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Quantitative Evidence of Secondary Mechanisms of Overpressure Generation: Insights from Parts of Onshore Niger Delta, Nigeria.[1]

By

K.K. Nwozor*
M.L. Omudu**
B.M. Ozumba**
C.J. Egbuachor***
A.G. Onwuemesi****
O.L. Anike****

Abstract

Accurate understanding of the mechanisms that generate abnormal fluid pressures is vital to the success of any approach to be applied in predicting or modelling such overpressures and their impacts on the associated exploration risks and drilling challenges. In the Niger Delta Basin, it is conveniently believed that overpressures are generated solely by disequilibrium compaction arising from rapid burial of Tertiary sediments and ineffective dewatering due to low permeability deposits especially shales but this belief has not been fully supported by empirical data. However, this study utilised log data to assess pore pressures in some fields in the onshore part of the basin. The results indicate that the observed high overpressures may not entirely be products of undercompacted rapidly buried sediments.

Through velocity-density cross-plots, velocity – vertical effective stress and density-vertical effective stress relationships, it becomes evident that unloading mechanisms of overpressure generation may significantly be at play. In computing the pore pressures, profiles based on modified Eaton unloading exponents conformed acceptably to the measured pressures (RFT) data whereas calculations using undercompaction equations failed at certain depth ranges. It is,

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*Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, AB24 3UE, UK.

**Shell Petroleum Development Company Limited, Port Harcourt, Nigeria

***Department of Geology, University of Port Harcourt, Nigeria

****Department of Geological Sciences, Nnamdi Azikiwe University, Awka, Nigeria.

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therefore, pertinent to deploy pore pressure prediction strategies that will take into account the likely contributions of secondary overpressure generating mechanisms such as clay diagenesis, hydrocarbon maturation and aquathermal expansion relevant to the geologic setting of this prolific hydrocarbon province.

Keywords: Niger Delta, overpressure, disequilibrium compaction, unloading, pore pressure prediction.

Introduction

The Nigerian oil and gas industry is presently faced with the challenge of achieving the national crude oil reserves target of 40 billion barrels and production of increased volumes of Liquefied Natural Gas (LNG) in order to meet export and domestic needs. The domestic need is bolstered by the current government policy thrust for additional gas turbines for power generation and industrial projects. This strategic growth plan therefore requires drilling of more wells in deeper and more challenging geologic settings.

One of the major constraints to exploration and development of oil and gas especially in deep geologic settings is the prediction of formation pressures ahead of the drilling bit. On a global scale, overpressured formations pose significant threats to exploration success and drilling safety with associated high costs of mitigation. Proper planning is the key to lowering costs and increasing safety. A good understanding of overpressure distribution in an area is very important for the safe and cost effective drilling especially in a Tertiary basin like the Niger Delta. The most successful approach to pore pressure prediction is one that combines a good understanding of rock properties of subsurface formations with good geological understanding.

Geologic setting

As already detailed in literature[2], the Niger Delta Basin is made up of three main lithostratigraphic formations namely the topmost Benin Formation which consists of massive

[2] Hospers, J., 1965. Gravity field and structure of the Niger Delta, Nigeria, West Africa: Geological Society of America Bulletin, v. 76, pp. 407-422.; Frankl, E.J., and Cordry, E.A., 1967. The Niger delta oil province – recent developments onshore and offshore: Mexico City, 7th World Petroleum Congress Proceedings, v.1B, p.195-209.; Short, K.C., and Stauble, A.J., 1967. Outline of geology of Niger delta: AAPG Bulletin, v.51, p. 761-799.; Burke, K., 1972. Longshore drift, submarine canyons and submarine fans in development of Niger Delta: AAPG Bulletin, v.56, pp.1975-1983.; Weber, K.J., and Daukoru, E., 1975. Petroleum Geology of the Niger Delta. Proc. 9th World Petroleum Conf. Tokyo 2 (Geology), 209 -221.; Avbovbo, A.A., 1978 (a). Geothermal gradients in the Southern Nigeria basin. Bulletin of Canadian Petroleum Geology 26, 268-274.; Avbovbo, A.A., 1978 (b). Tertiary lithostratigraphy of Niger Delta: AAPG Bulletin, v.62, pp.295-306.; Whiteman, A., 1982. Nigeria: Its Petroleum Geology, Resources and Potential: London, Graham and Trotman, 394 p. Doust, H., and Omatsola, E., 1990. Niger Delta, in, Edwards, J.D., and Santogrossi, P.A., eds.Divergent/Passive Margin Basins. AAPG Memoir 48: pp. 239-248.; Kulke, H., 1995. Nigeria, in, Kulke, H., ed., Regional Petroleum Geology of the World. Part II: Africa,America, Australia and Antarctica: Berlin, p.143-172.; Klett, T.R., Ahlbrandt, T.S., Schmoker, J.W., and Dolton, J.L., 1997. Ranking of the World's oil and gas provinces by known petroleum volumes: USGS Open-file Report-97-463.; Tuttle, M.L.W., Charpentier, R.R., and Brownfield, M.E., 1999. The Niger Delta Petroleum System: Niger Delta Province, Nigeria, Cameroon and Equatorial Guinea, Africa. USGS Open-File Report 99-50-H.

continental, fluviatile gravels and sands; the paralic Agbada Formation with its succession of interbedded fluviatile, coastal, fluviomarine sands and marine shales and the over 5 km thick Akata Formation made up of marine mudstones and silt with stringers of sands interpreted to be deposited by turbidity currents as deep sea fan sands during the development of the delta. The Akata Shales which is significantly overpressured is believed to be the main source rock within the Niger Delta complex. In the last 55 Ma, the delta which is predominantly known to be composed of regressive clastic sequence has prograded southwestward, forming depobelts (Figure 1) namely Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp, Shallow Offshore and Deepwater.

Few drilling efforts have penetrated the deep abnormally pressured parts of the Niger Delta Basin with reported incidents of mud losses, well kicks, stuck pipes and caving of the well bore leading to costly down time, tool losses and extra-budgetary sidetracks. Thus as the quest for deeper-lying reservoirs increase, it becomes of greater interest to broaden our knowledge of the overpressure generating mechanisms with a view to develop and deploy accurate predictive strategies for optimal success. Key to this is a good understanding of the processes that create overpressures and best practice solutions to recognizing these processes in sedimentary basins such as Niger Delta.

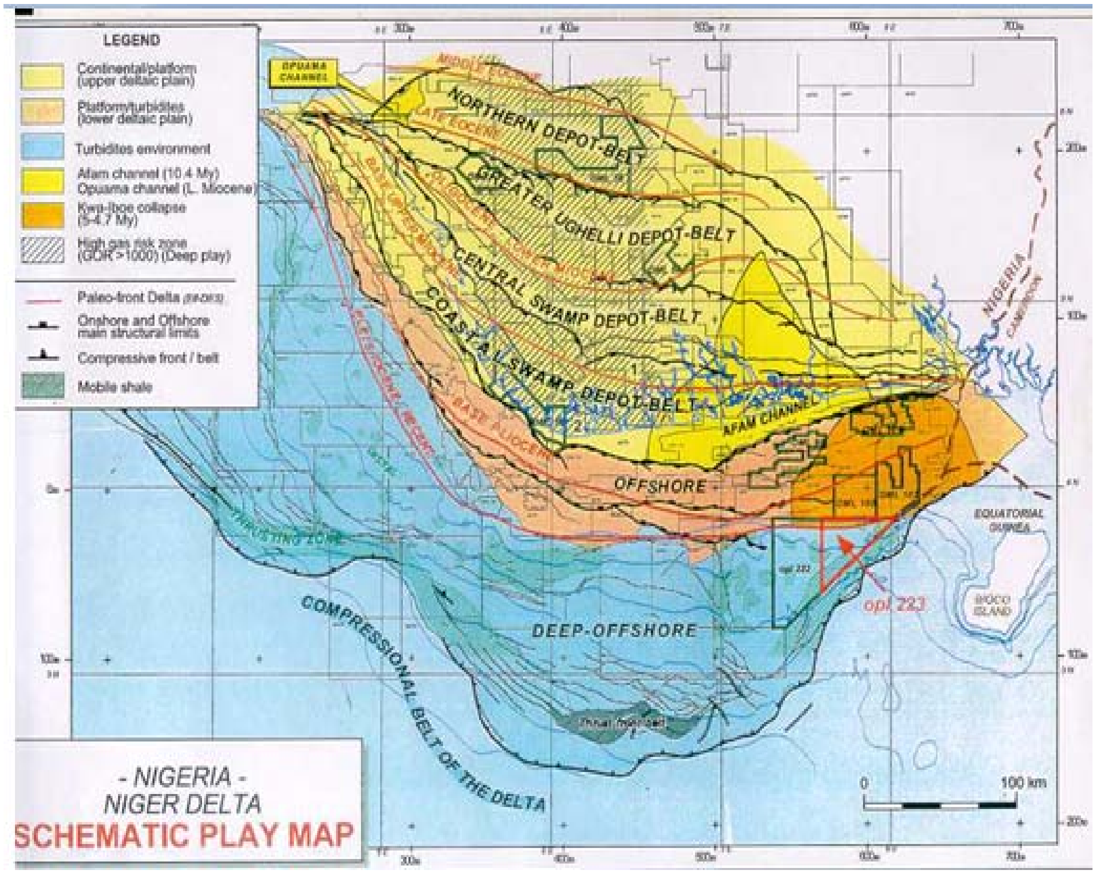

Figure 1: Section map of Nigeria showing the study area and depobelts (modified from Whiteman, 1982).

Overpressures in the Niger Delta

Overpressures in the Niger Delta have attracted the attention of operators and researchers quite early into the development of oil and gas activities in the basin where the depth of penetration of exploration wells were hitherto determined more or less by the occurrence of first kicks in such wells. This practice seemed to be borne on the belief that the occurrence of first kick should mark the onset of overpressure hence the termination of drilling. With precautionary increases in mud weight, target depths were often achieved with many of such wells erroneously classified as non-overpressured on the basis that no kicks were experienced. Earlier studies[3] relied on the kicks data and reversals in log trends to develop a series of pressure graphs and rudimentary maps aimed at delineating the onset of overpressures and their distribution in the basin based on such convictions that undercompaction was the cause of the overpressures. Most of these maps and accompanying data were however not published. These background pressure studies mapped the delta into four pressure zones. As more data became available from the drilling campaigns, it

[3] Wegmann, R., 1963. Progress report on subsurface pressures in the Niger Delta. Shell internal report.; Daukoru, E. 1973. Overpressures in the Niger Delta. Shell-BP Nigeria Exploration Report EP-45244.

was further proved that onset of overpressures varied widely between 4494 ft (1370 m) tvdss to 14006 ft (4270 m) tvdss with a very diffuse trend in spatial distribution thus diminishing the relevance of isobar maps in pressure prediction. Results and data presented in Anowai et al.[4] demonstrate that the top of overpressure is relatively shallower in the Northern and Greater Ughelli Depobelts when compared with the Central Swamp Depobelt and other near-to-offshore fault-bounded megastructures. This follows from recommendations in Krusi[5] which took a more quantitative approach by investigating the relationship between the top of overpressures with both shaliness and rate of subsidence and noted a pattern of pressure increases where net-to-gross ratio drops below 35% – 20% in proximity with discontinuous or detached reservoirs such as beach and channel sands. This was explained as due to restrictions to normal dewatering of the compacting sediments leading to the imposition of further weights on pore fluids by an increasing overburden pressure. The study went a further step to evaluate the contribution of aquathermal pressuring and yielded values of 1.3psi/ft as post-compaction pressure gradients which interestingly were higher than the 1.0 psi/ft commonly attributable to pure loading and explained that this could impact on pressure redistribution through severe leakage or lateral transmission. Despite presenting a good background for follow-up holistic investigations of mechanisms of overpressure generation in the Niger Delta, perhaps the bold recommendation in the Krusi[6] report for a wholesale application of the method of undercompaction pressure prediction in all future exploration and appraisal wells formed the backbone of the practice in subsequent prospect risking and drilling operations until recent times.

The wells used in this study situate in the onshore part of the Niger Delta sedimentary basin. Retention of overpressures in this part of the delta most likely are due to a general lower degree of continuity of the reservoir sands which Krusi[7] described as high percentage of channel sands in a river dominated delta versus predominantly bars/ beach sands in a wave-dominated delta. Excerpts from the well files show that two of the wells (Wells A and B) sampled fields located in the Greater Ughelli Depobelt while Wells C and D penetrated fields in the Central and Coastal Swamp Depobelts respectively. Well A consists of a stacked sequence of channel and shoreface deposits. The structure is an elongated dip closure towards the northwest with an approximate dip of 3.5^{o} and bounded to the south by an East-West trending fault and to the east by NE-SW trending fault. The structure at Well B is formed by a NNE-SSW trending footwall closure against a fault heading to the southeast. The sediments comprise series of sand and shale successions that have been deposited during different relative sea level changes. The sands are separated by regional shale units which form vertical seals. Well C is located in the seasonal fresh water swamp area (distal Central Swamp) and penetrated a stratigraphy that reflects interplay of incised-valley fills sedimentation and growth fault tectonics while Well D is a vertical exploration well that penetrated a large rollover anticline in the hanging wall of a boundary fault but on encountering high overpressures well beyond the pre-drill predicted pressure values had to be terminated at 16688.64 ft (5088 m), some 1400.6 ft (427 m) shallower than planned. Incidents such as this and other overpressure-related operational difficulties experienced while drilling some deep wells in the onshore part of the Niger Delta demonstrate

[4] Anowai, C.A., Ejedawe, J.E., and Adeoye, S.S., 2003. Regional Overpressure Study of the Niger Delta using seismic velocities. EP2003 – 5382.
[5] Krusi, H.R., 1990. Overpressures in the Eastern Niger Delta. EP 2000-2513.
[6] Ibid
[7] Ibid

the limitations of pore pressure prognosis based solely on disequilibrium compaction methodologies for these particular settings. The reason is not farfetched, relying only on conventional undercompaction models and the inherent assumptions for pore pressure analysis means measuring porosity retention while undercutting the contributions of secondary overpressure generating mechanisms that post-date rapid sedimentation. Although Anowai et al.[8] just like Krusi[9] noted the possibility of geopressuring from inflation mechanisms; this however has not been fully evaluated.

Mechanisms of Overpressure Generation

Pressure is simply understood as force per unit area. By the same token, formation fluid pressure is the pressure contained in the pore space of subsurface rock. In its normal state, it is the pressure exerted by the weight of the fluid on a static surface as a function of vertical height of the column and fluid density. Hydrostatic pressures range from 0.43 psi/ft to 0.48 psi/ft depending on the salinity of the formation water,[10] and the depth of extrapolation. Overpressure is said to occur when the formation pressure exceeds this normal or hydrostatic baseline.

In young Tertiary basins such as the Niger Delta, Gulf of Mexico, Nile Delta and Baram basins where rates of sedimentation are quite rapid with sufficiently thick intervals of shales; it permits technical convenience to rely on data (such as velocity and resistivity) that are actual measures of porosity retention to predict overpressures. The main assumption being that the overpressures are generated by disequilibrium compaction as a result of rapid sediment loading unaccompanied by equally rapid dewatering and compaction. Overpressure due to disequilibrium compaction is often recognized by higher porosity than expected at a given depth. This mechanism is characterized on pressure versus depth plots (figure 2) by a fluid retention depth where overpressure commences, and increases downwards along a gradient that can closely follow the lithostatic gradient[11].

[8] Op.Cit
[9] Op. Cit
[10] Krusi, (1990), Op. Cit
[11] Swarbrick, R.E., and Osborne, M.J., 1998. Mechanisms that generate abnormal pressures: an overview. In: Law, B.E., Ulmishek, G.F and Slavin, V.I., (eds) Abnormal pressures in hydrocarbon environments. AAPG Memoir 70, pp. 13 – 34.

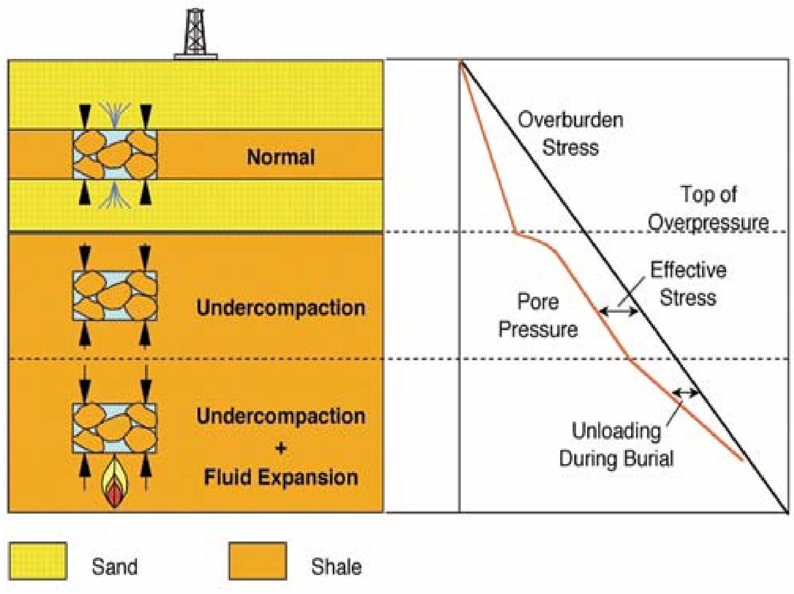

Figure 2: Pressure trends and response of vertical effective stress to different overpressure-generating mechanisms (source: Bowers, 2002)

The magnitude of overpressure in disequilibrium compaction is understood to be controlled by weight of the added sediment and any coupled responses in the lateral direction, mechanical properties of the rocks and any fluid redistribution through the seals or connected reservoirs.

This paradigm has been applied with varying success in the basin, often with dismal surprises. The typical pressure profile in this scenario as can be seen from some of the Niger Delta data is one that progressively increases with depth and overburden stress indicating a non-varying vertical effective stress gradient and a likely constant porosity. In addition to this overburden parallel pressure profiles, sharp transitions to overburden convergent pressure profiles can also be observed which suggest further that secondary mechanisms of overpressure generation are likely at play. O'Connor et al.[12] has used similar models to discriminate overpressure generating mechanisms in the Tertiary trans-tensional Malay Basin. The nature of the pressure transition zones which lithologically are thick shale successions observed in the onshore Niger Delta fields interpreted as maximum flooding surfaces using sequence stratigraphy no doubt qualifies as vertical pressure seals though not covered in this discussion.

A process related to undercompaction is lateral pressure associated with high overpressures generated by disequilibrium compaction and transmitted by fluid flow along laterally extensive inclined permeable aquifers[13]. This goes to present lateral transfer as being a more effective

[12] O'Connor, S., Swarbrick, R., Hoesni, J. and Lahann, R., 2011. Deep Pore Pressure Prediction in Challenging areas, Malay Basin, SE Asia. Proceedings, Indonesia Petroleum Association. IPA11- G-022.
[13] Yardley, G.S., Swarbrick, R.E., 2000. Lateral Transfer: A Source of Additional Overpressure? Marine and Petroleum Geology 17, 523 – 537.

mechanism in situations where rapid sedimentation is accompanied by tilting. Martinsen[14], and Osborne and Swarbrick[15], have extensively documented mechanisms of overpressure generation, transmission and retention.

Secondary mechanisms of overpressure generation post-date the normal sediment loading mechanism. These may be said to commonly stem from temperature-driven changes that occur in sediments as depth of burial increases. In this group are volume-alteration processes or fluid expansion mechanisms such as hydrocarbon maturation, clay diagenesis and expansion of sea water. Recent views by Nadeau[16] show how diagenetic processes may impact on overpressure development; first as dissolution/precipitation mechanisms in the formation of diagenetic illitic clays with increasing depth and temperature while the second is the formation of diagenetic cements in reservoirs. These according to him produce very low permeability shales that create effective pressure seals, thus further de-emphasizing the earlier-downplayed thoughts of overpressure generation due to release of bound water into sediment pores during the smectite to illite transformation process. It is understood that in many mud-dominated basins a gradual and systematic change from smectite to illite downwards in the stratigraphic section is observed, broadly coincident with the transition to high amounts of overpressure. This mechanism is also believed to produce barriers to fluid flow, as illite is more densely and efficiently packed than smectite[17]. Lahann et al[18] suggests that the primary role that clay diagenesis plays is to change the compaction response of the shale, where the clay-derived water released during the illitization reaction is a secondary pressure source and the change in the water volume is neglected. The coincidence of overpressure at the same stratigraphic levels as smectite to illite transformation may be related to the ensuing changes in the rock fabric, especially reductions in permeability trapping excess fluids generated by another mechanism[19].

Different phases of the hydrocarbon maturation process which progress along the kerogen-pathway impact on the fluid volume and under reduced effective stress conditions lead to overpressures. These reactions typically occur at depths of 2 km to 4 km and at temperatures in the range 70°C -120°C for kerogen maturation, and 3 km to 5.5 km and 90°C to 150°C for oil

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[14] Martinsen, R.S., 1994. Summary of published literature on anomalous pressures: implications for the study of pressure compartments. In: Ortoleva, P.J. (Ed) Basin Compartments and Seals. AAPG Memoir 61, pp. 27-38.
[15] Osborne, M.J., and Swarbrick, R.E., 1997. Mechanisms for Generating Overpressure in Sedimentary Basins: A Reevaluation: AAPG Bulletin, v. 81, p. 1023-1041.
[16] Nadeau, P.H., 2011. The 2010 George Brown lecture Earth's energy "Golden Zone": a synthesis from mineralogical research. Clay Minerals 46, 1-24.
[17] Ibid
[18] Lahann, R.W., McCarty, D.K., and Hsieh, J.C.C., 2001. Influence of Clay Diagenesis on Shale Velocities and Fluid-Pressure. OTC 13046.
[19] Nadeau, P.H., Peacor, D.R., Yan, J., and Hillier, S., 2002 (a). I/S precipitation in pore space as the cause of geopressuring in Mesozoic mudstones, Egersund Basin, Norwegian Continental Shelf. American Mineralogist, 87, 1580-1589.; Nadeau, P.H., Walderhaug, O., Bjørkum, P.A., and Hay, S., 2002 (b). Clay Diagenesis, shale permeability, and implications for petroleum systems analysis. EAGE Annual Meeting, Florence, Program Abstract G003.; Nwozor, K.K., Omudu, M.L., Ozumba, B.M., Egbuachor, C.J., and Odoh, B.I., 2012. A Relationship Between Diagenetic Clay Minerals and Pore Pressures in an Onshore Niger Delta Field. PTDJ Vol. 2 No. 2 pp. 1-18.

cracking to gas[20]. The reactions that convert organic matter into hydrocarbons during progressive burial release fluids which add more volumes to the aqueous fluids in the system and go to increase the pore pressures in the already undercompacted low permeability shale aquitards[21]. Here, the excess of pressure results from the rock matrix constraining as the pore fluid tries to increase in volume. Where an effective seal exists, the process and its products can raise the pressure over lithostatic pressure and cause fracturing and leakage through the seal[22].

Aquathermal pressuring is viewed differently as a viable overpressure mechanism by some authors because it requires a perfect seal. The question is, do perfect seals exist? Perfect seals are considered geologically untenable[23] which places the physical basis that controls aquathermal expansion as an overpressure mechanism on the thermal expansion of water when heated above 4°C. As the compacting sediments are subsiding in a basin, an increase in the temperature causes the pore waters to expand more than the enclosing rock matrix. If the body of water is contained in a sealed compartment with no change in pore volume the pressure rises rapidly. Overpressures are transient and gradually leak away when the generation mechanism ceases to operate. In some areas, such as the central North Sea, fluid pressures have built up until the failure envelope of the seal is reached.

Overpressure generation as a result of fluid movement and redistribution may include such often less understood processes as osmosis, hydraulic head, and lateral drainage and buoyancy effects due to density contrast.

Geologic Controls on Overpressure Retention and Distribution

Generally, it is recognized that the key controls are timing, geology and structures. Structure and stratigraphy generally control overpressure distribution in a basin (Figure 2). For instance, pressure cells are pockets of pressures of different regimes (gradients) that are compartmentalized mostly by structures (faults) within a particular basin. This could be as result of the differences in the sealing capacities of the faults, hydrocarbon migration rates and porosities of the reservoir rocks. With reference to the Geologic Time Scale (GTS), overpressure magnitude decreases rapidly once the generating mechanism ceases. More than one mechanism may even be acting together. Rapid burial rate gives sediments less time to dewater. Lithologically, fine grained sediments reduce the permeability thus impeding dewatering. Fluid retention leading to overpressures is largely controlled by the low-permeability, non-reservoir rocks such as shales, evaporites and well cemented carbonates often referred to as seals. Hence, the primary control on the presence and distribution of overpressure is permeability, which is a

[20] Swarbrick, R.E., and Osborne, M.J., 1998. Mechanisms that generate abnormal pressures: an overview. In: Law, B.E., Ulmishek, G.F and Slavin, V.I., (Eds) Abnormal pressures in hydrocarbon environments. AAPG Memoir 70, pp. 13 – 34.

[21] Bjølykke, K., Jahren, j., Aagaard, P., and Fisher, Q. 2010. Role of Effective Permeability Distribution in Estimating Overpressure Using Basin Modeling. Marine and Petroleum Geology 27, 1684 -1691.

[22] Martinsen, R.S., 1994. Summary of Published Literature on Anomalous Pressures: Implications for the Study of Pressure Compartments. In: Ortoleva, P.J. (Ed) Basin Compartments and Seals. AAPG Memoir 61, pp. 27-38.

[23] Magara, K., 1975. Reevaluation of montmorillonite dehydration as a cause of abnormal pressure and hydrocarbon migration. AAPG Bulletin **59**, 292-302.; Magara, K., 1978, Compaction and Fluid Migration – Practical Petroleum Geology, Elsevier Scientific Publishing Company, New York, 319 p.; Martinsen, (1994) Op. Cit; Swarbrick and Osborne, (1998), Op. Cit.

function of the sealing properties of the rock retaining the overpressure. These rock properties include grain size, grain shape, grain tortuosity together with the density and viscosity of the contained fluids.

Methods to Identify Overpressure Generating Mechanisms

Understanding the mechanism of overpressure generation is the key to accurate pore pressure prediction. Various authors[24] have demonstrated that the use of Vertical Effective Stress versus Velocity (VES-Vp), Vertical Effective Stress versus Density (VES-density), and Velocity versus Density cross-plots (figures 3 and 4) are effective tools in analyzing and discriminating disequilibrium compaction and secondary mechanisms of overpressure generation. This is founded on the theory that compaction increases the grain-to-grain contact of rock matter leading to progressive increase in the density and velocity in these intervals. It is further understood that present day effective stress approximates maximum historic stress where mineralogical changes in shales are negligible thus the derived normal compaction trends should approximate the behavior of the well dataset including the overpressured successions. Disequilibrium compaction follows the normal (virgin) curve while any significant deviation from the normal trend reflects either a change in the shale composition or a different overpressure mechanism such as an episode of unloading.

[24] Tosaya, C.A., 1982. Acoustic Properties of Clay-Bearing Rocks. PhD thesis. Stanford University.; Bowers, G. L., 1995. Pore Pressure Estimation from Velocity Data; Accounting for Overpressure Mechanisms Besides Under compaction. SPE Drilling & Completions, June, 1995.; Bowers, G.L., 1994. Pore Pressure Estimation from Velocity Data: Accounting for Overpressure Mechanisms Besides Under compaction. IADC/SPE 27488; Bowers, G.L., 2001. Determining and appropriate pore-pressure estimation strategy. OTC 13042.; Bowers, G.L., 2002. Detecting high overpressure: The Leading Edge, v. 21, p. 515-530.; Hoesni, M.J. 2004. The origin of overpressure in the Malay Basin and its influence on petroleum systems. Unpublished PhD thesis, University of Durham.; Chopra, S., and Huffman, A. 2006. Velocity determination for pore pressure prediction. The Leading Edge, Vol. 25 (12). PP. 1502 - 1515; O'Connor, S., Swarbrick, R., Hoesni, J., and Lahann, R., 2011. Deep pore pressure prediction in challenging areas, Malay Basin, SE Asia. Proceedings, Indonesia Petroleum Association. IPA11-G-022.

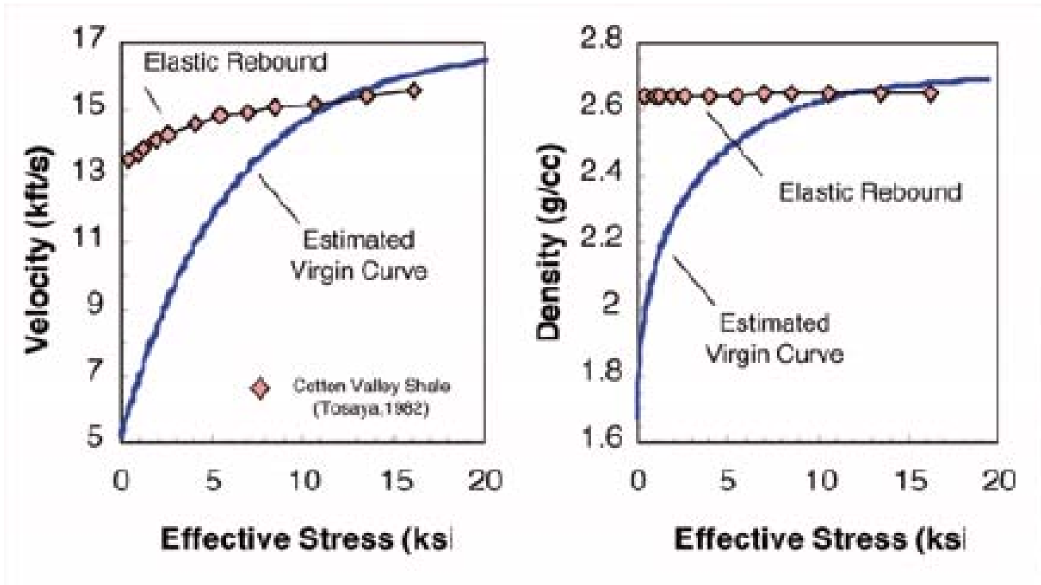

Figure 3: Typical VES-Velocity and VES-density signatures for shales in unloading situations (source: Bowers, 2002).

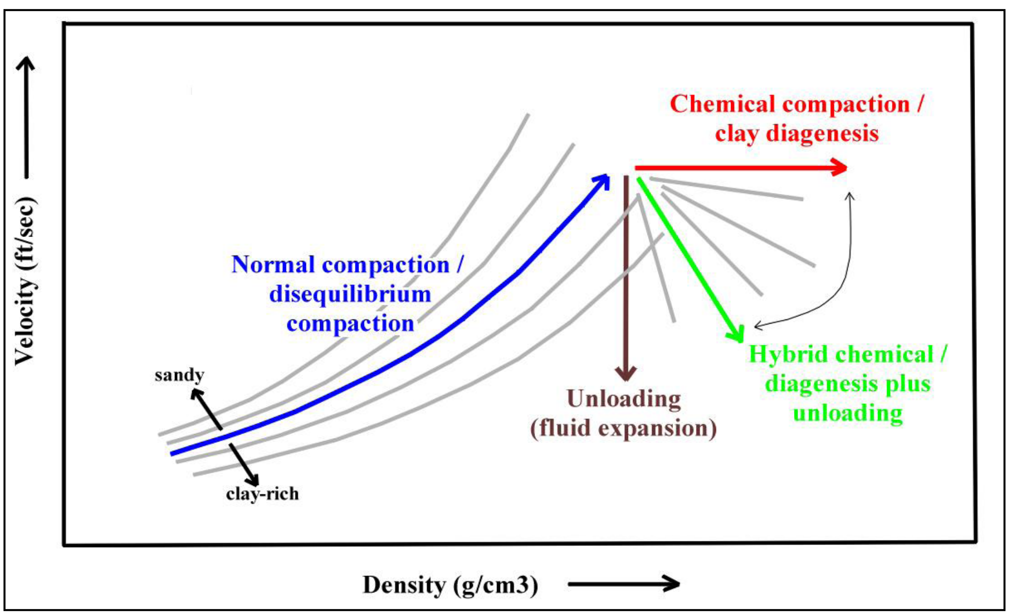

Figure 4: Typical Hoesni curve-types from Velocity-Density crossplots with associated overpressure generating mechanisms. (Source: O'Connor et al., 2011).

Overpressures due to disequilibrium compaction cause sediment properties to plot on the normal compaction / virgin (loading) curve while unloading scenarios plot above and away from the normal compaction curve. The unloading curve more often is not as coordinated as the virgin/loading curve but rather behaves variably in response to the dominant secondary mechanism. As explained in O'Connor et al.[25], increase in density may be favoured if fluid volume expansion mechanisms such as hydrocarbon maturation and diagenetic transformations are accompanied by load transfer leading to a corresponding decrease in both velocity and effective stress whereas cementation will reduce permeability and strengthen the rock framework leading to increase in velocity with density being controlled by the nature and size of the cementing material.

Results and Discussion

Having extracted and quality-checked relevant data to clean shales intervals as determined from the gamma-ray cutoff, cross-plots were made using the Tosaya and Hoesni models described above to investigate the mechanisms of overpressure generation. The virgin curves were modeled from Well D, an "ideal" hydrostatic well with sufficient log quality and depth coverage as well as the shallower intervals that are hydrostatically pressured in the other study wells. The trend was used as a datum baseline in the various cross-plots involving the other study wells in order to identify possible overpressure generating mechanisms.

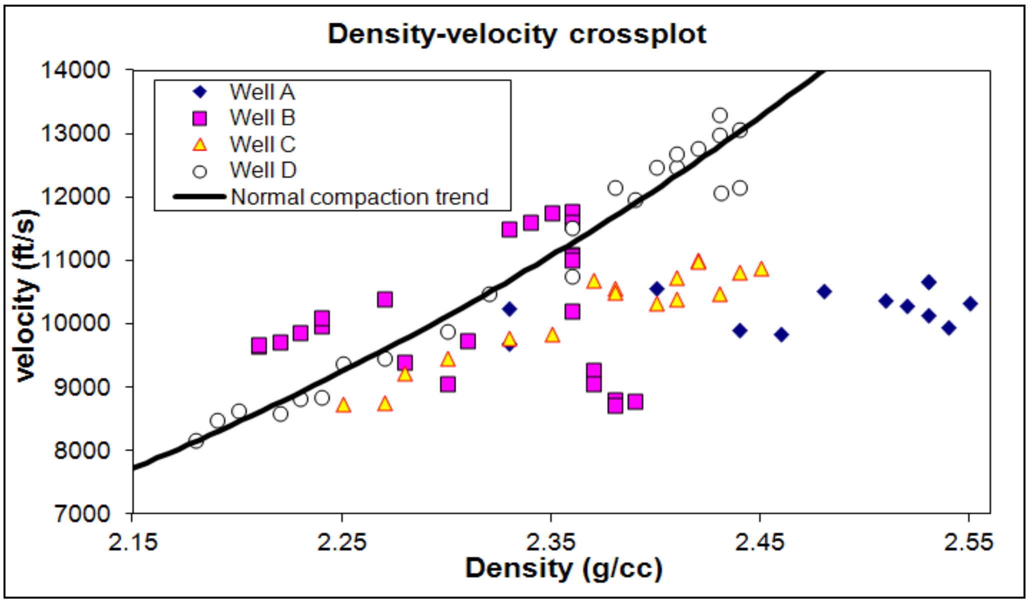

Figure 5: Density versus Velocity crossplots for the Onshore Niger Delta study wells.

Well-specific normal compaction trends are obvious in Figure 5 above. Significant deviations from the trend are observed in the data from Wells A, B and C which is interpreted with insights from O'Connor[26]; Chopra and Huffman[27] as signatures due to significant contributions of fluid expansion mechanisms.

5.1 Vertical effective stress (VES) versus velocity relationship

[25] Op. Cit
[26] Ibid
[27] Op. Cit

In tectonically relaxed young basins such as the Niger Delta, compaction can be related to the vertical effective stress. Drawing from Tosaya[28] laboratory data for Cotton Valley shale, Bowers[29] explain how vertical stress and velocity relations could be diagnostic of overpressure causes. The normal compaction trend in this instance is defined by the velocity-effective stress relation for non-decreasing effective stress. Unloading mechanisms of overpressure generation cause decrease in effective stress as burial progresses with more significant reversals in velocity trends. Against this background, crossplots of velocity versus vertical effective stress data for the Niger Delta wells are plotted and presented as Figure 6. The plots show that all data points from intervals where measured pressures suggest normal pressure and mild-overpressure values follow the virgin trend. On the other hand, the highly overpressured data in wells A and C deviate from this trend with reversals in velocity as the vertical effective stress decreases. This behavior is consistent with the unloading scenario.

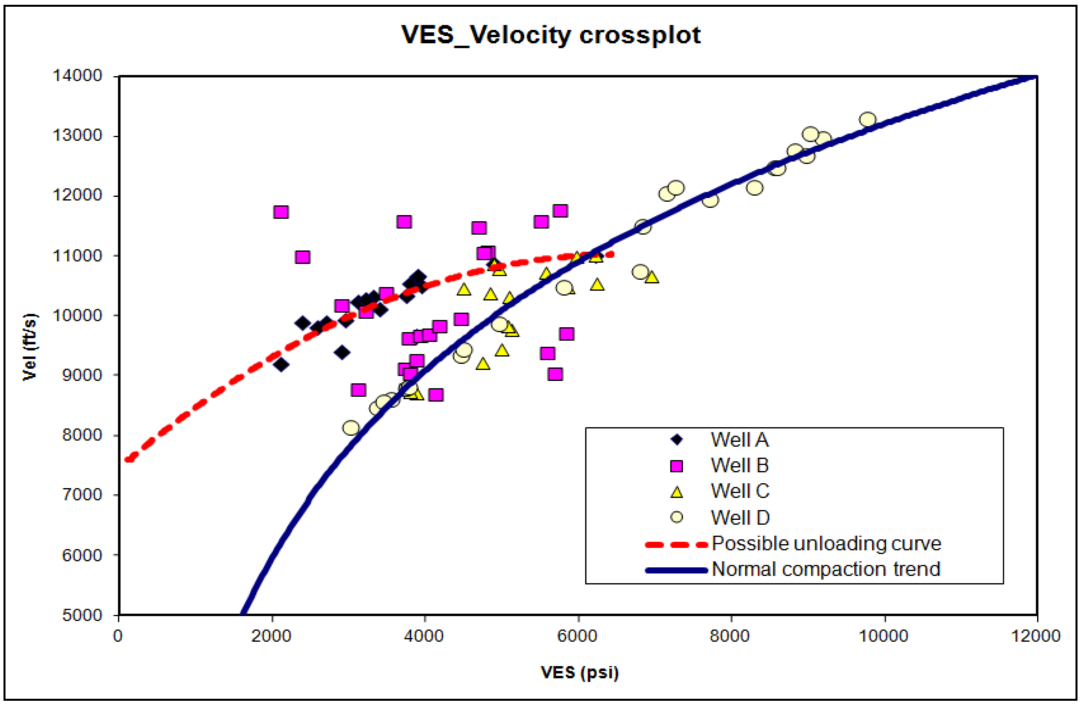

Figure 6: Crossplot of Vertical Effective Stress and velocity data for the wells. Note the unloading limb (black dots and red dotted line) established by well A data and closely followed by data points from deep sections of well B.

Vertical Effective Stress (VES) Versus Density Relationship

Further evidence for unloading can be seen from the crossplots of vertical effective stress and density data. Several authors[30], noted that transport properties such as sonic velocity and by

[28] Tosaya, C.A., 1982. Acoustic Properties of Clay-Bearing Rocks. PhD thesis. Stanford University;
[29] Bowers (1995 and 2002) Op. Cit
[30] E.G. Tosaya, C.A., Ibid and Bowers, G.L., 2002. Detecting high overpressure: The Leading Edge, v. 21, p. 515-530.

extension the derived vertical effective stress undergo larger reversal due to unloading effects than bulk properties like density. Figure 7 shows that the density data is more constant even with decreasing vertical effective stress where the VES-density trend in the high overpressure zone deviates from the normal trend just like in the VES-Velocity trend.

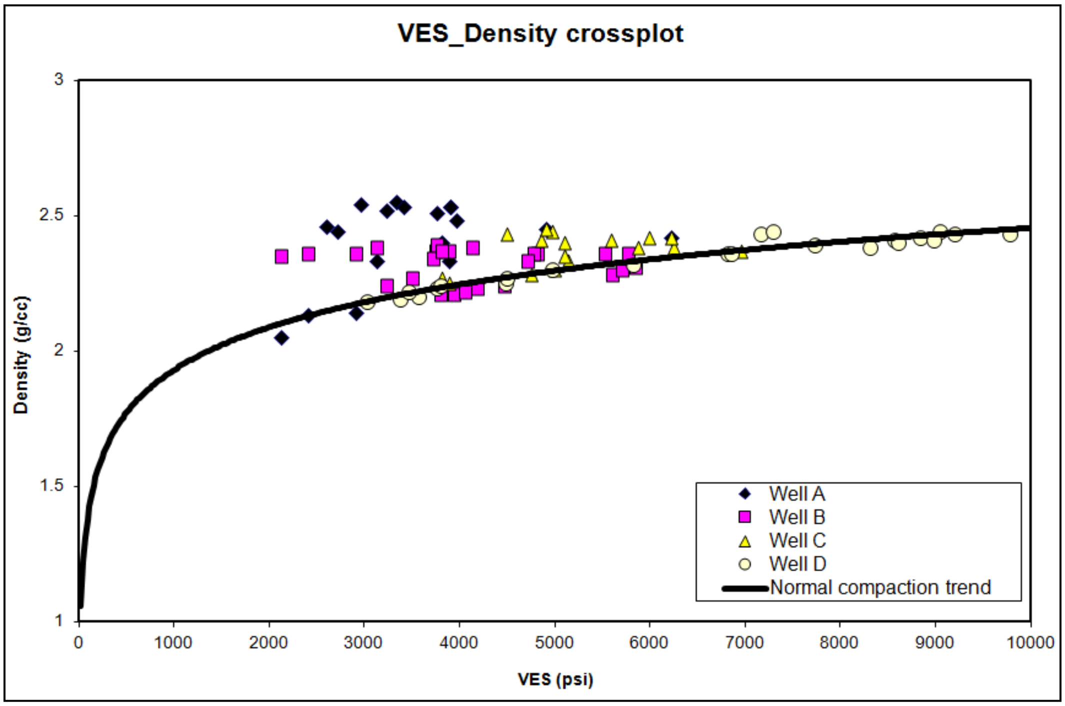

Figure 7: Crossplot of Vertical Effective Stress and Density for the wells. Deep section data in both well A and B trend as reversals away from the normal compaction curve.

Predicting the pore pressures

Having established the likely contributions of secondary overpressure generating mechanisms, predictions of pressure values were made using the original Eaton method for undercompaction overpressures and the Bower's Modified Eaton method. Eaton[31]proposed an empirical approach to predicting effective stress from sonic or seismic velocities. The effective stress σ is computed from the equation:

$$\sigma = \sigma_{norm} \, (V / V_{norm})^{\,n} \qquad (1)$$

where V is the observed shale velocity, and σ_{norm} and V_{norm} are the effective stress and velocity under normal conditions. The normal compaction shale velocity trend (V_{norm}) and the exponent *n* value of 3.0 are required inputs in this method. However, considering the limitations of the

[31] Eaton, B. A., 1975. "The Equation for Geopressure Prediction from Well Logs", SPE 5544.

original Eaton's technique as demonstrated in Bowers,[32] the analysis also incorporated the Modified Eaton Method of the form:

$$\sigma = \sigma_{norm} (V / V_{norm})^{n>3} \qquad (2)$$

Observations[33] on the previous equations indicate that original Eaton's method of predictions are unphysical at low effective stress and only becomes able to simulate unloading curves when the exponent is raised to higher values (n>3.0) which deals with different models of overpressure, and obeys physical constrains at low effective pressure. Therefore, pore pressure is determined from the effective vertical stress and the overburden stress by the fundamental[34] Terzaghi relationship:

$$OBP = \sigma + PP \qquad (3)$$

where *PP* is the pore pressure, *OBP* is the overburden stress and σ is the vertical effective stress. The principle states that the overburden stress is supported by the rock framework and pore fluids. The frame-supported stress is called vertical effective stress (VES), while the fluid stress component is referred to as pore pressure which typically is isotropic in nature. In this study, it is assumed that in the relaxed structural settings of the Niger-delta growth fault environment, sediment mechanical compaction is primarily controlled by the matrix-supported weight of sediments (vertical effective stress).

Results from the computations were compared with actual measured pressure data. The resolving power of the various Eaton exponents gave first pass suggestions of the possible mechanisms generating the overpressures. Eaton exponent of n = 3.0 resolves issues of normal / disequilibrium compaction while exponents modified above n = 3.0 acceptably predicted unloading overpressures as shown in figures 8 – 11 below.

The depth plot of measured versus predicted pressures for well A (figure 8) shows that an Eaton exponent of 5.5 produced better match with the measured values than the Eaton exponent of 3.0. The n = 3.0 exponent only produced good correlations from 7724.8 ft (2355.12 m) to 11172.46 ft (3406.24 m). This conforms to the depth ranges of the hydrostatic and moderate overpressures. Below this depth, where the high overpressures were recorded, the predictive power of this exponent failed. This could be an indication that in addition to disequilibrium compaction, unloading overpressures probably have set in.

[32] Bowers (1995), Op Cit

[33] Such as Katahara, K., 2006. Overpressure and Shale Properties: Stress Unloading or Smectite-Illite Transformation? 76th SEG Annual International Meeting Extended Abstracts, Pp. 1520 – 1524.

[34] Terzaghi, K., 1943. Theoretical soil mechanics: New York, John Wiley and Sons, p. 510.

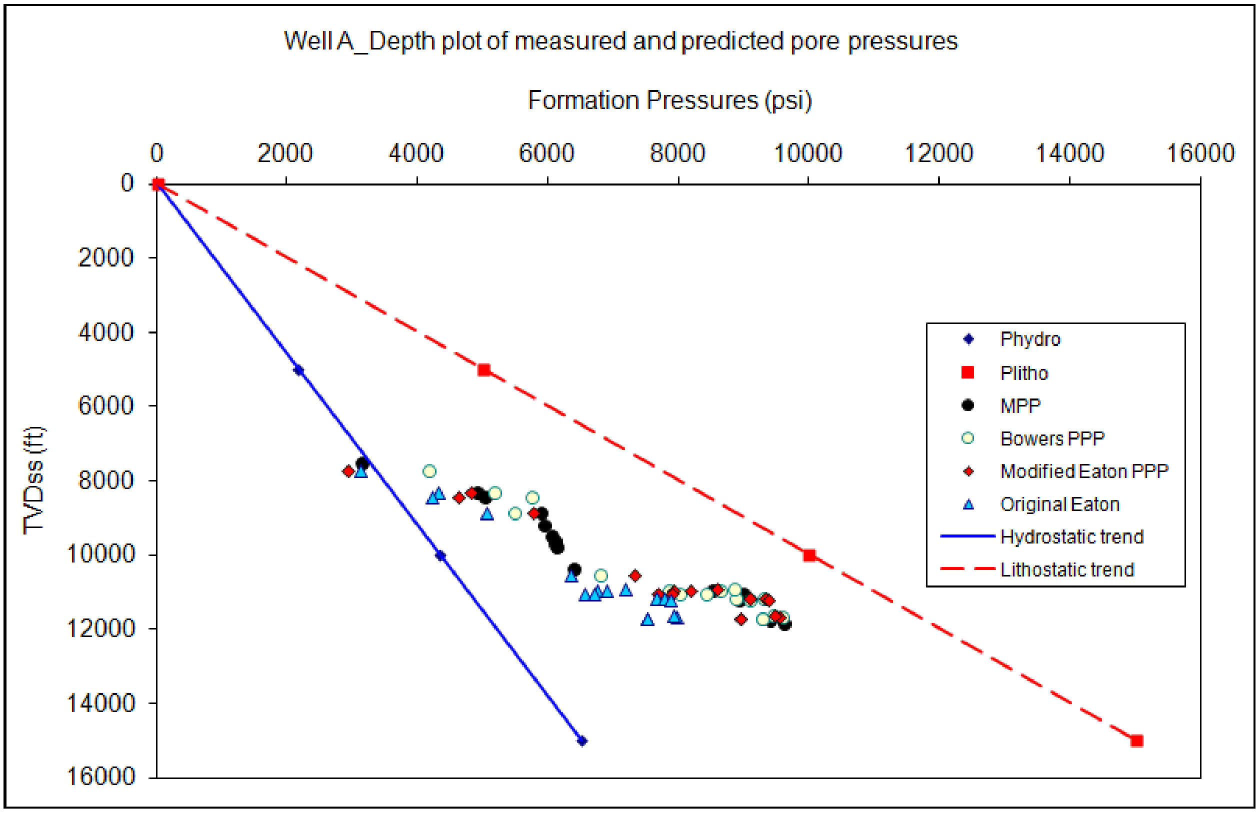

Figure 8: Comparison of Measured and 1D Predicted Pore Pressures for Well A. Original Eaton exponent under predicts formation pressures in the deeper sections of the well whereas modified Eaton yields a good match.

Information from well files categorized this well as overpressured and drilled to a total vertical depth of 11903 ft subsea (3628.96 m) to test a large, downthrown fault-dip closure. The targets were a conventional sequence between 8760 ft – 10400 ft (2670.73 m – 3170.73 m) and a deep-seated marine paralic sequence between 10400 ft and 12000 ft (3170.73 m – 3658.53 m). Pressure measurements between 7535 ft (2297 m) to 7703 ft (2348.48 m) are hydrostatic at 0.42 psi/ft. The well was drilled slightly overbalanced to this point. Onset of overpressure is indicated by RFT measurements from 8591 ft to 8665 ft which were obtained from thin sand stringers within a shale-dominated interval. The shale dominated interval is interpreted as transition zone-seal to overpressure regime. A final RFT at 11159 ft shows a further jump in overpressures across another deeper shale unit. Pressure gradients were obtained as 0.60 psi/ft at 10388 ft (3167.07 m) which increased to 0.8 psi/ft at final depth of 11903 ft (3628.96 m).

The predictions made for Well B could not cover the entire drilled section due to the limitations of the log length. The well which was originally planned to test a deep overpressured reservoir section between 9900 ft (3018.3 m) and 13000 ft (3963.41 m), reportedly experienced a kick of 0.852 psi/ft at 11321 ft (3451.53 m) and was terminated without reaching the planned target objective. The available RFT pressure measurements made over the deeper objective interval between 10099 ft – 10543 ft (3078.96 m – 3214.33m) were used for the comparison. The first two RFT measurements at 10098 ft and 10108 ft are hydrostatic, 0.436 and 0.437 psi/ft respectively. The second two points at 10133 ft (3089.33 m) and 10315 ft (3144.82 m) are slightly overpressured, 0.459 psi/ft and 0.460 psi/ft respectively. The deepest measurement at 10542 ft (3214.02 m) is clearly overpressured at 0.711 psi/ft but recorded as having incomplete buildup as at the time of reading. The well experienced a kick of about 0.852 psi/ft at 11321 ft (3451.52 m).

Predictions using both the original and modified Eaton exponents (Figure 9) yielded similar results to those in well A. Modified Eaton method produced a pressure profile that could have better guided the well planning process thus showing that the recorded kick that forced the termination of the well would have been predicted with some precision and avoided too. This again suggests possible complex overpressure generating mechanisms and limitations of pressure predictions based only on undercompaction paradigms.

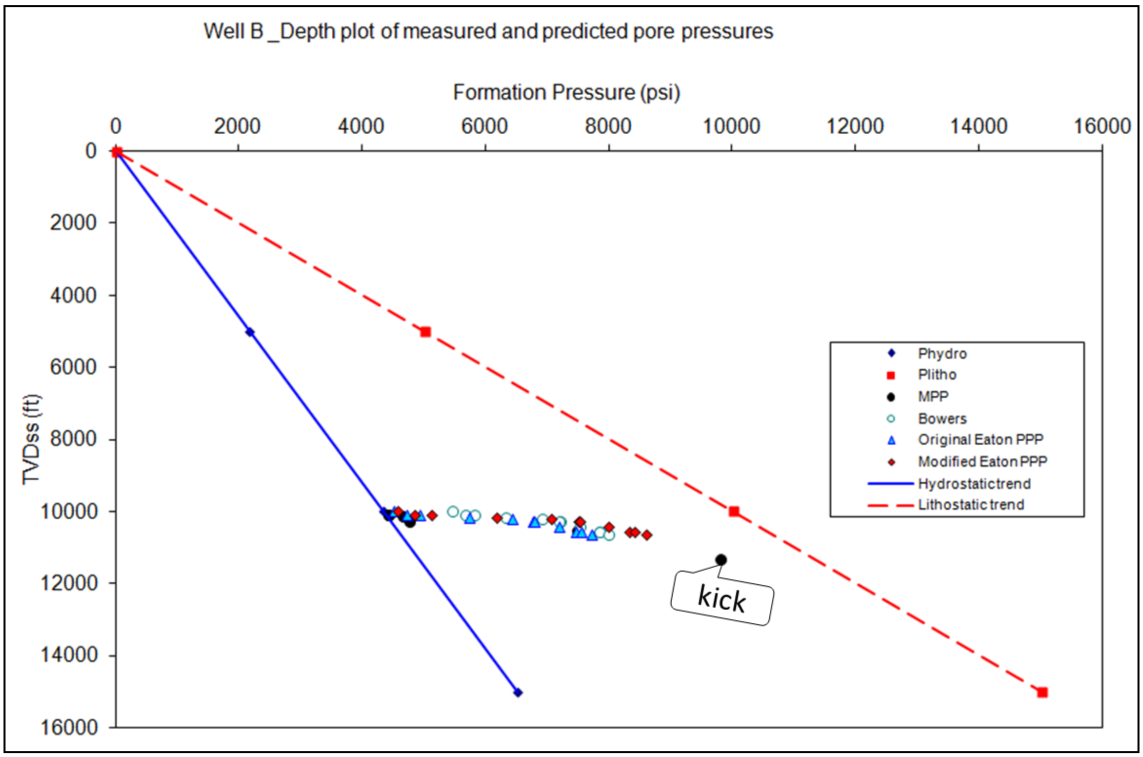

Figure 9: Comparison of Measured and 1D Predicted Pore Pressures for Well B.

Further to this, comparison of predicted pressures with the 75 RCI (reservoir characterization instrument) readings of the 14589.52 ft (4448.02 m) deep well C reveals (figure 10) that the predictive power of the original Eaton method started failing from around 12000 ft (3659 m) and deeper. Three pressure jumps could be observed as hydrostatic pressure values from 10815.42 ft – 11279.32 ft (3297.38 m – 3438.82 m), a seemingly depleted (underpressure) zone of approximately 0.289 psi/ft within the 11754.52 ft – 12110.52 ft (3583.70 m – 3692.23 m) interval while overpressures became prominent from 12371.42 ft (3771.77 m) and continued to TD.

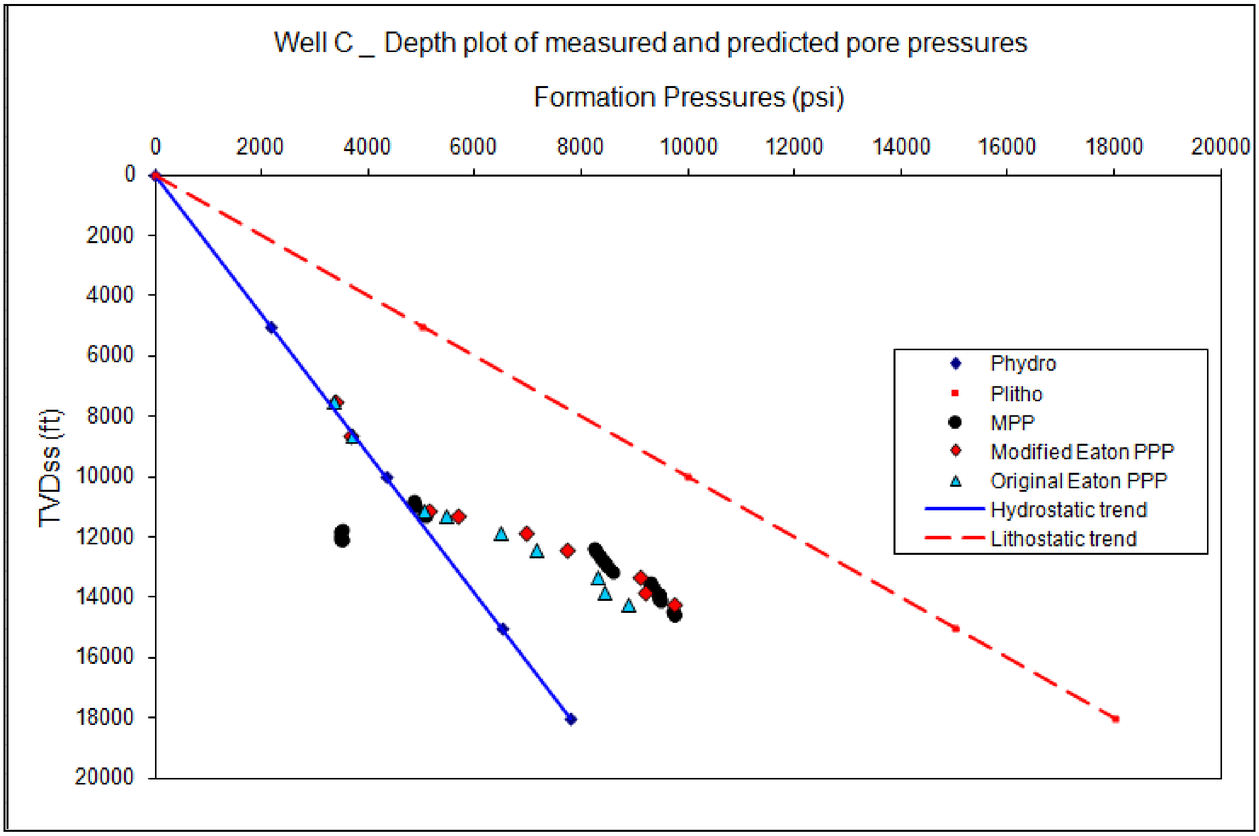

Figure 10: Comparison of Measured and 1D Predicted Pore Pressures for Well C

Figure 10 above illustrates a likely complex pressure system in well C. The predictive process obtained concordant pressure profiles with the measured values at the hydrostatic depths of 11105.97 ft (3385.97 m) to 12000 ft (3658.54 m) but however could not resolve the underpressured points between 11754 ft (3583.54 m) and 11938.62 ft (3639.82 m) as indicated by the formation pressure test. Only the modified Eaton computations provided values that reflect the downhole pressure measurements.

In addition to this, analysis of data from Well D presented a different scenario where drilling challenges owing to reported mud losses and pipe sticking necessitated a side track that eventually managed to reach 16666 ft (5081.10 m) without testing the target objectives lying deeper below this depth. Considering the RFT measurements in the well, the tested reservoirs are shown to be hydrostatically pressured (approximately 0.433 psi/ft) demonstrating a mud weight overbalance of some 5000 psi with moderate overpressures of 0.451 psi/ft and 0.592 psi/ft recorded at 15271.5 ft (4655.95 m) and 15995.5 ft (4876.68 m) respectively.

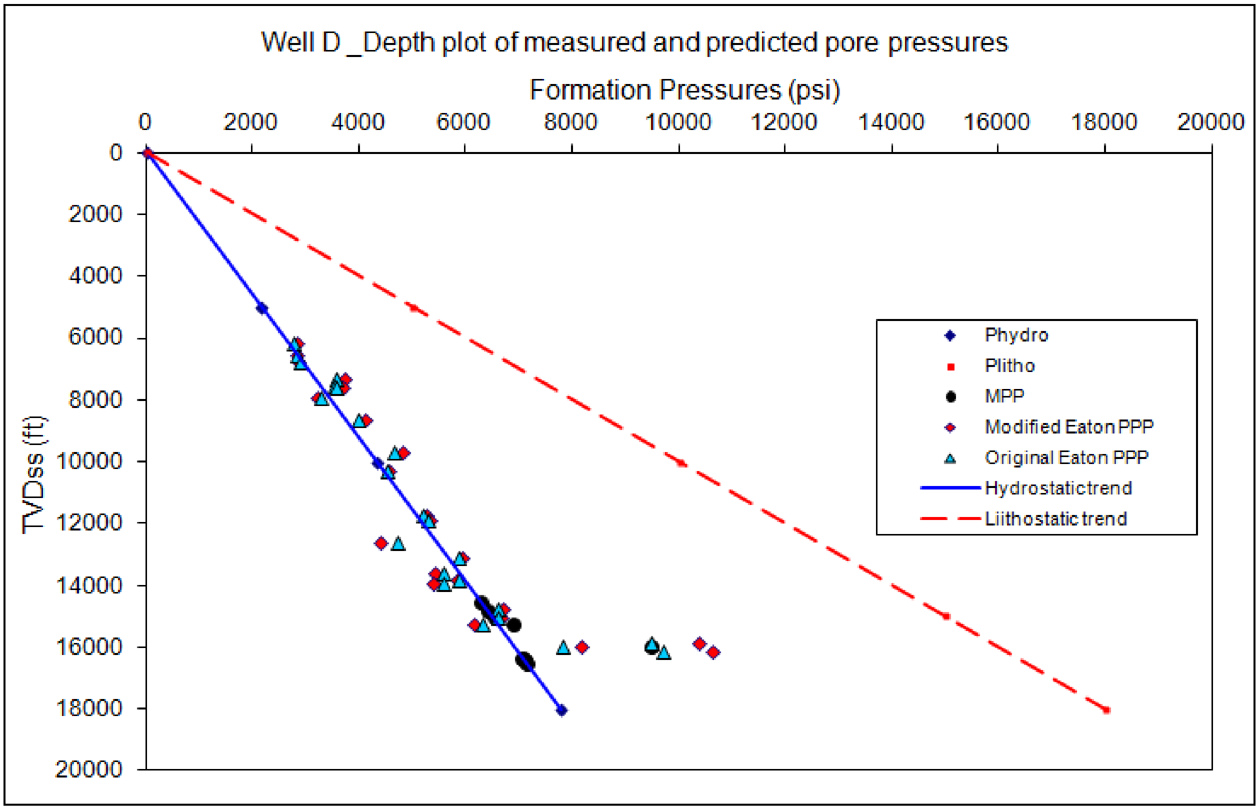

Figure 11: Comparison of Measured and 1D Predicted Pore Pressures for Well D

Measured and predicted pore pressure values indicate that Well D is essentially hydrostatic with significant pockets of under pressured intervals. An outlier high pressure value was also observed and also captured by the predictive process. Hydrostatic pressures were predicted between 6152.14 ft (1875.65 m) and 12593.85 ft (3839.59 m) before sub-pressure conditions became apparent. This might account for the reported mud losses in the course of drilling. Sub-pressure section extended from 12593.85 ft (3839.59 m) to 13832.3 ft (4217.16 m). All the measured pore pressure values plotted on the hydrostatic line except the outlying point recorded at 15890.44 ft (4844.65 m). Since, the prediction process also matched this rather discordant value; it could be taken into account as valid data that may give some clues on the possible origin of the pressuring mechanisms and the bleed-off event. As stated earlier, Well D is empirically within the realm of normal compaction but the drilling depths unarguably may not have penetrated the domain of secondary mechanisms of overpressure generation.

Conclusions

From the foregoing analyses and results, the following points need to be noted:

- Granted that overpressures in the Niger Delta are widely accepted to be generated by disequilibrium compaction, this study however highlights that such oversimplified generalizations may no longer be tenable as there seem to be instances where overpressures in deep onshore fields of the Niger Delta Basin bear the imprints of secondary mechanisms that post-date disequilibrium compaction.

- Cross-plots of relevant rock properties such as density, velocity and vertical effective stress (VES) produce patterns that suggest likelihood of interplay of disequilibrium compaction and post-undercompaction mechanisms.

- Quantification of formation pressures using conventional Eaton exponent works well in normal and mechanical compaction disequilibrium settings but fails where post-undercompaction processes contribute to over pressuring. In such deep and challenging areas, the modified Eaton method may provide better solutions and increase ability to quantify exploration risks especially for HPHT campaigns.

- It is logical to note from relevant literature that earlier phases of sedimentation may progress with normal and efficient compaction and dewatering until such stage when the fluid dissipation becomes impeded giving rise to undercompaction generated overpressures. As depths continue to increase, temperature effects on the compacted sediments may become significant such that where temperatures range as high as 100° C, thermally driven geologic processes may favour overpressure generation by secondary mechanisms due to fluid volume increase and severe permeability reduction in the sealing shales. Typical of the Niger Delta, deeply buried channel levee sands and pinch outs are few examples of such scenarios where higher shale-to-sand-ratios could provide vertical and lateral seals to retain the generated high pressures; up-dip redistribution of fluid pressures is possible where hydraulically conductive systems are inclined.

- It is here recommended that a reliable pore pressure prediction strategy for deep wells especially the high-pressure high-temperature campaigns in the onshore Niger Delta should be such that is based on a robust geologic model that considers the no-longer-to-be-neglected contributions of secondary mechanisms of overpressure generation. Critical to this will be the development of regional and depocentre-specific clay diagenetic models based on clay transformations and temperature relations, thermal history regimes and likely contributions of hydrocarbon maturation processes to overpressure generation in the Niger Delta oil and gas province.

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