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Present In-Situ Stress, Overpressure and Wellbore Stability Analysis in HPHT field of Mumbai High-DCS area and its implications in Petroleum Exploration: A Case Study

Abstract: This study investigated and identified zones of overpressure along with present in-situ stresses and the wellbore instability issues in HPHT wells of Bombay High-Deep Continental Shelf (BH-DCS) field of Western Offshore Basin. Models are generated and used for predicting pore pressure and the corresponding fracture pressure using offset wireline logs and drilling data. Panna formation along with part of Devgarh formation in this field is characterized by very high abnormal pore pressure and high temperature. Thus, shale compaction disequilibrium theory along with other mechanisms are described and utilized in this study. The studied wells showed not only compaction disequilibrium of sediment to be the major mechanisms that gave rise to overpressure but also unloading mechanism (fluid expansion, hydrocarbon generation) as the secondary overpressure generation mechanisms in wells of the field.

An attempt has been made to perform the advanced wellbore stability analysis to understand borehole instability issues in the region which can be minimized in the future wells. Shear Failure gradient and safe mud weight window has also been established in general to prevent wellbore collapse. In our workflow, offset well information have been incorporated judiciously to generate pore pressure, fracture pressure, in- situ stresses and shear failure gradient for which rock strength parameters have been calculated from the offset wireline sonic logs.

Keywords: Bombay High-DCS block, Overpressure Compartment, In-situ principle stresses, Shear Failure Gradient.

Introduction:

As E&P industry in India runs into more difficult and challenging offshore HPHT environments, need for understanding wellbore stability conditions is becoming more vital as the problems associated with wellbore stability costs the industry several billions of rupees per year. The wells encountering High Pressure-High Temperature (HP-HT) conditions face severe mud losses, well kicks and other operational difficulties such as stuck pipes, borehole instability and borehole caving's while drilling of the well.

Geomechanics is an effective tool which has proven to be a highly beneficial in understanding the stress field of a region, calculating geomechanical parameters and thus recommending a safe mud window for drilling can lead to less well cost implications and greater drilling productivity.

Seven vertical wells so far been drilled in this area were selected to create the models. All the wells under case study are HPHT wells and have faced poor wellbore conditions with regard to washouts (pertaining to borehole instabilities) along with narrow mud weight window which led to a loss of time that had a direct impact on well cost.

Methodology:

There is a series of data in the seven offset wells to construct the geomechanical model which included wireline logs, formation pressure data, geological well completion reports, drilling complications etc. The pore pressure is estimated from Eaton's and Bowers compaction analysis using offset wireline sonic log data and validated with formation pressure data. The vertical stress (Sv) is estimated from overburden pressure which is computed from density logs recorded in offset wells. The minimum horizontal stress (Shmin) is obtained using the Matthew-Kelly fracture gradient equation and calibrated with available leak-off test (LOT) data. Since maximum horizontal stress Shmax cannot be measured in-situ, it is then derived using the empirical equation simulations. Rock strength parameters is estimated from sonic velocity, porosity data and calibrated with the analysis of four arm caliper logs. However, in the absence of core data, calibration of rock strength could not be corroborated. The calculated rock strength parameters then integrated to the stress field analysis output to investigate the safe wellbore analysis by generating Shear Failure Gradient (SFG). All the analysis was carried out in Drillworks Predict and Geostress module at different depths giving corresponding recommended safe mud weight window in general as output.

Geological Setting of Area:

Mumbai offshore basin is a pericratonic basin occurring along the passive western continental margin of India. The area under present study is located in the Bombay High-Deep Continental Shelf (BH-DCS) tectonic block between adjoining shelf margin (Fig.1a). These structures are separated from the main Mumbai High structure by a gentle southerly dipping homocline. The BH-DCS platform area remained submerged throughout the rifting episode of the Indian plate with Bombay High. Clastics Sediments of Panna formation were deposited in the depocenter which have accumulated huge thickness in the area. Subsequent shallowing of the sea led to the deposition of carbonates of Bassein and Mukta formations. The shallow marine conditions with oscillations persisted from the Late Oligocene with the Bombay High being submerged. Carbonates of the Panvel, Bombay and Bandra were deposited followed by the finer clastics of the Chinchini Formation. The generalized stratigraphy of the DCS area encountered within the study area is given in (Fig.1b)

Fig 1: a) Location map showing wells under study b) Generalized stratigraphy of studied area

Pore Pressure and Fracture Pressure Analysis:

In the study area, pore pressure gradient was estimated using Eaton and Bowers normal compaction trend analysis by incorporating offset wireline sonic logs and validated with measured pressure data (MDT, RFT, etc.) and well events. Formation pressure gradient in this field is nearly hydrostatic (upto 9 ppg) except for the middle of Devgarh formation and Panna section (Fig. 2). Pressure build-up observed in transition zone from ~3400m in Devgarh formation whereas depths deeper than 3400m which corresponds to clastics of Panna formation indicates a different overpressure compartment. Our preliminary pore pressure model studies has suggested that both compaction disequilibrium of clastics along with secondary mechanisms like hydrocarbon generation and accumulation may have contributed to overpressure which gave rise to a overpressure compartment in Panna.

Causes of Overpressure and mechanisms:

Overpressures caused by compaction disequilibrium are generally associated with vertical stress gradient (Tingay et al., 2013). As a result, the mean effective stress remains constant with depth. If overpressure is generated after the compaction by fluid expansion or vertical transfer (Unloading), then very subtle change of porosity anomalies will be observed. Velocity vs. density cross-plots can be used to identify the presence of overpressure generated by these other secondary mechanisms (Hoesni et al, 2004).

In this study area, compaction disequilibrium is the primary source of overpressure generation caused by high sedimentation rates. Paleogeography studies for WOB suggested that a depocenter was existed in south Mumbai low area which have accumulated thicknesses greater than 600m when sedimentation rates were high during paleocene rift phase. This caused overpressure generation over time as pore fluid could not be squeezed out of the formation.

Fig.2 a) MDT and LOT data plotted against depth. b) PP-FG-OBG model for the field under study

As post-rift sedimentation rates were lower, no overpressure was generated. Evidence from our analysis suggests that additional overpressure mechanisms may exist in this field, mechanisms that are not associated with a porosity anomaly. Analysis of velocity vs. density cross-plot from two wells indicates deviation from typical shale trends characteristic of normal compaction/disequilibrium compaction (Bowers, 2001). The deflection to higher density and lower velocity is characteristic of load transfer or unloading, where rock compressibility is affected, resulting in a different compaction profile. However, this study would propose that there may be evidence for additional processes that generate overpressure in this field also due to high geothermal gradient.

Fig. 3 Sonic velocity vs. density cross plot shows unloading mechanism in overpressure formation

In Situ Stress Magnitudes in the Field:

Vertical stress magnitude(Sv):

The calculation of vertical stress requires knowledge of bulk density from the sea bed to the depth of interest Overburden stress at any depth z was determined by integrating density log data using the

$$S_V = g\left(\int_0^{Z_B} \rho_{sea}\,dz + \int_{Z_B}^{Z} \rho_b\,dz\right),$$

equation:

where, Sv is the overburden stress, ZB is the sea bottom depth, ρb is the bulk density from density logs, ρsea is the density of sea water, and g is the gravitational acceleration. Combining data from several wells within the study area provides regional profiles of overburden stress with depth in field. Fig.2b shows average overburden gradient for all wells studied in the field. It indicates that wells have a consistent overburden gradient of 19+ ppg at a depth of 4000m.

Minimum horizontal stress magnitude$(Shmin)$:

To obtain minimum horizontal stress, the Fracture Closure Pressure (FCP) from the extended leak off test is required. In the absence of the Extended Leak Off test data in this field, for the determination of the least principal stress magnitude, $Shmin$, available data sets of LOT has been considered. The LOP of each test (corresponding to a distinct breaking-slope from the linear pressure build-up) is approximately equal to the $Shmin$ magnitude (Zoback et al. 2003). Matthew-Kelly method was used to construct the fracture pressure gradient. In the study area, maximum $Shmin$ gradient observed is 18ppg in Panna formation. Effective stress ratio $(k0)$ of 0.75 calculated from the LOT data is utilized for above calculation.

Maximum Horizontal Stress $(SHmax)$ magnitude and direction:

Maximum horizontal stress is calculated by using the equation of tectonic factor (tf).

$tf=SHmax\text{-}ShminSv\text{-}Shmin$

By rearranging the equation, it can be written as:

$SHmax=Shmin+tf^*\,(Sv\text{-}Shmin)$

The tectonic factor (tf) of 0.6 is used in this study area. The magnitude of $Shmax$ in this area is found to be closer 18.8-18.9 ppg which is closer to Vertical stress, Sv. The direction of $SHmax$ is taken from the existing nearby data in this region of Mumbai Offshore. The orientation of maximum horizontal stress $(SHmax)$ is taken ~10° N from world stress map report (2016).

Wellbore instability in the field and wellbore collapse:

The wells in this field has faced wellbore instability issues like tight pulls, held ups, wellbore collapse, stuck ups, hole washout, etc. Analysis was done to understand the issue. Rock mechanical parameters such as Poisson’s Ratio (PR), Cohesive Strength (C_0), Friction Angle (Ø) and Uniaxial Compressive Strength (UCS) was estimated from processed sonic compressional and sonic shear data recorded in the drilled well. In this case, the Lal’s correlation law (1999) is used to derive rock strength parameters from compressive sonic velocity which gave the excellent correlation with the wellbore instabilities duringdrilling.

Compressive wellbore failure is the result of hoop stress concentration around the wellbore that arises during time of drilling of well into an already stressed rock mass. In the case of wellbore instability, the radial stress is one of principal stress while the other two principal stresses are normal to the radial stress, and hence are tangential to the vertical wellbore wall. Wellbore instability occurs when the radial stress by mud is the minimum or when the tangential principle stresses are both greater than radial stress.
Shear Failure Gradient (SFG) was then generated with help of derived rock mechanical parameters with the following Mohr-Coulomb criterion

$$\sigma_{max} = \sigma_{min}\frac{1+\sin\phi}{1-\sin\phi} + \frac{2CS\cos\phi}{1-\sin\phi}$$

where σmax and σmin are the maximum and minimum principle effective stresses and the friction angle (ϕ) and the cohesive strength (C_S), are parameters that describe how the rock strength varies with its stress conditions.

Fig.4 a) Principle stresses gradient b) Shear Failure Gradient, Four arm caliper analysis and borehole enlargement analysis.

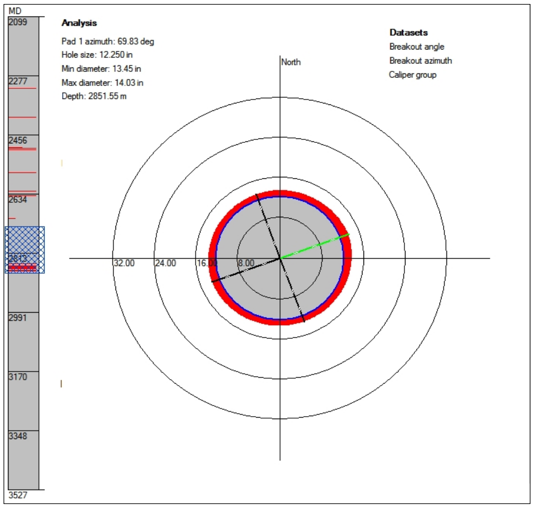
Analysis
Pad 1 azimuth: 69.83 deg
Hole size: 12.250 in
Min diameter: 13.45 in
Max diameter: 14.03 in
Depth: 2851.55 m

Fig. 5: Wellbore Breakout view indicates Washout in Panvel formation

Shear Failure gradient (SFG), also called Collapse pressure gradient is plotted with mud weight maintained in the well during drilling along with four arm caliper data for analysis (Fig 4b). This revealed that whenever the mud weight maintained in the well was less as compared to horizontal stresses, washout has happened in the wellbore (Fig.5) which is validated as complications like held ups, stuck ups, tight pull, severe caving generation at shale shaker is observed during drilling. The wells in this region is having the problems of wellbore instability and thus more studies are required and well data is to be further analyzed and interpreted to prevent wellbore instability issues.
With these analytical results, Wellbore Orientation Analysis to show how the minimum mud weight of 16.3 ppg will be required in Panna formation to prevent shear failure or to cause fracture initiation in intact wellbore. With wellbore inclination and azimuth, mud weight has to be increased to maintain wellbore stability (Fig. 6a).

Fig. 6 a) Wellbore Orientation Analysis b) Safe Operating Mud Weight sensitivity Analysis

Safe Operating Mud Weight sensitivity Analysis (Fig. 6b) was done which shows the safe operating effective downhole mud weight pressures defined by pore pressure, the shear failure gradient (SFG) and to prevent loss circulation (defined by minimum horizontal stress, Shmin, or fracture gradient, FG).

Conclusions:

This study provides the first assessment of the present day state of stress in this field along with overpressure and wellbore stability analysis model. In conclusion, BH-DCS area shows a strong correlation between rate of sedimentation and overpressure development by compaction disequilibrium and later by unloading mechanism. Shear failure analysis based on Mohr's Coulomb method shows the maximum shear failure gradient is in range of 13.6 ppg above the overpressure zone which goes upto16ppg in Panna formation. Accordingly, Mud weight should be maintained to avoid shear failure/collapse failure while drilling. In-situ stress magnitude estimation shows that the region is in the Normal fault stress regime $(Sv > Shmax > Shmin)$ as per Anderson's classification. New relationships will need to be developed based on integrating an understanding of field and basin history, rock mechanical studies of core samples for more robust geomechanical analysis.

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World Stress Map Database Details -2016.