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Determination of In-situ Stress Magnitudes for an Offshore Basin of Eastern India

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Summary

Offshore basins located at Eastern continental margin of India has drawn considerable interest due to its major hydrocarbon potential. Sonic and density log data have been used to estimate pore pressure and overburden stresses for four deepwater wells. These wells located at water depths varying from 585 m to 1265 m, where, their penetrated vertical depth reaches up to 3960 m in clastic sediments. In order to compute effective in-situ horizontal stress magnitude, Poisson's ratio for four wells at different depths has been calculated. Effective vertical and effective horizontal stress magnitude varies from 2.04 MPa to 25.08 MPa and from 1.60 MPa to 17.43 MPa respectively.

Introduction

Deepwater reservoirs located in the eastern continental margin of India is continued to provide many new technical challenges for hydrocarbon development and production. Drilling shallow overpressured sands may cause large and long-lasting uncontrolled flows, well damage and foundation failure, formation compaction, damaged casing, and re-entry and control problems (Ostermeier et al., 2002). 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. In deep water areas the main exploration focus is on sandstone reservoirs deposited as turbidites with a high volume of associated fine-grained sediments, dominantly shales (Bastia et al., 2006). The clay content of the fine-grained lithologies is likely to be high. Horizontal stress magnitudes are needed to optimally design drilling, completion and workover operations. In both fractured and non fractured reservoirs in-situ stresses can impact reservoir properties and reservoir performance. These stresses play an important role in borehole stability, productivity and injectivity. The main aim of this paper is to estimate (a) overburden stress or vertical stress, (b) pore pressure, (c) effective vertical stress and (d) effective horizontal stress from sonic and density logs for four deep water wells in an offshore basin of eastern continental margin of India.

Methodology

Well log data of four wells namely, Well-1, Well-2, Well-3 and Well-4 have been studied for estimation of Pore Pressure and In-situ stresses. These wells; Well-1, Well-2, Well-3 and Well-4 are located at water depths 585 m, 603 m, 706 m and 1265 m respectively where, their respective penetrated vertical depth reaches up to 3960 m, 2416 m, 2609 m and 2435 m in clastic sediments. The flow chart for in-situ stress magnitude determination have been shown below,

Density Calculation (From Well Log data)
↓
Overburden Stress or Vertical Stress Calculation
↓
Pore Pressure Calculation
↓
Effective Vertical Stress Calculation
↓
Effective Horizontal Stress Calculation

Density log data have been used for Well-1 and Well-3 directly for computation of overburden stress or vertical stress. Gardner's velocity equation has been used to get pseudo density for computation of vertical stress for Well-2 and Well-4. Gardner's velocity equation for density calculation (Gardner et al., 1974) is as:

$$\rho = A\ V^{B}$$

where ρ = density, A = coefficient, 0.23, B = exponent, 0.25 and V = velocity.

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The magnitude of overburden stress or vertical stress at any depth is produced by the pressure exerted by the rocks above that point. The magnitude of the vertical stress, S_v, is the force per unit area applied by the load above the point of measurement. S_v is usually inferred from the overburden load. The vertical stress at depth z is computed as the total weight of the overburden (Evans et al., 1989 and Plumb et al., 1991),

$$S_v = \int_0^z \rho(z) g \, dz$$

where, ρ (z) = formation bulk density of overburden rocks as a function of depth, z and g = acceleration due to gravity.

The Pore Pressure at any depth has been calculated from Miller's Sonic Equation (Miller, 1995 and Paul et al., 2009). 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, a = AV/V_u, the ratio of slope of virgin and unloading velocity effective stress curves σ_{ul}.

and $\frac{10^6}{DT_{uo}} = V_{ml} + (V_{matrix} - V_{ml}) \exp(-\lambda \sigma_{ul}) \left(\frac{1-a}{a} \right)$

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 matrix material (≈ 200) ft/sec, DT_{matrix} = Sonic Travel Time of sediment at mudline (asymptotic travel time at infinite effective stress, typical ranges from 55 microsec/ft to 70 microsec/ft, 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 at σ_{ul}, σ_{ul} = The effective stress from which the sediment unloads, V_{ul} = The velocity at which unloading occurred for sediments buried at depths greater than d_{maxv} and d_{maxv} = Depth at which unloading has occurred.

Effective Vertical Stress (S_{ev}) at any depth have been calculated by using the following equation,

Effective Vertical Stress (S_{ev}) = S_v - PP

Effective Horizontal Stress (**S_{eh}**) at any depth have been calculated by using the following equation,

Effective Horizontal Stress (S_{eh}) = [γ / (1 – γ)] S_{ev}

where, γ = Poisson's ratio.

For estimation of Effective horizontal stress and to know the variation of stress magnitude with depth for four wells, the prior knowledge of Poisson's Ratio is essential. For this reason, Poisson's Ratio (γ) of the study area was determined with the help of leak off test as horizontal Stress magnitude (S_h) and vertical Stress (S_v) at discrete depths for four wells as

Poisson's Ratio (γ) = S_h / (S_h+ S_v)

Table 1 is listing the Poisson's ratio of Well-1, Well-2, Well-3 and Well-4 which are calculated from the above equation. The average Poisson's ratio of each wells such as 0.41, 0.47, 0.40 and 0.44 for Well-1, Well-2, Well-3 and Well-4 have been used respectively for computation of effective horizontal stress for four wells.

Table 1: Estimated Poisson's ratio from Leak off test data for four wells.

Well Name	Depth (m)	S_v (MPa)	S_h* (MPa)	γ
Well-1	1300	25.75608	17.575	0.405602796
Well-1	2400	53.93379	38.567	0.416938520
Well-2	1230	18.42564	16.291	0.469252304
Well-2	1605	24.51890	23.572	0.490152926
Well-3	1425	28.49937	19.594	0.407409910
Well-4	1660	23.66061	19.323	0.449543317
Well-4	1790	28.20133	22.077	0.439099820

* S_h values are basically Leak Off Test (LOT) values.

Analysis of Stress and Pore Pressure

The effective vertical stresses for Well-1, Well-2, Well-3 and Well-4 were varied from 6.33 MPa to 25.08 MPa, 4.34 MPa to 18.46 MPa, 4.41 MPa to 9.85 MPa and 2.04

MPa to 8.02 MPa respectively and the effective horizontal stresses for the same respective wells were varied from 4.39 MPa to 17.43 MPa, 3.85 MPa to 16.37 MPa, 2.94 MPa to 6.57 MPa and 1.60 MPa to 6.30 MPa respectively (Figures 1 to 4). The ratio of effective horizontal stress to effective vertical stress varies from 0.66 to 0.88. Effective stress ratio is found less (0.66 to 0.69) in Well-1 and Well-3 whereas it becomes more than 0.80 in other two wells. The average effective stress ratio is about 0.75, considering the Poisson's ratio of 0.43 of the study area. The high value of Poisson's ratio is indicating the unconsolidated rock types in the study wells. Pore pressure changes result in changes of stresses acting in the reservoir and surrounding rocks. Pore pressure increase in Well-1, Well-2, Well-3 and Well-4 is reflecting the decrease in stress magnitudes. Pore pressure decrease in Well-2 around 2150 m to 2250 m due to depletion leads to an increase in stress magnitudes. Further, previously authors had found that from wells of shallow water regime to deep water regime the Overburden Gradient (OBG), Pore Pressure Gradient (PPG) and Fracture Pressure Gradient (FPG) decreases (Chatterjee et al., 2009) in these wells. The decrease in PPG and FPG indicate the decrease of γ (Poisson's ratio), which suggests that formation can be fractured at lower mud pressure. The effective stress ratio data can be used in Matthews and Kelly method (1967) for the analysis of FPG. The data shows that when water depth is more, the expected LOT's are low enough to be cause of concern. This indicates that if water column is more, the mud pressure would be lowered during drilling of a well of deep water regime with respect to a well of shallow water regime, otherwise if the same mud pressure is maintained as in case of drilling of a well of shallow water regime, then formation damage may occur in the well of deep water regime.

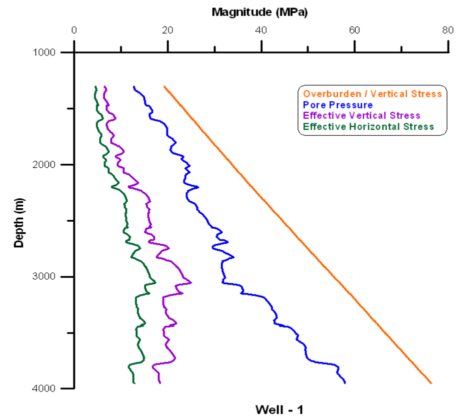

Figure 1: Variation of effective stresses and pore pressure with depth in Well-1.

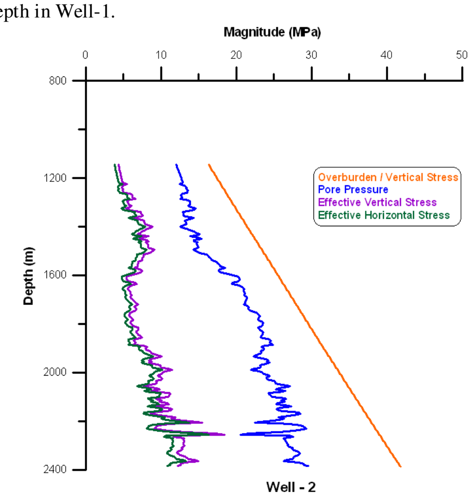

Figure 2: Variation of effective stresses and pore pressure with depth in Well-2.

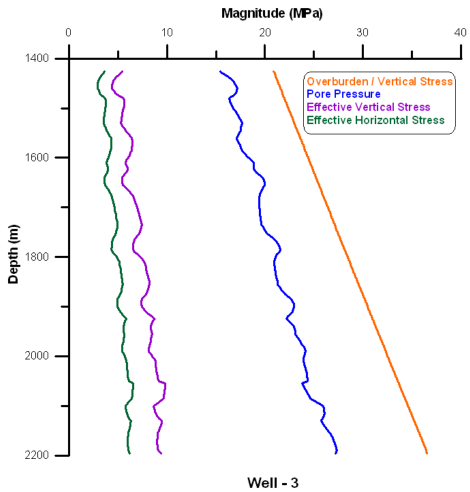

Figure 3: Variation of effective stresses and pore pressure with depth in Well-3.

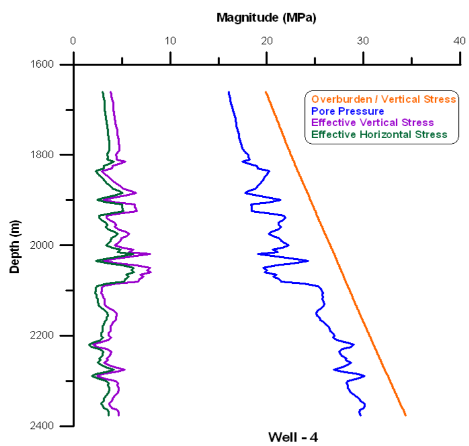

Figure 4: Variation of effective stresses and pore pressure with depth in Well-4.

Conclusions

From the above study it is observed that from shallower well (Well-1) to deeper well (Well-4) effective vertical stress and effective horizontal stress are decreased, which may indicate that the exploration for hydrocarbons in the part of when water depth is more difficult with respect to the shallower part. Unconsolidated rock types are characterised by high Poisson's ratio, ranging 0.41 to 0.47 in the four wells. The average effective stress ratio is found as 0.75 considering all four wells in the offshore basin of eastern continental margin of India. Estimation of in-situ stresses like effective vertical and effective horizontal stress will account for the stress sensitivity of reservoirs i.e. the changes of reservoir petrophysics or performance will vary as a function of in-situ stress.

From the computed Poisson's ratio from LOT's and validating by Poisson's ratio from shear and compressional slowness data from the acoustic logs the stress ratio can be predicted. Using the stress ratio data in Matthews and Kelly method the data shows that when water depth is more the expected LOT's are low enough to be cause of concern.

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