Since the dominant lithofacies in Paleocene are of claystone, the observed velocity lowering invariably led to the prediction of medium to high geopressures (10 – 12 PPG) in Paleocene. These elevated pore pressure estimates in the Paleocene demands extra casings in the well designs for safe drilling practices. Initially the cause for this velocity lowering was presumed to be because of overpressure. However the analysis of real time well behaviors and well events i.e. drilling parameters and mud log data from drilled wells does not support the presence of high pore pressures (10 - 12 PPG) in Paleocene section at least within the study area. Hence, the purpose of this study is first to establish a reason other than overpressure for the observed lowering of velocities in Paleocene section and secondly to minimize the uncertainty in predrill pore pressure estimation for future wells by modifying and calibrating the NCC parameters with the actual well behavior and well events.

Data and Methods

Five deep-water wells (Well A, B, C, D and E) plus one test well (Well X) from offshore Cauvery basin were studied for this project. Velocity logs (Compressional Sonic) along with stratigraphic tops were used to identify the zones of velocity lowering. Spectral Gamma Ray (SGR) logs and X-ray diffraction (XRD) data from sidewall cores have been analyzed to identify the possible changes in clay mineralogy as we move from Eocene to Paleocene sequence. Out of 5 wells, 4 wells (Well A, C, D, and E) have complete SGR log data in the zone of interest whereas only two wells (well A and B) have XRD data available in the zone of interest. Since the focus of this study is to understand the effect of clay mineralogy on velocity, all data from intervals containing significant amount of sands were discarded.

Spectral Gamma Ray tools are designed to separate the distinctive energy peaks of the individual radioactive elements, i.e. Uranium (U), Thorium (Th) and Potassium (K). Authors (Quirein, et.al. 1982 and Doveton, 1991) have suggested that dominant clay types can be identified by plotting cross plots of Thorium, Potassium, and Uranium ratios. X-ray diffraction method on the other hand provides quantitative whole rock (bulk) and clay mineralogy (<2 µm) estimates in terms of weight percentage. Though XRD analysis were carried out on sidewall core samples of 4 wells (Well A, B, C & E), only two wells (Well A & B) have samples from Eocene to Paleocene age.

Results of Velocity, SGR and XRD Analysis

Velocity (Compressional Sonic) trends as a function of burial depth for 5 studied wells are shown in **Figure.2**. Optimum normal compaction curves are also shown for each well. It can be clearly seen in **Figure.2** that in all the wells velocity trend shows consistent increase vis-s-vis burial depth upto the top of Paleocene. However, as we enter into the Paleocene sequence velocity data shows a reverse trend i.e. lowering of velocities in comparison to its NCC.

SGR log data plus the standard ratio plots (Th vs K and Th/K vs Th/U) of 4 well are shown in the **Figure.4, 5, 6, and 7**. For well A, **Figure.4** shows trends of Thorium and Potassium concentrations for Eocene and Paleocene section. The ratio plots, Th vs K and Th/K vs Th/U for both Eocene and Paleocene sections suggest that dominant clay type in Eocene is of Kaolinite nature whereas in Paleocene section it is dominantly of Smectite nature. This indicates a change in the dominant clay type from Eocene to Paleocene section. Similar trends are also observed in the Well C and Well E (**Figure.5 and 7**), however in well D, the ratio plots (**Figure.6**) do not show significant change in dominant clay type.

Analysis of XRD data for Well A and Well B is shown in the **Figure.8**. In well A, the dominant clay type in Eocene sample is Kaolinite (more than 50% of total clay), whereas in the Paleocene sample Smectite–mixed layer is dominant clay type (more than 42% of total clay). Similarly in the well B, Kaolinite clay type is dominant in Eocene sample (more than 51% of total clay), whereas in Paleocene sample Smectite–mixed layer clay is dominant (more than 46% of total clay).

Results of both SGR and XRD analysis suggests that there are direct evidences supporting the change in dominant clay type from Kaolinitic nature in the Eocene section to Smectite-mixed layer in Paleocene section. Based on these results, NCC parameters for Paleocene section are modified and calibrated in order to get the reliable pore pressure estimates in the drilled wells. The modified NCC parameters are then used for pore pressure estimation in a test well.

Implication on Velocity Based Pore Pressure Prediction

Normally occurrence of overpressure has been associated with the Smectite rich claystones, primarily because of their low compressibility, less permeability and higher porosity in comparison to other clay minerals assemblages (K. Bjorlykke et.al 2009). Low compressibility in Smectite rich clays results in low velocities, which may in part be due to bound water, extremely high surface area and very fine grain size (Mondol et. al 2007). However, numerical modeling studies show that smectite rich sediments should reach to a critical level of permeability in order to generate high pore pressures (Wangen. 2002, Marcussen. et.al. 2009).

Since both processes i.e. overpressure and change of dominant clay type can lower the velocities in smectite rich claystone, identifying the actual cause of velocity lowering can be done with the proper evaluation of well behavior and its integration with clay type identification methods (SGR and XRD). Pore pressure prediction in Cauvery basin prior to understanding the effect of clay mineralogy on velocity in Paleocene section tends to generate medium to high pore pressures with standard velocity based pore pressure prediction methods of Miller and Eaton. Miller method was used in the present study. As all the wells have been drilled with lower to equal mudwieghts (10 – 11 PPG) than the estimated pressures (10.5 – 12 PPG), it was clear from well behavior and well events that the pore pressures in Paleocene section at the study area are lower than what has been estimated using a single parameter NCC (**Figure.9**), which most likely to overestimates the pore pressure for Paleocene section. After it is established that the main cause for lowering of velocities in Paleocene is because of change in dominant clay type rather than overpressure, plus the fact that Smectite rich clays will have a different compaction then the Kaolinitic rich clays, the apparent log driven high pore pressure estimates were normalized by using a dual parameter NCC, i.e. using separate Compaction parameters for Smectite rich Paleocene section. This approach of using dual parameter NCC results in pore pressure estimation which is reliable and are in line with the well events and well behavior in all 5 drilled wells (**Figures.9**).

Test Case of Dual Parameter NCC

The dual parameter NCC approach is subsequently used in the next planned well (Well X) in the study area. As with the previous wells, in Well X too the predrill pore pressure derived from seismic velocities using a single parameter NCC showed medium level pressures (9.2 – 10.2 PPG) in the Paleocene section (**Figure.10**). Initial well design for this pore pressure profile shows the requirement of at least 6 casings to reach the final depth (**Figure.10**). However, with the application of dual parameter NCC (i.e. separate parameters for Smectite rich Paleocene section) the velocity driven pressures were normalized to a lower range (8.9 – 9.4 PPG) in the Paleocene section. The updated pore pressure profile enables us to deepen the planned 17-1/2" section by more than 400m, thereby utilizing only 5 casings in the final predrill well plan (**Figure.10**). In the real time the well was successfully drilled through the Paleocene section with the mud weight of 9.2 **-** 9.6 PPG, thereby suggesting that the pore pressure must be below 9.6 PPG in the Paleocene section. This is closer to the pore pressure estimated from dual parameter NCC than with the single parameter NCC.

Conclusion

Analysis of both SGR and XRD data shows direct evidence supporting the change in dominant clay type from Kaolinitic nature in Eocene section to Smectitie-Illite mixed layer in Paleocene section of the study area. Integration of drilled well data with the mineralogy information provided by SGR and XRD dataset in both Eocene and Paleocene formations suggests that main cause for velocity lowering in Paleocene section is because of change in dominant clay type rather than due to overpressure. We suggest using a dual parameter Normal Compaction Curve for Smectite rich Paleocene section of deepwater offshore Cauvery basin in order to normalize the log driven apparent high pore pressures. The reduced uncertainty and reduction in pore pressure regime for Paleocene sequence has helped in optimizing the well design through avoidance of extra casings and requirement of heavy mud weights, thereby substantially reducing the well cost and rig time.

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Figures

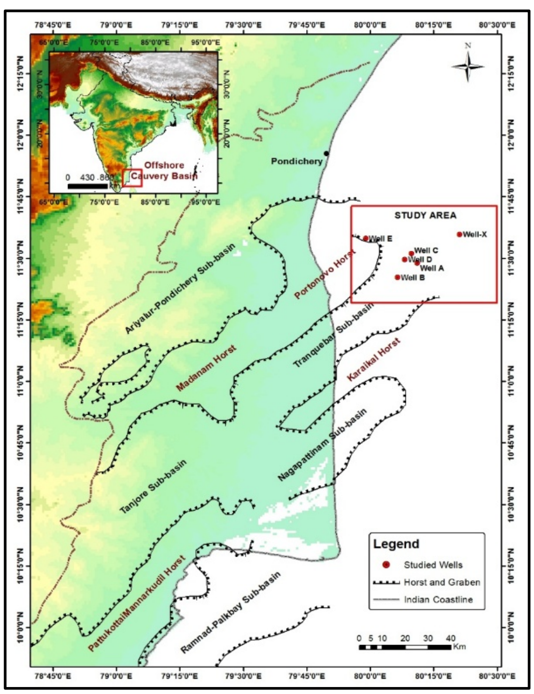

Figure.1: Location Map of the Study Area showing location of 5 studied wells plus boundaries of major sub-basins in the area.

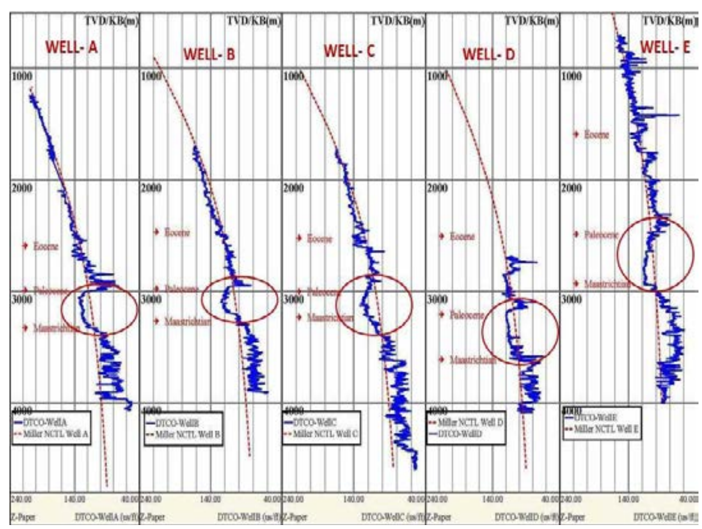

Figure.2: Velocity (Sonic) logs from 5 drilled well location. Red circles shows zones of substantial lowering of velocity and its deviation from NCC. Low velocity zone coincides with the Paleocene sequence. Solid Blue – Sonic logs, Dotted Red – Normal Compaction Curve.

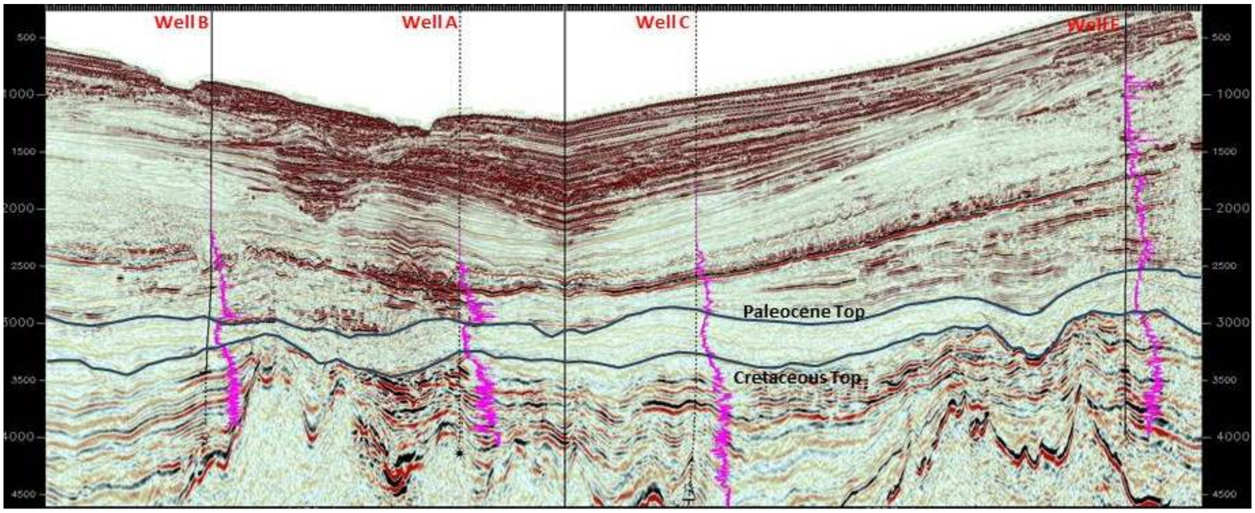

Figure.3: Seismic Section across the 4 wells of the study area. Pink Curves display the Velocity (Sonic) log of the wells. The seismic signature of Paleocene stratigraphy is visibly different (relatively of blank and of low amplitude) from the sequences above and below.

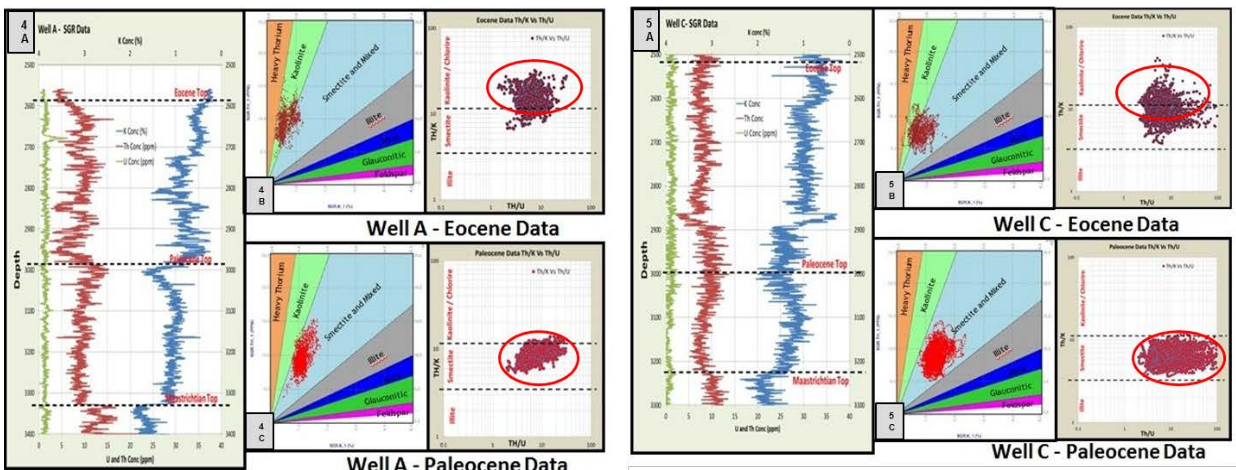

Figure.4 and 5: (4A and 5A) - SGR Data for wells A & C. (4B and 5B) - Th vs K and Th/K vs Th/U cross plots for the Eocene section for respective wells. (4C and 4C) - Th vs K and Th/K vs Th/U cross plots for the Paleocene section for respective wells.

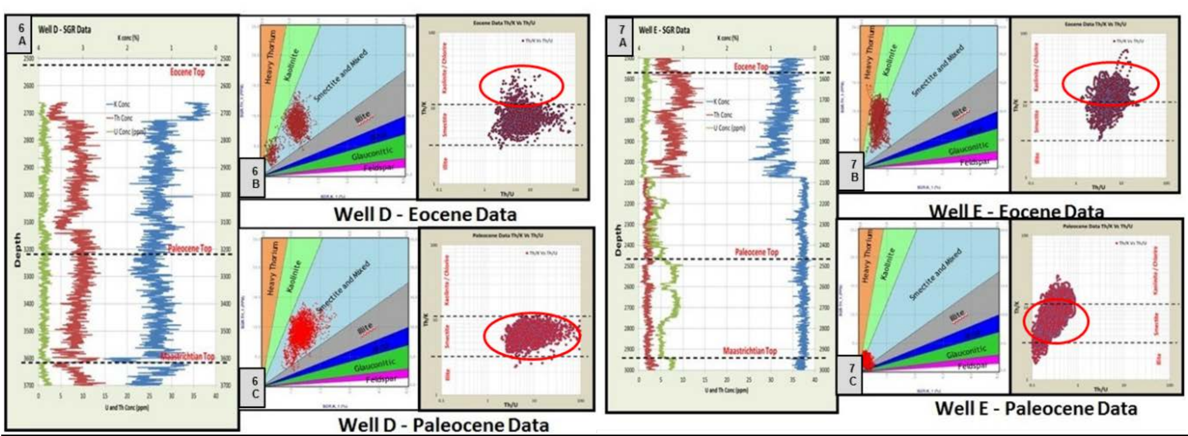

Figure.6 and 7: (6A and 7A) - SGR Data for wells D & E. (6B and 7B) - Th vs K and Th/K vs Th/U cross plots for the Eocene section for respective wells. (6C and 7C) - Th vs K and Th/K vs Th/U cross plots for the Paleocene section for respective wells.

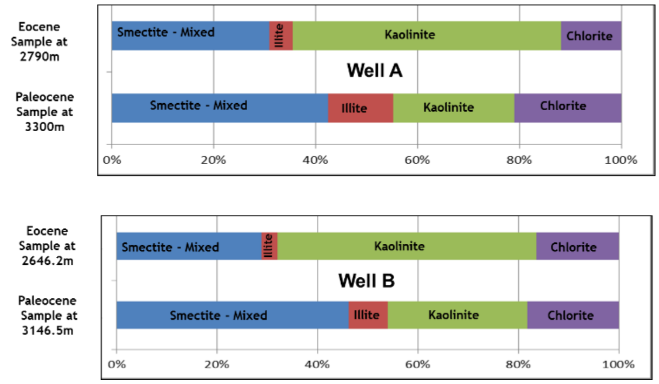

Figure.8: Analysis of XRD data for 2 studied wells. Dominant clay type in Eocene samples for both the wells was Kaolinite, whereas in Paleocene sample Smectite-Mixed was dominant clay type.

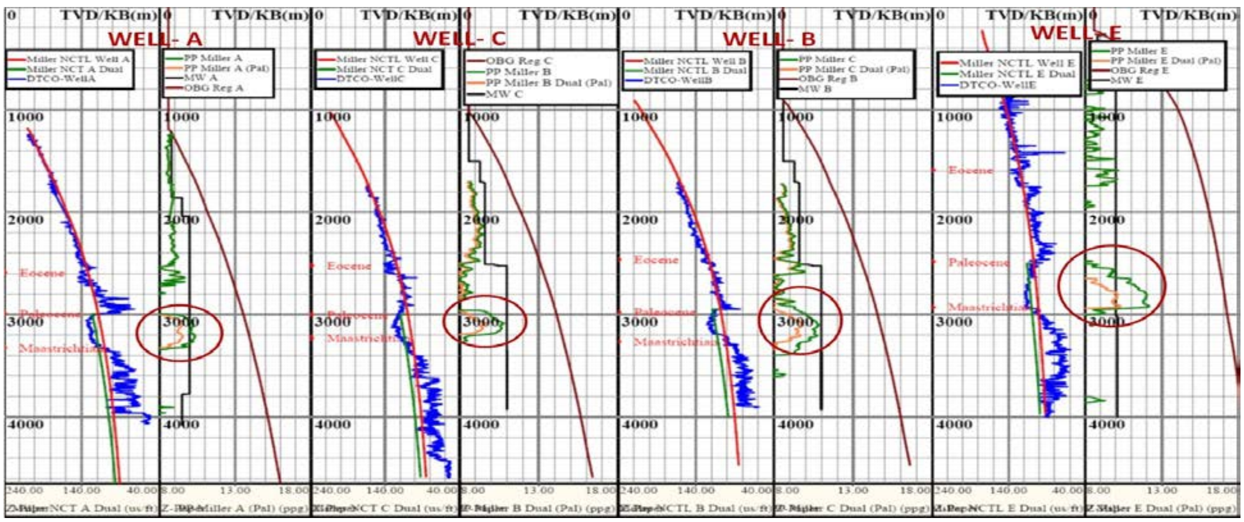

Figure.9: Difference between velocity based pore pressure prediction for 4 studied wells using Single and Dual parameter compaction curves. Results in pore pressure from Dual Parameter NCC for Paleocene section are in support to the well events and well behavior. Orange Curve – Pore Pressure from a dual parameter NCC. Green Curve – Pore Pressure from a single parameter NCC, Black Curve – Actual Mud weight, Brown Curve – Overburden gradient. Use of Single Parameter NCC overestimates the velocity based pore pressure.

Figure.10: Application of Dual Parameter NCC on a test Well X. Track I displays predrill seismic derived DT curve (Violet Curve) and both Single parameter NCC (Red Curve) and Dual parameter NCC (Green Curve). Track II display the single parameter NCC based Pore Pressure (Orange Curve) and Initial Mud weight and Casing plan (with 6 casings). Track III shows updated Pore Pressure (Violet Curve) derived from the Dual Parameter NCC and resultant modified Mud weights and Casing plan (with 5 casings), also shown are the actual Mud weight used (Black Dotted line) during the drilling.