Asian Journal of
Earth Sciences

ISSN 1819-1886

Academic
Journals Inc.

www.academicjournals.com

OPEN ACCESS Asian Journal of Earth Sciences

ISSN 1819-1886
DOI: 10.3923/ajes.2019.1.12

Research Article
Pressure Regime, Pressure Regression Detection and Implications in the SMK Field, Onshore, Western Niger Delta, Nigeria

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Abstract

Background and Objective: Pore pressure evaluations are crucial in assessing exploration risk factors and enabling reserve development models for well production and management, concepts affected by the presence of pressure regressions/reversals. The study aimed at quantifying encountered overpressures, understanding pressure regimes/distribution and suggesting possible implications in SMK field. **Materials and Methods:** Eight wells and two well reports were subjected to qualitative (log analysis) and quantitative analysis (pressure models). **Results:** Quantitative pressure analysis carried out using Wireline/MWD logs revealed that compaction disequilibrium was the dominant overpressure mechanism in the field with deviations from normal compaction trend around 9000 ft (2727 m) on the sonic logs. Shale pressures determined using standard Eaton and Equivalent depth methods revealed three pressure regimes, the normally pressured ($\leq$0.442 psi/ft-SMK 6), transitionally pressured (0.442-0.495 psi/ft; SMK 10 and 14) and abnormally pressured sections ($\geq$0.495 psi/ft) (SMK 1, 8, 11, 12 and 13). An important phenomenon observed from the pressure-depth plots was pressure regression/reversal typified by the presence of "shoulder effects", a consequence of dewatering of higher overpressured shale's above and below lower overpressured reservoir sand stones. These effects were very distinct in the overpressured wells (SMK 1, 8, 11, 12 and 13) with imprints in the normally (SMK 6) and transitionally pressured wells (SMKs 10 and 14). **Conclusion:** An overpressure implication was the suggested/probable occurrence of lateral reservoir drainage using pressure-depth plots and log analysis.

Key words: Overpressure, SMK fields, shoulder effects, lateral drainage, Niger-Delta, Wireline/MWD logs, lateral reservoir drainage

Citation: Ogunsakin Oluwakunle Moyofoluwa, Ehinola Ajayi Ehinola and Olopade Elijah, 2019. Pressure regime, pressure regression detection and implications in the SMK field, Onshore, western Niger Delta, Nigeria. Asian J. Earth Sci., 12: 1-12.

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The Niger Delta Basin (Fig. 1a) like other Tertiary deltas has rapid burial and sedimentation rates such that when pore fluid expulsion cannot keep up with the sedimentation rate, under-compaction of sediments occurs. Upon further burial, these zones become closed off and consequently dewatering is halted leading to overpressuring of such enclosed zones thus, posing risks of drilling safety, astronomical well costs and environmental pollution/damage. Posing greater concerns are the associated phenomena of overpressuring such as pressure regressions. In standard geopressure models, shale pressures are expected to increase with depth as more "incompletely-dewatered" deeper shales are encountered but a reversal of this idealistic trend indicates a possibility of lateral flow through pressure regression/reversal, in which overpressure differences between reservoirs (sandstones) and source rocks (shales) cause a pressure differential that enables overpressure transfer (from shales to sands) and subsequent secondary migration of fluids (water and hydrocarbons) across adjacent laterally extensive reservoirs. These regression effects transmit to lateral drainage of fluids causing hydrodynamic trapping of oil and gas, resulting in the formation of an unconventional aquifer (aquifers not driven by a hydraulic head). Pressure regression from regions whose overpressuring is fuelled by compaction disequilibrium have been documented in several basins namely the North Sea[1], Cooper Basin, Australia[2] and recently from the Niger Delta geopressure study of deep water acreage[3], the earliest study to identify this so far in the Delta.

There are two broad mechanisms for geopressure generation namely loading and unloading mechanisms[4,5]. Loading mechanisms include disequilibrium compaction and tectonic compression[6]. Unloading mechanisms include clay diagenetic processes such as smectite-illite transformation[7,8], hydrocarbon generation[9,10] and lateral or vertical transfers[11-14]. In the Niger Delta, compaction disequilibrium is thought to be responsible for overpressuring[15-18] but recently some papers[19,20] suggested that fluid expansion (an unloading mechanism) could be key contributors in high temp/high pressure ultra deep wells (Fig. 1a, b). An understanding of the geology of the basin is crucial for well site planning and pressure analysis[21,22].

The question now remains on whether pressure regressions exist on onshore portions of the Delta, what overpressure mechanism drives any pressure regression found, what possible consequences these regression effects may have on drilling and well planning scenarios and what (if any) impact on pressure in homogeneities, well placement and reserve estimation scenarios for the Delta.

This current study aimed at addressing these research gaps by understanding the mechanism of overpressuring encountered, quantifying overpressures, identifying pressure regression effects and proposing associated effects/consequences for the field and region. Pressure quantification and pressure regression analysis in this current study would help to fill the gap on how overpressuring affects pressure regressions onshore, Northern Delta Depobelt.

MATERIALS AND METHODS

Geologic setting: The study area (SMK Field) was located onshore (Latitudes 5°N and 6°N and Longitudes 5°E and 6°E) of the Niger Delta Basin. Stratigraphically, 3 major formations from the oldest to youngest have been observed in the Niger Delta namely the Akata (potential source rocks), Agbada (potential reservoir rocks) and Benin Formations[23-26]. The Niger Delta is one of the most prolific deltaic hydrocarbon provinces of the world (Fig. 1a).

Well drilling and control operations in the field have had a series of setbacks with several drillable prospects abandoned due to blowout problems while other prospects in the same field (reasonably close to the over pressured wells) have little or no overpressure problems creating a baffling scenario on overpressure distribution in the field. As a consequence, reserve estimation is affected. This current study would help to understand pressure regimes/distribution in the SMK field (Fig. 1b).

Data sets: The data set used for this study included suites of well logs (both Wireline and MWD) for 8 wells and two well reports. They were obtained from PanOcean Nigeria Limited through the Department of Petroleum Resources (DPR), Lagos state, Nigeria. The data was quality-checked for spiking, patching and corrected to true vertical depths, imported into RokDoc software.

This study was conducted from January-September, 2017.

Methodology: The work flow employed was as shown in Fig. 2 (drawn by the authors but not to scale). It involved well logs analysis, multi-well qualitative plots, pore pressure estimation and pressure-depth plots. All figures in the study utilized the RokDoc software.

Well logs analysis: The well logs were analyzed for pore pressure (both qualitative and quantitative) using the RokDoc software. Well logs (Wireline/MWD) data include gamma ray (GR), sonic (SON) density (DENS), resistivity (RES-LLD) and

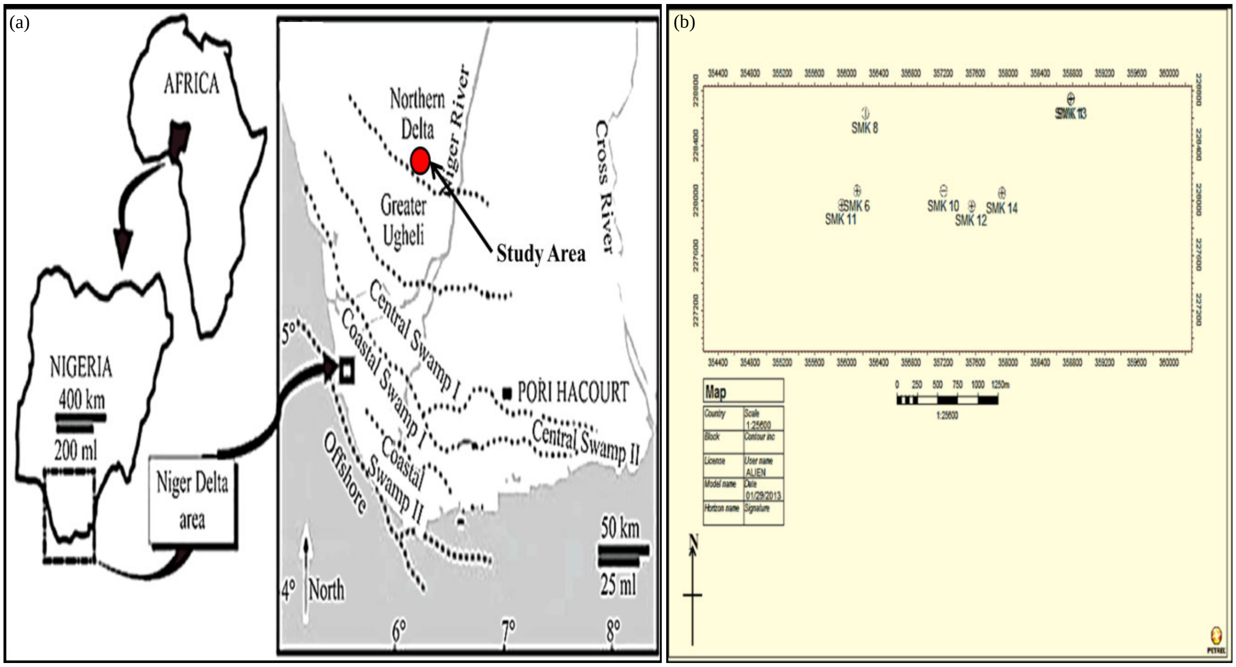

Fig. 1(a-b): (a) Map of the Niger Delta showing the SMK Field (inset is the map of Nigeria and Africa) and (b) Base map of the SMK field
Source: Ehirim *et al.*[27]

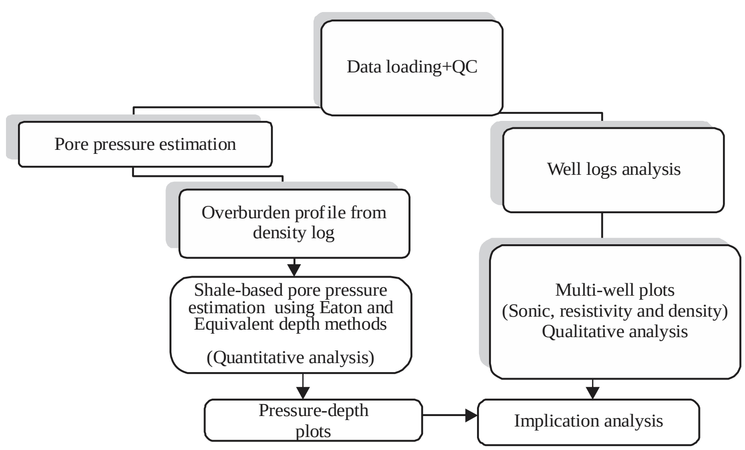

Fig. 2: Work flow of the study

neutron (NEU) logs. The Gamma ray log was utilized in differentiating sand (brown color) and shale (dark gray) units (lithology) and for well correlation to determine reservoir extent by using cutoffs. Sonic, density and resistivity logs were qualitatively used to indicate overpressure zones.

Pore pressure estimation: The deep resistivity (LLD), sonic (SON) and density (DENS), logs were utilised in pore pressure identification (qualitative) and estimation (quantitative) respectively by means of Eaton and Equivalent depth methods as shown in Eq. 1, 2 and 3. The quantified pore pressures were then presented as pressure-depth plots for the Field.

Eaton's method[28] comprised the following Eq. 1, 2:

$$\text{Formation pressure} = \left(S - (S - Pn)\left(\frac{\partial \text{NCTsonic}}{\partial \text{To}}\right)^{3.0} \right) \text{ for the sonic log} \quad (1)$$

$$\text{Formation pressure} = \left(S-(S-Pn)\left(\frac{R_o}{R_n}\right)^{1.2}\right) \text{for the resistivity log} \quad (2)$$

Where:

S = Overburden gradient in psi/ft
Pn = Normal pore pressure gradient in psi/ft
Tn = Normal sonic trend from NCT
o = Observed sonic value
Pn = Normal pore pressure gradient in psi/ft
Ro = Observed resistivity
Rn = Normal resistivity

Equivalent Depth/Vertical/Effective stress method for Resistivity, sonic and density logs utilized Eq. 3 in quantifying pore pressures:

$$P_a = \sigma_{vA}-(\sigma_{vB}-P_b) \quad (3)$$

Where:

P = Pore pressure (psi) at point A
σ_{vA} = Vertical stress at A (psi/ft)
σ_{vB} = Vertical stress at B (psi/ft)
A = Depth of interest in overpressure zone (ft)
B = Equivalent depth in normal pressure zone from A (ft)

Overburden profile: The overburden trend, derived from the overburden/lithostatic model gives the normal weight of overlying sediments and contained fluids with depth[28]. The density derived overburden model is converted from g cm^{-3} to psi (pressure) using the following Eq. 4:

$$\sigma_{ob} = 0.433\times\rho_b\times D \quad (4)$$

Where:

σ_{ob} = Overburden pressure
ρ_b = Bulk density of sediment in g/m^3
D = Depth in ft, ρ_b calculated from density logs and the overburden gradient is given by the following Eq. 5

$$\frac{\sigma ob}{D}(\text{psi/ft}) \quad (5)$$

Phydro (normal hydrostatic trend assumed from literature) as 0.433psi/ft.

Pressure-depth plots: These are quantified pore pressures with depth for each well in the field[29]. These were used to identify pressure regimes and distribution in each well and possible implications of such pressure distributions. Quantification/calculation of pore pressures utilized both Eaton and vertical effective stress methods in the RokDoc Software with calculated pore pressures by depth displayed on the pressure (psi) window (bold blue, red and orange lines). (Fig. 3, 4).

RESULTS AND DISCUSSION

These included Pressure-depth plots obtained using overburden profile model and Eaton/Equivalent depth methods.

Pressure regime: The pressure regime was as indicated by the pressure-depth plots in Fig. 3a-e and 4a-c, delineating the overpressured wells as shown in Fig. 3a-e and the normally/transitionally pressured wells, as delineated in Fig. 4a-c.

Overpressures were as observed in wells SMK 1, 8, 11, 12 and 13 as shown in Fig. 3a-e with encountered pore pressures higher than the normal or hydrostatic pressure of 8.5 ppg (pounds per gallon) i.e., $\leq$0.442 psi/ft for the Niger Delta. The pressure gradients of the wells fall within the hard overpressure range ($\geq$0.495 psi/ft) with quantified pressures as high as 0.76psi/ft (SMK 13) at final drill depth. There was observed a departure from the hydrostatic for all wells, a well defined transition zone for most wells and an overpressured section ($\geq$0.495 psi/ft) for some wells (Fig. 3).

Well report for SMK 1 contained information on mud weights and recorded pore pressures specifically at start/stop drill depths and these were used to validate quantified pore pressures for this study.

This hard overpressure regime was identified in all the wells with shale pressures ‘tramlining’ one another showing the relative similarity. Shale pressures (blue, red and orange lines on the pressure-depth plots) showed sublithostratic parallel to the overburden showing any mechanism of overpressuring in that field from disequilibrium compaction[3,14,18] (Fig. 3).

Casing depth selection and kick zones provided information about the accuracy of pressure estimation where encountered (Fig. 3d, 3e-apparently as calibrators).

The normally/transitionally pressured wells have quantified pore pressures either at normal/hydrostatic or in the transition zone (Fig. 4a-c). The pressure gradients range from $\leq$0.442 psi/ft (SMK 6) to 0.495 psi/ft (SMK 10 and SMK 14).

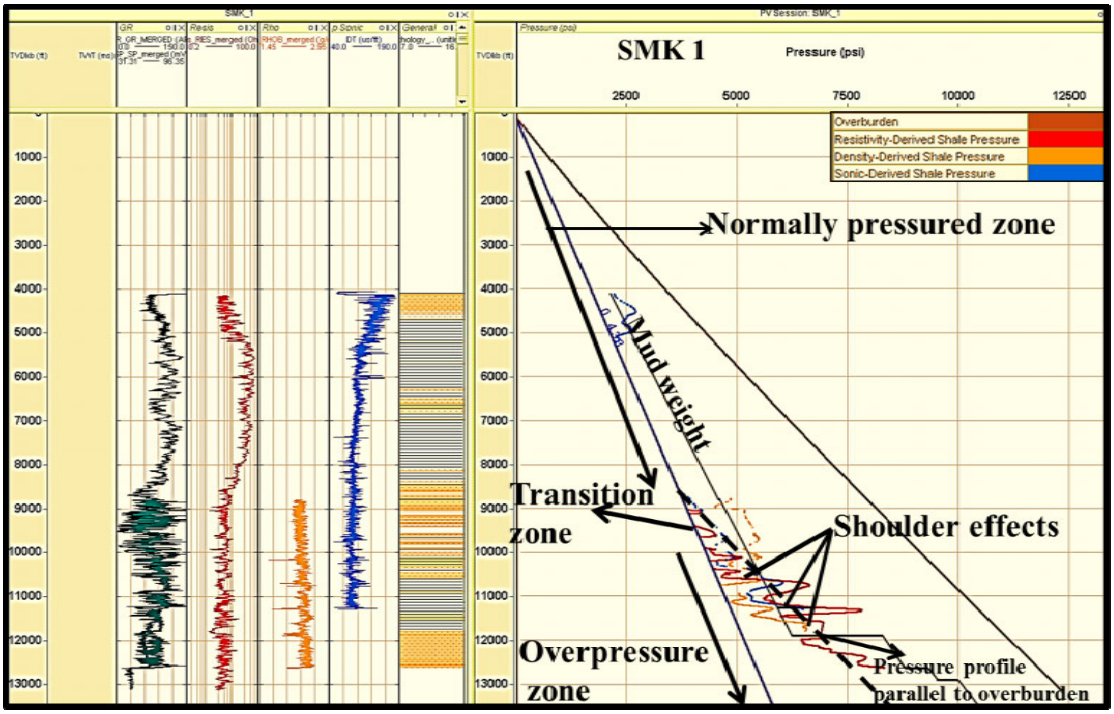

Fig. 3a: SMK 1 pressure-depth plot delineating pressure zones and shoulder effects

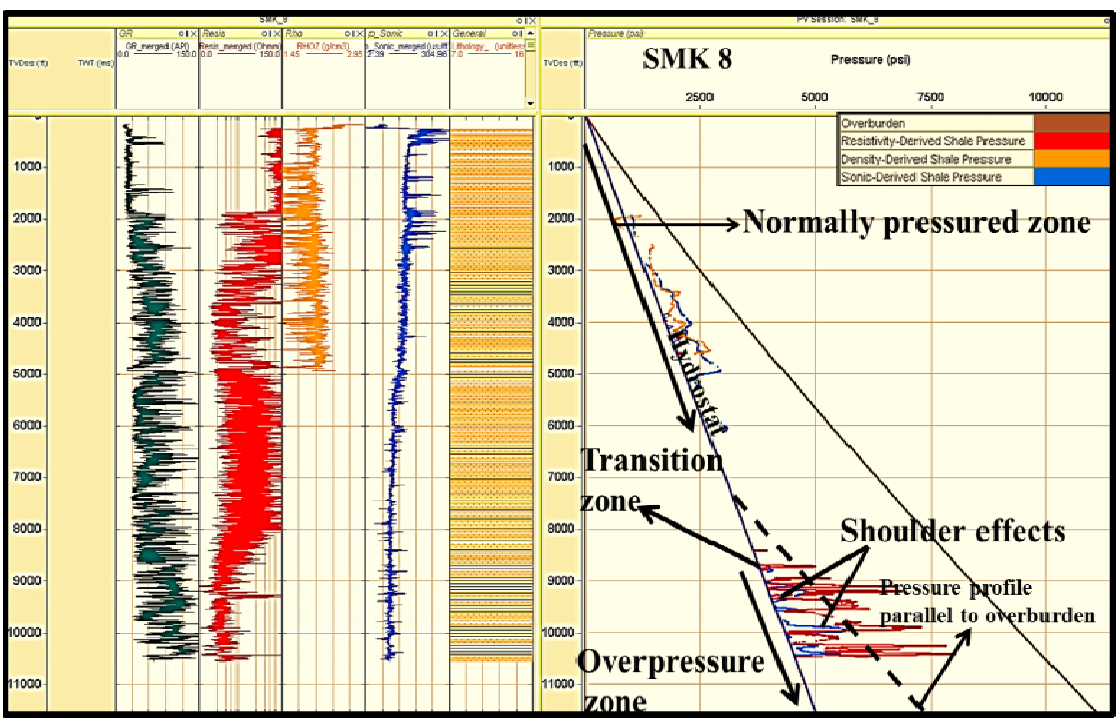

Fig. 3b: SMK 8 pressure-depth plot delineating pressure zones and shoulder effects

No appreciably higher pore pressures were observed till final drill depths for both pressure regimes (Fig. 4a-c).

Pressure regression: The pressure-depth plots (Fig. 3a-4c) revealed information on the nature of pressure distribution

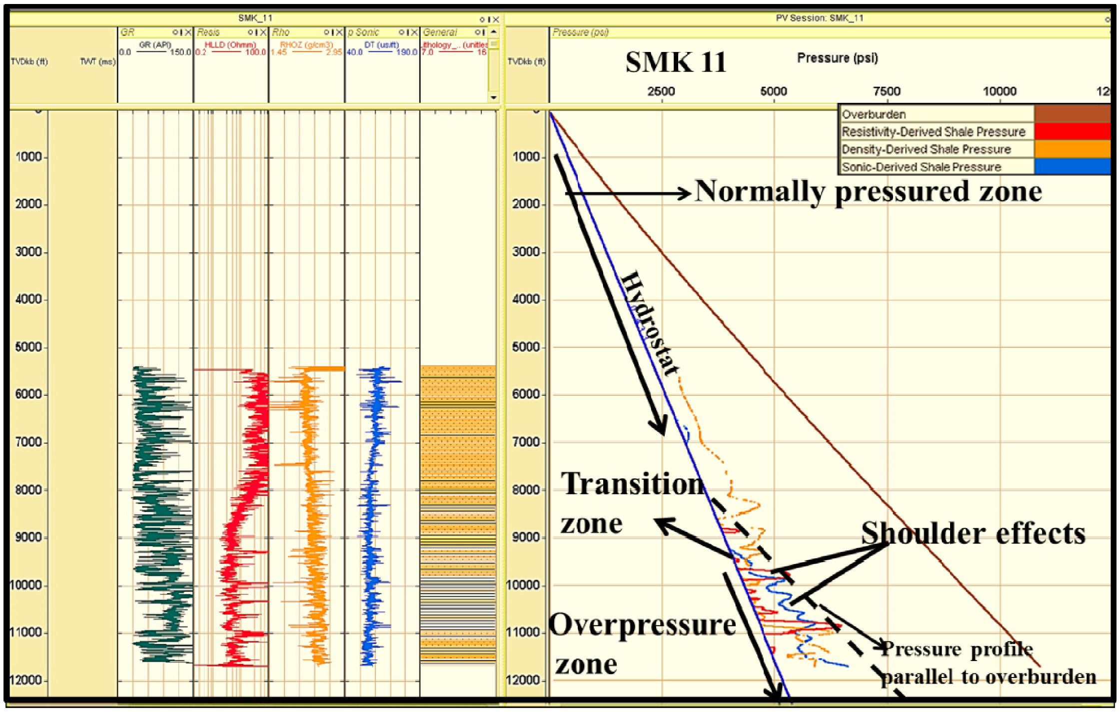

Fig. 3c: SMK 11 pressure-depth plot delineating pressure zones and shoulder effects

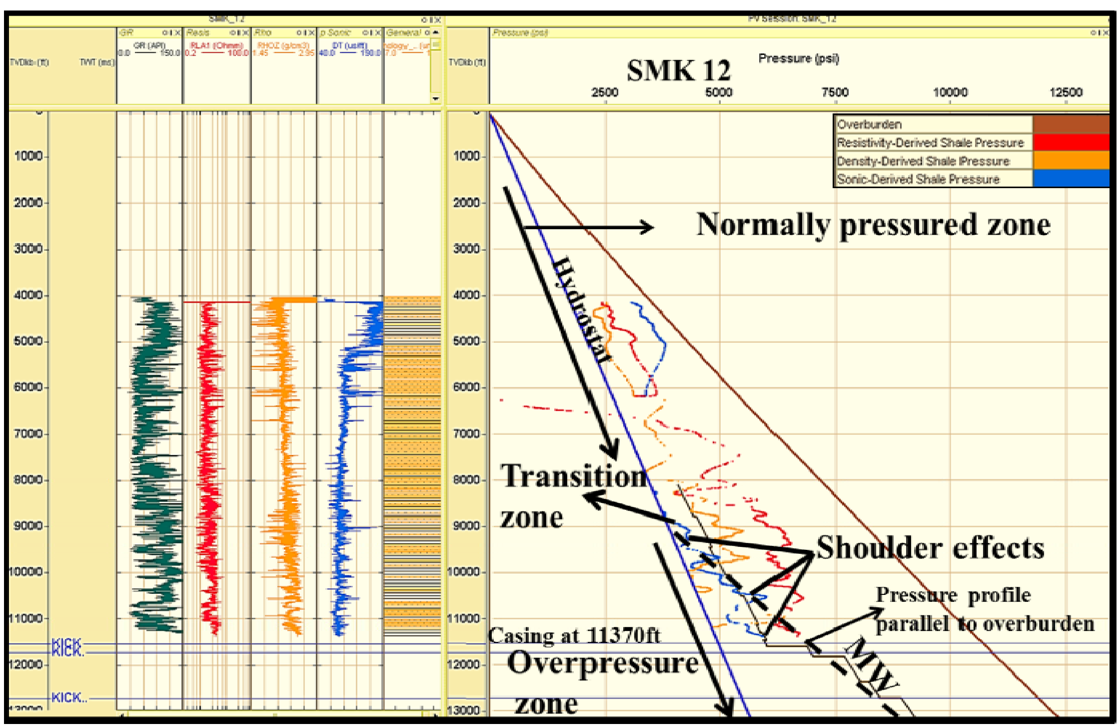

Fig. 3d: SMK 12 pressure-depth plot delineating pressure zones and shoulder effects

across the field notably in the area of pressure regression/reversals. Pressure reversals/regressions refer to envelopes or cascades of pore pressure signatures between mud rocks and reservoirs respectively with the mudrocks

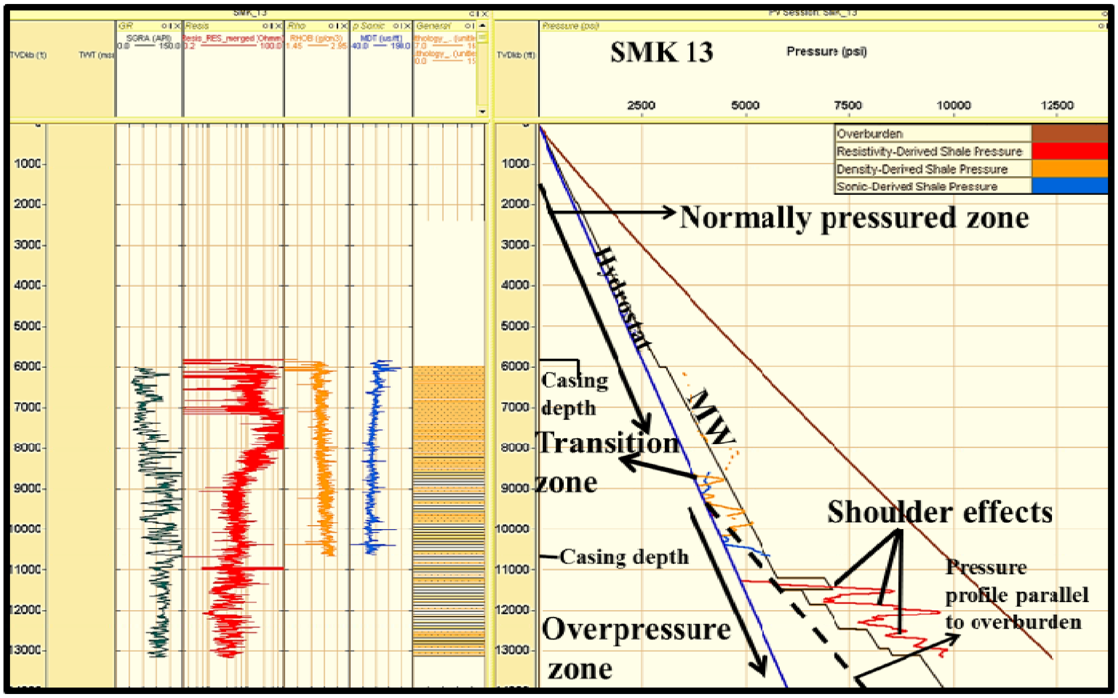

Fig. 3e: SMK 13 pressure-depth plot delineating pressure zones and shoulder effects

having the higher pressure signatures compared to the reservoirs. This regression phenomenon is usually discernible as "shoulder effects" on pressure-depth plots (Fig. 3a-e). In the SMK field, these "shoulder effects" were very prominent in all the 'hard' overpressure wells {SMKs 1, 8, 11, 12 and 13) and implies that in these wells, deeper buried sediments (sandstone) are at a lower overpressure than the sediments (shales) above and below them[30,31]. Such "shoulder effects" are characteristic signatures of shale dewatering where lower overpressure sandstone reservoirs are surrounded vertically above and below by the more highly overpressured shales triggering fluid flow from the shales to the sandstones (Fig. 3a-e). It is observed that the "shoulder effect" is less prominent in the normally pressured SMK 6 well and as imprints in the transitionally pressured SMK 10 and SMK 14 wells (Fig. 4a, c).

Shale pressures show marked increase with depth for all the overpressured wells examined (Fig. 3d-from 0.442 psi/ft at 9,000 ft through 0.52 psi/ft at 10,200 ft to 0.58 psi/ft at 11,200 ft) while some sandstone pressures dropped drastically, some to hydrostatic or sub-hydrostatic levels (Fig. 4a-0.446 psi/ft at 9,400 ft to 0.44 psi/ft at 10,800 ft) highlighting the pressure regression phenomenon[32,33].

Identifications of pressure regressions in the SMK field particularly in the overpressured wells could be indicative/suggestive of the presence of a phenomenon called lateral drainage.

IMPLICATIONS

It was well documented that in all cases where compaction driven overpressuring occurred with pressure regressions, lateral flow or lateral drainage and/or unconventional hydrodynamics follow. Comprehensive accounts on how shoulder effect (pressure regression markers) driven lateral fluid flow or drainage, influenced hydrocarbon trapping in various basins are well documented. Examples include Offshore Norway[30], UK Central North Sea[31], UK North Sea[32], Niger Delta basin[3,33], Central North Sea[34,35], Gulf of Mexico[36], Offshore Labrador[37], Tahiti Embayment[38], North Sumatra Basin[39], East Java Basin[40], South Caspian Sea[41] and Indonesia[42,43].

These studies[30-43] itemised pressure regressions (from higher overpressured shales to lower overpressured sands) as indicators of lateral drainage from deeper reservoirs (through laterally extensive, lower overpressured sands) to the surface. These studies closely approximate observed results in the SMK Field. On the basis of pressure-depth Plots, log analysis of the normally pressured wells, thickness of reservoir units and location/arrangement of these wells in the study area, a probable scenario was postulated.

Figure 1b showed a map of the study area with SMKs 6, 10 and 14 showing similarities in location (laterally situated). Log analysis showed remarkable similarities in

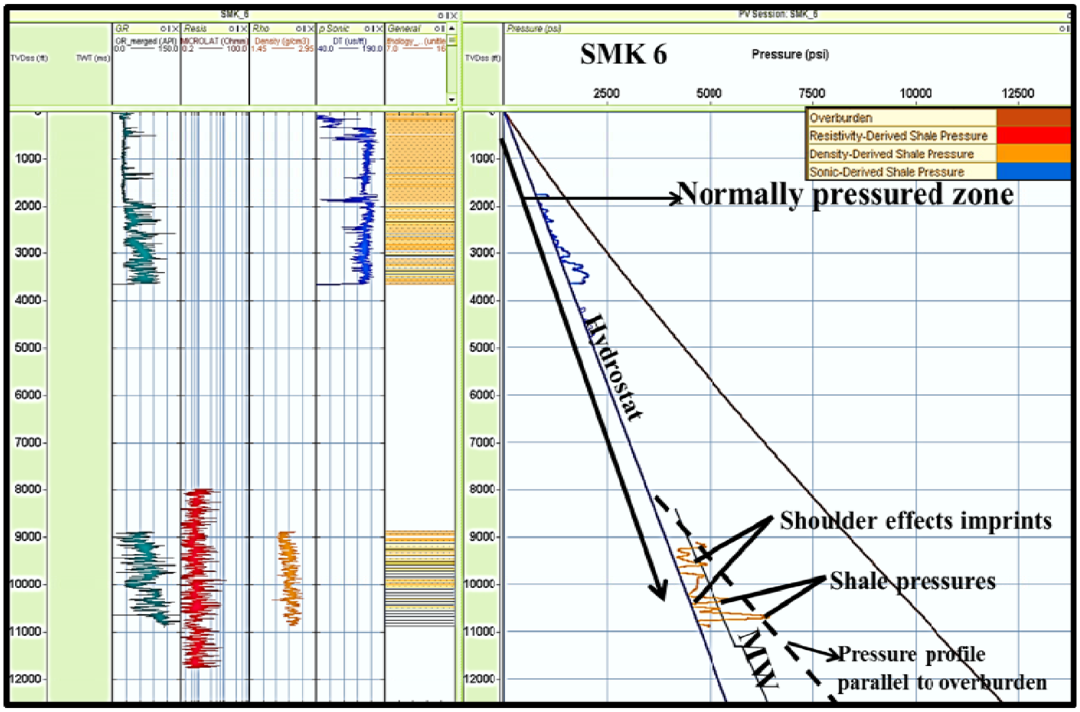

Fig. 4a: SMK 6 pressure-depth plot delineating pressure zones and shoulder effects

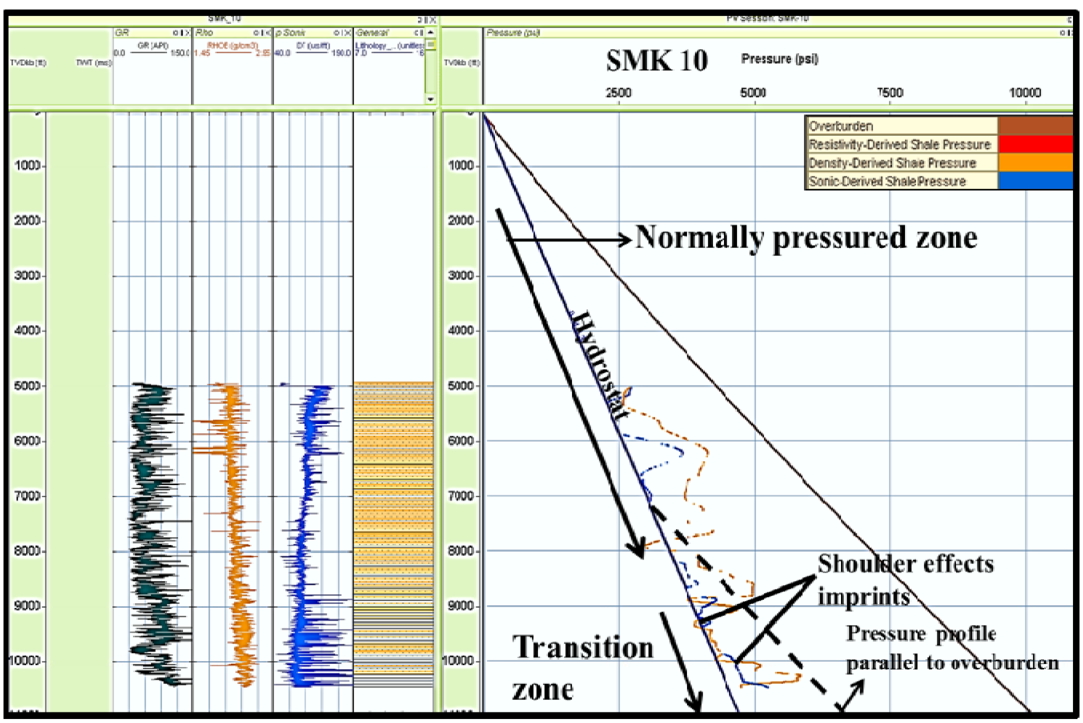

Fig. 4b: SMK 10 pressure-depth plot delineating pressure zones and shoulder effects

thickness, lateral extent and pressure magnitudes (there are no overpressures). Ghost prints of shoulder effects are indications that these wells have lost their pressures in the past through drainage and as such the shales are at

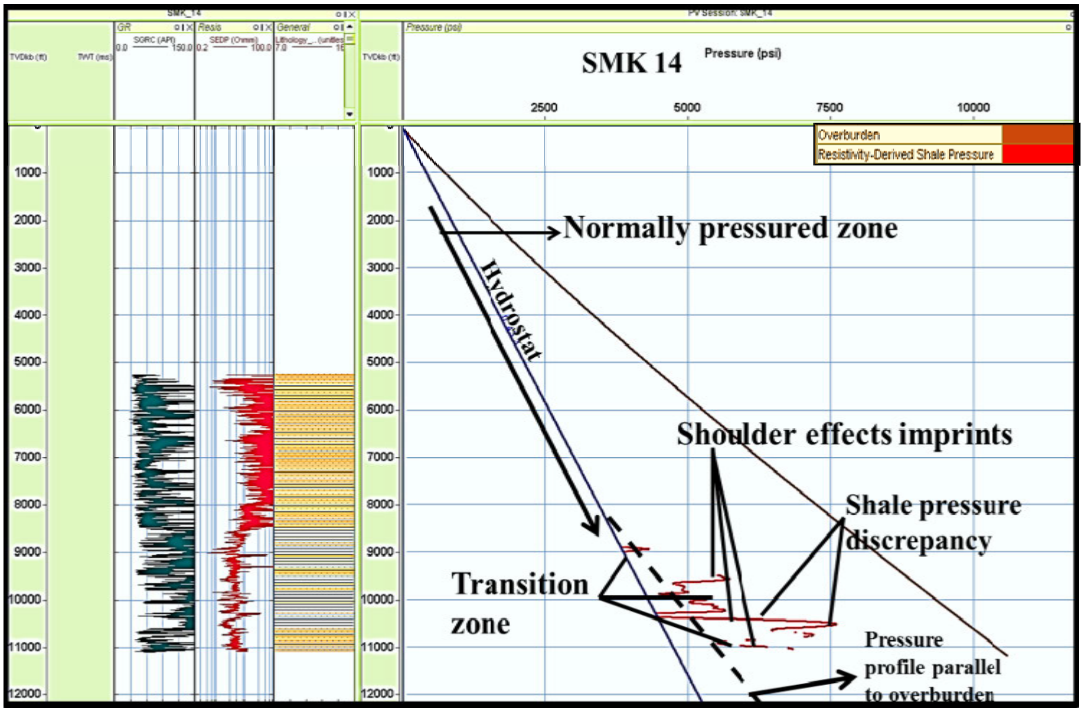

Fig. 4c: SMK 14 pressure-depth plot delineating pressure zones and shoulder effects

pressure equilibrium with the reservoirs[3,33]. SMK 11, situated to the southwest of SMK 6 and SMK 12, situated south of SMK 10 and SMK 14 have hard overpressures ($\geq$0.495 psi/ft) with clearly defined shoulder effects and as such they are actively undergoing pressure drainage at present. Based on the relative proximities of SMK 11-6 and SMKs 10 and 14 to SMK 12, SMK 11 and 12 appear to be the draining wells while SMKs 6, 10 and 14 appear to provide the draining conduits out of the SMK field. Similar scenarios have been recorded in other basins[9,15]. SMKs 1, 8 and 13 are farther off from the three normally pressured wells and maybe draining towards them. Based on current data, the authors hypothesized that SMKs 6, 10 and 14 maybe draining conduits for some of the overpressured wells in the field (SMKs 1, 8, 11, 12 and 13). Available literature[29-43] and current study therefore, showed similarity in agreement on the fact that compaction driven pressure regressions implies lateral flow/drainage through laterally extensive reservoirs as a consequence of reservoir-source rock uneven pressure distributions, as observed in the SMK Field. It is therefore plausible that lateral reservoir drainage is present in the SMK Field as well as the Northern Depobelt, Onshore Niger Delta with important consequences on well drilling and reserve estimation scenarios for this region of the Basin.

OVERBURDEN TREND

The density derived overburden gradient for the SMK Field was 0.88 psi/ft and this was utilized in pore pressure calculations. This calculated gradient was slightly less than the Gulf of Mexico maximum standard/default overburden gradient of 1 psi/ft (Fig. 4c).

CONCLUSION AND RECOMMENDATION

Pressure quantification using porosity/effective stress relationships such as the Eaton and the equivalent depth methods revealed three pressure regimes namely the overpressured wells (SMKs 1, 8, 11, 12 and 13), the normally pressured (SMK 6) and transitionally pressured wells (SMKs 10 and 14). The most readily recognized possible relationship between overpressure and the petroleum system in the SMK field of onshore Niger Delta is the pressure regression/reversal phenomenon evidenced by the presence of "shoulder effects" on pressure-depth plots. All the overpressured wells (SMKs 1, 8, 11, 12 and 13) in the field exhibit this phenomenon with imprints/ghost prints in the normally pressured (SMK 6) and the transitionally pressured wells (SMK 10 and 14). A possible implication of pressure regression is the suggested/probable presence of lateral reservoir drainage. Ghost prints of shoulder effects are indications that these wells have lost their pressures in the past through drainage. SMK 11, situated to the southwest of SMK 6 and SMK 12 situated south of SMK 10 and SMK 14 have hard overpressures ($\geq$0.495 psi/ft) with clearly defined shoulder effects. SMKs 11 and 12 are actively undergoing pressure drainage at present as well as SMKs 1, 8 and 13. Based on current data and documented evidence from other basins with pressure regression phenomenon, the authors theorize that SMKs 6, 10 and 14 maybe draining conduits for some overpressured wells in the field (SMKs 1, 8, 12 and 13).

Further studies are recommended in the SMK Field using PVT (Pressure-Volume-Temperature) plots, well reports and well production history to validate this study, pinpoint direction of drainage, thereby, giving clues of where hydrodynamic trapping (closely linked to pressure reversals, lateral drainage and very crucial for reserve estimation) could occur in the SMK Field. Other datasets like 3D Seismic and RFTs (Repeat Formation Tester) will go the extra mile in complimenting this work, build confidence on overpressure occurrence and distribution in the SMK Field.

SIGNIFICANCE STATEMENT

The significance of this study is to identify pressure regressions in the onshore portion of the Niger Delta Basin and the probable implications of pressure regression effects in an Onshore Niger Delta field. The presence of “shoulder effects” in all the overpressured wells signified that pressure regressions are actively present onshore, as a result of compaction driven overpressuring. Log analysis and pressure-depth plots hinted that these pressure regressions could be causative of asymmetric pressure distributions, indicative of lateral flow/drainage and potential precursors of hydrodynamic trapping scenarios, thus, presenting potential new reserve targets for the basin’s onshore portion. Further studies on onshore hydrodynamic trapping quantifications are currently being done by this research group.

ACKNOWLEDGMENTS

The authors are grateful to PanOcean Oil Corporation Nigeria Ltd., for providing data for this study. Gratitude is extended to Ikon Geoscience for the use of their RokDoc software.

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