8th Biennial International Conference
& Exposition on Petroleum Geophysics

"HYDERABAD 2010"

P-217

Estimation of Pore Pressure from Well logs: A theoretical analysis and Case Study from an Offshore Basin, North Sea

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Summary

This paper concerns itself with the theoretical analysis of techniques in use for estimating Pore Pressure Gradient and some case studies of North Sea log data. Miller's sonic equation has been used to determine pore pressure from four deep water wells. The variation of over burden gradient (OBG) and Pore pressure gradient (PPG) with depth have been studied. Pore pressure has been estimated for selected depth intervals; 4462-9063ft, 6605-8663ft, 6540-7188ft and 6890-7546ft for wells 1, 2, 4 and 5 respectively. The OBG changes from 16.0-32.0ppg, 16.0-22.0ppg, 15.5-18.0ppg, 18.6-20.4ppg for wells 1, 2, 4 and 5 respectively. The PPG values have been changed in these depth intervals: 15 to 25 ppg, 15 to 22ppg, 15 to21ppg and 15-25 ppg from wells 1, 2, 4, and 5 respectively.

Introduction

Pore Pressure Gradient considerations impact the technical merits as well as the financial aspect of the well plan. In areas where elevated Pore Pressure Gradients are known to cause difficulty for drillers, having an accurate pressure prediction at the proposed location is critical to a successful drilling operation. Pre-drill estimation of Pore Pressure Gradient is the standard practice for major oil companies. This should come as no surprise, as the reasons are quite compelling. Pore Pressure Gradient information guide the development of the mud schedule, the casing program, rig selection and wellhead ratings. Each of these aspects of well planning is capital intensive and benefit from having a good pre-drill estimate of Pore Pressure Gradient. In fact, it is hard to imagine budgeting a multi-million dollar well without this crucial information.

Pore Pressure Gradient analysis can be useful in understanding geological influences on hydrocarbon accumulation. It is better to drill the flank of a structure rather than its highest point where higher pressure within the gas cap present more difficult drilling problems. Further, hydrocarbon accumulation favours slightly lowered Pore Pressure within zones of elevated pressures. Identification of these zones, aids in the overall exploration of petroleum reserves. Gas, due its buoyancy, can induce abnormally high formation pressures at very shallow depths. Shallow gas hazards present an important risk while drilling. Pore Pressure from seismic, together with lithology discrimination, can often identify these zones. Pore Pressures can be either normal or abnormal or subnormal. Normal Pore Pressure will be the hydrostatic pressure due to the average density and vertical depth of the column of fluids above a particular point in the geological section, that is, to the water table or sea level. The convention is that abnormal pressures are higher than normal and subnormal pressures are lower.

Theory

Pore Pressure

Pore Pressure is the pressure of fluids within the pores of a reservoir, usually hydrostatic pressure, or the pressure exerted by a column of water from the formation's depth to sea level but not always so. When impermeable rocks such as shale form as sediments are compacted, their pore fluids cannot always escape and must then support

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the total overlying rock column, leading to anomalously high formation pressures.

During the drilling two types of pressures can be predicted which are, 1) Reservoir Pressure and 2) Shale Pore Pressure (Paul et al., 2009). Shale Pore Pressure can be predicted and from that predicted Shale Pore Pressure Sand Pore Pressure can be predicted.

Causes of Pore Pressure

The causes of Pore Pressure formation are as follows,

a) Sedimentation disequilibrium,
b) Connection through conduits (Piezo connectivity),
c) Association to sand,
d) Effects of burial digenesis of mud supported rock,
e) Thermal effects,
f) Tectonic loading / unloading effects owing to block movements and rotations,
g) Hydrocarbon columns,
h) Deformational tectonics
i) Erosion.

Variations of Pore Pressure due to man-made causes are,

a) Withdrawal of hydrocarbon fluids and phase transformations,
b) Sediment subsidence from withdrawal of fluids and contaminated effects,
c) Effect of void age compensation and pressure maintenance methods such as water injection.

Importance of Pore Pressure Estimation

The reasons behind studying Pore Pressure are,

a) For Drilling Safety,
b) For Borehole Stability,
c) For Rig Selection,
d) For Mud Schedule,
e) For Protection from accident due to abnormal pressure.

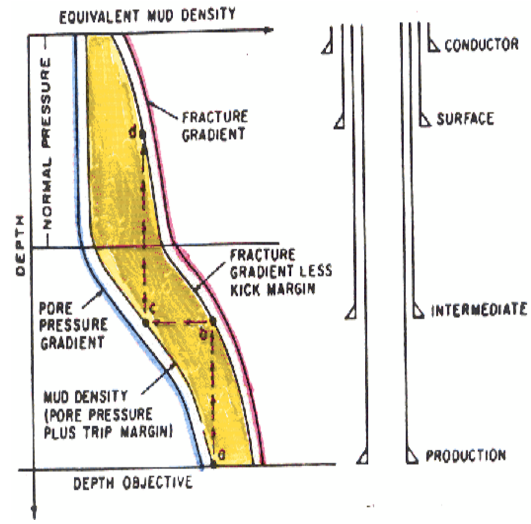

Figure 1: sample relationship among casing setting depth, formation pore pressure gradient and fracture gradient.(Sarker. and Batzle,)

From the well log data, Pore Pressure Gradient has been calculated as described in the **flow chart**

Log data (LWD / Density log / Porosity log data)

↓

Density (ρ) Calculation

↓

Overburden Gradient (OBG) Calculation

↓

Normal Compaction (NCT) Trend / Compaction Trend (CT) Calculation

↓

Pore Pressure (PP) Calculation

To determine Pore pressure Miller's Sonic Equation is used.

Miller's Sonic Equation (Miller, 1995)

The input parameter "Maximum velocity depth", d_{max} controls whether unloading has occurred or not. If d_{max} > Depth, unloading has not occurred and then,

$$PP = OBG - \frac{\left(\frac{1}{\lambda}\right)\ln\left\{\frac{DT}{DT_{ml}}\left(\frac{DT_{ml}-DT_{matrix}}{DT-DT_{matrix}}\right)\right\}}{Depth}$$

If $d_{max} \leq$ Depth, then unloading behavior is assumed. Pore Pressures are calculated as follows,

$$PP = OBG + \frac{\left(\frac{1}{\lambda}\right)\ln\left\{a\left(1-\frac{\frac{1}{DT}-\frac{1}{DT_{uo}}}{\frac{1}{DT_{matrix}}-\frac{1}{DT_{ml}}}\right)\right\}}{Depth}$$

Where,

Where, PP = Pore Pressure Gradient (psi/ft or lb/gal), (kPa/m or g/cc)

OBG = Overburden Gradient (psi/ft or lb/gal), (kPa/m or g/cc)

DT = Sonic Travel Time (microsec/ft, microsec/m)

DT_{ml} = Sonic Travel Time of sediment at mudline

DT_{matrix} = Sonic Travel Time matrix material

λ = Empirical parameter defining the rate of increase in velocity with effective stress (1/psi)

a = the ratio of the slope of the virgin curve to the unloading curve

d_{maxv} = Depth at which unloading has occurred

Analysis

The field to be investigated is located in the South Viking Graben in the North Sea. It is of Paleocene age, and represents turbidity sand deposits. The sands were eroded off the Scottish Mainland and East Shetland Platform, and transported to the "deep-sea" between Scotland and Norway, into the graben basins of the North Sea (Avseth et al., 2005). The sediments are today buried at a depth of ca. 2200m in the area of study. Still they are loosely consolidated sediments. Moreover, the episodes of sand deposition were separated by longer periods of high-stand shale deposition. Hence, the lithology variation can be complex and variable both vertically as well as laterally in these systems.

Normal Compaction Trend (NCT) is drawn from the variation interval velocity with depth for four wells (Figure 2a to Figure 2b).

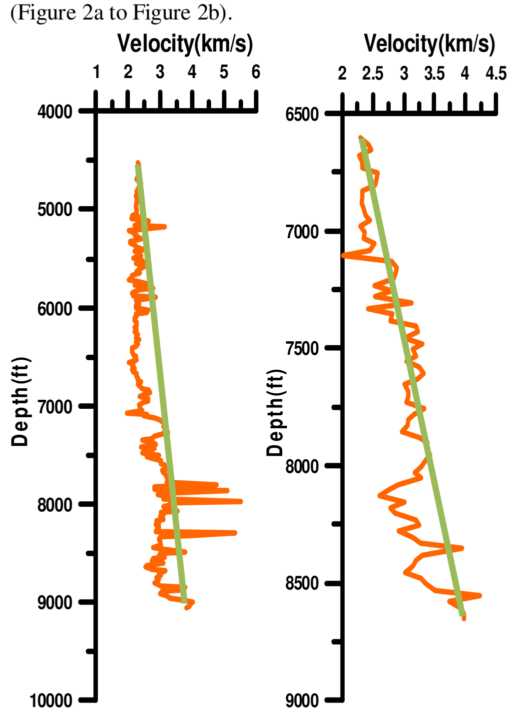

Figure 2a: normal compaction curve of well 1 & well 2.

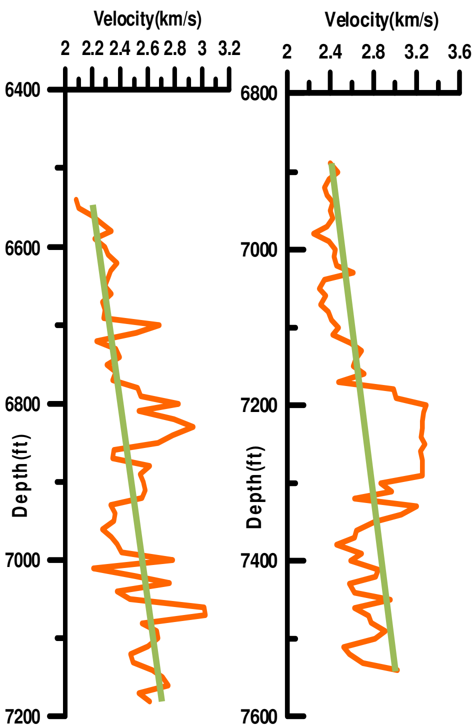

Figure 2b: normal compaction curve of well 4 & well 5.

In case known normally compacted section is absent in the candidate well, this curve has to be imported into the candidate well, from offset well or wells known to have normally compacted sections. DT_{ml} is obtained by extrapolating the normal compaction curve to mud line. Then if data points exist that fall above the virgin curve, unloading can be inferred. In that case, the depth at which the points above the virgin curve first appear can be taken to be what is sometimes referred to as 'unloading depth'. The velocity at that point is denoted $V_{ul.}$
And DT_{uo} =1000000/ V_{ul}

All the four wells viz. Well-1, Well-2, Well-4, Well-5 locating at the North Sea are served as deepwater - exploratory wells. The four wells namely; Well-1, Well-2, Well-4 and Well-5 have been drilled up to 9063 m, 86663.5 m, 7188 m, and 7546 m. Pore Pressure Gradient of each well has been estimated separately by using Miller's Sonic Equation. Overburden Gradient (OBG) has been calculated using bulk density equation. OBG and PPG have been studied for selected depth interval of 4462-9063ft, 6605-8663ft, 6540-7188ft and 6890-7546ft for four wells 1, 2, 4 and 5 respectively.

OBG and PPG curves for all four wells are displayed from Figs. 3 through 10.

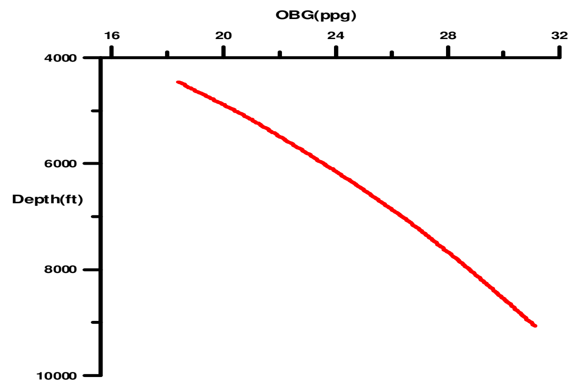

Figure 3: OBG Curve of Well-1.

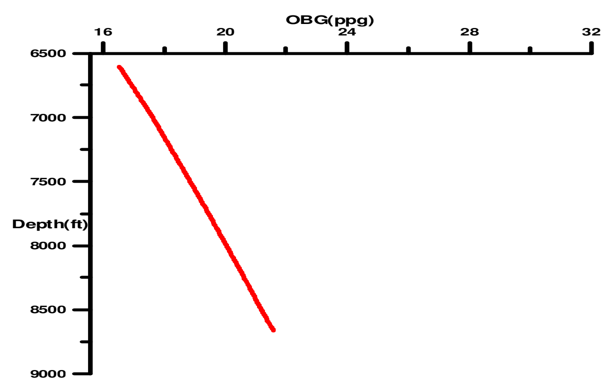

Figure 4: OBG Curve of Well-2.

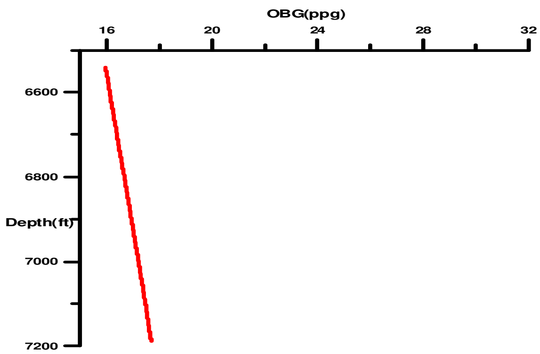

Figure 5: OBG Curve of Well-4.

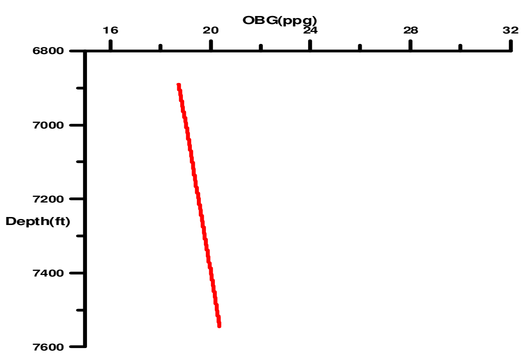

Figure 6: OBG Curve of Well-5.

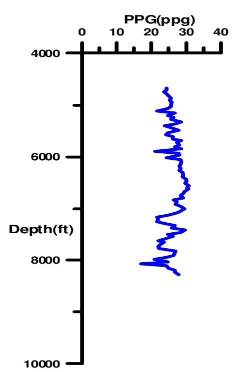

Figure 7: PPG Curve of Well-1.

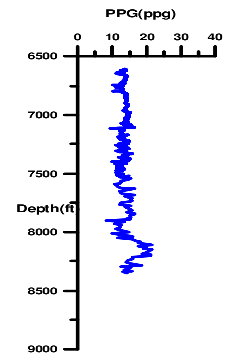

Figure 8: PPG Curve of Well-2.

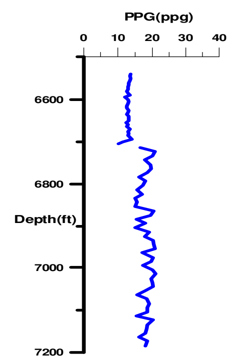

Figure 9: PPG Curve of Well-4.

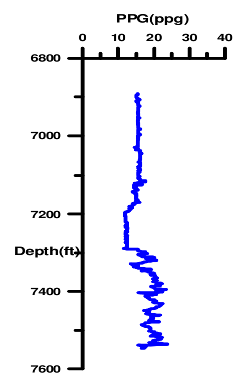

Figure 10: PPG Curve of Well-5.

The OBG changes from 16-32ppg, 16-22ppg, 15.5-18ppg, 18.6-20.4ppg for well-1, 2, 4 and 5 respectively for the selected depth interval as mentioned above.

Accordingly, the PPG values have been changed in these depth intervals: 15 to 25 ppg, 15 to 22ppg, 15 to21ppg and 15-25 ppg from wells 1, 2, 4 and 5 respectively.

For well 1 and well 2, the OBG curve is gentler than well 4 and well 5.It shows that overburden pressure is more in well 1 and well 2.That shows denser rock is there.

In well 2 NCT of PPG changes from 17ppg to 22ppg in corresponding depth of 3200ft to 3400ft(Figure 8). In well 4 ,NCT of PPG changes from 16ppg to 24ppg in corresponding depth of 6700ft to7200ft.(Figure 9). In well 5 NCT of PPG changes from 18ppg to 25ppg in corresponding depth of 7300ft to 7450ft. (Figure 10).

Since all the four wells are deepwater wells and sea water column has been acting as overburden for wells Well–1, Well–2, Well–4 and Well–5. It is indicated from figures (Figure 3, Figure 4, Figure 5 and Figure 6) that OBG is dependent on the water column, i.e., the well penetrating higher water column (Figure 3) has been characterized by lower OBG trend and the well with lower water column above (Figure 5) are characterized by higher OBG trend. It is obvious that from shallower to deeper depth the water column increases and OBG and PPG decrease. PPG decreases means μ (Poisson's Ratio) or K_i (Matrix Stress Coefficient) decreases which means at lower mud pressure that formation can be fractured. This indicates that if water column is more, the mud pressure would be lowered during drilling of a deeper well with respect to a shallower well, otherwise if the same mud pressure is maintained as in case of drilling of a shallower well , then formation damage may occur in the deeper well.

When pore pressure increases, pressure at the borehole increases and after crossing certain range of pore pressure, casing is needed. In Figure 8 &10, it is shown where casing is needed. In well-2 after 8200 ft casing is needed. Similarly in well-5 after 7300ft casing is needed.

Conclusions

OBG is dependent on the water column, i.e., the well penetrating higher water column has been characterized by lower OBG trend and the well with lower water column above are characterized by higher OBG trend.
Normally the PPG increases as depth increases.

If water column increases then OBG and PPG trends are decreases. PPG decreases means, that, for a given μ (Poisson's Ratio) or K_i (Matrix Stress Coefficient), the horizontal effective stress becomes lower which means at lower mud pressure that formation can be fractured.
Pore Pressure Gradient information guide the development of the mud schedule, the casing program, rig selection and wellhead ratings.

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Acknowledgement

I deeply acknowledge Dr. Rima Chatterjee, (Indian School of Mines, Dhanbad) for her guidance and constant encouragement.