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Application of Velocity Trend and Effective Stress in Prediction of Sediment Compaction and Overpressure for Drilling Operation in Gulf of Guinea

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Abstract

This study demonstrates the effectiveness of integrating both velocity trend and effective stress in overpressure and sediment compaction prediction. Incorporating both strategies into overpressure forecasting is shown to be helpful in this study. The gamma ray, density, neutron, acoustic, and deep resistivity records from the X-Field deep offshore Niger Delta were used. These wells were X-001, 002, 003, and 004. The sediment compaction mechanism, attributed to differential sedimentation rates and grain size component, was predicted using a cross plot of compressional sonic velocity versus depth color coded with gamma ray log. Compaction disequilibrium is the dominant overpressure mechanism, as evidenced by the cross plot of sonic velocity against density, color coded with depth for wells X-001 and X-004. The wells' effective stress was plotted using density logs to create an overburden trend, and gamma ray logs were utilized to create shale volume logs. Overpressure prediction focused on the deformation behavior of shale formations since they are more sensitive to overpressure phenomena than sands, being denser and characterized by less resistant minerals. Therefore, shale bodies within the same depth range are more likely to experience loss of porosity and rise in density with depth, as demonstrated in the wells. Well X-001's computed normal compaction trend (NCT) indicates normal compaction from the surface to a depth of 2500 m; however, the NCT line deflects to the left at this depth, signaling the onset of overpressure; at this point, the well pressure is expected to exceed hydrostatic pressure. Beyond this depth, an increase in porosity in the overpressured shale was detected, leading to a decrease in sonic velocity below the usual compaction trend line. In well X-001, the TOV is located at this depth. Overpressure zones were also first detected in wells X-002 and X-004 at depths of 2400 and 2500 meters, respectively. Based on these results, it is likely that sediment compaction trends normalize at depths below 2500 m in the research area. The innovation in predicting sediment compaction and overpressure for deep-water operations in the Gulf of Guinea involves advanced geophysical and geological modeling techniques.

Keywords: *Sediment compaction; Pressure; Overpressure prediction; Drilling operation; Logs.*

1. Introduction

The significant factor for an optimal well completion would be an adoption of appropriate Geopressure prediction exercise. This pressure profiling is more complex in green field locations with diverse geological terrains of little or no developed well [1]. Geopressure regimes are attributed to expansion of fluid, disequilibrium due to compassion or tectonics, and fluid movement mechanism [1]. Subsurface reservoir fluids within the pore channels are also the possible cause of pore pressure, an abnormal pressure regime environment can be experienced in varied domains within the known depths of hydrocarbon wells. A case of unexpected blowouts has been recorded in recent times, due to under prediction or inaccurate prediction of over pressured geologic Formations, which contributes in both human and material lose [2]. Efficient and more reliable drilling campaign requires a proper pore pressure analysis, however; the amount of mud weight needed to counter balance the borehole pressure during well completion can be obtained from the pore pressure evaluation results. Formation fracturing and fluid flow can occur due to high and low mud weight experience.

Depositional history analyses that take into account vertical and lateral stress regression in a sedimentary basin are suited to examining the pore fluid and rock failures in sedimentary rocks directly [3]. To notice the possible development of geopressured formations, one must have a "thorough quantitative understanding of compaction mechanics, the relationship between the total overburden stress, effective stress, and pore stress (pressure) in fine-grained clastics" [3]. Drilling data, seismic and well logs data are possible inputs in assessing pore pressure scenarios. Effect of local geology and possible causes of overpressured regime contributes in model adoption for a suitable or reliable prediction exercise [4]. Velocity to pore-pressure transform is a possible technique that can be used in evaluating geopressure regime from an elastic wave velocity [5]. This method is possibly adopted for a pre-drill geopressure situation [6]. The interval velocity has the tendency of predicting pore pressure through seismic signatures, and it takes into account that over pressured environment experiences lower velocities [7]. But there are limitations associated to this technique, since compaction has a significant influence on seismic velocity responses [8].

Victor *et al.* [9] investigated the hydrostatic pressure zones of Fabi field in an onshore environment of Niger Delta. From their findings, they noted that the over pressure zone commenced from 8,625 ft and this was due to rock compaction, as well as inability of pore fluid escape from rock pore space. Opara *et al.* [3] conducted a study on estimates of pore pressure and trap stability from a 3D seismic data. The outcome of their results proved that geometry and faulting system are the major contributors of both distribution and redistribution of pressure pattern within the location. Sayer *et al.* [5], illustrated the use of seismic data in predrill prediction of pore pressure, by adopting velocity to pore pressure transform method. Their declaration established the limitations associated with this technique, which can only be used in the strata description of diverse rock properties [10].

Furthermore, Asedegbeha *et al.* [1] conducted a study on the prediction of high pressure, high temperature (HPHT) reservoirs ambiguities in an onshore Niger Delta environment. They conferred that Eaton’s exponent variations does not show a clear regression path within the study location [11]. Uko *et al.* [12] explored the use of porosity data in pore pressure prediction in an onshore Niger Delta. Hydrocarbon field development activity within Niger Delta basin has shifted focus to deeper prospect of offshore plays. However, it is imperative to investigate the pore pressure effects for a deep-water environment of offshore Niger Delta, as an integral part of appraisal procedure, prior to drilling campaign for a possible safe exploitation. Hydrostatic pressures are similar to normal pressures and high formation pressures are greater than normal pressures in the subsurface, where pore pressure acts on formation fluids [10]. Effective stress and velocity trend approaches are utilized to anticipate overpressure. In the former, rock stress behavior is used as a surrogate for predicting overpressure, whereas in the latter, a departure from the typical compaction trend is used for that purpose. In this study, application of velocity trend and effective stress in prediction of sediment compaction and over pressure will be investigated.

Analysis of the data, along with familiarity with the burial, stress, and temperature histories, rock types and their distributions, subsurface structure, and reservoir connectivity, are essential for establishing pore pressures. Pore pressure influences compaction dependent geophysical parameters like density, resistivity, and sonic velocity, and this is exploited for over pressure detection. When interpreting pore pressure, shale is the lithology of choice since it is more sensitive to overpressure than other rock types. Therefore, shale deformation behavior is primarily focused on for overpressure detection. It is important for hydrocarbon exploration and resource estimation to determine the source of the overpressure and predict the pore pressure. Accurate prediction of pore and abnormal pressures have a significant impact on well costs, both at the design and operating phases [13].

Multiple processes, including compaction disequilibrium (under compaction), hydrocarbon generation and gas cracking, aqua thermal expansion, tectonic compression, mineral transformations, osmosis, hydraulic head, and hydrocarbon buoyancy, can contribute to the creation of overpressures. Disturbed pore pressure may be caused, in part, by improper formation compaction. Formation porosity is decreased and pore fluid is released during normal sediment compaction [13]. Well planning that incorporates precise forecasts of pore pressure and fracture gradients during the design phase might thereby prevent a wide variety of unintended outcomes. This project will study the effects of sediment compaction and how pore pressure is calculated in the deep-water environment of the Niger Delta basin because such knowledge is essential for efficient and risk-free drilling operations.

Recent observations on pressure prediction are particularly relevant to the impacts of shale formation diagenesis on compressive stresses, compaction trends, and pressure patterns, which are used to identify overpressure mechanisms and predict pore pressure. Mechanical compaction, chemical compaction, and the transition stage make up the three phases of shale formation compaction [14]. It is difficult to detect the source and distribution of overpressure using current methods, as the connection between effective stress and porosity is different for chemical and mechanical compaction. Studies have confirmed that the sonic migration time and density of shale formation clearly respond to overpressure, but the precise determination of pore pressure in shale formation is not easy to determine [15].

The massive expansion of oil and gas exploration in Golf of Guinea's deepwater basins has made it increasingly important to avoid geological hazards while drilling. The occurrence of overpressure can be associated with under pressure, under-compaction, generation of hydrocarbon, gas decomposition, hydrothermal expansion and mineral transformation. The progressive loss of pore fluid after loading new material causes normal compaction of sediments. The innovation in predicting sediment compaction and overpressure for deep-water operations in the Gulf of Guinea involves advanced geophysical and geological modeling techniques [15]. This includes the use of high-resolution seismic data, well log analysis, and basin modeling software to create accurate subsurface models. Regional application involves customizing these techniques to the geological and geophysical conditions specific to the Gulf of Guinea, accounting for its unique sedimentary basin characteristics, tectonic history, and fluid dynamics. The innovation enables more precise risk assessment and drilling strategies for oil and gas exploration in the region, improving operational safety and efficiency while reducing costly surprises during deep-water operations.

Therefore, settling, settling velocity, distribution area, and settling depth can all have an impact on the typical compaction process [16]. The purpose of this research was to identify and predict pressure in the "X" field, which is located in deep water offshore by analyzing well data to essentially detect, predict, and estimate overpressure and abnormal zones. Deepwater overpressure has been linked in the literature to issues with drilling safety and instability.

2. Methodology

2.1. Gulf of Guinea geologic and structural setting

The Gulf of Guinea in West Africa is a highly structurally and geologically complex area. The tectonic processes, sedimentary basin formation, and the interaction of numerous geological elements all play a role in shaping its geological and structural setting [17]. Several tectonic plates meet at the Gulf of Guinea, including the African Plate, the South American Plate, and the divergent Mid-Atlantic Ridge. The region's geological variety is in part due to this intricate interplay between plates. West African countries like Nigeria, Cameroon, Equatorial Guinea, and Gabon all have extensive coasts, and along these coastlines are a number of sedimentary basins. Sedimentary rocks, such as sandstones and shales, accumulate thickly in these basins, making them ideal for hydrocarbon extraction. Rifting and the creation of rift basins in the Gulf of Guinea area occurred during the Cretaceous period. Due to the burial and maturation of organic-rich sediments, many basins, such as the Niger Delta Basin and the Douala Basin, have become major hydrocarbon-producing locations [18]. Extensive salt diapirs, which are salt intrusions from below into the rocks above, are a geological feature unique to the Gulf of Guinea. These diapirs are significant exploration opportunities because they act as structural traps for hydrocarbons.

Compressive tectonics have resulted in the formation of fold and thrust belts in the eastern half of the Gulf of Guinea. The Dahomey Basin, for example, is home to several of these structural features as a direct result of the impact between the African and South American tectonic plates. Strike-slip faults, such the Cameroon Volcanic Line and the Pernambuco Fault, transverse the area and allow for lateral plate motion. Submarine canyons and channels in the Gulf of Guinea are carved into the continental slope and aid in the movement and deposition of silt [19]. Oil and gas reserves are examples of hydrocarbon resources. The Gulf of Guinea is one of Africa's wealthiest hydrocarbon provinces due to its complicated geology and structural makeup. Extensive oil and gas reserves in countries like Nigeria, Angola, and Equatorial Guinea draw major exploration and production efforts. Tectonic plate borders, large sedimentary basins, salt diapirs, and other structural elements characterize the geologic and structural setting of the Gulf of Guinea [20]. There are advantages and disadvantages to oil and gas exploration and production due to the area's geology, which has helped make it an important hydrocarbon-producing area.

2.1.1. Location of the study area

'X'-Field is located within the deep water in the Niger Delta basin of Nigeria (Figure 1). It lies within latitude of 05^0 01´ 8.6´´N and longitude of 04^0 68´ 30.13´´E. The name given is fictitious f or proprietary purposes and only valid for this research. It belongs to an active oil company.

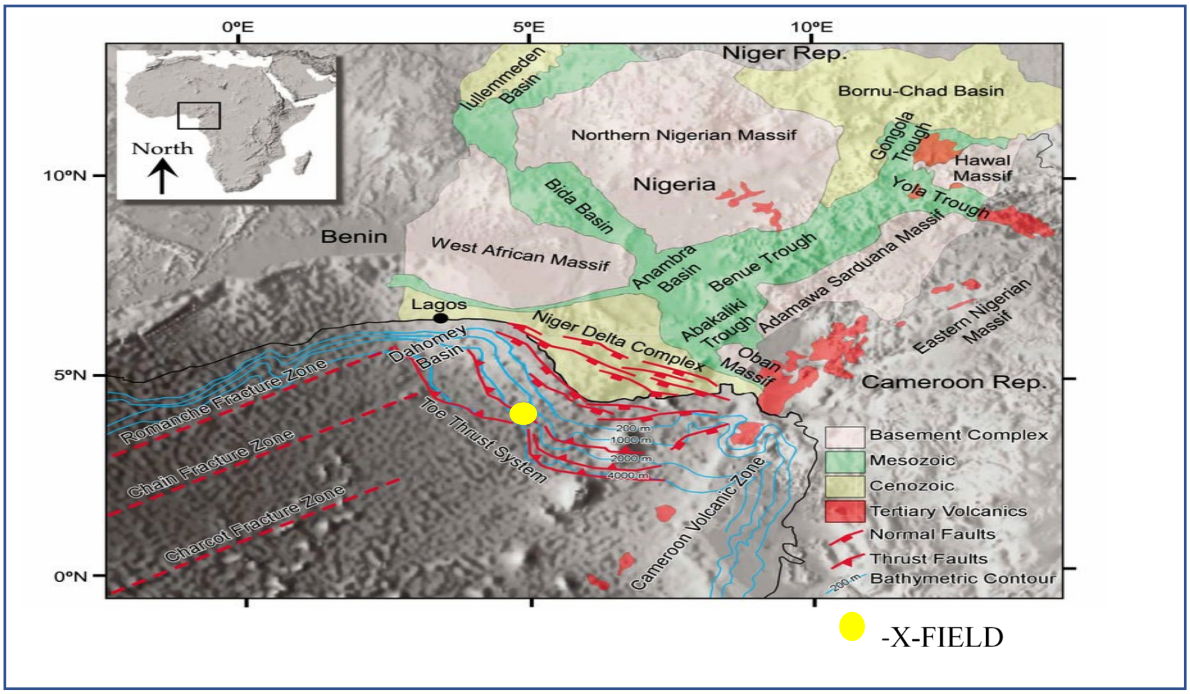

Figure 1. Regional map of niger delta showing study location (modified after [4]).

2.2. Data used for the study

The data used for this study include well log data acquired from a deep water offshore in Niger Delta and the field is identified as 'X'-field. The data set consist of borehole logs from four wells and a base map of the field. The borehole logs were in digital format which facilitated the use of software programs for analysis and interpretation. A suite of log from four wells was used for this study. It comprises caliper, gamma ray, deep resistivity, neutron, density and sonic logs. The data was acquired as both straight and deviated wells.

2.3. Base map

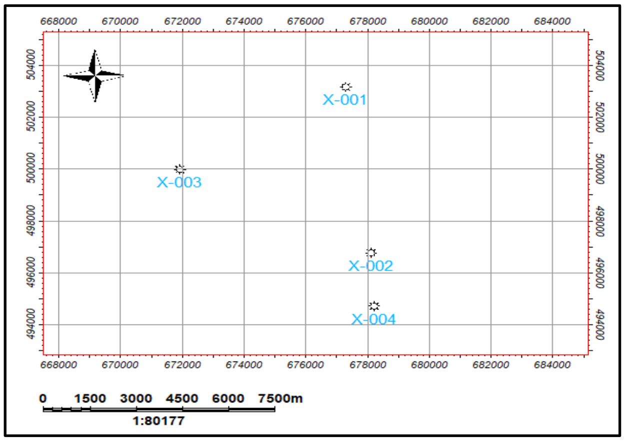

Figure 2. Base Map of 'X'-Field, showing the seismic grid lines and well locations.

The base map (Figure 2) was generated after loading the available well log data with petrel™ 2014 software. The map depicts the distribution, orientation and location of the wells as well as the seismic grid lines. It is composed of drilled wells, direction of north and a linear scale.

2.4. Software program

The available software used for the interpretation include petrel™ 2014 and RokDoc™. They were used for data interpretation of logs such as lithological interpretation, cross plots generation for pore pressure analysis after the data have initially been subjected to quality control checks such as depth reconciliation, filtering and de-spiking to improve the data quality for accurate interpretation.

2.5. Method of study

The workflow procedure employed in this study is presented in flowchart (Figure 3).

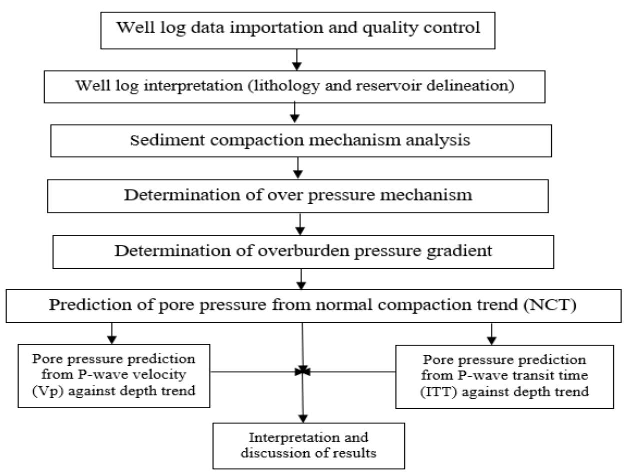

Figure 3. Research workflow employed for this study.

2.6. Data importation and well log interpretation

Data importation was done after data quality control. The well log data was loaded into petrel™ 2014 and RokDoc™ software respectively for analysis and interpretation. The logs comprised of caliper, gamma ray, density, neutron, sonic and deep resistivity logs. Well log interpretation involves the analysis of log responses with the aim of identifying the geology of the formations penetrated by the wells. The logs used were gamma ray, density, neutron, sonic and deep resistivity logs. Log values were read on well sections within the geologic window of interest (sand and shale formation). The process involved lithology identification and hydrocarbon reservoir delineation.

2.6.1. Lithology identification

Lithology identification was done using well log data for identification of lithology based on log responses. Gamma ray log was used to delineate the major lithology within the wells. Sand and shale baseline were calibrated on the logs. Regions of maximum gamma ray response were identified as shales while regions of minimum gamma ray identified as sands. The log was set to a scale of 0 - 150 API unit. A central cut-off of 75 API unit was used such that gamma ray values less than 75 API represents sand units while those with values greater than 75 API represents shale units.

2.6.2. Hydrocarbon reservoir delineation

The gamma ray and depth resistivity measuring tools were used for the delineation of hydrocarbon bearing zones. The resistivity log is displayed in track 2 of the log view. Since hydrocarbons are highly resistive, the reservoir window was characterized by high resistivity and low gamma ray response. Low resistivity response within sand bodies is suggestive of water bearing sands. This was employed to qualitatively delineate hydrocarbon bearing sand intervals.

2.7. Sediment compaction mechanism analysis

In order to detect overpressure, it is necessary to understand the mechanism of compaction. The loss of pore water during loading is what causes compaction, which is defined as a decrease in porosity. To reach a state of stress equilibrium, a loaded rock formation will compress and release as much water through its vertical permeability as possible. The phenomena that influence sediment compaction and the controls on the studied field was investigated. This was done via analysis of cross plots of some rock properties such as velocity against density and depth against velocity.

2.8. Pore pressure

Pore pressure analysis was done using the four (4) wells data provided. Normal compaction trend (NCT) line was generated using shale volume and velocity logs. At depth intervals where the log signature pattern diverged from the typical trend line, overpressure zones were located. The factors that lead to overpressure were uncovered by comparing velocity and density logs in a cross plot. Overpressure zones were estimated using the different cross plots of reservoir and elastic parameters. Estimates for the attributes were developed using empirical relationships found in previous works. Shale trend, overburden pressure gradient, and hydrostatic pressure are also estimated throughout the forecasting procedure [21].

$$P = [\sigma_V - (\sigma_V - aP_n)^{\frac{\ln\phi o - \ln\phi}{cz}}]/\ a \quad (1)$$

$$P_n = \rho_f gh \quad (2)$$

$$\sigma_V = \rho_f gz_0 + \int_0^z \rho(z)gdz \quad (3)$$

where, P is the pore pressure in MPa; σ_V is the overburden stress in MPa; P_n is the normal pore pressure (hydrostatic pressure) in MPa; a is the Biot effective stress coefficient within the range $\phi \leq a \leq 1$, and is assumed to be $a = 1$; c is the normal compaction coefficient; z is the depth below the mudline in m; φ_0 is the porosity in the mudline; φ is the porosity in the relevant depth; ρ_f is the density of the sea water in g cm^{-3} (ρ_f = 1.024 g cm^{-3}); ρ_b is the formation bulk density as a function of z; h is the vertical depth below sea level (vertical height of fluid column) in m; g is the acceleration due to gravity in ms^{-2} defined as g = 9.8 ms^{-2}; and z_0 is the water depth in m.

3. Results and discussion

The results of the study were grouped into lithological delineation and cross plots analysis using different rock properties. The interpretation incorporated information from well logs for sediment compaction studies and pore pressure predictions.

3.1. Lithology interpretation

The interpreted lithology of the four wells studied (X-001, 002, 003 and 004) are presented in Figs 4 to 7. The lithologies were identified using gamma ray logs from the four wells. Generally, two main lithologies were delineated within the four wells, identified as sand and shale. Sand lithology is characterized by low radioactive contents and was displayed using colour yellow. Sand lithology has the capacity to accumulate fluid since it is porous and permeable. Shale on the other hand, is the lithology on the gamma ray log with gamma ray value above the cut-off of 75 API. It is characterized by high radioactive contents and was displayed with grey colour. The lithology is known to be porous but impermeable and it can serve as source rock for petroleum accumulation and also as seal for reservoir rocks.

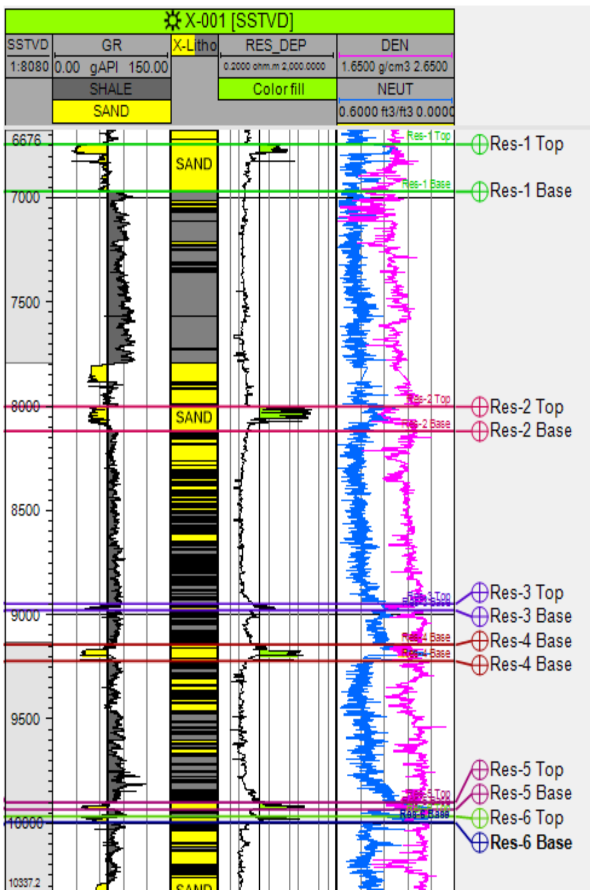

Figure 4. Lithological Delineation for Well X-001.

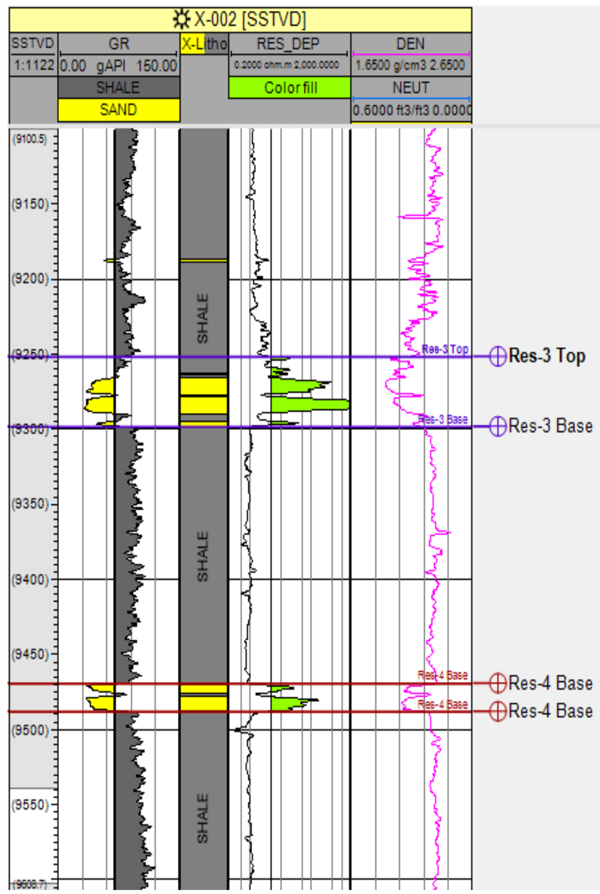

Figure 5. Lithological Delineation on Well X-002.

3.2. Sediment compaction mechanism

Sediment compaction refers to the process by which sediments experience compression and consolidation beneath the weight of underlying layers in deep-water operations. Geoscientists and engineers can examine the geomechanical behaviour of the sediments, evaluate reservoir characteristics, and optimize drilling and production techniques in deep-water operations by researching the mechanism of sediment compaction. This information aids in minimizing reservoir hydrocarbon recovery costs, minimizing drilling risk, and constructing well completions. Cross plot of P-wave velocity against depth, colour coded with gamma ray (GR) log for Well-X001 is shown as Figure 8. For sand, chemical compaction events are required to explain the sharp ascent in velocity with depth. Mechanical compaction (a function of effective stress) and chemical compaction (regulated by the dynamics of fluidrock interactions) can both cause sediments to compress, leading to a loss of porosity and an increase in density [20].

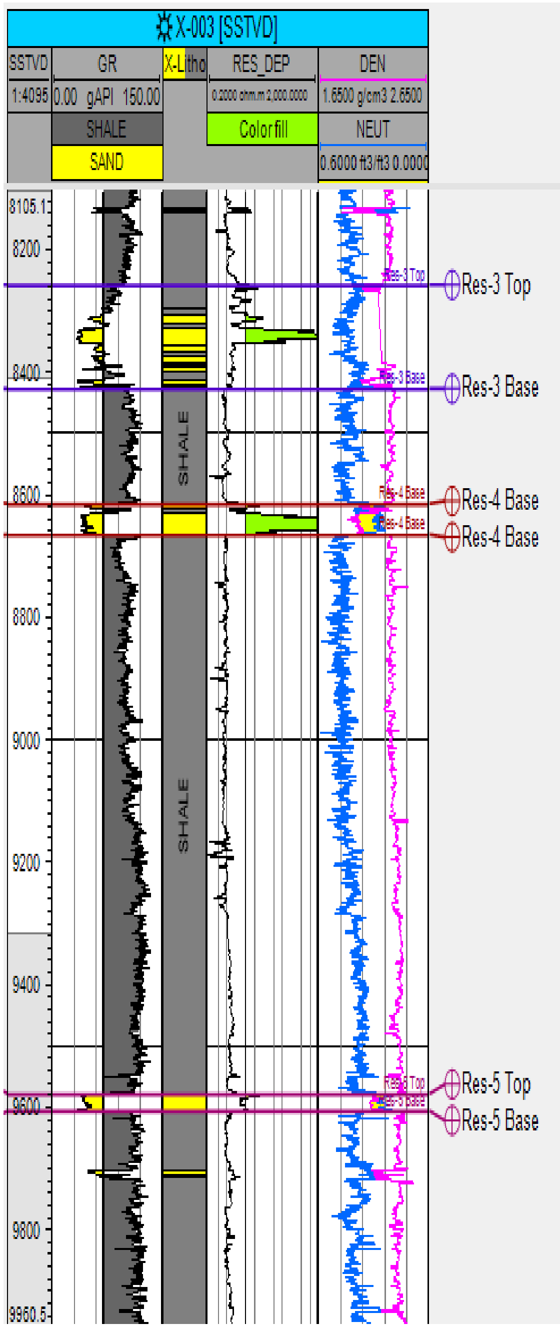

Figure 6. Lithological Delineation for Well X-003.

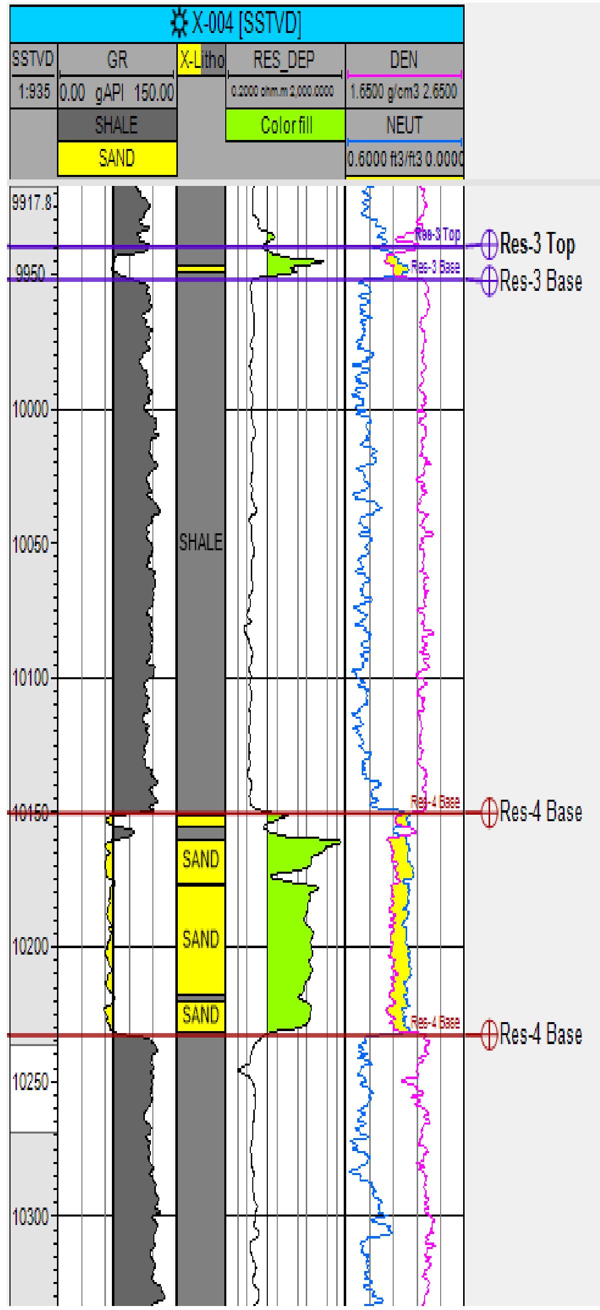

Figure 7. Lithological Delineation for Well X-004.

3.3. Overpressure mechanism

P-wave velocity (Vp) versus density (rho), color coded by depth, is depicted in Figures 9 and 10. The graph was used to identify the overpressure mechanism responsible for compaction of the sediment (either disequilibrium compaction or secondary causes).

3.4. Overburden pressure gradient

Figures 11, 12, 13 and 14 show the computed overburden pressure gradient for the four wells (X-001, 002, 003 and 004) respectively. The stress or strain exerted on a layer of rocks from the weight of the materials above it is known as overburden or lithostatic pressure. For pore pressure prediction and Geomechanics, this parameter is crucial [19]. It was calculated using the bulk density log's cumulative weight above the depth of interest. A red line between the shown density log points represents the overburden gradient. This line was compared to the line of lithostatic pressure (Pres_Litho) in mega Pascal fixed gradient to the right.

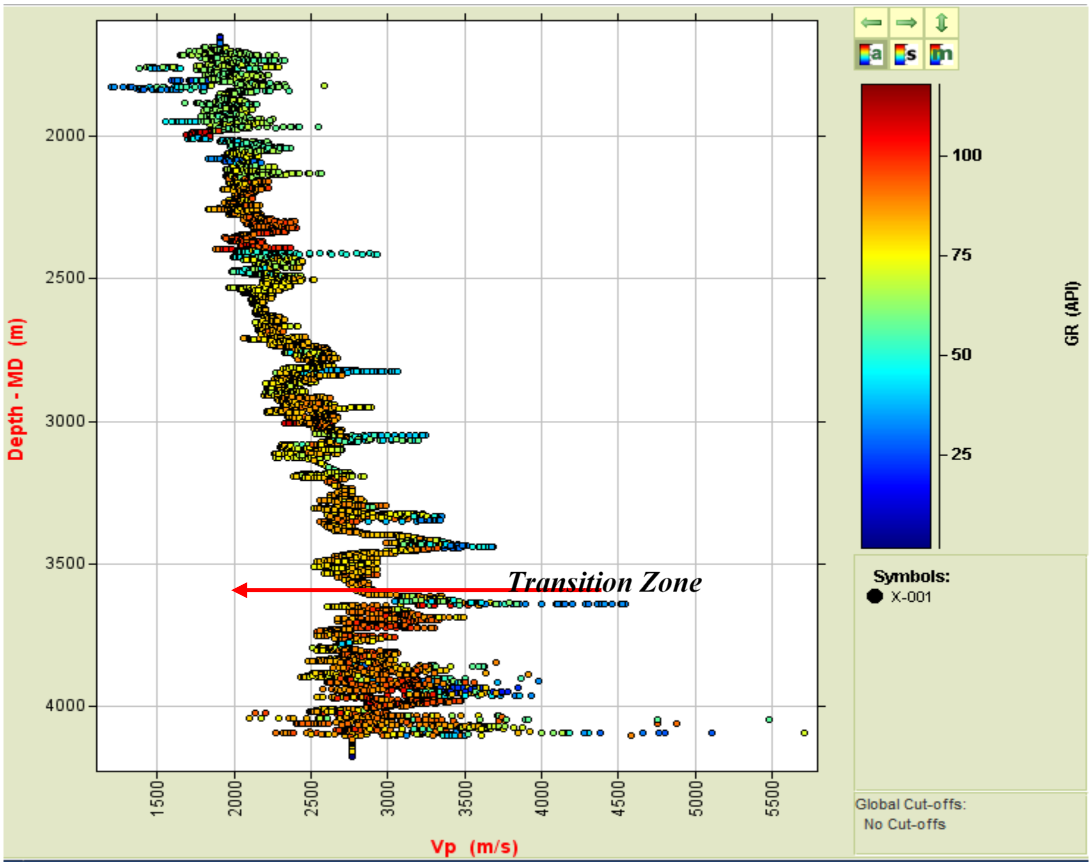

Figure 8. Cross plot of depth against P-wave velocity (V_p) colour coded with GR for X-001 well.

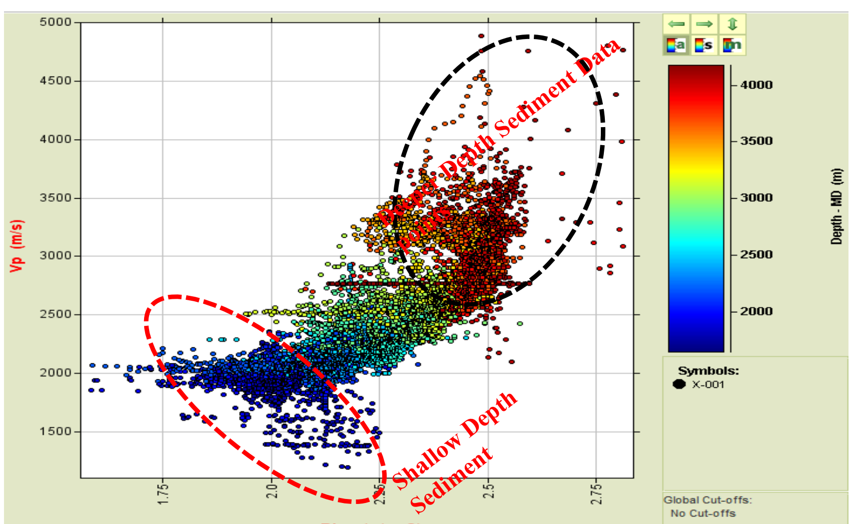

Figure 9. Cross plot of P-wave velocity (V_p) against density (rho) with depth for Well X-001.

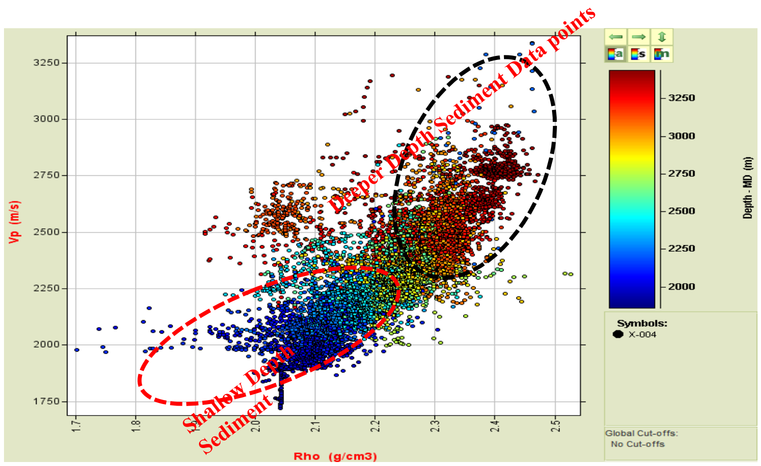

Figure 10. Cross plot of P-wave velocity against density (rho) with depth for Well X-004.

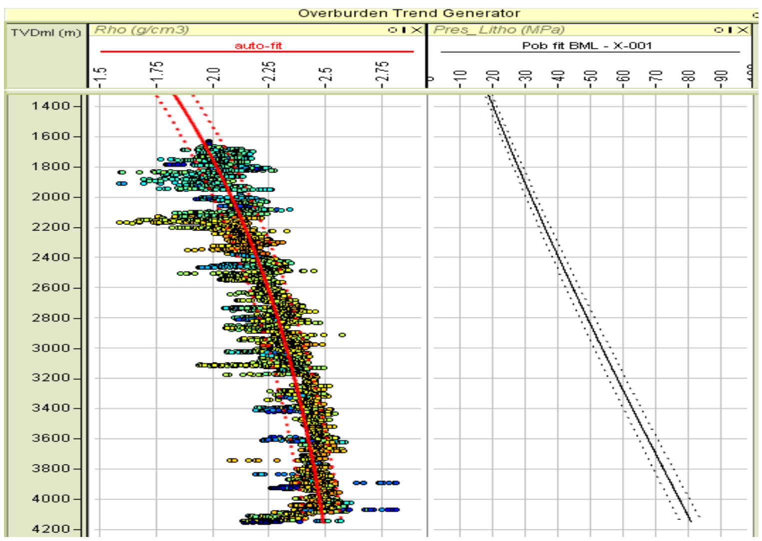

Figure 11. Overburden trend generated from the density log for Well X-001.

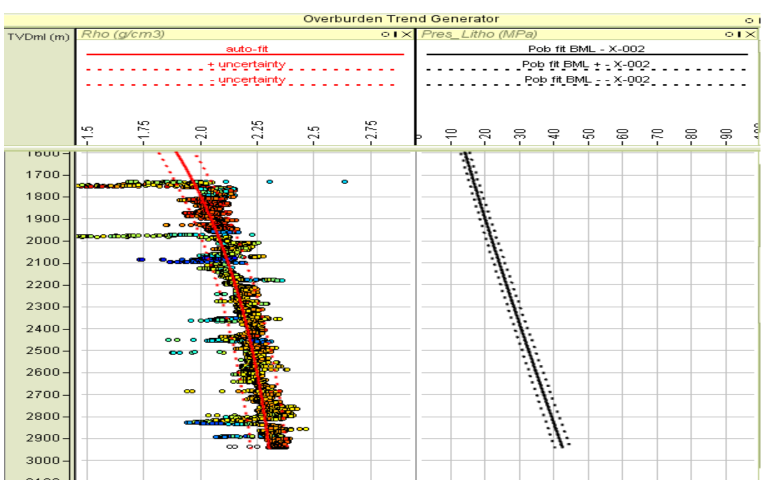

Figure 12. Overburden trend generated from the density log for Well X-002.

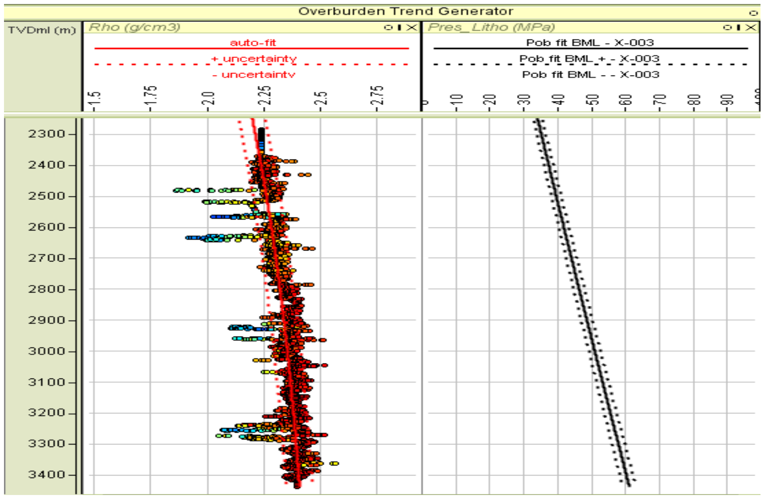

Figure 13. Overburden trend generated from the density log for Well X-003.

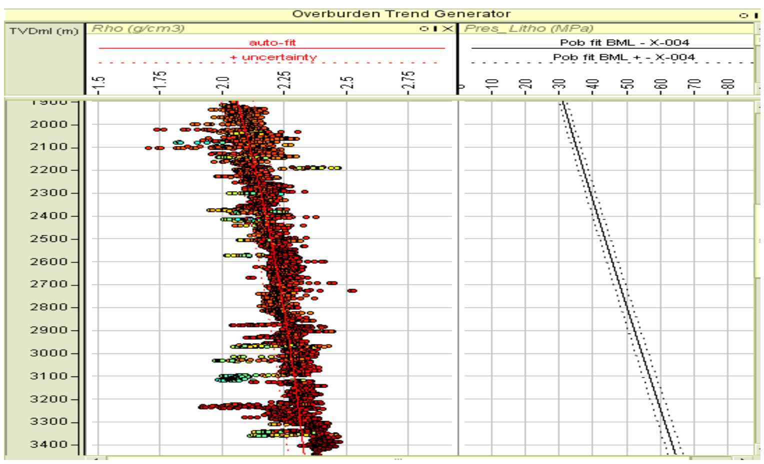

Figure 14. Overburden trend generated from the density log for Well X-004.

3.5. Pore pressure prediction using normal compaction trend

Figures 15, 16 and 17 show the computed shale trend for Well X-001, 002 and 004. Since shale lithology typically exhibits aberrant pressure rise, a shale cut-off was implemented to eradicate velocities within the sand interval. When compared to sandstones, which typically contain quartz and other resistant minerals, shale formations are more vulnerable to compaction phenomena due to the presence of materials that are less resistant to compaction. Thus, shale bodies tend to lose porosity and become denser than sandstone bodies do over the same depth range. Figures 18, 19 and 20 show the normal compaction trends of Wells X-001, 002, and 004.

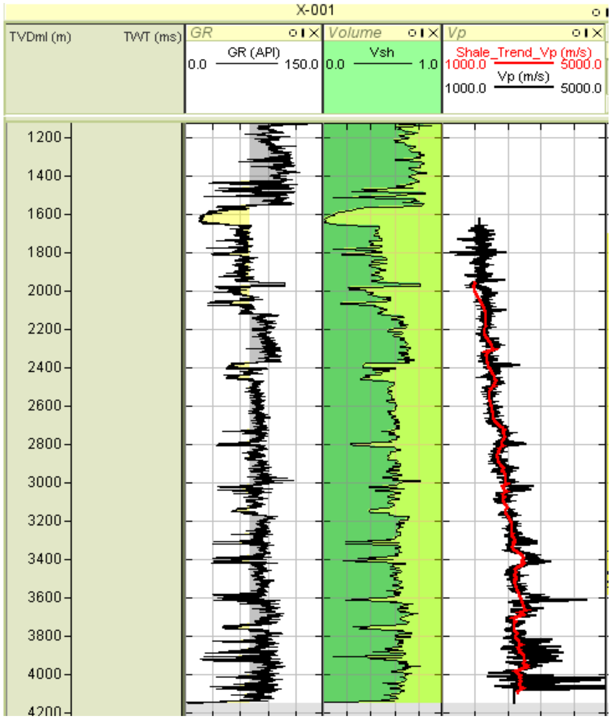

Figure 15. Display of Lithology and Compressional Velocity Shale trend for Well X-001.

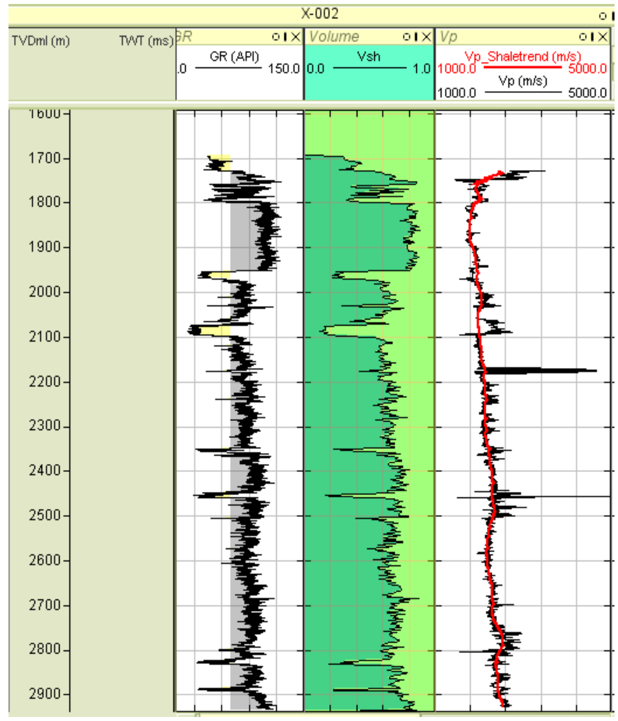

Figure 16. Display of Lithology and Compressional Velocity Shale trend for Well X-002.

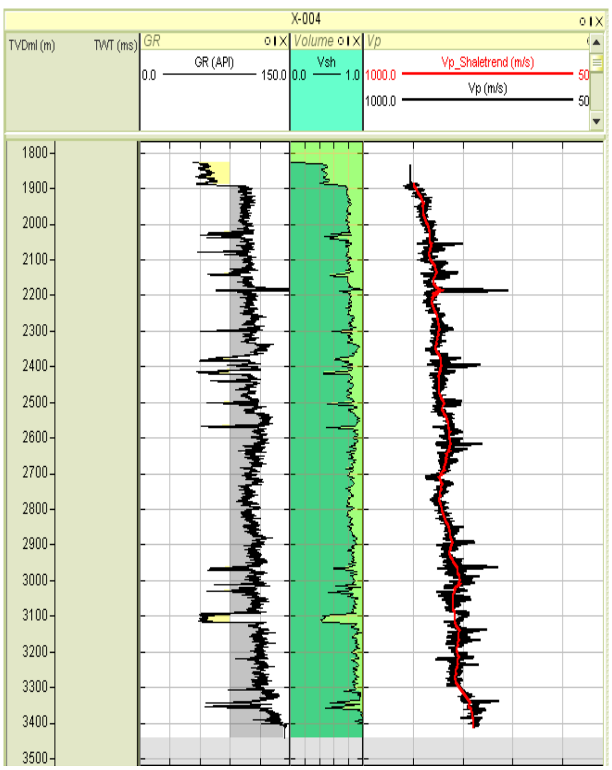

Figure 17. Display of Lithology and Compressional Velocity Shale trend for Well X-004.

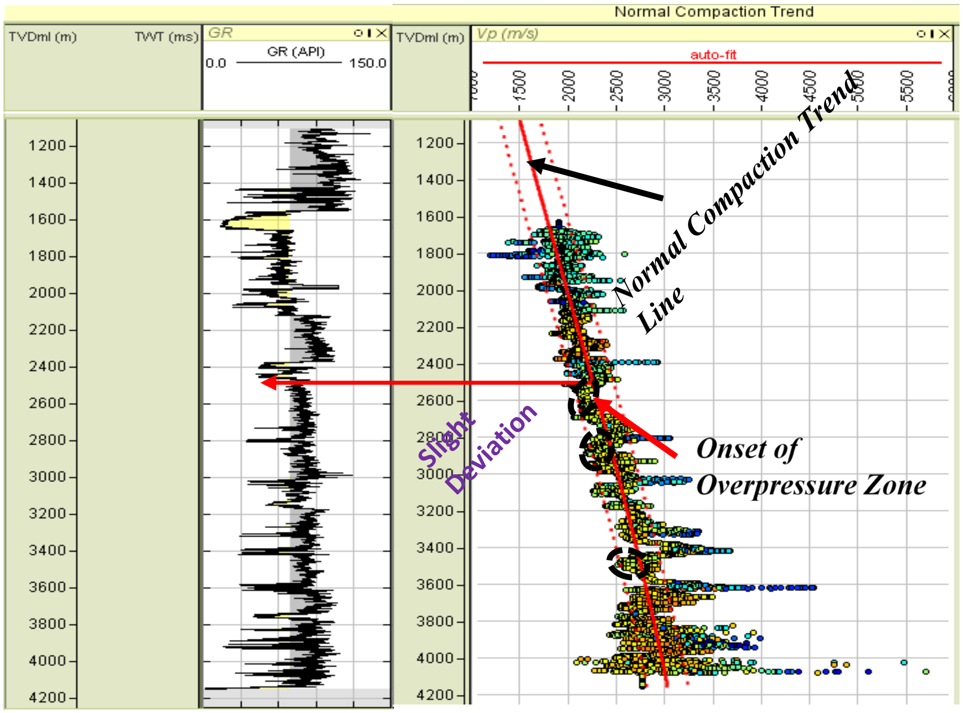

Figure 18. Normal Compaction trend on Compressional Velocity for Well X-001 indicating Onset of Overpressure and its Zones.

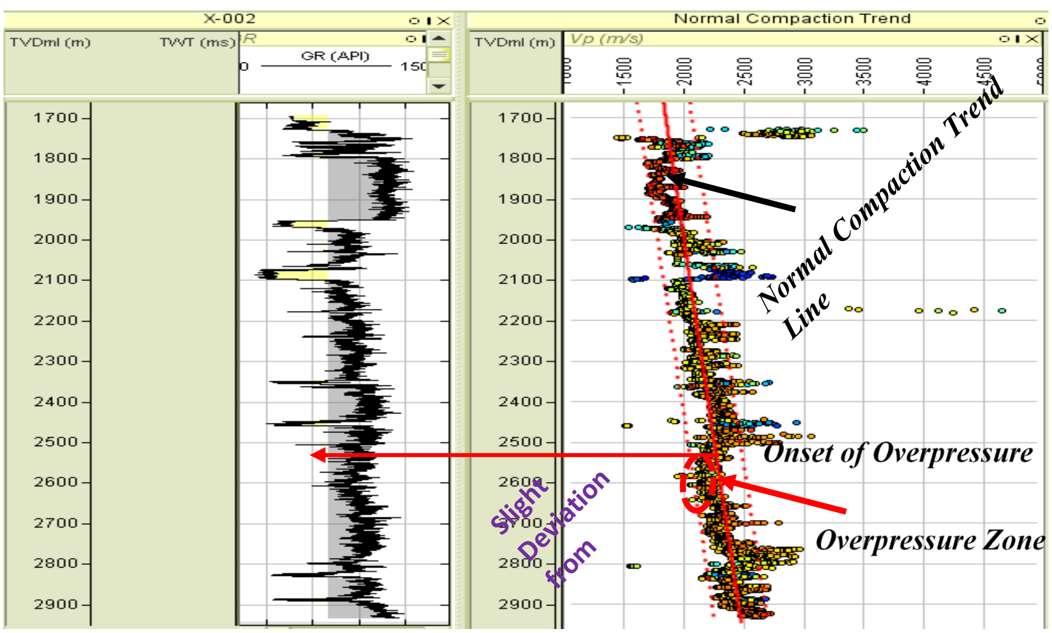

Figure 19. Normal Compaction trend on Compressional Velocity for Well X-002 indicating Onset of Overpressure and its Zones.

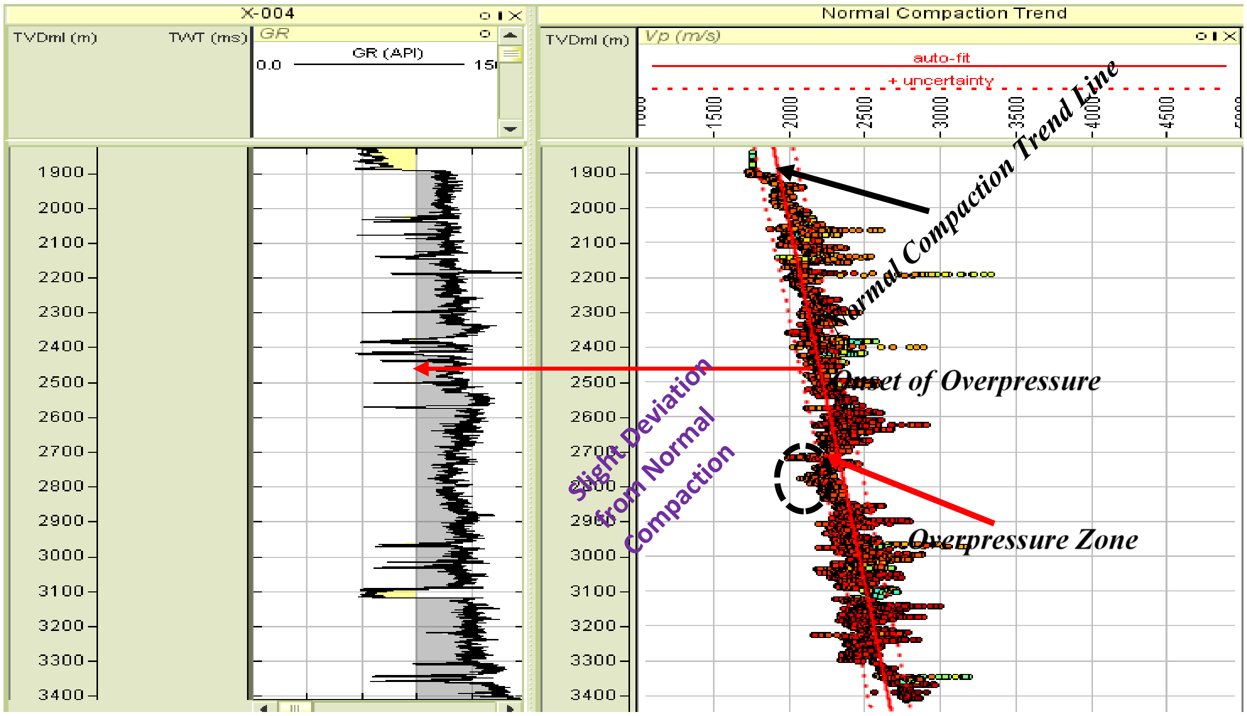

Figure 20. Normal Compaction trend on Compressional Velocity for Well X-004 indicating Onset of Overpressure and its Zones.

3.6. Application of interval transit time in predicting pore pressure

Pore pressure zones were also identified and predicted by plotting interval transit time (compressional-sonic) against depth. Figures 21, 22 and 23 show plots of three Wells (X-001, 002 and 004).

Lithology is a key factor in determining how easily sediment layers can be compacted. Porosity, permeability, and mechanical strength are only a few of the compaction characteristics that differ amongst different lithologies. Geophysicists can determine the sediments' initial porosity and forecast how they would compact over time as a result of the weight of underlying layers by analyzing the lithology [18]. The design of suitable drilling and completion procedures as well as assessments of well stability and reservoir quality depend heavily on this data.

The gamma ray log (GR) for each well was displayed alongside their deep resistivity log (LLD) to delineate the reservoir window in the wells. The reservoir windows were delineated on the basis of low gamma ray and high resistivity contrast. Six reservoirs designated as Res-1, Res-2, Res-3, Res-4, Res-5 and Res-6 (Figure 4) were identified and delineated on well X-001. Two reservoirs were delineated on well X-002 (Figure 5), three reservoirs delineated on well X-003 (Figure 6) and two reservoirs on well X-004 (Figure 7). The advantage of log data is their high precision geological information with respect to depth.

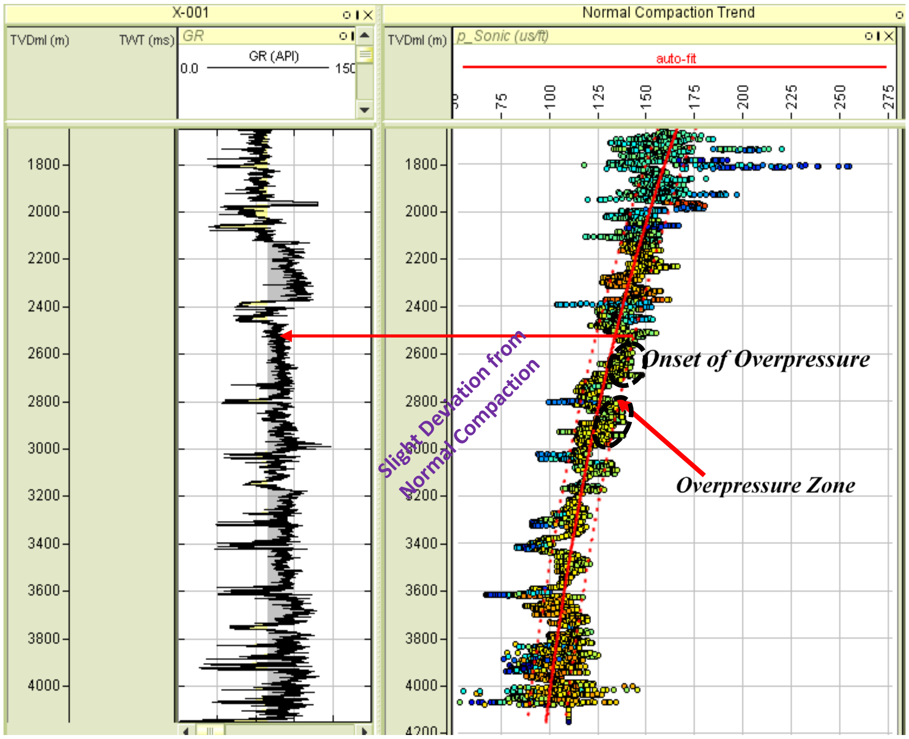

Figure 21. Normal Compaction trend on Compressional Sonic for X-001 Well indicating Onset of Overpressure and its Zones.

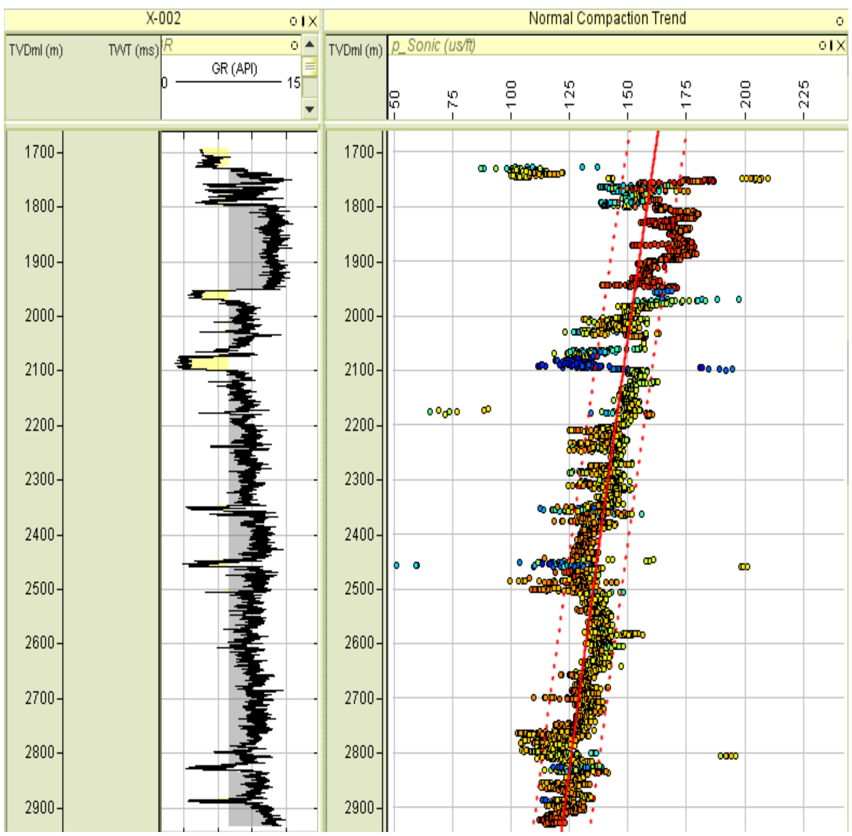

Figure 22. Normal Compaction trend on Compressional Sonic for X-002 Well indicating Onset of Overpressure and its Zones.

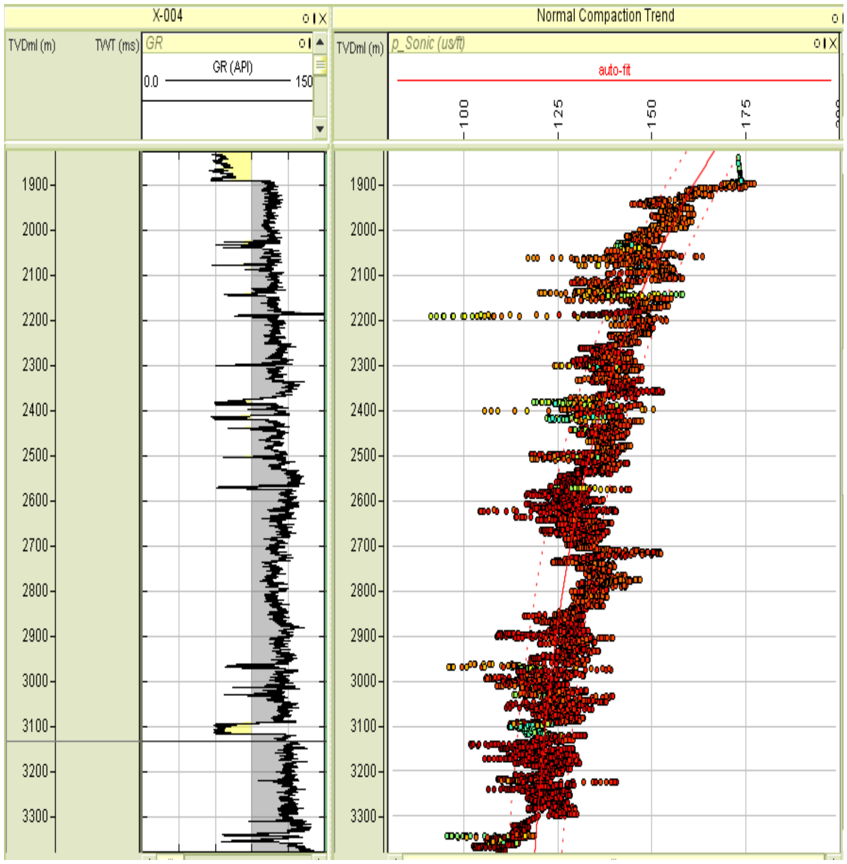

Figure 23. Normal Compaction trend on Compressional Sonic for X-004 Well indicating Onset of Over-pressure and its Zones.

Due to the development of hydrocarbons or the existence of impermeable layers, certain lithologies, such as shales, might display anomalous fluid pressures. Geophysicists employ lithological changes that might point to the presence of overpressured zones to identify seismic data, well logs, and other geophysical techniques. In order to minimize expensive drilling issues, well location must be optimized and potential drilling dangers must be identified in order to build suitable wellbore stability solutions. The capacity of particular lithologies to function as reliable seals is crucial in deep-water operations, where hydrocarbon accumulations are frequently discovered in reservoirs beneath many sediment layers. To find lithological changes that can point to the presence of sealing formations, geophysicists analyze seismic data and well logs. In order to characterize reservoirs, calculate hydrocarbon contents, and manage drilling risks associated with fluid migration, it is helpful to assess the lithology and its sealing ability. The capacity of particular lithologies to function as reliable seals is crucial in deep-water operations, where hydrocarbon accumulations are frequently discovered in reservoirs beneath many sediment layers. To find lithological changes that can point to the presence of sealing formations, geophysicists analyze seismic data and well logs. In order to characterize reservoirs, calculate hydrocarbon contents, and manage drilling risks associated with fluid migration, it is helpful to assess the lithology and its sealing ability.

This leads to changes in petrophysical properties of rock, and an increase in compressional velocity also led to a decrease in porosity with depth. Purely, mechanical compaction would have resulted in a gradual increase in velocity as observed in shales. The jump in velocity of sand formation observed at 3600 m depth (indicated as transition zone) in Figure 8, is caused by chemical compaction phenomena. This trend has also been observed in literature by Li *et al.* [22], were they also introduced sediment depth to analyze compaction effect. In investigation the stability of sediments. Hence, it is assumed that mechanical compaction predominates at depth below 3600 m, while chemical compaction predominates at 3600m and beyond.

Similarly, compaction coefficient (b in 1/m) which help to know the factors that influenced sediment compaction in the field of study was computed for the four wells. The results reveal that well X-001 has compaction coefficient ranges from 0.0004198 to 0.000541817, well X-002 ranges from 0.000132934 to 0.000460166, well X-003 ranges from 0.000482446 to 0.00173069 and well X-004 ranges from 0.000441923 and 0.00143497. In general, the results show a wide variation of coefficient of compaction from 0.000133 to as high as 0.0017 across the four wells in the study field. Large variations in compaction coefficients in the study area can be due to both sedimentation rates and component of grain size.

The primary mechanism of overpressure is the normal sediment loading that happens with increasing burial depth, while the secondary process of disequilibrium compaction occurs as a result of rapid sediment loading, quick dewatering, and compaction. Overpressure mechanisms in the Bohai Bay Basin, China, were also identified in literature [16]. They noted that sealing condition and capacity of the source rocks control the overpressure variation mechanisms. Both Figures 9 and 10 show an increase in velocity with increasing density with corresponding depth increase. The highest densities and velocities were also observed at the deepest depth. When compaction disequilibrium is the cause of the overpressure, this is the norm. Therefore, a standard compaction disequilibrium is the cause of the observed overpressure in the investigated fields.

The rule of thumb in the oil gas industry has been to assume a range of values (1.0 – 1.1 psi/ft) as overburden pressure gradient in onshore drilling operation. But literature has shown that this practice is not acceptable for deep water and ultra-deep offshore drilling operations [23]. The repeated accumulation of sediment in one layer over time exposes the corresponding layers to greater overburden pressure. Deep-water sediment compaction is significantly influenced by the overburden pressure gradient, which measures the rate at which pressure increases with depth as a result of the weight of overlying sediments and fluids. Deep-water sediment compaction is significantly influenced by the overburden pressure gradient value. Porosity reduction, sediment consolidation, diagenetic changes, the development of overpressure, geomechanical behaviour, and reservoir characteristics are all directly impacted. In deep-water sedimentary basins, managing geomechanical hazards and optimizing drilling operations need an understanding of and accounting for the overburden pressure gradient. Therefore, it should also be noted that the overlying sedimentary weight is subsequently affected to lithology changes. Therefore, the loads on these sediments during natural destructive vibrations can change from lower or upper sediments [24].

A method for estimating the pore pressure distribution in sedimentary formations based on the compaction behaviour of the sediments is known as deep-water pore pressure prediction using the normal compaction trend. In a basin where sediments compact uniformly, the normal compaction trend is the correlation between depth and porosity reduction. It is crucial to keep in mind that the typical compaction trend presupposes that the sediments compact uniformly and that there are no appreciable lateral differences or unusual pressure regimes. Predictions may need to be adjusted and further study performed if there are variations from the typical compaction pattern.

The ability to anticipate deep-water pore pressure using the typical compaction trend is a useful resource for offshore operations' drilling and well planning. The management of drilling hazards, the creation of suitable mud weights, and the assurance of wellbore stability in deep-water situations are all aided by accurate pore pressure estimation. Normal compaction trend generation required a good match with the computed shale trend within the well. The Normal Compaction Trend (NCT) is the ideal velocity line in the low permeability bed transition zone [5].

The computed NCT of Well X-001(Figure 18) revealed that there is normal compaction from the top of the well to about 2500 m. At a depth of 2500 m, however, there is a leftward deviation from the typical compaction trend line, indicating the start of overpressure. It is predicted that the well pressure will be greater than the hydrostatic pressure at this depth. This signifies that the onset of wellbore overpressure occurs at a depth of 2500 m (where the arrow turns red). At depths beyond this zone, a rise in porosity in the overpressured shale led to a decrease in compressional velocity below the usual compaction trend line. Top of overpressure (TOV) depth is when this transition begins, and it is at this depth that shale begins to form. Pore pressure zones corresponding to shales were delineated on this well beyond this depth.

Similarly, the onset of overpressure zones was also identified and observed to occur at depth of 2400 m and 2500 m in wells X-002 (Figure 19) and X-004 (Figure 20) respectively. Increased porosity in the overpressured shale was also seen to cause a decrease in compressional velocity below the typical compaction trend line. These depths correspond to shale formations in both wells. Pore pressure zones were also delineated beyond this depth. The results suggest that the normal compaction of sediment in the study area is less than the depth of about 2500 m. This depth is important because the build-up of overpressure begins at a depth of 2500 m. For economical and safe drilling operations, it is necessary to ensure proper drilling structures to avoid drilling hazards and their corresponding wellbore instabilities. Recent observations on pressure estimation, particularly the effect of lithology on compaction propensity and pressure patterns, can have a significant impact on conventional methods used to identify overpressure mechanisms and estimate pore pressures [22]. Mechanical compression mechanisms and petrophysical reactions have been widely studied. As a function of porosity and depth, the normal compression tendency (NCT) of the chosen mechanical compaction technique can be written as an exponential or power. This was used to predict pressure and identify overpressure mechanisms in this study. Li *et al.* [13] noted that chemical compaction, governed by the transformation of lithology, often occurs in deep mudstones and significantly affects their petrophysical properties and fluid flow. The results of their study showed that a net transformation of clay minerals with increasing depth and that the transformation peak of clay minerals is approximately equal to the overpressure pressure depth.

Typically, compressional sonic (transit time) usually decreases with depth during normal compaction. This observation is due to increase in sonic velocity with depth, which reduces the transit time it takes for compressional waves to pass through the rock formations. However, as compressional wave enters an under compacted zone (overpressure), the travel time increases sharply. Overpressure zones were discovered and identified at the depths where the log signal pattern deviated from the trend line. For Well X-001 (Figure 21), the onset of overpressure zone was identified at a depth of approximately 2500 m. This depth corresponds to shale formation. Pore pressure zones were delineated on this well beyond this depth and they correspond to shale formations. The onset of overpressure zones was also identified and observed at depths of 2400 m and 2500 m in both Wells X-002 (Figure 22) and X-004 (Figure 23) respectively. The depth corresponds to shale on both wells. Pore pressure zones were also defined below this depth. The results suggest normal compaction before the depth of overpressure onset in the field of study. Overpressure build up started at the depth of about 2500 m and hence, this depth is significant. The results obtained from this analysis are consistent with the results obtained from normal compaction trend on compressional velocity analysis.

4. Conclusion

Hydrostatic pressures are similar to normal pressures and high formation pressures are greater than normal pressures in the subsurface, where pore pressure acts on formation fluids. Effective stress and velocity trend approaches are utilized to anticipate overpressure. In the former, rock stress behavior is used as a surrogate for predicting overpressure, whereas in the latter, a departure from the typical compaction trend is used for that purpose. Predictions of sediment compaction and pore pressure were made at X-field, far from coast in the Niger Delta, as part of this research. The results of this research show how anomalous pressure can be predicted and used in the planning of a drilling program to compact sediments. Caliper, gamma ray, deep resistivity, neutron, density, and acoustic logs from four wells were used in the analysis.

There are two main types of lithology recognized. Both the sand units and the shale units have reservoir and seal/source rock potential. Well-X001 has six reservoir windows (Res-1, Res-2, Res-3, Res-4, Res-5, and Res-6) while Well-X002 has two, Well-X003 has three, and Well-X004 has two. The results of sediment compaction mechanism show wide variations in the compaction coefficient across the four wells. Overpressure is likely caused by disequilibrium compaction, as indicated by the crossplot for mechanism of overpressure. The sediments in the research area are normally compacted to a depth of less than roughly 2500 m, as predicted by the overpressure trend resulting from typical compaction. Around 2500 m was the starting point for the buildup of overpressure. Above and below this depth, pore pressure zones have been identified. Compressional velocity analysis showing a normal compaction trend is compatible with the results of this investigation. This consensus lent credence to the accuracy of the study's interpretations.

Overall, this research provides valuable insights into overpressure and sediment compaction prediction, utilizing a combination of innovative techniques and comprehensive data analysis. These points collectively justify the publication of the study as it contributes new knowledge to the field of petroleum engineering and geosciences, particularly within the context of the geologically challenging deep-water environments.

Declaration of competing interest

The authors confirm that they have no financial or personal ties to other parties that could be seen as influencing the results presented in this paper.

Data availability

The data that has been used is confidential.

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