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Geomechanics Study Involving Pore Pressure Estimation and Sanding Analysis to Aid Drilling Optimization and Well Testing

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Abstract

Better understanding of the pore pressure is crucial to avoid well kicks and associated wellbore instability events with reduction in additional costs. Abnormal formation pressure is a result of processes like undercompaction, tectonic compression, higher geothermal gradients, and chemical changes of minerals, hydrocarbon generation, and migration of hydrocarbon gases along faults and BCGS system. This paper presents the study of optimization of the drilling performance on a well A in high pressure environment by post-drill analysis of offset well B and pre-drill analysis for remaining open hole section of well A. There were severe drilling events in form of cavings, kicks, higher gas percentage and overguaged hole condition in the offset well from 4000m onwards. Similar events were observed while drilling planned well till 4500m. In order to avoid drilling problems in target zones~ 4600-4800m, pore pressure study was conducted using LWD and Wireline measurements. Pre-drill pore pressure model was built for remaining section to identify safe mud weight window to be in range of 13.8 -14.4 ppg. Current mud weight of 12.6 ppg was increased immediately to avoid further kicks and successful well TD with no further NPT. Testing equipments with corresponding pressure ratings (>11000psi) were mobilized for safety and avoid failures. With the objective of open hole testing, sand production was concern which could have resulted in extra well cost and reduced well productivity. A quick look sanding analysis was conducted to identify critical drawdown limits across target zones at different depletion percentage. Overall geomechanical analysis helped the operator to reduce costs while drilling in comparison to offset well and achieve the goal of successful well testing.

Introduction

For safe and cost effective drilling optimization, mud weight and casing design are two critical factors. Knowledge of the expected pore pressure and fracture gradient is the basis to make the best of modern drilling techniques, i.e., efficiently drilling wells with correct mud weights and proper casing programs. This also prevents a breakdown of exposed formations and contains the high-pressure fluids in deeper formations, thereby reducing blowout hazards. Much of the entire cost in the search for and development of hydrocarbon reserves is for drilling fluid and casing programs. An additional, quite expensive item is the properly selected completion method, which must be effective, safe and allow for killing of the well. Here, too, reliable pore pressure and fracture gradient data are a prerequisite.

Normal pressure is pore fluid pressure that equals the hydrostatic pressure of a column of formation water extending to the surface and overpressure is pore fluid pressure greater than normal pressure. For limestone and sandstone, pore pressure is equivalent to the fluid pressure in the pores in the formation. Shales are very fine-grained, clastic rocks that lose porosity through compaction. Sedimentary basins typically contain about 70% shale. Because shales lose porosity via compaction, they have been used to forecast and quantify pore pressure. Though, only one of the many controls on shale porosity is effective stress. The key to proper shale pore pressure interpretation is by isolation of the effective stress control on porosity. Pore pressure in sands is in long-term equilibrium with the shale. Pore pressure is estimated in shales using different methods and subsequently calibrated with measured formation pressure in permeable units. Pore pressure has overburden stress as it upper limit. The phenomenon of overpressure in sedimentary basins has been attributed to a wide range of mechanisms that can be related to the following processes: increase in stress applied to a compressible rock, fluid expansion within a restricted pore space, fluid movement, buoyancy, digenesis, and osmosis (Osborne and Swarbrick, 1997). The ability for each of these mechanisms to generate pressures above hydrostatic pressure depends on the rock and fluid properties of the sedimentary rocks and their rate of change under the normal range of basin conditions. The magnitude of overpressure varies from basin to basin. Present-day pressure distribution can be interpreted from direct measurement in permeable units (e.g., MDT, XPT, DST pressures). The pressures in low-permeability lithology cannot be measured directly but can be inferred from indirect measurements. In the absence of offset well data seismic, velocities are the only available pre-drill tools to estimate the formation pressures. Pore pressure prediction in geologically challenging areas such as anticlines and fold thrust faults combined with possibility of abnormal pressures elevates this prediction to a high level of uncertainty (Swarbrick *et al*., 2010)

Overpressure detection is based on the theory that pore pressure affects compaction-dependent geophysical properties such as density, resistivity, and sonic velocity. Shale is the preferred lithology for pore pressure interpretation because they are more responsive to overpressure. Most of the techniques are linked to porosity and assume that the porosity is controlled by the maximum effective stress the sediment has experienced. However, process like fluid expansion is accounted using velocity vs. effective stress method as proposed by Bowers, 1995.
Porosity and density are *bulk properties*, while sonic velocity and resistivity are *transport properties (Bowers et al. 2002).* Bulk properties only depend on net pore volume, while transport properties are sensitive to pore sizes, shapes, and interconnectivity of pores. A combination of relatively large, high aspect ratio *storage pores are* linked together by a network of lower aspect ratio *connecting pores*, where transport properties are controlled by the connecting pores. Storage pores can undergo primarily inelastic volume losses with the more flexible connecting pores capable of elastic rebound. Hence, during unloading or reduction in effective stress cause connecting pores to increase in width without significant change in storage pore sizes. As connecting pores widen, flow path sizes are increased for conducting electrical current, and the number of intergranular contacts are reduced for transmitting sound. The final effect is on transport properties than bulk properties which suggest that an indicator of in-situ rebound (unloading) is a depth interval in which sonic velocity and resistivity data appear anomalously low in comparison to bulk density measurements.

Overpressure mechanisms

Normally pressured formations are able to maintain hydraulic communication with the surface during burial. Consequently, their pore fluid can easily be squeezed out to accommodate compaction, and their pore pressure follows the hydrostatic pressure curve for formation water. Effective stresses in normally pressured environments continually increase with depth. On velocity vs. effective vertical stress plot, normal pressure points lie on the virgin curve as seen *Figure 1*.The causes of overpressure can be divided into four general categories: undercompaction (compaction disequilibrium), fluid expansion (aqua thermal expansion; hydrocarbon generation and gas cracking; mineral transformations), lateral transfer, and tectonic loading. The conditions that produce normal pressure and the four types of overpressure are described below.

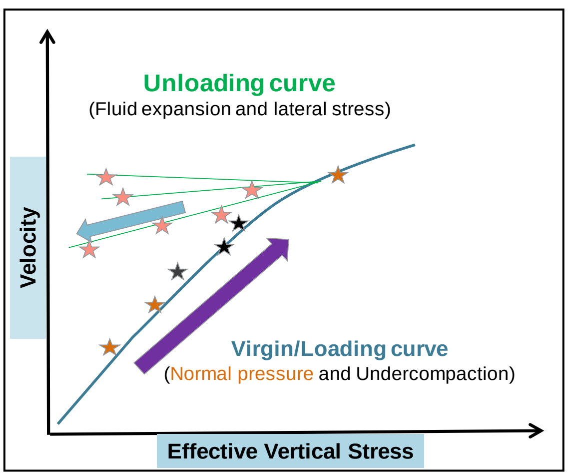

Figure 1. Effective stress vs velocity plot showing virgin and unloading curve

(a) *Undercompaction*

With increase in overburden pressure during loading, there can be incomplete dewatering with part of the weight of the load being added to the pore-fluid pressure. This mechanism is commonly termed “disequilibrium compaction,” and the physical manifestation in the bulk rock is excess pore pressure and a higher porosity relative to the normally pressured and fully compacted rock at the same depth. The onset of overpressure is controlled by the loading rate and the porosity and permeability evolution of the sediment during burial. For an impermeable seal and an incompressible pore fluid, pore pressure would increase at the same rate as the overburden stress once sealing occurred. However, undercompaction will not drive pore pressure toward the

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overburden stress curve. This also means that undercompaction cannot cause effective stress reductions as seen in *Figure 1*.

(b) Fluid expansion

Overpressure can be generated by fluid expansion in low permeability rocks, where pore fluid volume increases with lesser change in porosity and at a rate that do not permit effective dissipation of fluid. Different causes of fluid expansion can be clay dehydration, smectite-illite transformation, maturation of source rocks to oil and gas, gas cracking, aquathermal pressuring and mineral precipitation/cementation reactions. Increasing temperature during burial causes both rocks and fluids to expand. The volume expansion of rock is approximately one order of magnitude smaller for rock than for water and therefore can be ignored. The fluid volume change due to aquathermal expansion is 1.65% for an increase in temperature of 40 degC (Osborne and Swarbrick, 1998). Volume changes occur when kerogen transforms to oil and gas and when oil cracks to gas. The volume change depends on the kerogen source and the density and volume of the petroleum products generated during maturation. This leads to reduction of effective stress with less change in sonic velocity (*Figure 1*).

(d) Lateral transfer

It can occur along dipping sand enclosed in shale. The sand transmits pore fluid and pore pressure from deeper shale up dip (Yardley and Swarbrick, 2000). Lateral transfer can generate crustal pore pressures high enough to fracture overlying shale seals, especially when there are long gas column. Sometimes this can be caused by charging along faults.

(e) Tectonic loading

Trapped pore fluid squeezed by tectonically driven lateral stresses induces overpressure in the same way that undercompaction does. However, unlike undercompaction, tectonic loading is capable of generating high overpressure (Yasser and Addis, 2002). This also means that tectonic loading can cause vertical effective stress to decrease, but in tectonic environments, compaction is no longer controlled by vertical effective stress alone. Areas of thrusting and folding typically contain overpressured rocks, and the magnitude of overpressure in these regions relates to both the amount of stress and strain in the rocks and their physical properties. North-East of

India is tectonically active and folded belt is even under E-W stress field even to present day. It is one of main reasons for overpressure region in Middle Bhubhan formation. Crossplot between Velocity v/s Effective stress in Figure 1 and Velocity v/s density in Figure 2 validates the existence of unloading behavior of Middle Bhuban formation. Some of the porosity loss or velocity gain is because of inelastic behavior of rock. As a result sonic velocity will not decrease with the decrease in effective stress and it will fall on unloading curve.

Cauvery Basin: Overpressure detection using well logs

An appropriate knowledge of formation pressure is required for safe well design and avoids drilling risks. Usually pore pressure is estimated using compaction dependent petrophysical measurements like sonic compressional slowness (velocity), density, resistivity, porosity etc. Normal pressure sonic trend is demarcated with decreasing sonic compressional slowness in shale with depth due to compaction in same depositional unit. In over-pressurized formations, sonic compressional slowness in shale will show a deviation from their normal compaction trend and remain same or increase with depth (Figure 3). All these estimated pore pressure values need to be calibrated using actual measured formation values using *MDT*, XPT** and well test in reservoir zones. Abnormal pressures are very much evident in this area as suggested by past drilling history. Two main reasons for their occurrence i.e. compaction disequilibrium, tectonic activity and uplift appear to be the major causes of over pressure generation aided by clay transformation and aqua thermal phenomena in the sediments in north eastern India. (Bhagwan *et al*, 1998).
The Cauvery basin has been formed by block faulting of the basement ranging in age from Late Jurassic to Miocene (Sastri et al., 1981). The basin covers an area of about 25,000 sq km. over onland and offshore extending upto 200 m isobath. The Cauvery basin is under active exploration by Oil and Natural Gas Corporation Limited (ONGC), India, for more than past three decades. Extensive geological and geophysical

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surveys as well as a large number of wells drilled in the basin have established the presence of 4 – 7 km thick sedimentary pile of Late Jurassic to Recent age lying below the alluvium cover (Pabhakar et al., 1995). As on date about 130 prospects are proved, of which, 30 structures are hydrocarbon bearing in the sediments of Early Cretaceous-Oligocene age (Naidu and Giridhar, 1999).

Case Study

Well-A is the offset well in Cauvery basin, onshore, India. Operator faced sever drilling problems in term of cavings in shale and kicks in sandstone region. Well -B was next well being drilled near to it with expected lithology to be of same properties as present in Well -A. Client drilled Well-B till A8m and started facing similar problem of gas kick. Geomechanical model for Well-A and Well-B were constructed using available wireline and LWD dataset (Figure 2 & 3). Based on the study, estimated pore pressure around A9m was a13.8ppg against mud weight of 12.6ppg being used while drilling. Hence, it was advised to increase mud weight accordingly. Later on, section TD was done with mud weight of 14.30 ppg. Earlier expected pressure to be less than 10,000 psi at A13m for well testing. Based on pore pressure model, it was identified that pressure exceeds 11000 psi. Hence, plan was changed and new equipments with higher rating was used for testing.

A Mechanical earth model has been constructed to calculate stress profile, rock elastic and strength properties and history match with field observations. Rock unconfined compressive strength varies between 3000-6000psi in target sand. Based on these properties, analysis has been performed for open hole completion as seen Figure 4. Bottom hole flowing pressure across sand with low rock strength (~3000psi) is 6200psi as compared to initial reservoir pressure of 11000psi. It increases to 1100 psi in formation with UCS~4500psi.

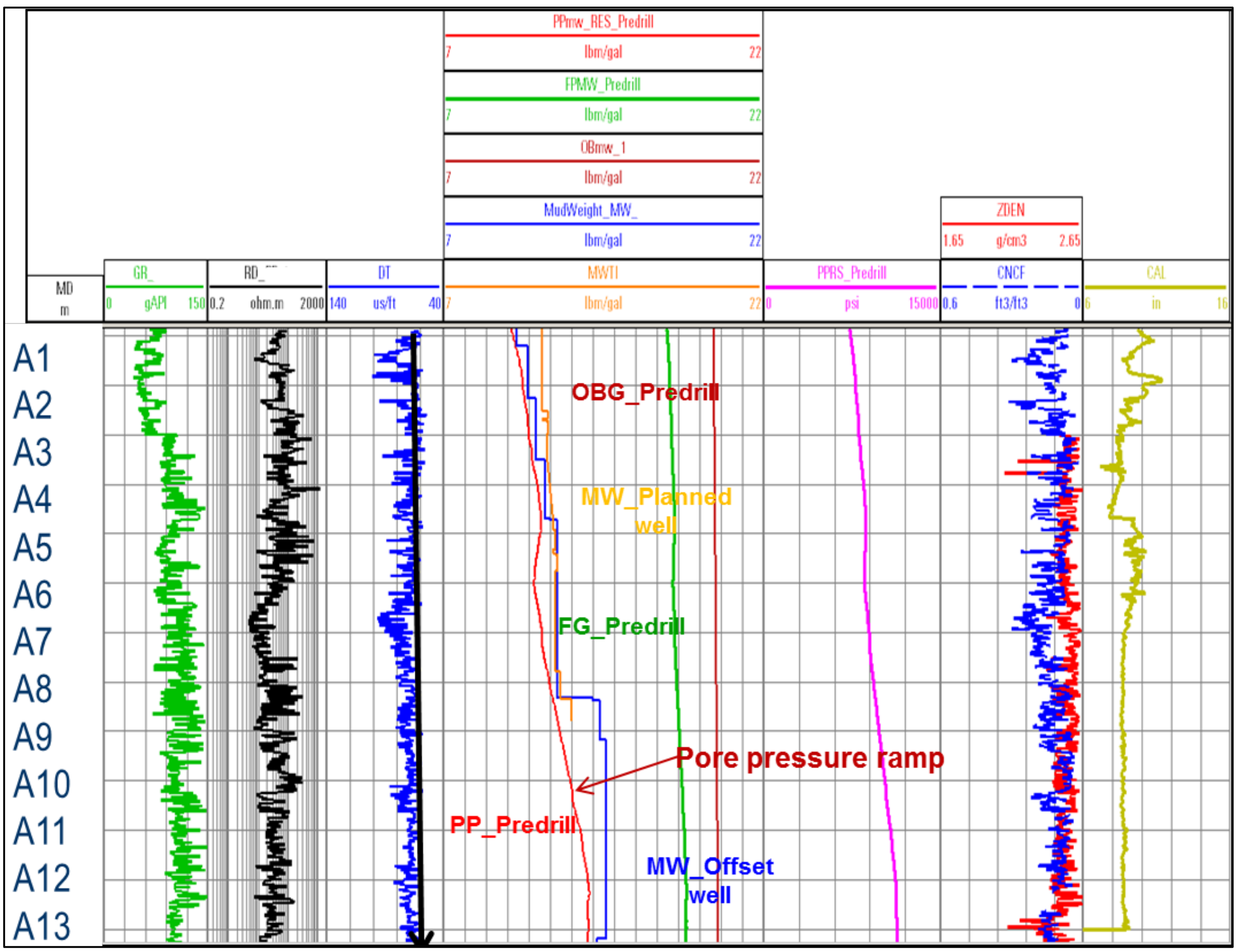

Figure 2. Pore Pressure Model for offset well-B

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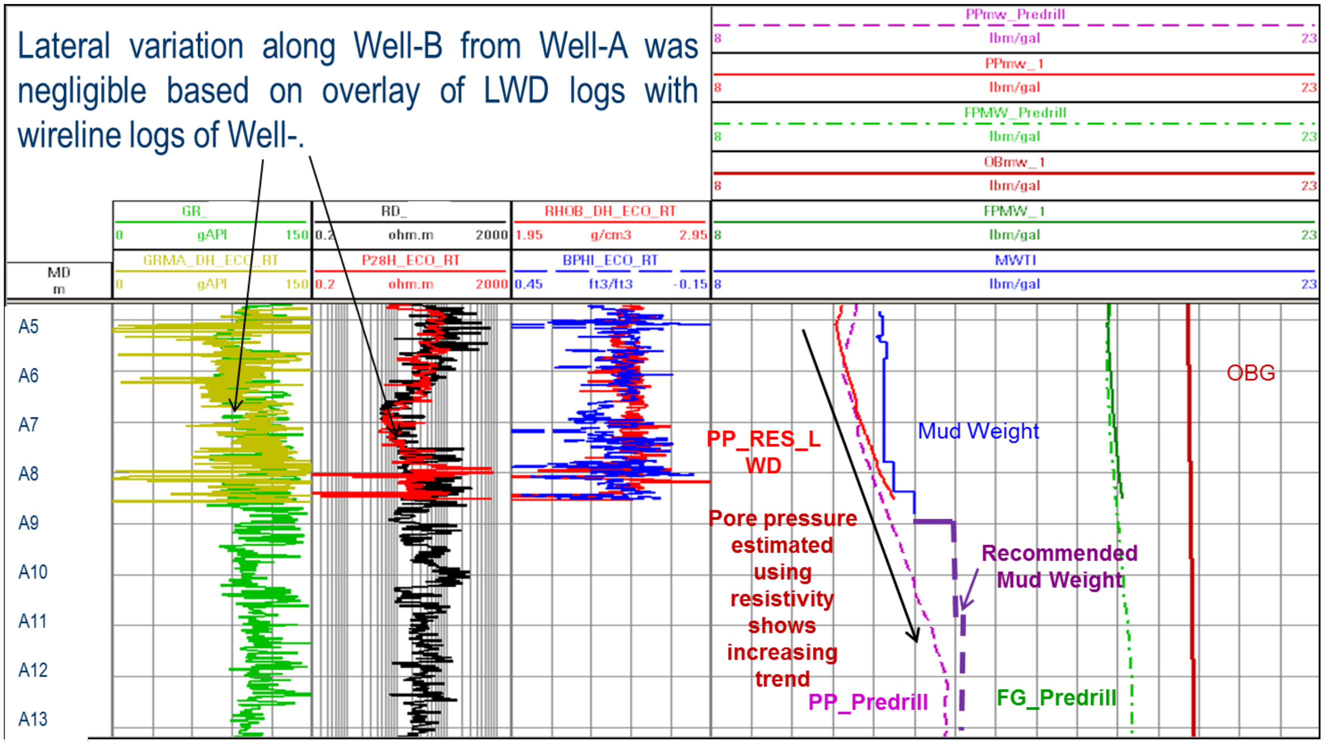

Figure 3. Pore pressure model built at ~A9m using LWD logs and offset well data for well-B

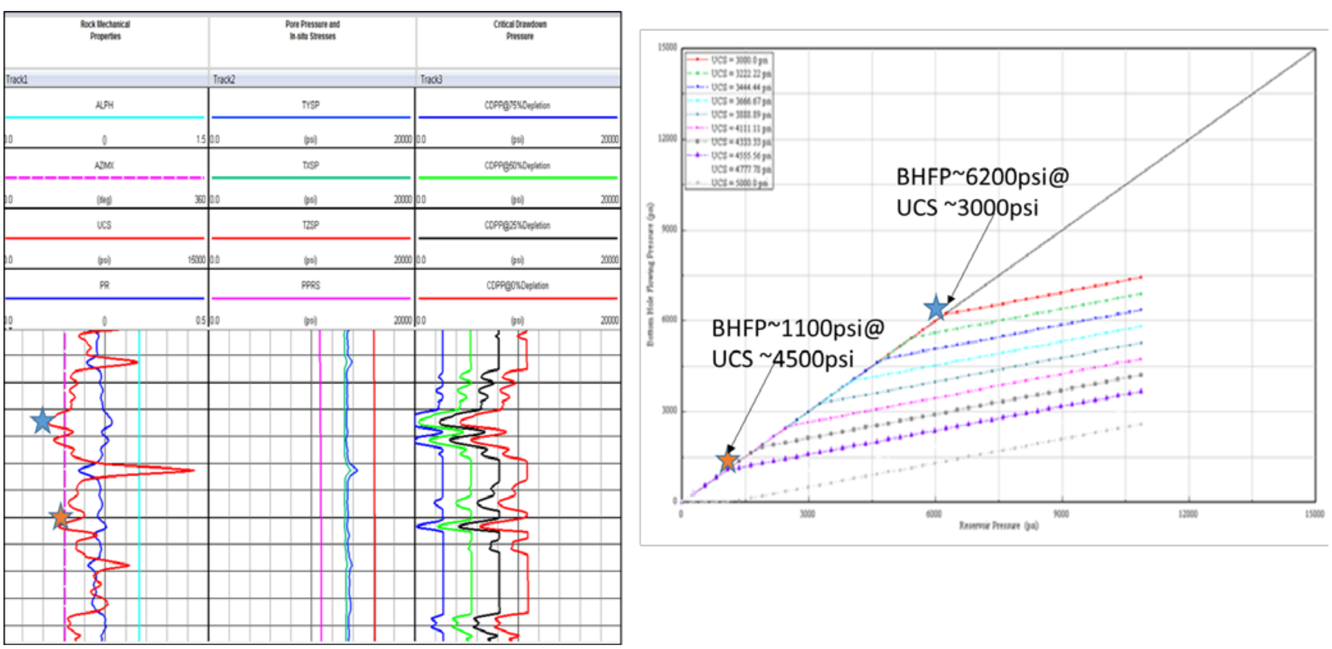

Figure 4. Geomechanical model for sand production analysis in open hole completion

Summary and Conclusions

High overpressure affects shale in a fundamentally different way than undercompaction, because it can cause elastic rebound. Therefore, rebound is an indicator of high overpressure. The geophysical signature of rebound is a depth interval in which shale sonic velocity and resistivity data undergo larger reversals than bulk density measurements. Accurate pore pressure prediction is one of the key factors for safe drilling of wells and casing design. Based on the study done It was recommended to increase mud weight to 13.8ppg immediately to avoid

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kick around A9m MD. Also recommendation was made for mud weight (14.25 – 14.50ppg) to be used for further drilling based on pore pressure model for section TD. Pore pressure was expected to be more than 11,000 psi at A13m which helped to improve well testing equipments. Borehole was successfully drilled till TD and casing were lowered down without any NPT by using recommended mud weight. Formation evaluation using LWD real-time logs helped to understand lithology and correlate with offset wells. Real-time LWD resistivity log has been used successfully to estimate pore pressure. Critical drawdown pressure and bottom hole flowing pressure to avoid sand production showed different rock type in thick target sand for open hole completion.

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