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Regional In-Situ Stress Map and Geomechanical Models: An Exploration Tool for Deep Tight Gas Reservoirs, A Case Study from Kuwait.

Hemant Singh, Satya Perumalla, Reem Al Naeimi, Abdulaziz Al-Fares, Riyasat Hussain, Rinaldi Mulyono, Nada Al-Ammar, Ahmad Al-kandary, Umesh Prasad, Colleen Barton

Baker Hughes, P.O. Box 567, Techno Park, Jebel Ali, Dubai, U.A.E.

Presenting Author, E-mail: *Hemant.singh@bakerhughes.com*

Abstract

With exploration and development activities moving to more challenging domains, geomechanical studies are becoming increasingly important to address drilling and production challenges in both conventional and tight gas reservoirs. Faults and natural fractures in tight reservoirs are of vital importance and any data that can relate them to sweet spots will be information of high value. In current study we observed that in case of deep gas reservoirs of Middle East, the stress orientation anomalies could explain various types of geomechanical anomalies in the reservoir formations and can provide decision support for exploration and development.

The current study reveals the value of integration of regional in-situ stress maps and geomechanical models to natural fractures. A novel and first of its kind approach was developed for quantification of uncertainties related to stress orientation. Defining reliable stress orientation is absolutely necessary in challenging tight gas/shale gas reservoirs for well positioning and fracturing purposes. However, there are inherent uncertainties in determining stress orientation from wellbore failures (breakouts and induced fractures) and they can be quantified with proper statistical analysis to enhance confidence in predictions.

The results of this study indicate that the maximum principal stress azimuth in Cretaceous formations is consistent with the regional Zagros tectonics even across major fault systems. However the sub-salt Jurassic formations exhibit high variability in stress orientation across faults as well as in the vicinity of fracture corridors. Strong detachment in stress state observed between Cretaceous and Jurassic formations which are separated by salt body. Local variation in stress orientation near geological features like faults and fractures in Jurassic sequences suggest that they might be at the verge of frictional equilibrium. When compared to fractures in cretaceous reservoirs, higher horizontal stress anisotropy and elevated pore pressure further make natural fractures in Jurassic reservoir more favourable to contribute in production. Additionally it was observed that differential depletion in various fault blocks of a reservoir can lead to changes in horizontal stress orientation.

Introduction

Mapping of sub-surface structures and *in situ* reservoir properties have been in practice by explorationists for more than a century. The structural maps and profiles provide understanding of geological history and conditions that are essential for play evaluation. However, limited data are available to map the present day *in situ* stresses in these fields, as typical conventional exploration techniques assume theoretical stress estimations based on a regional understanding of tectonic history related to the evolution of a particular field structure. Occasionally, seismic attributes have been used to complement these geological estimates. Consequently, there has been little appreciation of the influence of *in situ* stresses on exploration and development strategies. More recently, it has been realized that geomechanics plays a key role in various ways from exploration through field development including wellbore stability analysis (for improved drilling experience) to reservoir geomechanical analysis (for optimization of production).

In general, unexplored or under-explored plays exist in the vicinity of well-developed fields (near-field exploration); these fields often share a similar structural geometry and tectonic history. Due to reservoir quality issues, those fields and formations were left unexplored in the past. As the developed reservoirs have significant volumes of well-based data, additional value can be obtained by combining these data sets with seismic and regional geological data to enhance the exploration strategy for new plays. In addition, the current exploration focus aims to evaluate the production feasibility of shale/tight gas plays for which it is essential to understand the mechanical response of the reservoir during drilling, stimulation and production. These shale and tight unconventional reservoirs are low in porosity/permeability, contain natural fractures and their flow properties can be highly sensitive to *in situ* stresses.

The benefits of understanding the regional stress regime at different horizons of sub-surface formations across a number of oil and gas fields in Kuwait prompted KOC to build *in situ* stress maps using data from over 400 wells from 23 fields. The primary focus of building these stress maps is to establish reliable correlations between stress orientation and geological features (especially faults), so that any anomalous stress behavior can be used as an input for exploration or field development planning. The stress anomaly observations are not only expected at regional scale, but also within a well where the presence of natural fractures could locally perturb the stress regime.

Analysis and Results

Analyzing data from nearly 400 wells from 23 fields and extracting the stress orientation results in a comparable quality is a challenge due to diversity in data type. World Stress Map quality control criteria were helpful to classify the data and results. However, few additional considerations were used to add value to the QC procedures. This level of stringent quality control was necessary to distinguish the stress orientation anomalies from data artefacts.

Extracted stress orientation results have revealed that Cretaceous and Jurassic formations are separated by thick Salt called Gotnia Formation. There is a clear de-coupling of the present day stress field above and below the Gotnia salt. This can be explained by visco-elasto-plastic character of the salt where the stress field becomes near isotropic within the salt (SHmax ≈ Sv ≈ Shmin) and isolates the horizontal stress magnitudes above and below the salt. In this way, Cretaceous and Jurassic formations appear to be experiencing different present day in situ stress fields (different stress magnitudes, pore pressures or both).

In Cretaceous reservoirs, the stress orientation is mostly N45°E with some local variation within the range: N35°E-N65°E across most of Kuwait oil fields. This pattern is consistent with regional Zagros tectonic trend. The generalized stress orientation in various fields of Kuwait is shown in Figure 1. In contrast to the stress regime in Cretaceous reservoirs, Jurassic reservoirs exhibit variable stress orientations. The stress orientations in various Kuwait fields at Jurassic formations are shown in Figure 2. While there is a clear pattern of North East-South West stress orientation (similar to most of Cretaceous formations), there are also a significant number of wells that have anomalous stress orientation patterns: East-West, EastNortheast-WestSouthwest and North-South. Overall, the stress orientations in Jurassic formations ranged from N-S to E-W.

Along with the observations of stress orientation distribution, geomechanical modeling was performed to verify the observations from stress orientation maps. Based on the geomechanical modeling, a mild strike-slip stress regime or transitional to normal faulting regime (SHmax ≥ Sv> Shmin) is determined at the Cretaceous formations, whereas a strong strike-slip regime (SHmax >> Sv> Shmin) is determined for Jurassic formations below the Gotnia salt (Figure 3). Such stress anisotropy supports the phenomenon of stress de-coupling between Cretaceous and Jurassic formations.

In addition to the stress orientation anomalies observed in proximity to faults at the field/regional scale especially in Jurassic reservoirs, localized stress perturbations (in the form of borehole breakout rotation) are observed within a few Jurassic reservoir wells at the depth of the well intersection with natural fractures. That said, there is expected to have a significant population of natural fractures that are critically stressed in Jurassic reservoirs of some fields. These fractures can play critical role in terms of contributing to enhanced production from deep tight gas reservoirs (Figure 4).

Implications

Considering the challenges for exploring new prospects, especially with regard to Jurassic tight shale plays, the stress map ties the stress orientation anomalies to field scale geological structures as well as to natural fracture patterns within a well. By integrating the stress map with geological structures, natural fractures and seismic data, it may be possible to identify possible seismic attributes that can link stress, geology, and acoustic impedance.

From exploration through development, it is important to consider the mechanical response of natural fractures as these fractures can be sweet spots and are likely to have direct impact on production performance of fractured reservoirs. This phenomenon is also relevant in the case of tight shale reservoirs where natural fractures are present. This is because *in situ* stresses, pore-pressure and stress sensitivity of natural fractures play vital roles in determining the flow efficiency of such a reservoir.

From field development point of view, Uncertainty in stress orientation can influence the ultimate well productivity due to difficulties with fracture initiation and growth. The stress map can provide invaluable insights about variability in stress orientation w.r.t the geological structure in each field, which can be included in well design and field development plans. Production related depletion of reservoirs (particularly reservoirs with high initial in situ stresses and pore pressures) can change the stress field and can have direct influence on the stability of faults, risk of casing failure, or even loss of a well. With an understanding of the distribution of stress magnitudes with respect to the geological structures, high quality field specific 3D geomechanical models can be developed and used to optimize the reservoir drainage and future injection plans in the context of fault stability.

Conclusions and Recommendations

With the overall geomechanical modelling and stress determination, It was found that stress field in cretaceous formations are significantly different from that in Jurassic formations. Gotnia Salt appears to be decoupling the stress regimes between Cretaceous and Jurassic formations in all fields analyzed. Maximum horizontal stress orientation has a narrow range (N35°E-N60°E) and is almost unaffected across faults within Cretaceous formations. The SHmax orientations from sub-salt Jurassic formations have a wide distribution range (N0°E-N90°E) in most of the Kuwait fields based on the proximity of the well to faults and fracture corridors. The Jurassic formations generally have much higher stress anisotropy and stress magnitudes compared to Cretaceous formations. Through our analysis of the stress sensitivity of natural fractures, results indicate that there is a significant population of natural fractures from the Najmah-Sargelu formation that are likely to be critically stressed, and hydraulically conductive and thereby contribute to production.

Although every possible effort was made to put stringent quality control over existing data in order to constrain existing stress field, there are some inherent uncertainties due to lack of well and field data. The lack of sufficient Leak-Off Test/Extended Leak-Off Test/MiniFrac data leads to uncertainty with estimation of minimum horizontal stress (S_{hmin}) in some fields. Direct pore pressure measurements were available within specific formations in limited number of wells. Considering variation of pore pressure in different fault blocks, further acquisition of formation pressure points is recommended.

Acquiring good quality image logs are of vital importance for constraining maximum horizontal stress orientation and magnitude. Poor quality image logs often do not reveal information about stress induced borehole breakouts and can lead to inconclusive breakout interpretation.

Production or temperature logging provides an indication of fluid flow along natural fractures and faults intersected along the wellbore, and as such can be used to verify interpreted critically stressed fractures. This data would improve the understanding of fluid flow behavior along natural fractures in a particular formation or field. Seismic attribute analysis could also be used to identify permeable fractures and may contribute to improved workflows for sweet spot exploration.

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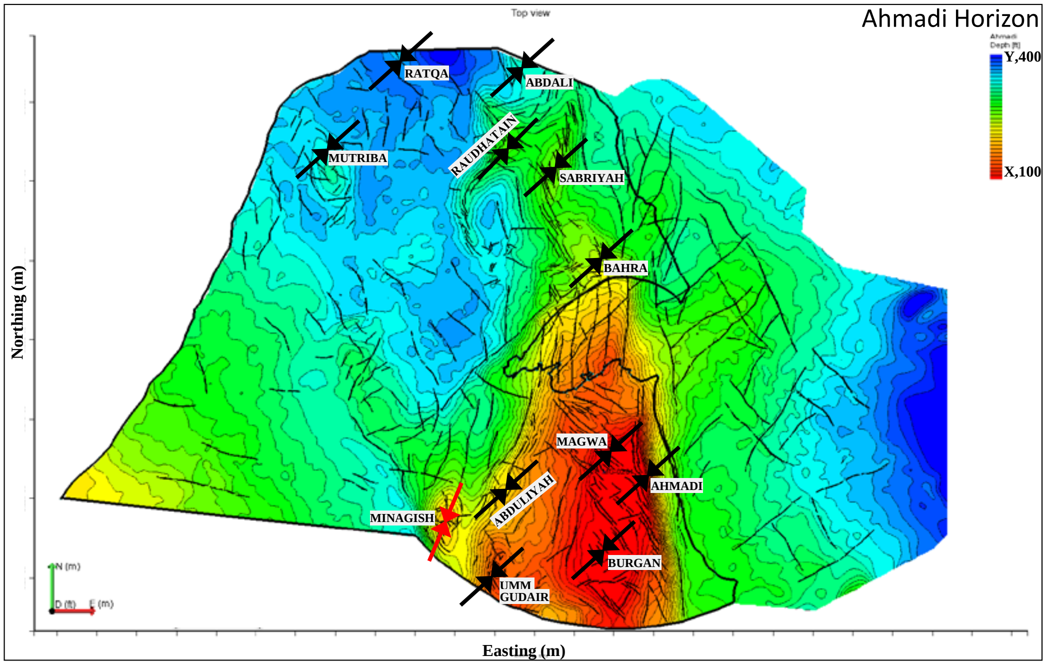

Figure 1: Generalized Stress Map for various Kuwait Fields in Cretaceous formations overlaid on the Ahmadi formation. The maximum horizontal stress orientation appears to be consistently oriented in the North East-South West direction with the exception of the anomalous stress orientation pattern of the Minagish field. (Arrows represent direction of SHmax).

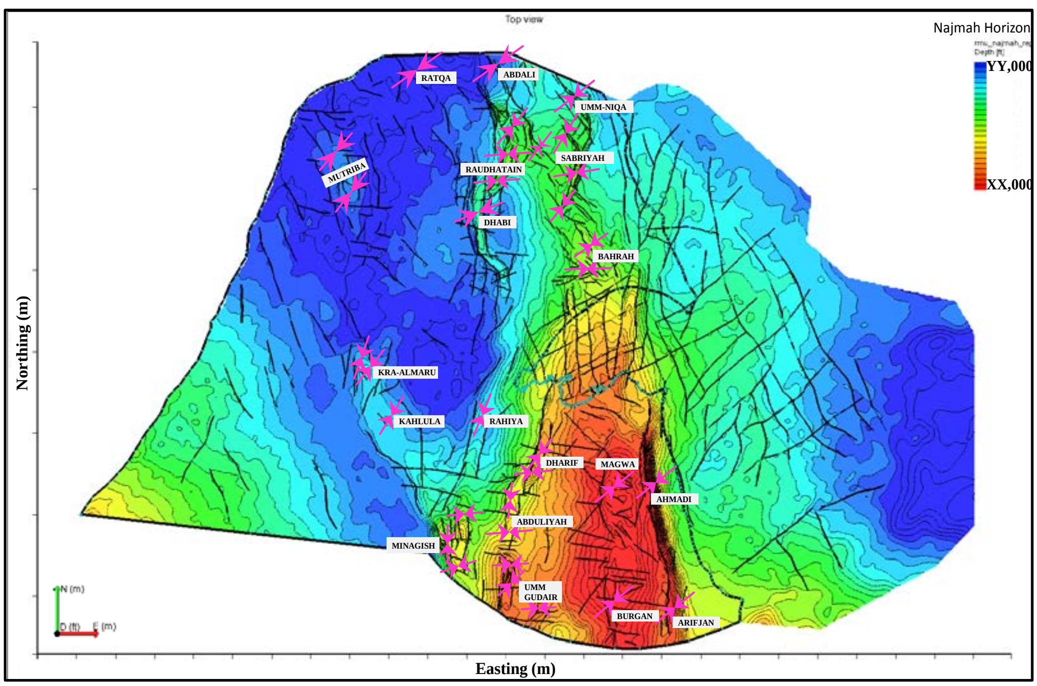

Figure 2: Generalized Stress Map of various Kuwait fields at the Najmah reservoir depth showing the stress orientation in Jurassic sequences. No consistent stress orientation at Jurassic formations is observed over the structure. Stress orientation is highly influenced by faults. (Arrows represent direction of SHmax).

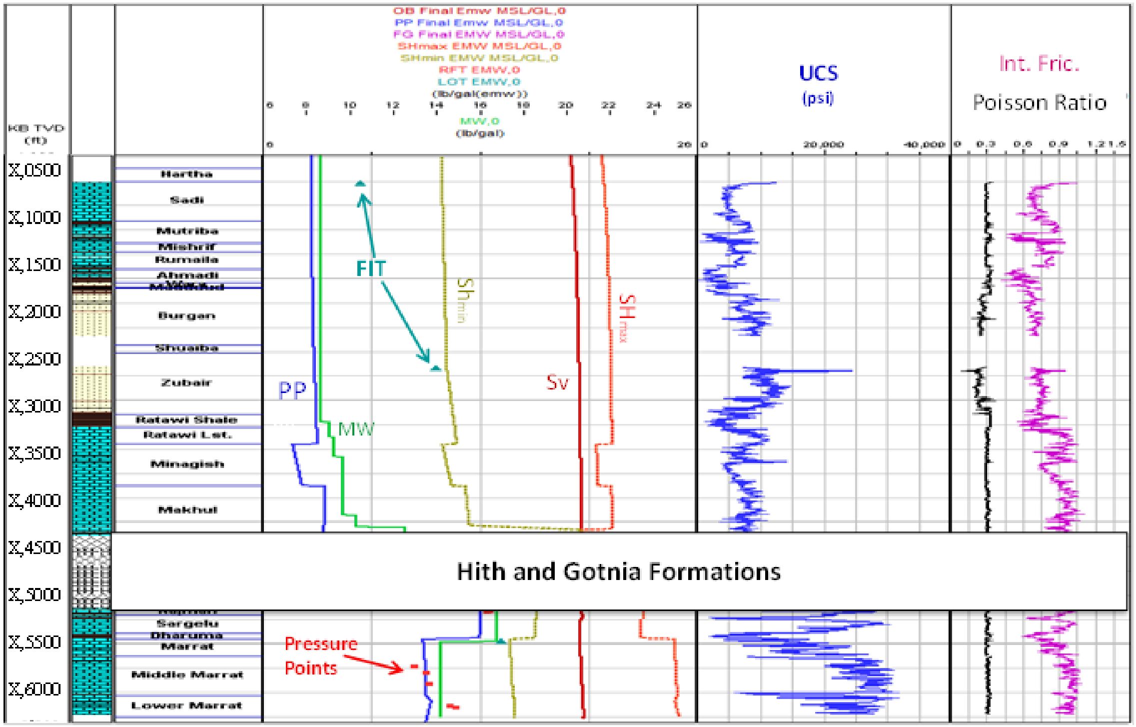

Figure 3: A typical geomechanical model for Cretaceous and Jurassic formations (from Minagish field). Stress de-coupling between Cretaceous and Jurassic formations is apparent. All stresses and pore-pressure are in pounds per gallon whereas UCS is in psi.

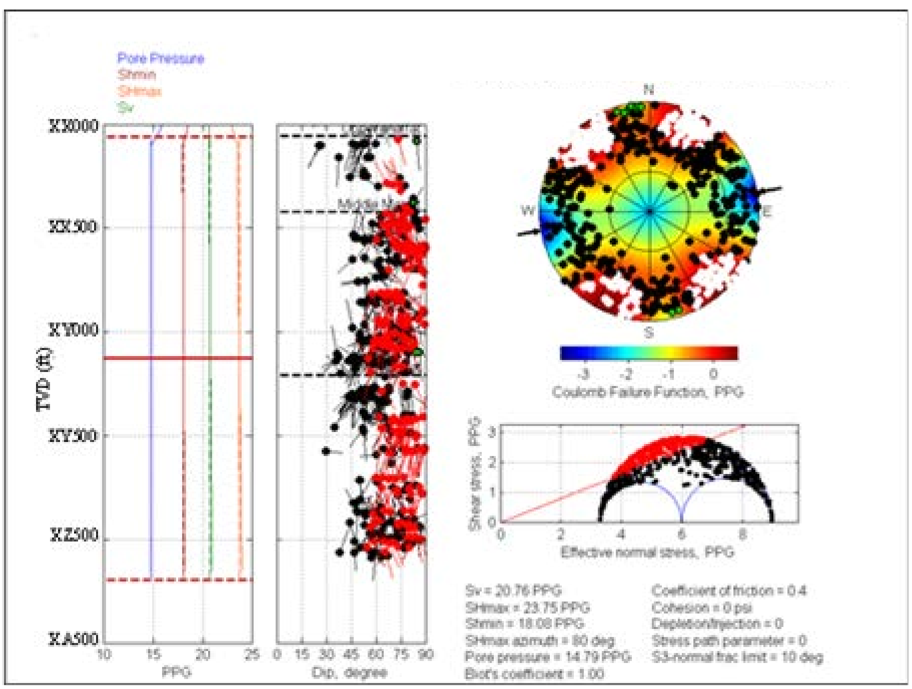

Figure 4: Critically Stressed Fracture analysis reveals that at original reservoir pressure, a significant percentage of fractures are critically stressed. Red colored dip/dip directions in the tadpole profile are critically stressed fractures for the modeled coefficient of sliding friction. White poles to fracture planes in the stereonet and red colored symbols of the Mohr diagram are critically stressed fractures.