

FAULT SEAL CAPACITY EVALUATION IN BLOCK 04-3 OF NAM CON SON BASIN, OFFSHORE VIETNAM

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Summary

The purpose of the study is to evaluate the fault seal capacity and hydrocarbon (HC) retention potential of the Miocene - Oligocene fault-bounded structures in Block 04-3, Nam Con Son basin, offshore southern Viet Nam. Seismic and well petrophysical interpretation data are used to build 3D fault model and stratigraphic model within the 6 selected structures. Parameters such as fault throw, bed thickness, Vshale, lithology, burial depth, and fluid density are incorporated into fault seal evaluation. The critical leak points at the Middle Miocene, Lower Miocene and Oligocene intervals on faults bounding the 6 structures are defined. Hydrocarbon column heights supported by the faults can be estimated using the empirical relationship between Shale Gouge Ratio and threshold pressure. The study predicts that the maximum gas column ranges from 136m to 252m in Middle-Lower Miocene reservoirs in the drilled structures and from 119m to 295m in Middle-Lower Miocene and Oligocene reservoirs in the undrilled structures.

Key words: Fault seal analysis, prospect, Shale Gouge Ratio (SGR), Clay Smear Potential (CSP), gas column height, hydrocarbon column height, hydrocarbon density, threshold pressure, spill-point.

1. Introduction

For fault-bounded structures, fault seal analysis is critical in evaluating risks, ranking prospects and optimising the drilling priority. The study aims to determine the seal capacity of the bounding faults, identify potential leak points on the faults, and calculate the theoretical maximum HC column height that can be supported by the fault. The 6 structures chosen for fault seal analysis are A, B, C, D, E and F in Block 04-3, among which structures A, B, and C are drilled, and structures D, E and F are undrilled. The targets of these structures are Oligocene clastic, Miocene clastic and Miocene carbonate reservoirs. The analysis from the drilled structures will be used to extrapolate and reduce uncertainties for the undrilled structures.

2. Geological overview

2.1. Structural geology

Block 04-3 is located in the northeast of the Nam Con Son basin (NCSB), offshore southern Vietnam. The structural map and the general stratigraphic column of Nam Con Son basin are illustrated in Figure 1. In Block 04-3, the western area is on the Mang Cau high (A2 in Figure 1), while the eastern area is in the Central trough (A3 in Figure 1).

The geological evolution of the basin can be divided into 3 episodes: pre-rift (Pre-Tertiary), syn-rift (Oligocene - Middle Miocene), and post-rift (Middle Miocene - Present) (Figure 2). The Oligocene formation is composed of interbedding sand-shale, deposited in fluvial, delta to lacustrine environment. The Early Miocene formation is composed of interbedding sand, shale and silt with occasional coal, and deposited in delta plain, coastal to shallow marine environment. The Middle Miocene formation can be divided into 2 parts: the lower part consists of interbedding sand, shale and silt with occasional carbonate; and the upper part consists of carbonate interbedding with sand, shale and marl (Figure 1b).

In the 6 structures chosen for fault seal analysis, the main trend of the faults is NE-SW, and they were formed either during the intra-Middle Miocene, or at the end of Middle Miocene. A number of main bounding faults were active until the Late Miocene. The structures in this study formed either at the end of Middle Miocene (structures C and D) or Late Miocene (structures A, B, E and F) (Figure 2).

2.2. Hydrocarbon occurrences

The study area and adjacent areas have several gas and gas-condensate discoveries in Middle-Lower Miocene and Oligocene sandstone, and Middle Miocene carbonate.

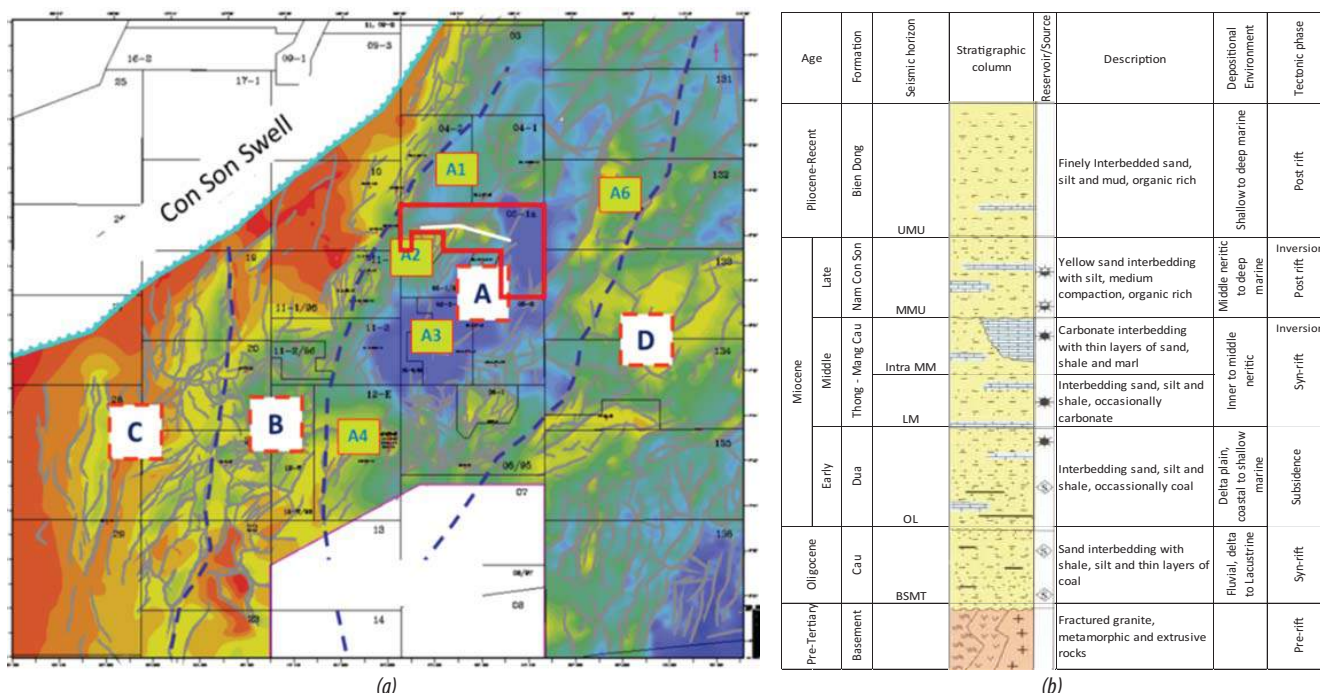
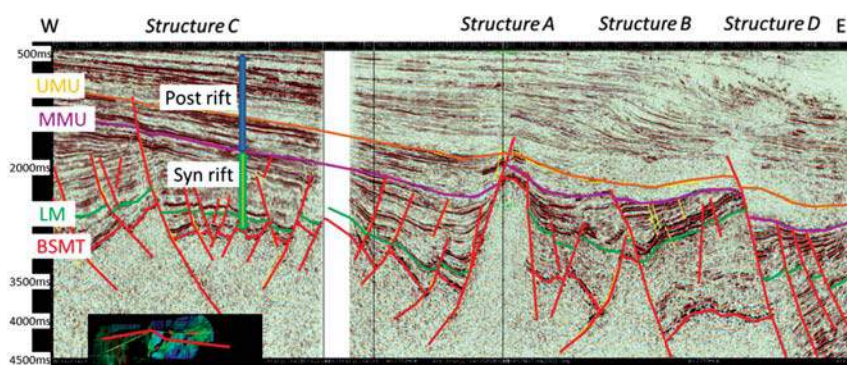


Figure 1. The structural map with major structural components (a) and the general stratigraphic column (b) of the Nam Con Son basin [1]. The study area is highlighted. The white line in the study area is the position of the seismic profile in Figure 2



UMU = Upper Miocene Unconformity, MMU = Middle Miocene Unconformity, LM = Lower Miocene, BSMT = Basement

Figure 2. A seismic cross-section through the study area [2]

2.3. Reservoir engineering

Available data are not sufficient to determine HC-water contacts, as well as pressure regimes on both sides of the faults. However, available DST (Drill-stem Test) data can be used to estimate gas density at reservoir condition. In the Early Miocene reservoir, the estimated HC density is 0.24g/cc, while in the Middle Miocene reservoir the density ranges from 0.27 to 0.28g/cc. These gas densities are essential to predict the maximum HC column height using the methodology in section 3.

3. Methodology

There are 2 kinds of seal at a given point on a fault:

- Seal by juxtaposition: it happens through juxtaposition of one interval against an impermeable interval, most commonly shales;
- Seal by fault deformation zone: fault deformation creates fault rocks that are significantly reduced in porosity and permeability. For this type of

seal, the dominating seal mechanism is capillary seal [3, 4].

For an interval of interest, the fault can seal if any of the above seal conditions are satisfied, and the fault has not been reactivated after the trap formed [5].

Seal by juxtaposition can be evaluated with a juxtaposition diagram, whereas seal by fault deformation zone needs to be evaluated using various parameters such as SGR, CSP and threshold pressure. The following sections present the methodologies involved in evaluating seal capacity of fault deformation zone.

The most common method to characterise fault zone deformation products is the Shale Gouge Ratio (SGR) method, which approximates the clay content of the fault zone. It is based on the assumption that the clay content of the host rock along the fault is evenly distributed on the fault plane. The basic formula for SGR [6] is:

$$SGR = \frac{\sum(\text{Layer clay content} \times \text{Bed thickness})}{\text{Throw}} = \frac{\sum(V_{cl} \times \Delta z)}{\text{Throw}}$$

The higher the SGR value, the higher the clay content along the fault is, and therefore the higher the sealing capacity. If the shale layers in the study area are thick, then the shale layers can be smeared along the fault and impeded HC flow. In such cases, we need to consider other methods such as Clay Smear Potential (CSP) and Shale Smear Factor (SSF) [7, 8]. The formulas for CSP and SSF are:

$$CSP = \frac{\sum(\text{Shale bed thickness})^2}{\text{Distance from source bed}}$$

$$SSF = \frac{\text{Fault throw}}{\text{Shale layer thickness}}$$

Fault seal potential can be further enhanced through diagenesis process, whereby cementation at great burial depth can reduce the porosity and permeability at the fault zone [9, 10].

After calculating SGR, we can calculate the threshold across fault pressure difference that the fault can sustain before being breached based on the empirical relationship from Bretan et al. [11]:

$$\Delta P = 10 \left(\frac{SGR}{27} - C \right)$$

In which ΔP is threshold pressure in bar, C is a constant varying based on the depth of the interval of interest: $C = 0.5$ at depth $< 3\text{km}$, $C = 0.25$ at depth between 3 and 3.5km , and $C = 0$ at depth $> 3.5\text{km}$.

SGR sealing threshold for HC-HC juxtaposition is $SGR > 0.4$, while for HC-water juxtaposition it is at least 0.2 . The threshold pressure does not increase in the SGR range of $0.4 - 1$, therefore the maximum column height does not increase in that range [11].

Based on the above threshold pressure, we can calculate the maximum HC column height corresponding to an SGR value by the following formula [11]:

$$H_{max} = \Delta P / \Delta \rho g = 10 \left(\frac{SGR}{27} - C \right) / \Delta \rho g$$

Where H_{max} is the maximum column height (m), ΔP is the threshold pressure (Pa), $\Delta \rho$ is the density difference between water and HC (kg/m^3), and g is the gravitational acceleration constant. As mentioned above, ΔP has a limit at around $SGR = 0.4$, therefore H_{max} will also has a limit at the respective value.

Since fault properties vary vertically and laterally along the fault surface, H_{max} will also vary accordingly. To account for such heterogeneity, we need to calculate H_{max} for every node on the fault model, and convert them into contact depth by adding the depth of the structural crest. Then the actual maximum HC column height supported by the fault is determined by the point with the shallowest contact depth.

In addition, the determined HC contact depth must not be deeper than the structural spill-point, and the maximum column height does not increase in the SGR range of $0.4 - 1$. Therefore, the steps involved in determining the maximum HC column height are as follow:

- Calculate H_{max} and the corresponding contact depth for every possible leak point on the fault model interval where $SGR < 0.4$. The contact depth will be limited by the spill-point depth;
- The deepest fluid contact depth supported by the fault will be the minimum value of the every possible leak point's contact depth.

4. Fault seal capacity evaluation

This study focused on 6 structures in Block 04-3, 3 of which are drilled (structures A, B, and C) and 3 are undrilled (structures D, E and F).

All the drilled structures are on the Mang Cau high (Figure 3). In this area, the Miocene sediments are deposited directly on the Pre-Tertiary basement. Among the undrilled structures, structure D is on the Mang Cau high, and structure E and F are in the central trough zone of the Nam Con Son basin. The study focused on major faults that can affect the structural closure of the prospect.

To construct a 3D model of the subsurface structure, fault sticks and horizon picks are imported into Petrel modelling software. Well log data (Lithology and Vshale) are used to populate the 3D model, so that fault plane properties can be extracted for further analysis. For undrilled exploration targets, a hypothetical well will be determined with its well data inferred from nearby wells and from the depositional environment trend.

There are no published articles on fault seal for carbonate, therefore in this study we use the following threshold values for determining reservoirs: The Vshale (Vsh) cutoff for reservoir is < 0.4 and non-reservoir is > 0.4 for both clastic and carbonate, and an additional effective porosity cutoff of $> 5\%$ is applied to the carbonate reservoir. This porosity cutoff

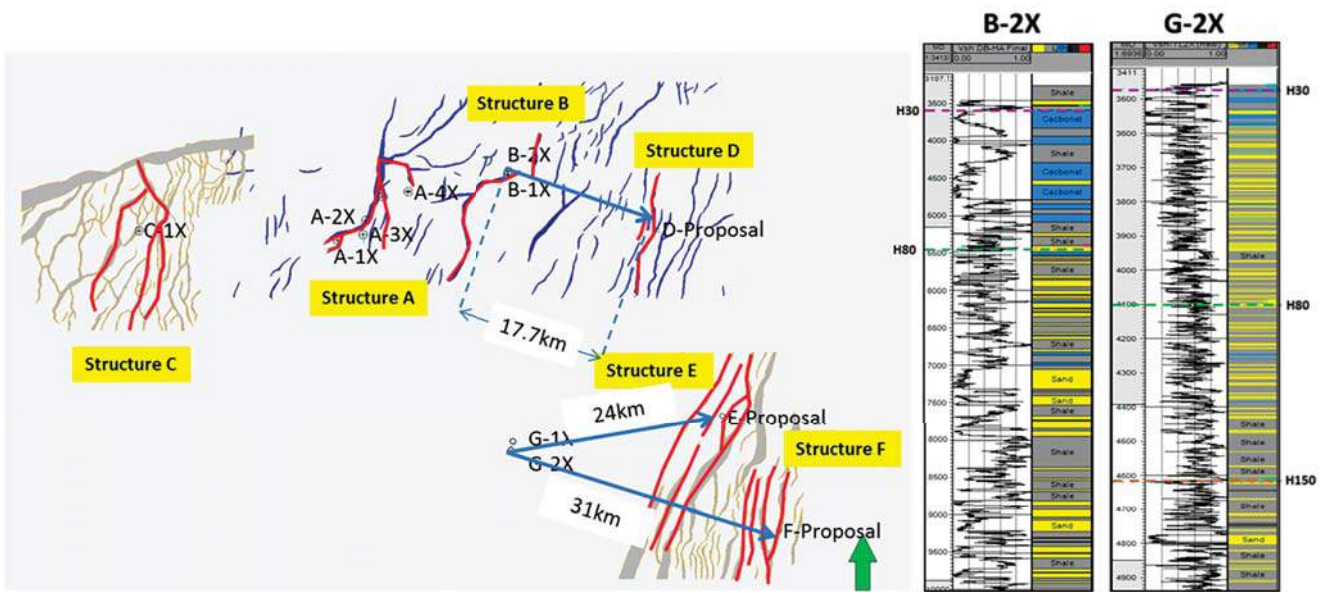


Figure 3. Structures and their chosen faults for fault seal analysis study in Block 04-3. Arrows indicate the wells used as lithology model for the proposal wells. The distances from the model well to the proposal well are also indicated

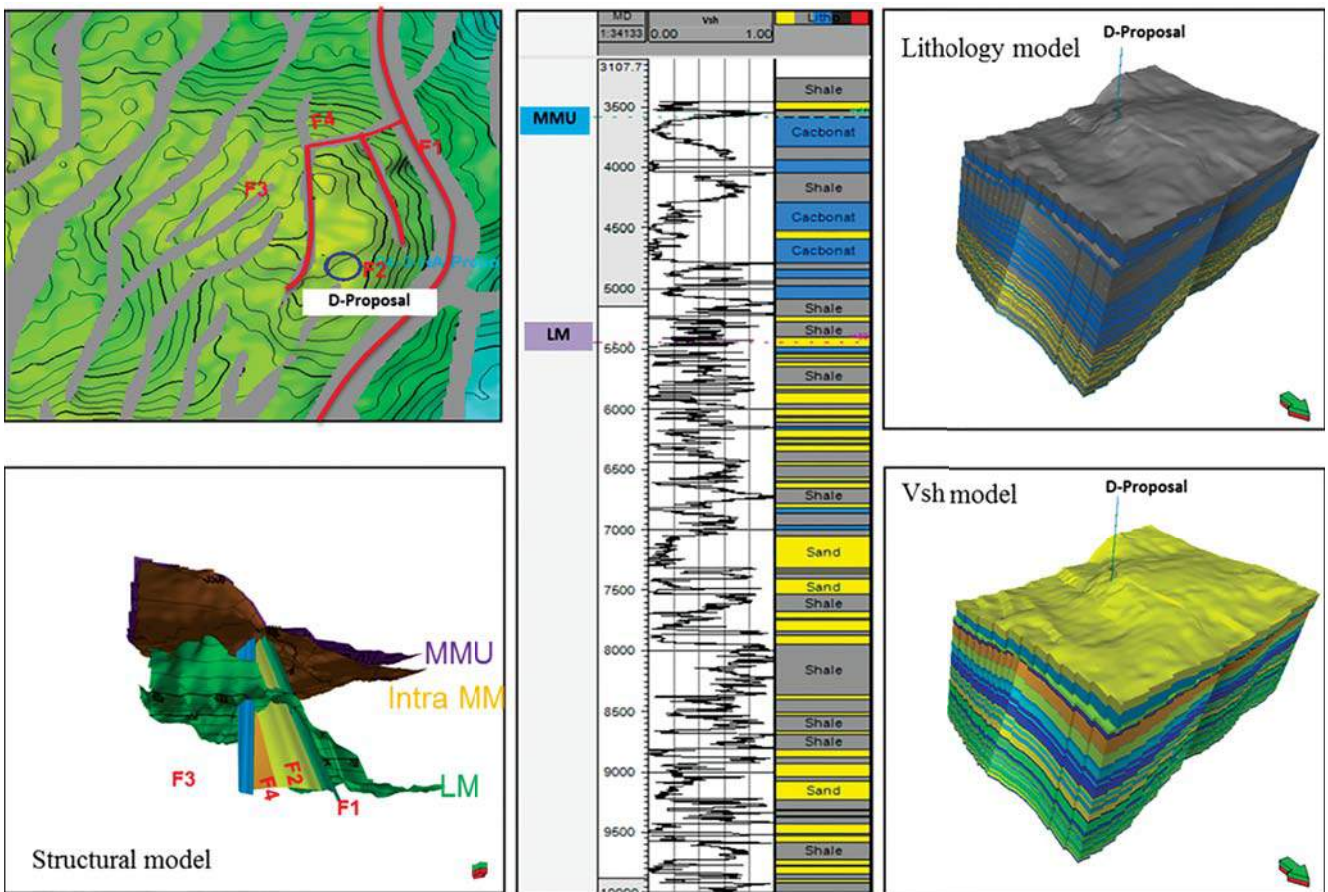


Figure 4. Lithological and Vshale models for the undrilled structure D are based on well B-2X

has been used for evaluating carbonate reservoirs in the Nam Con Son basin [12].

From the discussion in section 2.2, the Vshale, porosity and lithological model for the undrilled prospects are based on nearby wells as follow: structures E and F are

based on well G-2X, and structure D is based on well B-1X (Figure 3, 4). Since the reservoirs are mainly silty sands, clay mixing along the fault zone is probably the dominant fault seal mechanism. Therefore, SGR is chosen as the main algorithm.

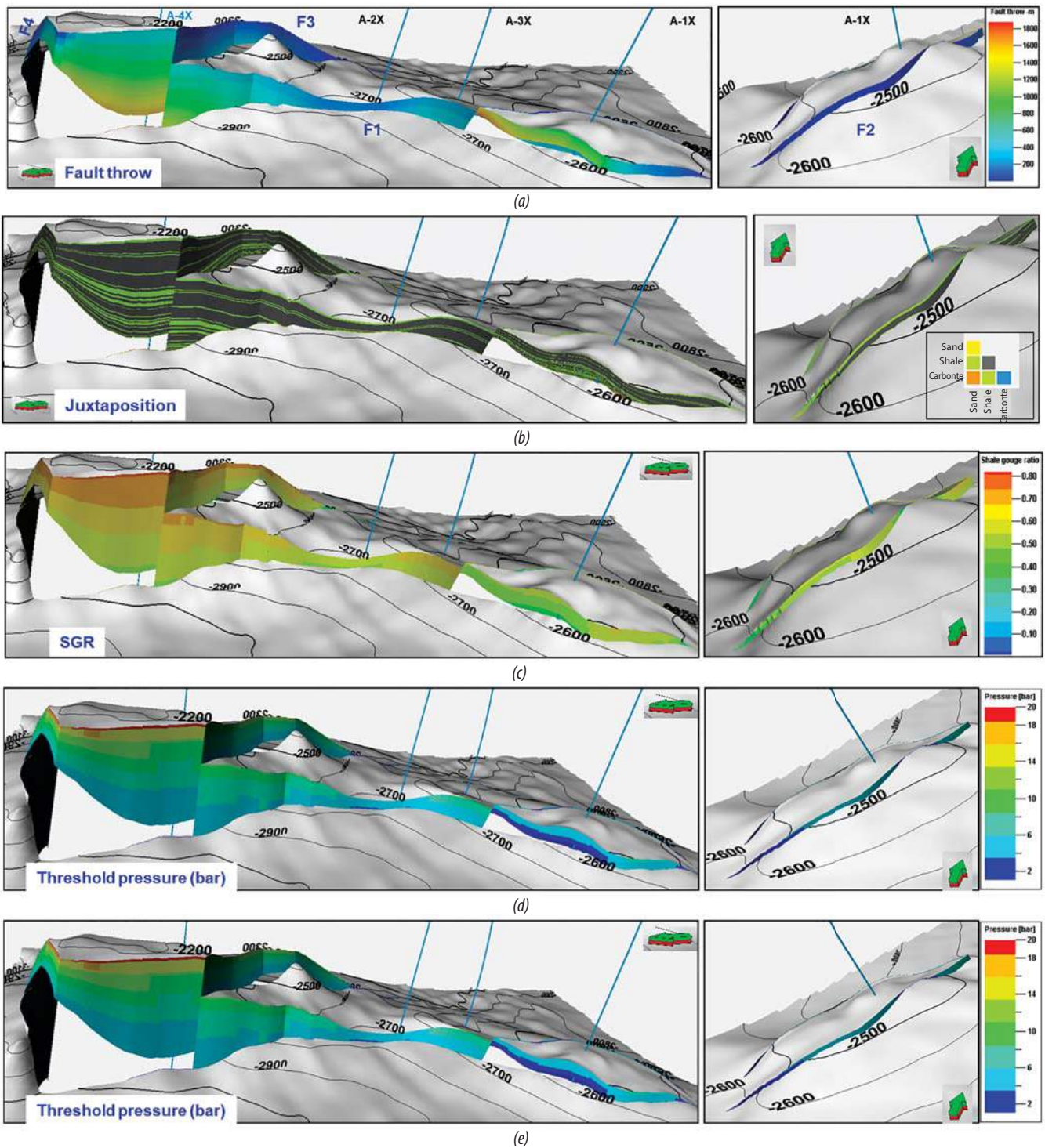


Figure 5. Fault throw, lithological juxtaposition, SGR, threshold pressure and predicted HC column height for structure A, illustrated on MMU horizon map

Lithological juxtaposition diagrams express the juxtaposition of various lithologies on the fault surface. It provides a quick look on the possible leak points on the faults, which are sand on sand, sand on carbonate, and carbonate on carbonate juxtapositions. Most of the structures have multiple leak points in each interval, therefore an analysis of fault rock processes based on SGR and CSP is critical in accurately evaluating the fault seal capacity.

Fault throws in the study area vary according to structural trend. Structures on the Mang Cau high (A, B, C, and D) have large throw (maximum throw can be over 1,600m), while in the Nam Con Son basin central trough (structures E and F) the throw is smaller (maximum throw 200 - 450m) (Figure 5a, Table 1).

SGR calculations for all faults bounding the structures are illustrated in Table 1. In the drilled structure A, DST

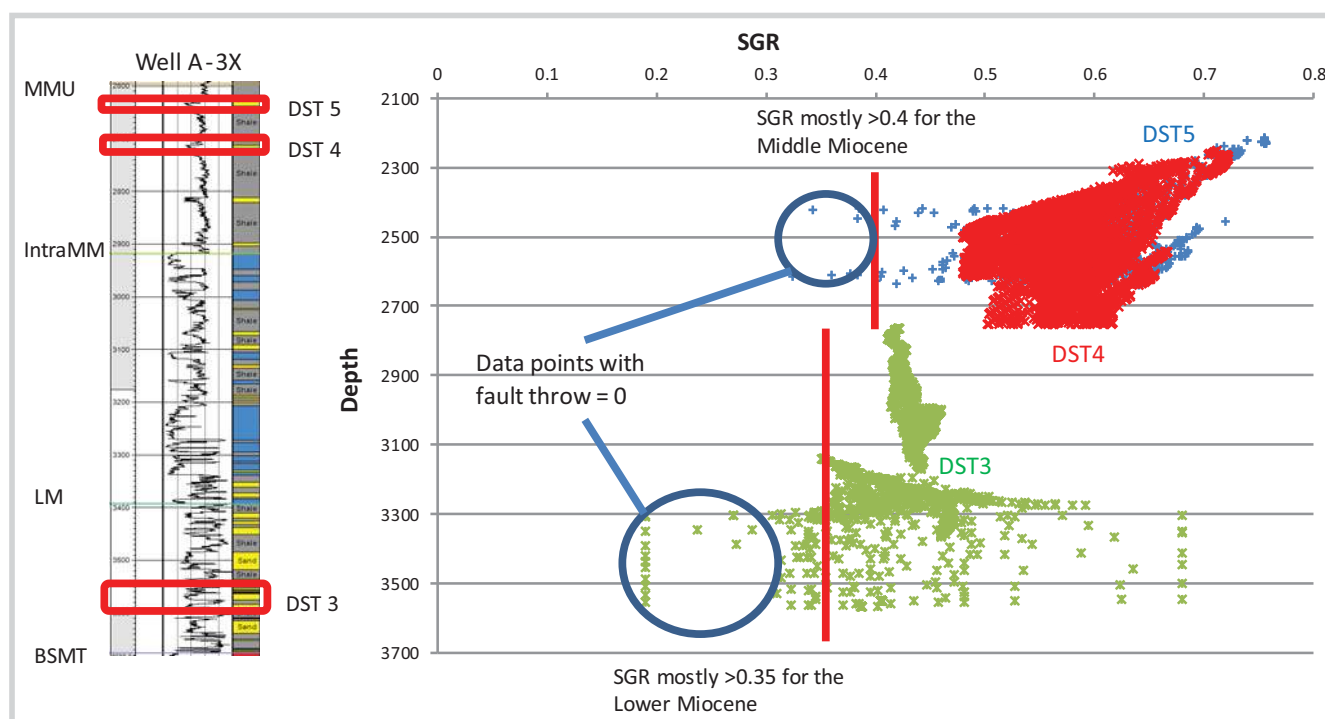


Figure 6. DST tests for clastic sections in well 3X of structure A. Gas discoveries intervals have SGR > 0.4 in the Middle Miocene and SGR > 0.35 in the Lower Miocene

Table 1. Predicted maximum gas column height and percentage of trap fill along faults. The trap fill percentage is calculated by dividing the HC column height by the vertical closure of the structure from crest to spill-point

Structure	Interval	Fault throw	SGR	HC column height	Vertical closure (crest to spill-point)	Trap fill along faults
		m		m	m	%
A	MMU - Intra MM	10 - 1600	0.5 - 0.8	136	377	37
	Intra MM - LM	10 - 1800	0.5 - 0.6	140	663	21
	LM - Top BSMT	Juxtaposed with basement, not evaluated				
C	Intra MM - LM	10 - 400	0.3 - 0.5	166	220	75
	LM - Top BSMT	10 - 500	0.3 - 0.6	252	344	74
D	MMU - Intra MM	50 - 250	0.2 - 0.3	174	200	87
	Intra MM - LM	10 - 600	0.2 - 0.8	136	151	90
F	MMU - LM	0 - 400	0.3 - 0.55	252	326	77
	LM - OL	0 - 300	0.5 - 0.75	292	648	45
	OL - Top BSMT	0 - 250	0.45 - 0.75	295	580	50

tests for clastic sections show gas bearing intervals with mostly SGR > 0.4 for the Middle Miocene formation and mostly SGR > 0.35 for the Lower Miocene formation (Figure 5c). The Lower Miocene formation has lower SGR yet it still seals. This is probably due to diagenesis effect by sediment burial, which in this case is 3,300m in burial depth. The deeper the burial, the more significant the mechanical compaction and chemical pressure solution processes will be, which will reduce the porosity and permeability of the fault zone, thus enhancing the fault seal capacity.

Calculated maximum HC column heights are shown in Table 1. In the Middle Miocene section, the drilled

structures (structures A and C) have the column heights in the range of 136 - 166m, while the undrilled structures have the column height in the range of 136 - 252m. In the Lower Miocene section, the drilled structure C has the column height of 252m, while the undrilled structures have the column heights in the range of 252 - 292m. In the Oligocene section, which is present in the undrilled structures only, the column heights are in the range of 251 - 295m.

5. Conclusion

SGR thresholds determined from drilled structures can be used for undrilled ones. SGR for DST intervals with

discoveries are greater than 0.4 for the Middle Miocene interval and greater than 0.35 for the Lower Miocene interval.

In case reservoir engineering data on both sides of the faults are lacking, the published empirical equation from Bretan et al. [11] can be used to evaluate sealing threshold pressure across faults. Calibration with known fields and discoveries in the Nam Con Son basin is necessary to get a reasonable maximum HC column height.

The predicted HC column heights and trap fill for drilled structures are 136 - 252m and 21 - 75% respectively, and for undrilled structures are 136 - 295m and 45 - 90% respectively. Trap fill is variable due to differences in vertical closure and clay content along faults.

HC column height is also dependent on the seal capacity of the cap rock, which is not considered in this study.

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