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Impact of Environmental Factors on Ability to Predict Abnormal Pressures a Case Study of North-Sea Oilfield

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***Abstract* - The ability to correctly predict pore pressures and the possible occurrence of overpressured zones is very crucial for the success of any drilling program, as it affects the mud program, number of casings and the casing setting depth.**

Ever since the first occurrence of abnormal pore pressures in the 1930's, several techniques and methods have been developed in trying to determine the possible occurrence of these abnormal pressures.

Deviation from established compaction trends of normally pressured zones using petrophysical logs such as resistivity, sonic and bulk density logs is one of the methods whereby these abnormal pore pressures could be predicted. This technique is however affected by environmental factors such as lithology changes, proximity to salt domes, borehole washouts, clay swelling and changes in formation salinity, which affects the response of these tools, thereby leading to errors in interpretation.

The objective of this project is to determine the impact of bulk density variation on equivalent mudweight calculations using data obtained from four North Sea Wells.

Results obtained from calculation show that an error of 0.2 g/cc in bulk density would lead to errors in equivalent mudweight of up to 1.6 ppg.

Keywords* - *overpressure; underpressure; abnormal pressure; environment

I. INTRODUCTION

In the global search for hydrocarbons and as the search goes into deeper offshore fields, abnormally pressured environments are continuously encountered in many parts of the world and in all types of formations.

Reference [1] observed that the occurrence of abnormal pressures is associated with the lithification of the shales and the sands during compaction, burial and entrapment of pore fluids aided by transformation of one clay type to another. Drilling for hydrocarbons is a particularly risky business, which is even made riskier with the ability or inability to accurately predict the occurrence of abnormal pressures. The ability to detect the presence of abnormally pressured formations is one of the most important factors affecting the success of any drilling operation. Pore pressure affects the mud weight of the drilling fluid used, casing setting depths, casing design, as well as the type of completion. Most of the extra costs associated with drilling of hydrocarbons are in drilling fluids and casing programs, thus the accurate prediction of abnormal pressures, would lead to a huge savings in drilling costs. The inability to correctly predict the occurrence of abnormal pressures could lead to difficult drilling problems such as kicks, blowouts and formation damage, which would not only alter the drilling timetable and increase drilling costs, but could even affect the viability of the whole drilling project.

The objective of any drilling program is to drill a well safely and economically without causing formation hole instabilities such as borehole collapses or fractures, without allowing the influx of unwanted formation fluids e.g. gas, oil, water, and without damaging the reservoir. This involves walking a very narrow margin of drilling with a mudweight that would not fracture the formation and at the same time would not allow the influx of unwanted formation fluids. The ideal mudweight used would be greatly influenced by the ability to detect abnormal pressures.

Several pore prediction methods have been used to predict the occurrence of abnormal pressures. These include direct and indirect measurements [2].

The aim of this study is to find out how these environmental factors affect petrophysical logs such as bulk density and sonic travel times, and how errors in these measurements could impact on the ability to predict the occurrence of abnormal pressures.

The economic consequences of inaccurately predicting occurrence of abnormal pore pressures, as it affects well control issues such as casing setting depths and number of casings cannot be over emphasized. Many oil rig blowouts have occurred as a result of using the wrong mudweight while drilling that has resulted in huge economic losses and even fatalities.

II. LITERATURE REVIEW

A. Abnormal Pressures

Under certain conditions, fluid pressures may depart substantially from the normal pressure which is the pressure of fluid contained in the pore spaces of rock and is equal to hydrostatic pressure [3]. Pore pressures are dependent on the salinity of the formation water and could vary from 0.433 psi/ft for fresh water up to 0.465 psi/ft for high salinity water

(100,000ppm). Abnormal pressure reservoirs occur and can either be overpressured where the hydrostatic pressure is greater than the normal pressure or underpressured where the reservoirs are below normal pressure. Overpressured reservoirs are common in Tertiary Deltaic Deposits such as the North Sea, Niger Delta and the Gulf Coast of Texas. **Fig. 1** below shows the different pressure profiles and also illustrates the transition from normal pressures to overpressures.

B. Origin overpressures

The burial of sediment such as low permeability clays and shales lead to undercompaction and give little time for trapped fluids to escape and therefore provide support to the overburden [4]. Faults may redistribute sediments and place permeable zones opposite impermeable zones, thus creating barriers to fluid movement; this may prevent water bearing expelled from shales leading to overpressures [5]. Lateral compression can also occur in orogenic belts resulting in development of abnormally high pressures, this may result either in uplifting weathered sediments or fracturing/faulting sediments and thus formations normally compacted at depth can be raised to a higher level and If the original pressure is maintained, the uplifted formation is now overpressured [6]. Paleopressures can also exist in older rocks which have been completely enclosed by massive, dense, and essentially impermeable rocks or in completely sealed formations uplifted to a shallower depth.

C. Origin of Underpressure

Thermal expansion of pore fluids occurs as a result of rise temperature with burial of sediments and pore fluids. If the fluid is allowed to expand, the density will decrease and this would result in a pore pressure less than the normal pore pressure gradient of 0.45 psi/ft. Formation Foreshortening which occurs during a compression process results is some bending of strata with the upper beds bending upwards, while the lower beds bend downwards and forcing the intermediate beds to expand in order to fill the void and thus creating a sub normally pressured zone. Production of large amounts of reservoir fluids known as depletion can also drastically reduce formation pressure [7]. Fluid withdrawal causes a decline in pore fluid pressure if no strong aquifer compensate for it [8]. Reference [9] postulated that withdrawal of ground water could result in surpressures, especially in arid and semi-arid regions, where the hydrostatic pressure gradients start at the water table which could be several hundreds to thousands of feet below the surface [8].

D. Predictive and Detective Techniques

Ever since the first occurrence of overpressures, several techniques have been used to predict or detect the occurrence of these overpressures. These techniques could be broadly classified as: 1) Predictive methods from offset well data or seismic data, 2) detective methods using measurement while drilling (MWD) and other drilling parameters such as rate of penetration and 3) Post drilling methods (from well logs).

Pore pressures could also be estimated using direct and indirect methods [3]. Direct pressure measurements include downhole pressure bombs, modular formation dynamic testers (MDT) and drill stem tests (DST). "*Although these direct measurements give an accurate estimate of pore pressures, they are rarely used because of difficulty in locating permeable zones in overpressure sections, risks of differential pipe sticking, and the high cost of rig time and tools"*[2]. Indirect measurements are those methods that utilize well logging and drilling data to estimate pressures. This usually requires the use of a porosity dependent parameter such as resistivity, sonic velocities, and bulk density logs to help in detecting abnormal pressures.

Predictive and detective techniques could also be broadly classified into "Qualitative" methods and "Quantitative" methods. "Qualitative" techniques are those techniques which aim to detect the occurrence of overpressures, while "Quantitative" techniques aim to estimate the magnitude of the overpressures. The rate of penetration of drilling bits is an example of a qualitative technique which aims to give an indication of the occurrence of overpressure without necessarily showing the magnitude of the overpressure.

Reference [10] suggested that the best approach in determining the presence of abnormal pressures is to combine all the different predictive and detective techniques and find convergence of results of the different techniques to build confidence on the presence of overpressures. This is to avoid errors that could lead to costly implications for the drilling operations.

The fundamental concept used in estimating pore pressure which is based upon Terzaghi's original equation as shown in equation (3) below

$$P = S - \sigma_v \qquad (3)$$

Where P is the overburden pressure, the overburden stress (S) is the total pressure exerted by the weight of the overlying sediments, while the vertical stress (σ_v) is an upward force which is diametrically opposing the overburden pressure and is exerted by the rock matrix [11]. An additional parameter known as the equivalent mud density (EMD) is combined with pore pressure to design drilling fluid density [3].

Table 1 below summarizes the various pressure prediction and detection techniques.

Table 1 Pressure Detection and Evaluation Techniques after [10]

Data Source	**Parameters**	**Time of Recording**
Seismic Methods		Prior to spudding the well
Drilling Parameters	Drilling rate, "d" exponent, "d_c" exponent, drilling rate equations, Torque, Drag, Drilling Porosity Log.	While drilling
Drilling Mud	Gas Content, Flow Line Mud Weight, Kicks, Flow Line Temperature, Pit level	While drilling (Bottoms Up)
Shale Cuttings	Bulk Density, Shale Factor, Electrical Resistivity, Volume, Shape and Size	While drilling (Bottoms Up)
Well Logging	Electrical Surveys: resistivity, Conductivity, Shale Formation Factor, Salinity Variations, Transit Travel Time, Bulk Density, Neutron Log, and Pulsed Neutron Logs.	After pulling the drill string
Direct Pressure Measuring Devices	Pressure Bombs, Drill Stem Test, Modular Formation Dynamic Testers (MDT)	When well is tested or completed

E. Environmental Factors Affecting Predictive and Detective Techniques

The ability to predict the occurrence of abnormal pore pressures is greatly affected by environmental factors which could lead to errors in the estimation of the pore pressures. Reference [12] suggested that one of the environmental factors affecting estimation of pore pressure is the origin of the overpressure itself. He asserted that most pore pressure estimation techniques fail to account for other origins of overpressure apart from undercompaction such as aquathermal pressuring, hydrocarbon maturation, charging from other zones and this could lead to errors in mudweight of up to 4ppg. Other possible cause of overpressures besides undercompaction may not be detected by either measurement whilst drilling (MWD) tools or seismic because they assume the undercompaction model, thus readjustment of the normal line on the basis of a pressure kick can be wrong if the overpressure was not caused by undercompaction [13].

Clay diagenesis also affects pore pressure estimation. Many basins have smectite/illite dominated shales. Previous studies observed that smectite and illite have significantly different compaction trends and that transition from smectite to illite is primarily driven by the temperature gradient in the region [14]. The studies also suggested that any compaction trend that does not take into consideration smectite/illite transition and also the unloading effects on erosion would lead to errors in pore pressure estimation [14]. Smectite affects acoustics methods in establishing normal compaction trends, as the presence of interlayer water makes it difficult to distinguish it from pore water thus overestimating the porosity on conversion [15].

Flowline temperature gradient technique is affected by the variation of the thermal conductivity and heat content of materials with pressure and depth. This technique could also be affected by changes in mud circulation system such as temperature changes in flowline as a result of trips, mud additions, circulating without drilling etc. [16]. Though these effects are minimal, keeping the circulation rate constant could reduce errors.

All well logging techniques used in establishing normal compaction trends for the estimation of geopressures are subject to misinterpretations due to response of the logging tools. These include large borehole washouts, drastic lithology changes e.g. increased lime content, and even tool malfunctions. Resistivity logs in particular are affected by mud type used (oil/water based), water salinity, formation fluid properties, presence of hydrocarbons, clay mineralogy and presence of originally rich clay sandstones. One of the most significant influences on resistivity logs is proximity to salt bodies which overestimates the pore pressure increase due to the rapidly changing formation salinities [17]. Pressure gradient variations due to proximity with sandstone or sandstone reservoir rocks will also affect prediction techniques. Bulk density measurements are also known to be affected by factors such as multiple readings due to variance in sample data, presence of shale gas which decrease apparent density values, selection of proper pieces to distinguish between cuttings and cavings, and presence of high lime content, or silica and pyrite content [10].

Table 2 is a summary of the environmental factors affecting the different abnormal pore pressure detection techniques.

Table 2 Environmental Factors affecting Pore Pressure Prediction and Detection Techniques

Prediction Technique	**Environmental Factor**
Flowline Temperature	Mud circulation system, circulation rate, penetration rate, tripping effect, proximity to salt domes
Rate of penetration	Increase in ROP could be due to presence of geopressures in shales, but also due to bit balling, bit wear, mud weight
"d"exponent	Mudweight. Temperature and pH in argillaceous formations. Faults and sealing systems in permeable formations
Drag	Presence of transition zones could be due to drag, but also extra cuttings coming into wellbore when drilling transition zones
Bulk Density	multiple readings due to variance in sample data, presence of shale gas decreases density values, difference between cavings and cuttings, high lime content and presence of minerals such as pyrite.
Shale formation factor	Variation in formation salinity between sands and shales
Well logging techniques	Errors due to response of logging tools caused by large borehole washouts, steep and very thin formations, increased lime content, tool malfunctions, proximity to sandstone reservoirs.
Log derived resistivities	Large washouts in borehole
Resistivity Logs	Water salinity changes could account for anomalies in low sand-shale ratio intervals. Mud type used (oil/water based), formation fluid properties, mineralogy of clay, proximity to slat bodies
Porosity determination from Wireline logs	interlayer hampering as a result of clay swelling, smectite affects acoustic logs, smectite increases transit time , even without overpressured zones being encountered
Shale physical properties	Smectite content, kerogen type, micro fractures and physiochemical interaction with pore fluids
Acoustic Properties	Tectonic Stresses, variable mineralogy in shales and presence of Sedimentary and structural anisotropy. Difficulties in differentiation between inter layer water and pore water.
Sonic Velocity	Velocity reversal could be due to transition from normally pressured sand

III. METHODOLOGY

The data used in carrying out this project was obtained from part of the data used in the field development project in northsea region of UK. It consists of a suite of petrophysical logs comprising of gamma ray, acoustic logs, bulk density logs, and caliper logs from four wells.

One of the limitations of the data set used was the limited intervals at which the different log readings were obtained. Thus the ability to establish very good compaction trends was quite difficult. Except for well Z1 which had no bulk density data, all four wells had gamma ray and sonic logs, thus making it possible for delineating between sands and shales, and also calculation of porosity using the sonic log data.

The concept adopted in carrying out this work was to plot the different well logging responses with depth to define compaction trends for the normally pressured zones.

Gamma ray data was used for lithology identification to differentiate between the sands and the shales. Compaction trends for normally pressured zones in shales were established using the sonic log data and the bulk density data. Deviations from these trends were observed to determine the presence or otherwise of overpressures and at the depths they might have occurred in each of the wells. Data from the four wells were compared against each other to correlate compaction trends across the field.

Caliper log data from each well were observed for borehole washouts, which could possibly affect the response of the tools and the readings.

Porosity was calculated from the bulk density data using the equation below

$$\phi = \left(\frac{\rho_{ma} - \rho_g}{\rho_{ma} - \rho_f} \right) \qquad (8)$$

Where ρ_f is the average fluid density (g/cc), ρ_g is the grain density (g/cc), ρ_{ma} is the matrix density (g/cc).

The Wyllie time average equation was also used to calculate porosity from sonic log data, the equation is shown below

$$\phi = \left(\frac{\Delta t - \Delta t_m}{\Delta t_f - \Delta t_m} \right) \qquad (9)$$

Where Δt is the transit time (µsec/ft), Δt_f is the fluid travel time (µsec/ft), Δt_m is the matrix travel time (µsec/ft).

The following assumptions were made for the calculation of porosity

ρ_g = 2.65 (g/cc)
ρ_f = 1.0 (g/cc)
Δt_m = 55.6 (µsec/ft)
Δt_f = 189 (µsec/ft)

Pore pressures were calculated using Terzaghi's equation shown below

$$P = S - \sigma_v \qquad (10)$$

The overburden pressure (S) was calculated using the equation below;

$$S = \rho * \Delta H * 0.433 \qquad (11)$$

Where ΔH is the interval height (ft) with 0.433psi/ft being assumed as the gradient of water. Pore pressure values obtained were then converted to equivalent mudweight by using the conversion factor of 0.052. Sensitivity analysis was also carried out to determine impact of bulk density on mudweight calculations.

IV. RESULTS AND DISCUSSION

A. *Lithology*

The gamma ray log was used to identify lithology. All the four wells were broadly divided into sands and shales. All wells had several hundreds of feet sand and shales except for Well Z4 which had alternating sand and shale sequences. **Table 3** below is a summary of the different lithology in all the four wells.

Table 3 Lithology Identification in Wells

Well	**Interval**	**Lithology**
Well Z1	7000-8500	Sand
	8500-11600	Shale
Well Z2	6800-8100	Sand
	8100-10500	Shale
Well Z3	8300-9100	Sand
	9100-9600	Shale
Well Z4	9000-9600	Shale
	9600-10200	Sand
	10200-10500	Shale

B. *Compaction Trends*

Sonic logs were used in establishing these trend lines in Wells Z1, Z2 and Z3, while in Well Z4 both the sonic log and acoustic log were used in establishing compaction trend lines. The Figures for all the wells are shown in appendix and show the normal pressured zone compaction trend lines and possible overpressured zone compaction line.

Table 4 below is a summary of the possible overpressured zones in all the wells and evidences of their possible occurrence.

WELL	**Possible Overpressured Zone (ft)**	**Evidence**
Z1	9500-9900	Observed deviation from established normal pressure trend line from sonic log, increase in wellbore diameter observed at 7800-8600 ft. No bulk density data available for well.
Z2	9900-10300	Possible overpressured zone might exist, borehole washout at 8400-9700 ft. Deviation from normal trend line observed from sonic log. Normal compaction trend line could not be established with bulk density data.
Z3	8900-9000	Small deviation from established normal compaction trend line from the sonic log, no changes in well bore diameter, thus it might just be a 100ft overpressured zone.
Z4	10300-10600	Clear deviation from established trend line for normally pressured zone using both the sonic log and density log. Reduction in well bore diameter observed from caliper log at 9600ft. Extent of the overpressured zone is uncertain due to unavailability of data below 10600ft.

C. Pore Pressure Prediction

Using Terzaghi's equation pore pressures were calculated, and were converted to equivalent mud weights. Table 5 below is a summary of the pore pressure calculations for well Z3.

Table 4 Mudweight calculations for Well Z3

Dept	Dens	Pressure	V/Stress	PP	psi/ft	ppg(Z3)
8300	2.54	9143	4441	4702	0.57	10.90
8400	2.50	9096	4494	4602	0.55	10.53
8500	2.49	9170	4548	4623	0.54	10.46
8600	2.50	9315	4601	4714	0.55	10.54
8700	2.52	9479	655	4825	0.55	10.66
8800	2.45	9320	4708	4612	0.52	10.08
8900	2.42	9311	4762	4550	0.51	9.83
9000	2.48	9674	4815	4859	0.54	10.38
9100	2.54	10000	4869	5132	0.56	10.85
9200	2.48	9897	4922	4975	0.54	10.40

The figures below show the equivalent mud weight profiles for Wells Z2, Z3 and Z4.

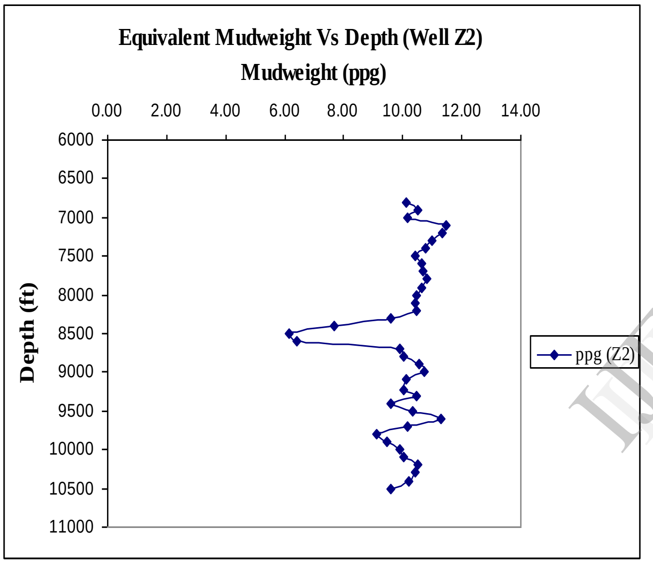

Figure 1 Equivalent Mudweight Vs Depth Plot for Well Z2

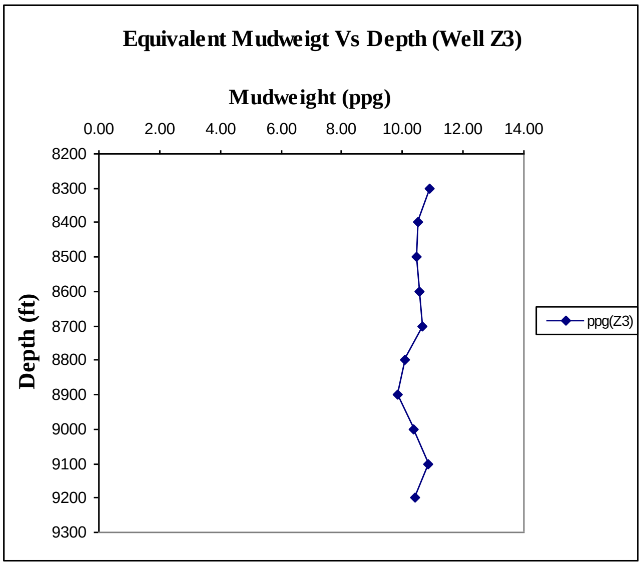

Figure 2 Equivalent Mudweight Vs Depth Plot for Well Z3

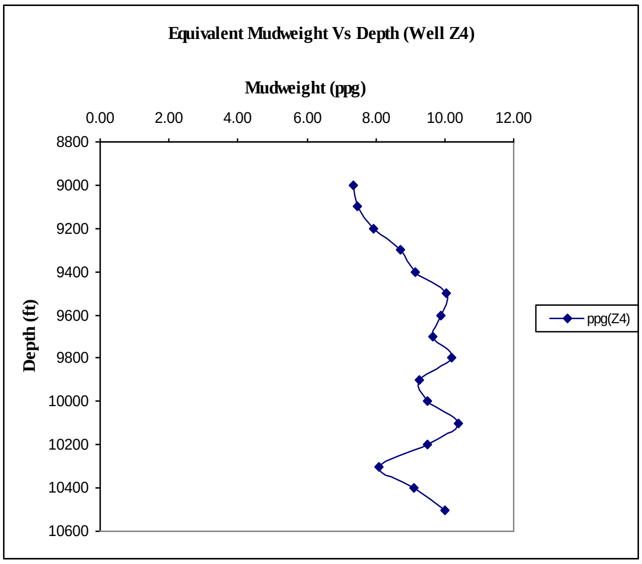

Figure 3 Equivalent Mudweight Vs Depth Plot for Well Z4

D. Equivalent Mudweight Sensitivity to Bulk Density

Results for the sensitivity of the equivalent mudweight and varying bulk density were plotted against each other to determine the magnitude of mudweight variation.

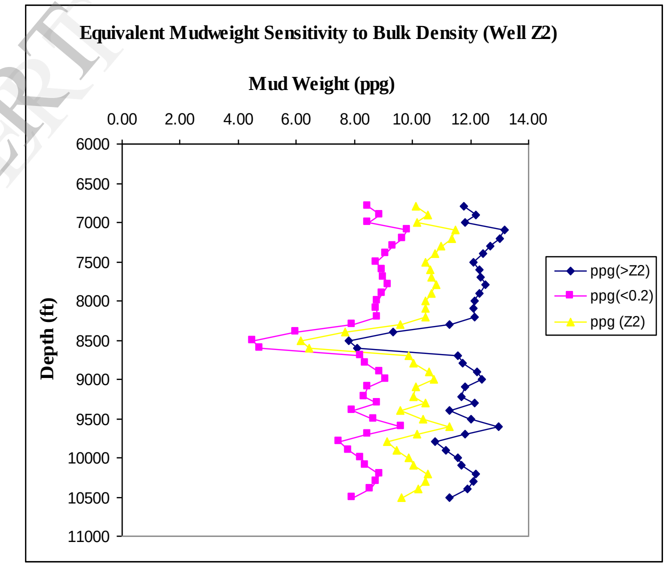

Figure 4 Equivalent Mudweight Sensitivity to Bulk Density (Well Z2)

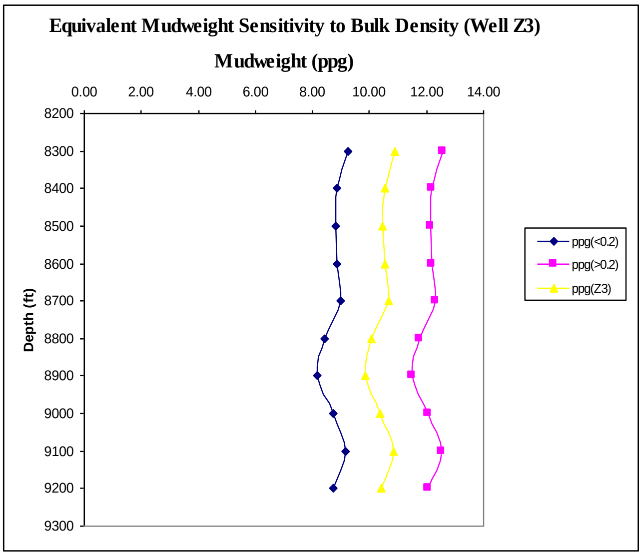

Figure 5 Equivalent Mudweight Sensitivity to Bulk Density (Well Z3)

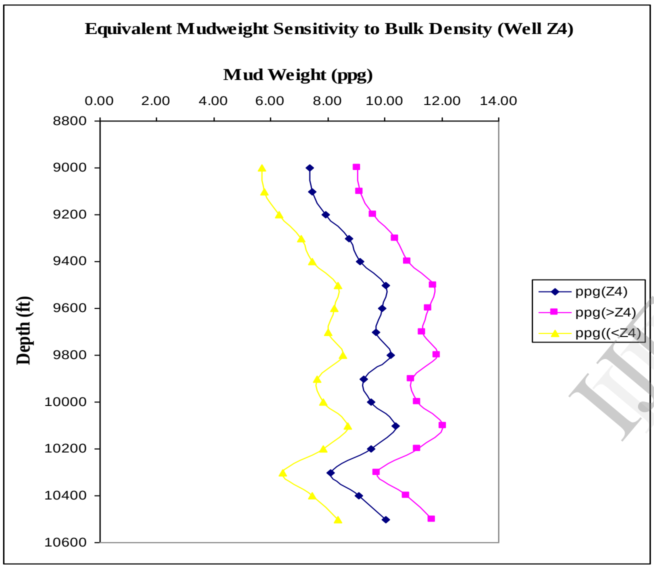

Figure 6 Equivalent Mudweight Sensitivity to Bulk Density (Well Z4)

E. *Porosity Calculations*

From the two models used in calculating porosity, the Wyllie Time Average equation seems to overestimate the porosity more than the bulk density method. Compaction trends for normally pressured zones could not be easily established. Figure 14 below shows a porosity depth plot for Well Z3, a clear deviation from the decreasing porosity trend is observed possibly indicating the presence of an overpressured zone.

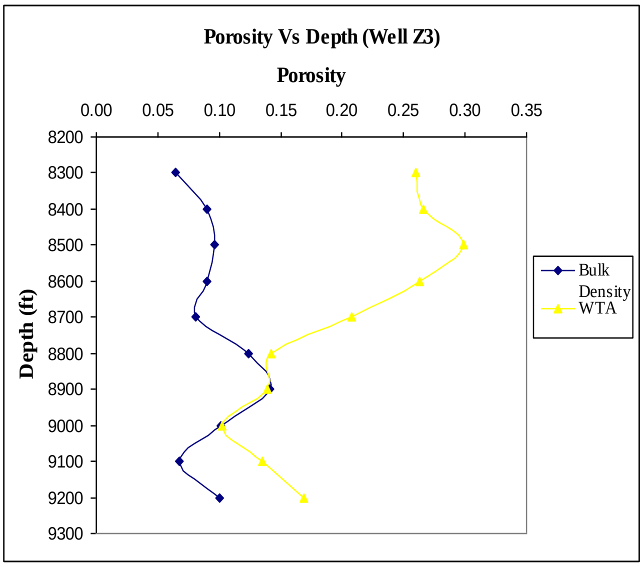

Figure 7 Porosity Vs Depth Plot (Well Z3)

F. *Discussion of Results*

From the compaction trends for the normal pressured zones established for each of the wells, a very clear zone of overpressures was observed in Well Z4. This is supported by the clear deviation from the normally pressured zone trend line from both the sonic log and the bulk density log at the depth intervals of 10300-10600 ft. The extent of this overpressured zone is uncertain due to the unavailability of data below the depth of 10600 ft. A very thick transition zone of about 800 ft. was observed between the depths 9700-10300 ft., although the gamma ray log shows that interval as being a sand region. Another uncertainty is the reduction in wellbore diameter at that depth as evidenced from the caliper log.

Overpressured zones were also observed from deviations of sonic log from normal trend lines in Well Z1 at 9500-9900 ft and in Well Z2 at depth interval 9900-10300 ft. Borehole washouts occurred at both these wells at depths 7800-8600 ft. in Well Z1 and 8400-9700 ft. in Well Z2 as evidenced from the caliper log.

Although the total logged interval of Well Z3 is just 900 ft., a slightly overpressured zone of just about 100ft was observed in Well Z3 at depths 8900-9000 ft., as evidenced from the slight deviation from trend line. Wellbore diameter remained constant as evidenced from the caliper log.

Sensitivity analysis on the impact of variation in bulk density with varying lithology showed that a difference in bulk density by 0.2g/cc would lead to errors in equivalent mudweight calculations of 1.6 ppg. In narrow window mudweight environments, this is quite significant, as an underestimation would most probably lead to drilling problems such as kicks, and if not properly controlled, could results into blowouts.

V. CONCLUSION AND RECOMMENDATION

Well logging data from resistivity, sonic and bulk density logs are important techniques used in pore pressure prediction and determining of the possible occurrence of overpressured zones. By establishing compaction trend lines in normally pressured zones, observed deviations from this trend could give an indication of the presence of overpressures.

These logs however, are affected by several factors which affect their response and would subsequently lead to errors in pore pressure evaluation. These factors include but are not limited to proximity to salt domes, borehole washouts; steep and very thin formations, variable mineralogy in shales, clay swelling, and presence of shale gas and salinity of the formation water.

The impact of bulk density variation due to varying lithology was analysed to determine how much change in bulk density would affect equivalent mudweight calculations. Using data from the four wells in this report, it was observed that an error of 0.2 g/cc in bulk density could lead to errors in equivalent mudweight of up to 1.6 ppg. This is quite significant in narrow window mudweight environments, especially in deep offshore fields, which would lead to drilling problems.

The development of logging while drilling (LWD) tools has been an extremely valuable tool that reduces the effects of washouts and other environmental factors associated with drilling that affect traditional well logging techniques, in the prediction of pore pressures.

To minimise the impact of environmental factors, well logging techniques of abnormal pore pressure prediction should not be used in isolation, rather, they should be used in conjunction

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APPENDIX

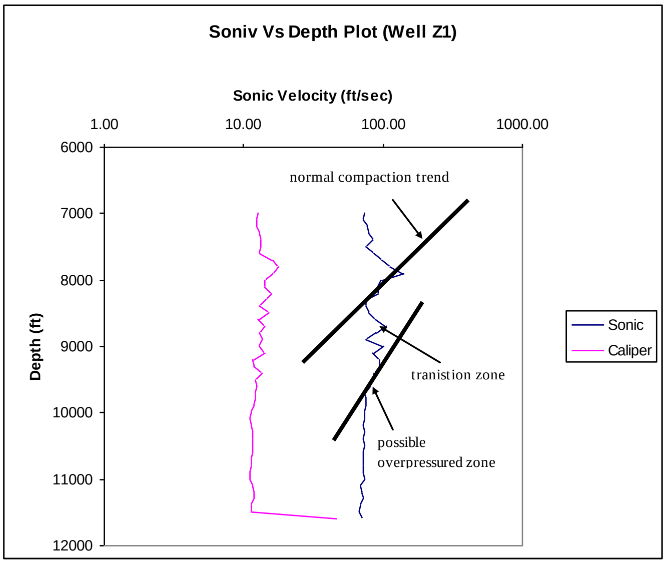

Figure 8 Well Z1 Compaction Trend

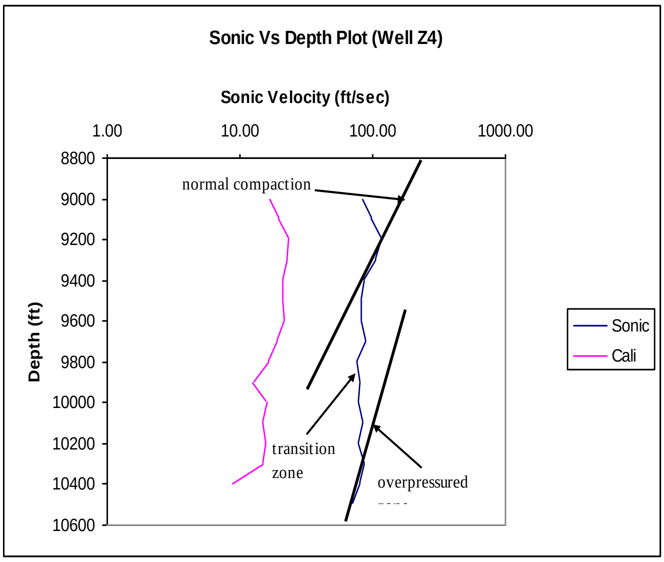

Figure 11 Well Z4 Compaction trend using sonic logs

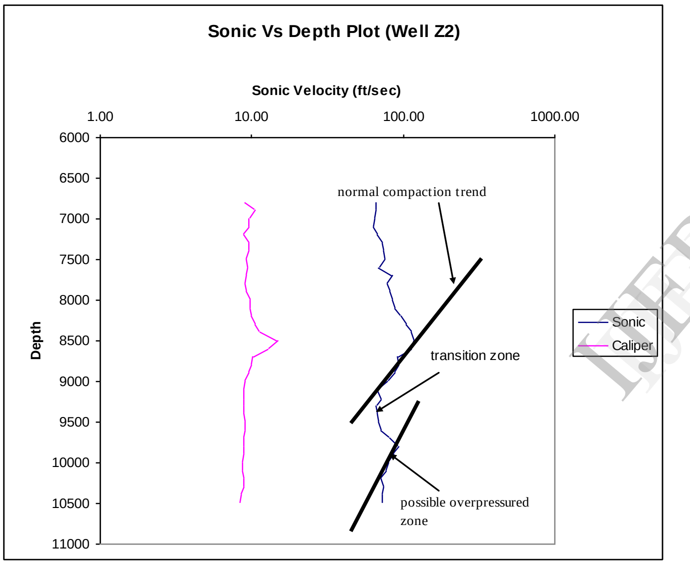

Figure 9 Well Z2 Compaction Trend

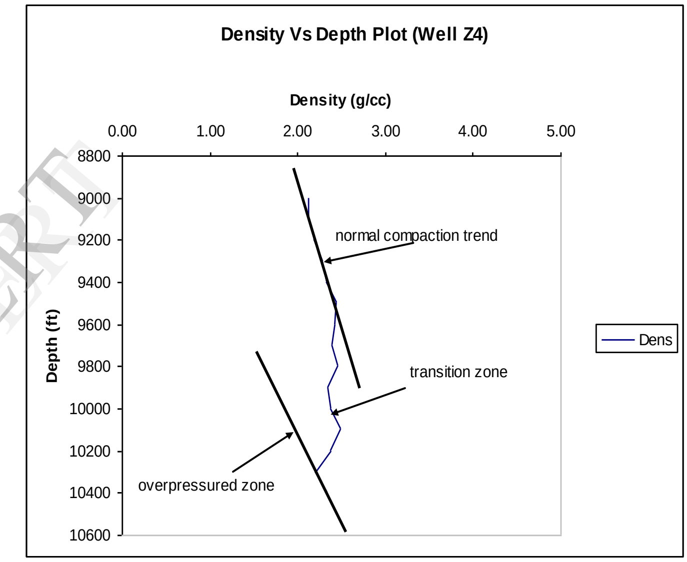

Figure 12 Well Z4 Compaction trend using bul density log

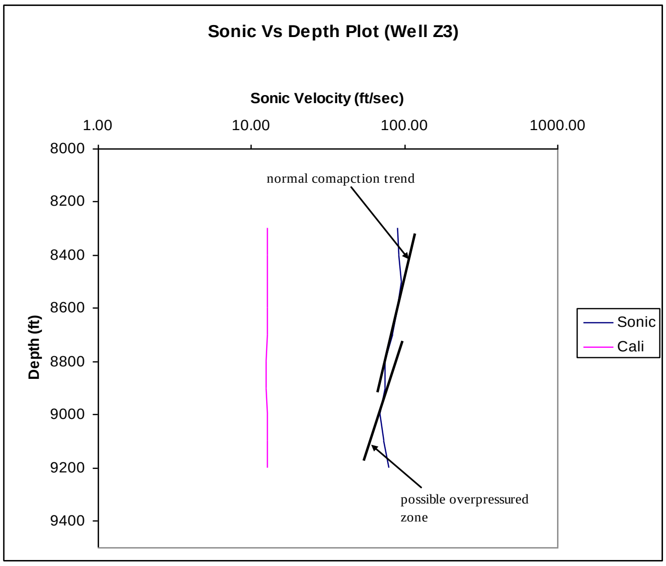

Figure 10 Well Z3 Compaction Trend