A Relationship between Diagenetic Clay Minerals and Pore Pressures in an Onshore Niger Delta Field

By


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Abstract
One of the major challenges for exploration and development of oil and gas especially in deep
dissection settings is accurate evaluation of formation pressures. A good understanding of dominant
overpressure generating mechanisms and distribution in an area is the backbone to achieving
reliable subsurface pressure predictions well ahead of the bit for safe and cost-effective drilling
especially in a Tertiary basin like the Niger Delta. The integration of X-Ray diffraction (XRD) data
of sidewall cores, wireline logs, pore pressure measurements and reservoir temperatures has
provided scintillating insights into likely relationship between overpressures and clay mineral
distributions at an Onshore Niger Delta field. A characteristic feature of the clay mineral distribution
is the remarkable depletion and disappearance of kaolinites at about 100-130°C while the
proportions of illite/illite-smectite types increased to about 65-85% at this same temperature
interval corresponding to three distinguishable pressure ramps across three distinct thermal
regions. Normal compaction (hydrostatic pressures ≤ 0.45 psi/ft) occurs around the 60°C interval.
Moderate overpressures (0.45-0.70 psi/ft) tie to the 70°C – 100°C range while high overpressures
(≥0.70 psi/ft) prevail at and above the 100°C isotherm. The relationship probably suggests that
clay diagenesis may be playing a role in the generation and retention of high formation pressures
in parts of Onshore Niger Delta.

Keywords: pore pressure prediction, clay diagenesis, unloading, Niger Delta

Introduction
The Onshore Niger Delta has been a very prolific hydrocarbon province for over fifty years. Key
amongst the technology enablers for the successful exploration, appraisal, development and
production in this region has been the ever increasing resolution, application and integration of
seismic technology with other tools. However, with increasing maturity of the Onshore Niger
Delta, operating companies are drilling deeper and one of the major constraints to deep drilling is a
full understanding of the nature and diversity of overpressure generating mechanisms which will
form the background for an accurate pore pressure prediction strategy. On a global scale,
overpressured formations pose significant threats to drilling safety and the cost of mitigation is
always astronomical. It is estimated that the oil and gas industry spend well in excess of a billion
dollars annually on pressure-related issues. A major feature of overpressure generation is the
retardation of fluid dissipation in relation to sediment loading. Common mechanisms include
disequilibrium compaction; fluid expansion mechanisms such as hydrocarbon generation, clay
diagenesis, aquathermal pressuring, porosity loss due to cementation effects; as well as lateral
transfer via inclined beds. Overpressures that are generated by disequilibrium compaction can be
evaluated using routine porosity-based techniques. However, with increasing depth of burial,

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1 Opara, A.I., 2011. Estimation of multiple sources of overpressures using vertical effective stress approach: case study
temperature driven processes may become active within the pore space leading to secondary mechanisms of overpressure generation better known as fluid expansion mechanisms such as kerogen transformation, gas generation, clay diagenesis and sea water expansion. These changes cause high fluid generation in the presence of severely reduced permeability thus constraining the pore fluid within the rock matrix as the fluids increase in volume. Unlike undercompaction, fluid expansion can cause the pore fluid pressure to increase at a faster rate than the overburden stress giving rise to such characteristic overburden convergent profiles in a pressure-depth plot. This is due to the fact that the effective stress decreases as burial continues and the formation is therefore said to be unloading. Cross-plots of shale velocities versus densities can be used to identify the presence of overpressure generated by these post-undercompaction mechanisms.

Literature Review

The Niger Delta is situated in the Gulf of Guinea and extends throughout the Niger Delta Province as defined by Klett and others with sedimentation patterns that reflect response to basement tectonism. From the Eocene to the present the delta has prograded southwestward forming depobelts (Figure 1) namely Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp, Shallow Offshore and Deepwater (Knox and Omatsola, 1989) that represent the most active portion of the delta at each stage of its development. These depobelts form one of the largest regressive deltas in the world with an area of some 300,000km² (Kulke), a sediment volume of 500,000 km³ (Hospers), and a sediment thickness of over 10 km in the basin depocenter (Kaplan and others). The most recent and comprehensive summaries of the geological history of the Niger Delta can be found in Doust and Omatsola (1990) and Weber and Daukoru. These depobelts which range up to 40 km wide and 300 km long contain characteristic sedimentary and structural styles developed during repeated phases of delta tectonism and associated sedimentary responses. Megastructures are bounded by counter-regional faults (oceanward boundary) and down-to-basin faults (landward boundary). Down-to-basin faults are associated with crestal collapse faulting.

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Figure 1: Section map of Nigeria showing the study area (red circle) and depobelts that make up the Niger Delta Basin (modified from Doust and Omatsola, 1990)\textsuperscript{11}.

The Tertiary section of the Niger Delta is divided into three formations, representing prograding depositional facies that are distinguished mostly on the basis of sand-shale ratios (Figure 2). The type sections of these formations are described in Short and Stauble\textsuperscript{12}; Frankl and Cordy\textsuperscript{13}; Weber and Daukoru\textsuperscript{9}; Avbovbo\textsuperscript{14}; Doust and Omatsola\textsuperscript{5}; Kulke\textsuperscript{6}; Knox and Omatsola\textsuperscript{4}; Tuttle et al.\textsuperscript{15}. These are from top to bottom, the Benin Formation made up of massive continental, fluvial sands and clays, up to 2000 m thick; the Agbada Formation that is characterized by interbedded fluvial, coastal, fluvio-marine sands and marine shales measuring up to 5000 m thick and the Akata Formation that comprise massive, marine shales or clays with stringers of sands and silt.

\textsuperscript{11} Op. cit
with thickness in excess of 5000 m. Together, they form a thick, overall progradational passive-margin wedge.

Figure 2: Section stratigraphy of the Niger Delta Basin (modified from Kulke, 1995)^6.

Overpressure studies in the Niger Delta

A good number of overpressure prediction studies have been done in the Niger Delta mostly for prospect risking and drilling and most of them were never published. From these previous documentations such as Krusi^16, it could be understood that pore pressure prediction in the Niger Delta has a history based primarily on empirical data analysis from pressure measurements, drilling data and sonic log data with convictions that disequilibrium compaction is the sole mechanism of the observed overpressures in the Niger Delta basin; the key assumption being that seismic velocity primarily reflects the degree of compaction of the dominant shales while other factors such as varying lithology, mineralogy, burial history and pressure equilibrium between lithologies were considered to be of secondary importance. Interestingly, SPDC in 2005 initiated a

regional study of clay minerals in the Niger Delta with one of the objectives being to use the result of the study to investigate if there is any relationship between clay mineralogical changes and observed overpressures in some of the operational fields. Although the study has documented the regional distribution of clay minerals in the Niger Delta, however no known attempt has been made to integrate this fascinating data with pore pressures.

In this paper, the effects of clay diagenesis on shale properties and their possible influence on the magnitude and mechanisms of overpressure generation were investigated for an Onshore Niger Delta field. The analysis and results have precedence from other overpressured basins of the world. The occurrence of overpressure at certain depths in sedimentary basins has been correlated with the formation of diagenetic clay (illite) in shales. Clay minerals can exist as detrital shale components or authigenic/diagenetic clays in the form of pore-filling kaolinite, pore-lining chlorite and pore-bridging illite while cement in shales may be in the form of dissolved clay minerals and quartz. Some studies on clay diagenesis/pressure generation have emphasized the possible volume change associated with the clay reaction. It was further suggested that the primary role clay diagenesis plays is to change the compaction response of shale and as such considered clay-derived water released from hydrated interlayer cations in expandable mixed-layer illite-smectite (I-S) during the illitization reaction as secondary pressure source. However, very small amounts of newly formed illite-smectite (even less than 5%) could result in pronounced reductions in shale permeability by blocking the effective pore network. The lower limit to which mechanical compaction can reduce the permeability of clay-rich sediments has been estimated to approximately $10^{-6}$ D but Bethke et al had already shown that lower permeabilities were needed to maintain high overpressures over geologic time. Thus, it is plausible to relate further permeability reductions to chemical reactions inside the shale. Nadeau et al provide evidence

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for a very effective mechanism by which the precipitation of relatively minor amounts of neoformed illite-smectite (I-S) within shales/mudstones can greatly reduce permeability and thereby render them prone to overpressure.

Table 1: Clay fraction mineralogy of sidewall core samples in Well B as documented in the SPDC 2009 Second Interim Report of Regional Distribution of Clay Minerals in the Niger Delta (courtesy: SPDC Geological Integration Team).

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Depth (ftss)</th>
<th>K+D+H (wt%)</th>
<th>Chlorite (wt%)</th>
<th>Total NEC (wt%)</th>
<th>Total EC (wt%)</th>
<th>S+P (wt%)</th>
<th>Illite+I-S (wt%)</th>
<th>Mica (wt%)</th>
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<td>37</td>
<td>33</td>
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<td>25</td>
<td>51</td>
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<td>17</td>
<td>83</td>
<td>34</td>
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Materials and method

The data for the study was graciously provided by Shell Petroleum Development Company Ltd and as such the detailed procedure and technicalities for the data generation is domiciled with the company. These data include wireline logs such as gamma ray, density, sonic, resistivity, caliper and neutron; regional hydrostatic gradient, overburden gradient, geologic, reservoir temperature and pressure data. Measured pressures such as RFT, MDT and drilling events were posted at the
depths where they occurred along the well trajectory. Clay fraction data (Table 1) presented in Shell’s internal second interim report of regional distribution of clay mineral in Niger Delta formed the basis for constraining and correlating dominant clay groups and mineral with observed pore pressures and thermal regimes. The shales were identified using a combination of gamma-ray logs and composite logs in the well file while compromised well sections as indicated by the caliper log were filtered out thus building a high-confidence database of shale-only properties. Cross-plots of shale-only densities and velocities were used to determine the nature of the overpressure generating mechanism whether disequilibrium compaction or post-undercompaction sources such as fluid expansion mechanisms like clay diagenesis. The original Eaton and modified Eaton methods were applied for the 1D pore pressure prediction process.

Results and discussion

Clay mineralogy of sidewall core samples and velocity analysis

X-ray Diffraction data (XRD) of the sidewall core samples of the study well as shown in table 1 was used to assess the relationship between overpressures and clay mineral changes.

The dominant minerals are:

1. Non-expandable clays (NEC) of kaolinite-dickite-halloysite (K+D+H) series with chlorite.
2. Expandable clays (EC) of mixed-layer clays comprising essentially interstratified illite/smectite of montmorillonite character with sepiolite and palygorskite.
3. Varying proportions of muscovite (mica).

Total non-expandable clays decrease from 70% at 6699.02ftss (2042.38m) to 17% at 11847.27ftss (3611.97m) whereas the expandable clays increase from 21% to 83% along the same depth interval (Figure 3). At 9758.7ftss (2975.21m), the kaolinite group disappears while the sepiolite-palygorskite and illite/illite-smectite montmorillonite type increases significantly (Figure 4). On a fair approximation, the non-expandable clays bear an inverse relationship with the expandable clays in the same manner as the kaolinite group and the illite/illite-smectite (I-S) series (Figure 5).

![Figure 3](image-url): Depth trend of proportions of total Non-expandable clays and expandable clays.
**Figure 4:** Depth trend of proportions of kaolinite and Illite/illite-smectite types.

**Figure 5:** Possible trend of transformation of kaolinite group to illite-smectite types.
Density and velocity cross-plot and pressure prediction at clay sample depths

Normal compaction and disequilibrium compaction typically trail the virgin curve. As diagenetic clay mineral changes often cause decrease in grain-to-grain contact with the implication of steep decline in the velocity trend as a result of reduced effective stress with minimal / variable impact on densities, density-velocity cross-plots that exhibit steeply plunging trends (figure 6) may be diagnostic of unloading overpressures although cementation effects may in some instances mask this trend. Eaton exponents in excess of 3.0 fairly predicted the pressure regimes when compared to the actual formation pressure measurements.

![Density-velocity crossplot](image.png)

**Figure 6**: Density versus Velocity cross-plots for some Onshore Niger Delta wells. Note the two distinct limbs in well B where the undercompaction limb is trailing the virgin curve while the unloading limb is marked by a steep-downward trend in velocity and a near-isodensity. Well B is the candidate well for the clay diagenesis-overpressure study indicating the presence of an unloading mechanism.

From figure 6, analysis of velocity-density crossplot produced a deviation from primary shale trend. The observed deflection to lower velocity and near-isodensity may be indicative of alterations in the compressibility of the rock typically associated with clay diagenesis\(^\text{26}\). Further analysis may help determine the process affecting rock compressibility, reducing grain-to-grain contact and transport properties like velocity. In order to investigate any possible relationship

between the observed depth-varying clay minerals and overpressures, petrophysical data (sonic velocities and densities) were “cored” from the same depths at which the petrologic clay samples were cored. This yielded depth-correlatable data for 1D pore pressure prediction for the cored “clean shale” well section. The pore pressure prediction process followed the empirical modified Eaton method. Using an Eaton exponent of 5.5 in the well provided a best match in the trends of the RFTs and the predicted pressures for the clay sample depths (figure 7). This may further be indicative of unloading overpressures.

**Figure 7:** 1D predicted pore pressures at depths of cored clay samples compared with actual measured pressures in the encased sands.

Having obtained pore pressures at the depths of the cored shale/clay samples as shown in figure 7 above, the proportions (weight %) of the various clay mineral groups detailed in Table 1 were cross plotted with corresponding predicted pore pressures (Figures 8 - 11). The results indicate a high probability of clay diagenesis contributing to the generation of high overpressures in the area. Along the pressure profile, moderate overpressures coincide with the depths of kaolinite-rich clays (6890 – 9230 ftss) while high overpressures are in the illite/illite-smectite mixed-layer dominated sections.
Figure 8: Inverse relationship of pore pressures with non-expandable clays. Note the progressive increase in magnitudes of subsurface pressures with decrease in quantities of non-expandible clays (NEC) mainly made up of kaolinite-dickite-halloysite (K+D+H) series with chlorite further shown in Figure 9.

Figure 9: Inverse relationship of pore pressures with kaolinite group (the main constituents of the NEC).
Figure 10: Pore pressure magnitudes are here observed to be increasing with weight proportions of expandable clays made up mainly of the illite + illite / smectite members with sepiolite and palygorskite as also shown in Figure 11.

Figure 11: Direct relationship of pore pressures with Illite/ Illite-Smectite group.
Temperature Analysis

Thermal modeling of sedimentary basins has attracted increasing attention in recent times due to its application as a tool in hydrocarbon exploration (oil and gas generation, migration, seal integrity analysis and overpressure modeling). Temperature values obtained from these models have frequently been related to clay mineral distribution in diagenetic series\(^\text{27}\) and to organic maturity indicators, mainly vitrinite reflectance\(^\text{28}\). Although a direct relationship between temperature and organic maturity exists in many fields and basins, correspondence with clay mineral composition is not as common, as it depends on several additional factors\(^\text{29}\). Temperature is commonly the key factor in dissolution and precipitation of clay minerals, since increased temperatures make some of the minerals unstable; at 60-80°C, smectite can react to form illite and quartz\(^\text{30}\). Precipitation of illites at temperatures of 80-100°C reduces the already low permeability by several orders of magnitude\(^\text{31}\).

This study demonstrates albeit on a field scale that such temperature-correlatable processes and products can be cross-correlated to model overpressure magnitudes. Clay mineral distribution, particularly indicators of the diagenetic history such as smectite illitization steps and kaolinite disappearance are evaluated in the most realistic thermal regime in accordance with available data and finally related to corresponding pore pressures. Table 2 shows reservoir temperature data in well B as extracted from the well file.


Table 2: Reservoir (PVT) Temperature data for the study well as sourced from the well file (courtesy: SPDC Geological Integration Team).

<table>
<thead>
<tr>
<th>Depth (ftab)</th>
<th>TVDss (ft)</th>
<th>TVDSS (m)</th>
<th>Temp (°F)</th>
<th>Temp (°C)</th>
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<tbody>
<tr>
<td>8512</td>
<td>8320.81</td>
<td>2536.83</td>
<td>194</td>
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<td>9787.81</td>
<td>2984.09</td>
<td>220</td>
<td>104.44</td>
</tr>
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</table>

Figure 12: Plot of reservoir temperature for the field.

A plot of the PVT temperature data (Figure 12) seems to indicate two thermal gradients defined by a temperature knee at about 9000ftss (2743.90m) with a best fit regression of the form: Temp (°C) = 0.009*Depthftss + 11.12
The regression for the temperature profile was used to evaluate possible prevailing temperatures at the depths of the cored shale samples. Corresponding clay mineral values were plotted against the temperature values as shown in Figure 12.

![Temperature vs Clay Mineral Distribution](image)

**Figure 13:** Thermal model for clay mineral distribution in the study well.

Plots of temperature with weight percent of corresponding mineral groups suggest the clays are likely affected by thermal processes. Different proportions of specific clay mineral phases have been observed and related to different thermal regimes. The data show an approximate balance in the proportion of both kaolinite group (≈ 25% - 40%) and illite/illite-smectite types (≈ 20% - 50%) at 70°C - 90°C (≈ 80°C) isotherm. This possibly is the early stage of diagenetic reactions. As diagenetic alterations advanced, severe depletion and disappearance of kaolinites became the dominant event at about 100°C - 130°C while the proportions of illite/illite-smectite types increased to about 65% - 85% at this same temperature interval. From Figure 13 above, it could be noted that a large proportion of the cored clay samples are below the 100°C isotherm where thermally-driven mechanisms could be a strong influence. Therefore, it could be noted that the transformation process (shown in figure 5) is characterized by possible dissolution of kaolinites and precipitation of illite/illite-smectite mixed-layer clays. This process has been proposed by several authors as a high magnitude permeability reduction process capable of sustaining high overpressures meaning that the impact on overpressures is more on permeability reduction through framework weakening and pore collapse rather than release of bound water. Further to this, the
temperature distribution of the mineral groups coincides with the thermal index for hydrocarbon generation\(^{32}\) thus highlighting its applicability as an exploration tool in the Niger Delta.

**Thermal modeling of overpressures**

Having established a relationship between temperatures and the proportions of major diagenetic clay mineral groups, a further correlation of temperature and pore pressure values enabled a delineation of overpressures in a thermally realistic model.

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**Figure 14**: Temperature constrained pore pressure model. Note the delineation of pressure magnitudes into normal (ringed in blue), mild (ringed in black) and high (ringed in bright red) with corresponding temperature regimes.

The analysis involved iteration of the gradients of both RFTs and predicted pore pressures in clean shales with corresponding temperature information. The results indicate three distinguishable pressure ramps across three distinct thermal regimes (Figure 14). Normal compaction (hydrostatic pressures \(\leq 0.45\) psi/ft) plotted around the 60°C interval. Moderate overpressures (0.45-0.70 psi/ft) earlier interpreted as products of disequilibrium compaction dominated the 70°C – 100°C range. Beyond the 100°C isotherm, high overpressures (\(\geq 0.70\) psi/ft) interpreted as products of unloading mechanisms were the dominant overpressure plots. Interestingly, this remarkably correlates with the thermally zoned clay mineral distribution patterns (Figure 13) earlier analysed and discussed. This reality further leads credence to the evidence of secondary mechanisms of overpressure generation in the Niger Delta.

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Conclusions

The study highlights the probability of clay diagenesis contributing to overpressures in the field under study. A petrologic framework for overpressures suggests a likely relationship between diagenetic clay mineral variations and the measured as well as computed pore pressures. A characteristic feature of the clay mineral distribution is the depletion and disappearance of kaolinite group with increasing depth and the increase in the proportions of illite/illite-smectite mixed-layer clays over the same depth interval. Mild overpressures coincide with the depths of kaolinite-rich clays while hard overpressures are in the illite/illite-smectite mixed-layer-dominated sections.

Empirical log-based 1D pore pressure analysis using the modified Eaton method further indicates that mechanisms other than undercompaction may be at play. Temperature analysis indicates that early stages of kaolinite dissolution and illite/illite-smectite precipitation reactions could be from 70°C -100°C corresponding to moderate overpressures while the advanced diagenetic reaction stages from 100°C with depleted kaolinite proportions and greater values of I-S mixed layer clays yield high overpressures. It could be understood from earlier works in similar basins of the world that the kaolinite to illite/illite-smectite mixed-layer clay transformation process is a high magnitude permeability reduction process capable of generating high overpressures.

This study calls for further analysis to bring this line of thought to a logical conclusion as this holds significant implications to hydrocarbon exploration. There is, therefore, need for full integration of geological conditions and processes into the pore pressure prediction and modelling workflow for optimal results and better understanding of subsurface realities.

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