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WELLBORE STABILITY STUDY: LESSONS AND LEARNINGS FROM A TECTONICALLY ACTIVE FIELD

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Abstract

Shales account for 75% of the formations drilled worldwide, while drilling troubles associated with shale represents 90% of wellbore stability problems reported. In this paper, a traditional wellbore stability study has been implemented at an onshore gas field in a tectonically active region. Despite following the program however, the drilling experienced significant challenges, particularly in the shales where the sonic logs have shown high velocity and therefore high rock strength.

To investigate the root cause, several mechanisms for the wellbore instabilities have been investigated, such as overpressure, weak bedding plane, chemical activity, insufficient mud weight, and fractured shales. The cavings collected and preserved from the wells, as big as several inches in size, have undergone XRD, SEM, thin-section, and strength tests. While most mechanisms have been ruled out, focus has turned to the fractured shales. With the evidence from the lab and collaborated with drilling experience in the field, it has found the troublesome shale formation has been extensively fractured during past and present tectonic movements. The presence of the fissure network becomes so significant that it dominates rock mechanical behavior and wellbore stability. More interestingly, it seems the sonic logs have overlooked the existence of fissures and still shown the response from a typical strong rock. Based on those findings, modified drilling strategies have been suggested and implemented in the region.

The field case presents a new challenge to the log-based wellbore stability interpretation routinely implemented in current drilling society. Being open-minded, closely monitoring and testing cavings, and updating the model with drilling experience may be as important as the model development itself.

Introduction

Shale is often blamed for wellbore stability problems during drilling operations. It is estimated 75% of the drilled formations are shales and 90% of wellbore stability problems occurred in shales¹. The significant amount of shales fallen into the hole could cause excessive cuttings or cavings, difficult circulation and hole cleaning, stuck pipe, tight hole, hole sloughing, and even hole collapse. It is not unusual to set an extra casing, redesign well trajectory, or abandon a well, because of a troubled shale formation.

There are several reasons why shales are more problematic than other lithologic rocks, e.g. ref^{2,3}. Generally speaking, it has to do with the unique nature of various shales.

- If shale is brittle, fractures may develop due to either tectonic movement or during drilling operations. Existence of fractures or fissures in the shale could significantly weaken its integrity. Coupled with higher in-situ stress anisotropy, this type of wellbore stability problems is well demonstrated in tectonic active area such as Cusiana field in Columbia^{4,6} and Rocky Mountains in Canada.
- If shale is ductile and plastic, excessive overburden may drive the shale into borehole like toothpaste, esp. when rock is buried deep. This may explain some of the borehole enlargement with no preferential breakout direction in deepwater GOM.
- If shale has high swelling clay content such as smectite and is chemically active, mud-shale reactions could lead to shale swelling, sloughing, accompanied by gumbo-type cavings returned on shakers. In some fields in West Africa, Cation Exchange Capacity (CEC), an index of shale chemical reactivity, could be as high as 60s.
- If shale is permeable, mud penetration could reduce the confining stress around a wellbore, and therefore increase the risk of shale failure. This effect, along with the chemical reactions, may contribute to so-called time-dependent wellbore stability problems in shale.
- If shale is not permeable, the fluid pressure trapped may not easily communicate with the surrounding formations. Overpressure may cause shale to expand into the hole if mud weight is not high enough.
- If shale is heterogeneous and in-situ stresses are anisotropic, borehole breakout could be more vicious and unpredictable⁵. This is particular important when a well penetrates faults or weak bedding planes.

It should be noted that in many cases changing mud weight and chemistry alone may not be sufficient to resolve shale-related wellbore stability problems. Good hole cleaning practice, optimized BHA design, improved casing design and well trajectory, and synchronized drilling operation, all become necessary to successfully drill through the troubled shale formations.

The industry has devoted enormous efforts to shale problems during drilling. This paper focuses on the shale encountered in an onshore gas field in Thailand, Southeast Asia. The drilling history and challenges have been reviewed, possible mechanisms have been investigated. A group of cavings at various depths have been carefully selected and tested. The tests include XRD, thin-section, SEM, ultrasonic, and strength. After ruled out several borehole instability factors such as overpressure, chemical reactions, plasticity, weak-beddings, etc., fractured shales with inadequate mud weight are determined to be the main player. Based on these findings, recommendations have been made to the future wells in the field.

Field Background and Drilling Histories

Phu Horm field is located on the Khorat Plateau in northern Thailand, Southeast Asia (**Fig. 1**). Located 60km north of Nam Phong gas field, the carbonate gas field is initially discovered by Esso in 1997. The structure of Phu Horm field is a tertiary inversion fold, thus mimicked on the surface by a long and steep sided hill standing above a generally flat plain (**Fig. 2**). The hill and all the surrounding areas above the plain have been designated as a forest reserve, even though most of the trees were logged decades ago. Because it is considered as an environmental sensitive area, access to the drilling site is limited and use of oil-based mud is prohibited.



Fig. 1-Location of Phu Horm Gas Field in Thailand

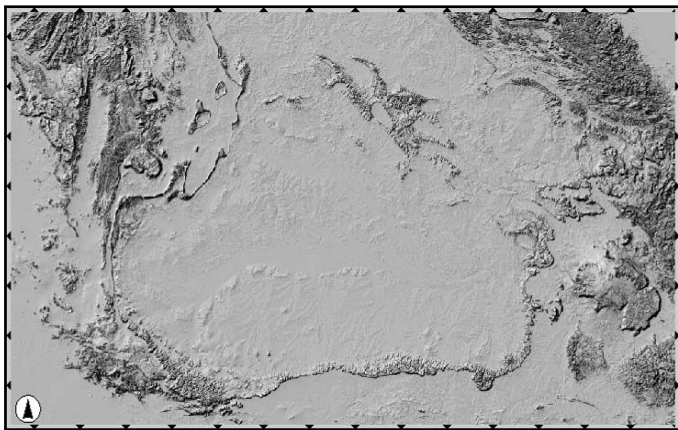


Fig. 2- The Khorat Plateau Elevation Data

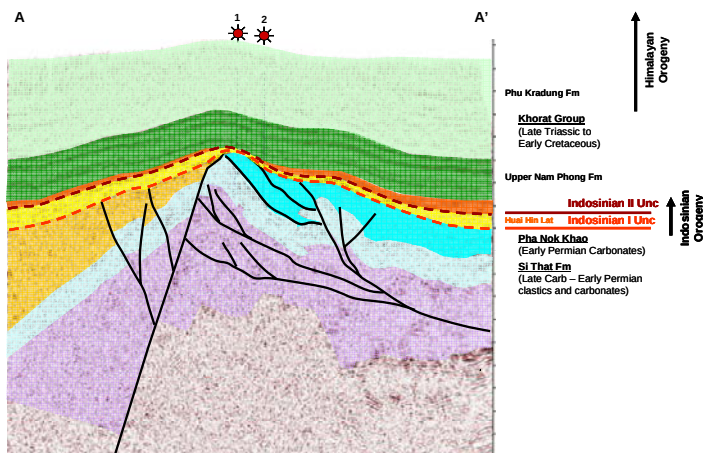


Fig. 3- Formation Structures of the Field

The Khorat basin was formed, uplifted, and eroded near the end of the Permian and during the early Triassic. Early erosion probably removed most of the Permian from the southern margin of the basin. It was folded and faulted during the Alpine orogeny in Eocene through Oligocene time, when most of the large-scale Khorat basin anticlines were formed. The basin was further uplifted in the regional Plio-Pleistocene Himalayan orogeny.

Among various formations shown in (Fig. 3), most drilling difficulties have been reported with 12 1/4" casing section, which penetrated the shale and claystone formations above the reservoir, including Phu Kradung formation (PKD), and upper Nam Phong formation (NP). Most of the drilling problems, such as tight spots with partial pack off, restricted pipe movement, stuck pipe, hole sloughing, pressure and torque spikes, occurred during RIH (Run In Hole) and POOH (Pull Out Of Hole). Mud weight increased from 10ppg, 11.5ppg, 12.5ppg, to 13ppg with little success. Medium to large quantity of pebble sized cuttings and cavings were constantly observed on the shakers. The cavings are generally flat with edges (Fig. 4). The cavings could be much larger at the hole bottom since those from the shakers had been "worked" by the drill string dynamics. The BHA pulled out of hole showed severe wear of the drill bit: five bits were consumed to drill the 1600m long 12 1/4" section (Fig. 4).

Subsequent wireline logs had also confirmed consistent hole enlargement between 600m TVD and 2200m, especially above 1400m where the hole was enlarged from 12" to 18" (Fig. 5).

Original Wellbore Stability Program

Initial wellbore stability program was developed based on the logs from two exploration wells. These include density, resistivity, Gamma-Ray, single arm caliper, and monopole sonic log. FMI image log was run in the reservoir section. The quality of the image log was too poor to identify any breakout or fracture.

Rock strength was estimated from compressional sonic wave velocity. The correlation of UCS and V_p was derived from some other fields not in the region. As the velocity is generally larger than 10,000 ft/sec, it indicates the shale is very strong. The UCS ranges from 5,000psi to 10,000psi.

In-situ minimum horizontal stress was estimated from FIT/LOT data while the overburden was integrated from density logs. In order to match the borehole enlargement that the caliper log had shown, unusually high maximum horizontal stress had to be applied. The ratio of the effective maximum horizontal stress and the effective vertical stress is 1.6. This is much higher than what had been reported in Columbian Andes and Canada Rockies (1.2-1.3) ⁶, where strike-slip tectonic stresses are overwhelm.

The predicted mud weight for the three development wells are listed in Table 1. Inclined 30-56 degree, the three wells were predicted to be able to drill with 9.8 to 10.8ppg for 1372m TVD, and 11.2 to 12.5ppg for the depth of 1516m TVD. However, the actual mud weights used were significantly higher. For example, 12.3ppg was used at 1372m TVD for Well 1, while 9.8ppg was predicted. The difference between the prediction and the actual is less than 1.5ppg in the deeper formation.

Well Name	TVD (m)	MD (m)	Inc. (°)	Azth. (°)	MW - Prediction (ppg)	MW - Actual (ppg)
Well 1	1372	1622	49.1	360	9.8	12.3
Well 2	1372	1702	56.2	230	10.8	12.8
Well 3	1372	1491	30.9	104	9.9	11.5
Well 1	1516	1840	48.9	359	11.2	12.3
Well 2	1516	2040	53.3	233	12.5	13.3
Well 3	1516	1663	33	101	11.6	13

Table 1- Mud Weight Predicted vs. Actual

Mechanisms Involved for Wellbore Instability

To investigate why borehole failed and the original prediction did not work, a comprehensive review of drilling history, cavings, and logs was undertaken. The mechanisms considered for the shale instability include overpressure, chemical reactions, fractured shale, weak bedding plane, and inadequate mud weight. Shale pore pressure is estimated from both resistivity and sonic logs (Fig. 6). The sonic derived pore pressure is based on Bower's method while the one derived from resistivity stems from Eaton's method. Instead of overpressure, both pressure curves indicate the formation could be as much as 1ppg underbalanced. Lack of wellbore flowing or kick from the interbedded sands also indicates the unlikelihood of the overpressure scenario. The caving pictures have ruled out the role of weak bedding plane: the cavings from the shakers are generally flat with edges, rather than blocky with apparent plane surface. Lack of gumbo-type of cavings may imply weak, if not at all, chemical reactions between the glycol mud and the shales. Further lab tests confirmed this.

Table 2 summarizes the Cation Exchange Capacity (CEC) from 13 caving samples taken from the three development wells. The lithologies cover shale, claystone, siltstone, and sandstone. Most CEC values are below 20. This is consistent with XRD results, which have shown around 5% smectite content, predominantly existed in mixed illite/smectite layers. Comparing to the reported values in other fields, both the CEC value and the smectite content indicate the shales in PKD and upper NP may not be much chemically active. Current glycol mud with high KCL salinity might be sufficient to inhibit mud pressure penetration into the shales.

Sample I D	Depth mMD	Cation Exchange Capacity meq/100g
Well 1 (PKD)	600-800	9.69
Well 1 (NP)	1760-1870	18.01
Well 1 (NP)	1860-1889	19.14
Well 1 (NP)	2208	18.92
Well 2 (NP SST)	2700	7.28
Well 2 (NP SST)	2817	1.15
Well 2 (PKD)	300/700	19.12
Well 3 (PKD)	400	15.08
Well 3 (PKD)	415	24.78
Well 3 (PKD)	1359	12.12
Well 3 (NP)	2053	10.80
Well 1	2072	10.82
Well 2	2210	11.22

Table 2- Cation Exchange Capacity (CEC) from Cavings at Various Depths



Fig. 4- Cavings from BHA and Shakers

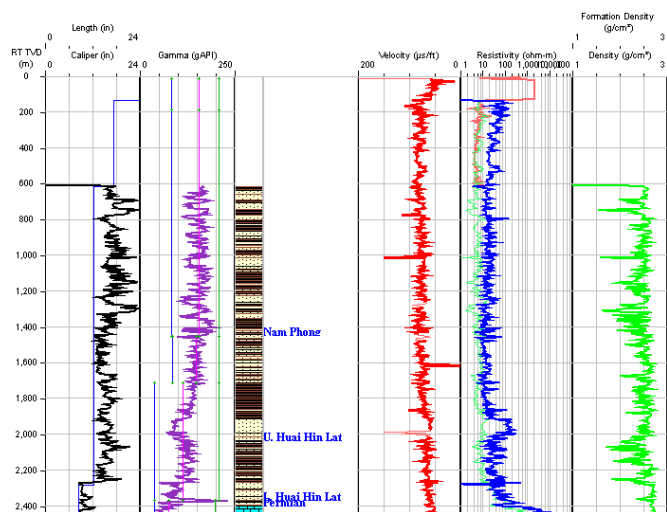


Fig. 5- Caliper, Compressional sonic, density, and resistivity Logs from a well

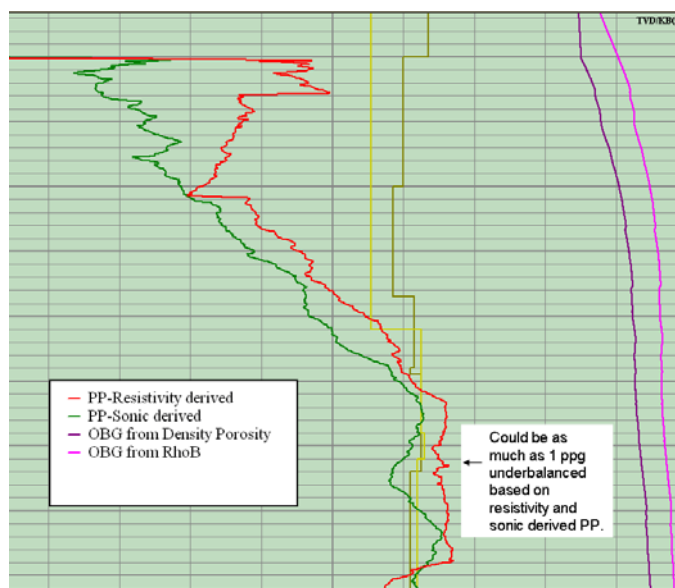


Fig. 6- Pore pressure profiles over the troubled shale/claystone formation

Therefore the possible mechanisms left are inadequate mud weight and fractured shales. If it was only due to inadequate mud weight, cavings might have occurred during and after the drilling. The fact that there is little trouble to drill through the formations and most problems have occurred during RIH and POOH may indicate there is more than just one player.

A group of big cavings (28-100mm) were sent to lab for special strength tests. The cavings were preserved in mineral oil to avoid further deterioration. Prior to the tests, ultrasonic compression velocities were performed in three directions for each of the cavings, as a means of determining the bedding orientation in the samples. The measurements were executed without any loading, the transducers were standard Panametrics 0.5 inch, and the frequency sent was 500kHz. The results are plotted in Fig. 7. Most p-wave velocities for the shales are between 10,508ft/sec and 13,257ft/sec. Some cavings from the depth 415m are between 15,898ft/sec and 17,444ft/sec. There are no relation between the shape of the cavings and the ultrasonic-indicated bedding plane. This confirms the weak bedding plane doesn't play any role in the borehole instability.

The lab findings agree with sonic logs very well: higher-than-normal compressional wave velocity above 10,000ft/sec. Comparing to some North Sea shales that are labeled "strong" in the similar depth range, the much higher p-wave velocity indicates the PKD shales are supposed to be even stronger. However, none of the coring from the cavings succeeded and all of the plugs broke into pieces (Fig.7).

The thin section and SEM have finally revealed the myth. As shown in Fig.8, most of the shales and claystones have been fractured and brecciated. Anhydrite and carbonate nodules are locally present in these samples, and some of them are fractured as well.

Conclusions and Recommendations

Shale instabilities in PKD and upper NP formations at Phu Horm gas field may be due to a combination of inadequate mud weight and fractured shales. The main reason the original wellbore stability program did not succeed is because weak rock strength has been disguised by unusually high compressional sonic log. This indicates the compressional-sonic based rock strength model may not apply when formation is fractured. Instead, a shear based strength algorithm may be more applicable.

Because fractured shales usually is a consequence of high tectonic stresses, high anisotropic in-situ stresses may accelerate borehole failure (Fig. 9). This is particularly true in Khorat Plateau in Thailand, Columbia Andes, and Canada Rockies. Because of the high ratio between the maximum horizontal stress and the overburden stress, in addition to low rock strength, drilling operations in those areas may have to live with and manage certain amount of cavings.

The following suggestions have been made based on above discussions:

1. We don't recommend OBM to the field because the shales are not chemically active and current high KCL glycol mud may be efficient. Certain amount of solids and LCM materials could be added to avoid mud penetration through the fractures in the shale. OBM may encourage such penetration with more lubrication.

2. High mud weight could be as harmful as low mud weight. Living with a manageable amount of cavings requires extra steps in hole cleaning and solids control.
3. Minimize operational vibration, pipe dynamics, swab and surge. Redesign BHA to reduce its contact with rock. Optimize reaming and back-reaming practice.
4. Optimize casing design and well trajectory. For example, set the 12 1/4" casing as deep as possible; build well angle in the lower section of Upper Nam Pong and the upper section of Lower Nam Phong where rock is relatively stronger, but drop angle to less than 20 degree when enter Huai Lin Lat.

The lessons and learns from the field have challenged the conventional approaches in wellbore stability modeling. The study has gained insights of the fundamental mechanisms for the borehole instabilities experienced in Phu Horm field.

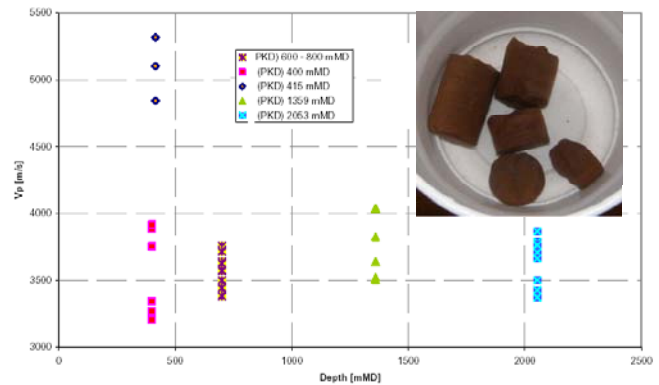


Fig. 7- P-wave Velocities as a Function of Depth for All Cavings. Each Caving Produces 3 Results for 3 Orthogonal Directions.

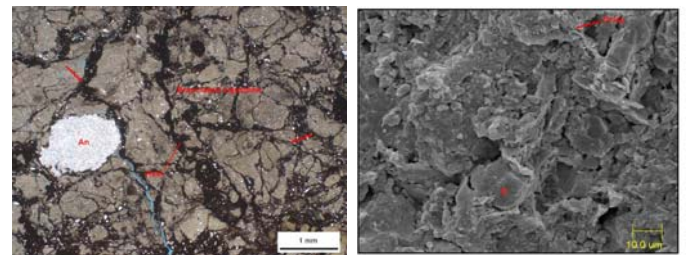


Fig. 8- SEM and Thin Section Indicate Most of Cavings are fractured and Brecciated.

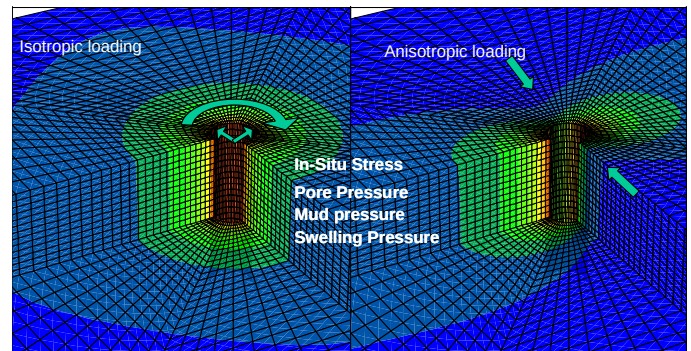


Fig. 9- Effect of Anisotropic Loading on Wellbore Breakout ⁷

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