Journal of Mining and Earth Sciences

Website: https://jmes.humg.edu.vn

# Fault seal analysis of fault F2 and its influence on oil and gas migration for VS prospect area, block 16-1/15, Cuu Long Basin, Viet Nam

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ARTICLE INFO

*Article history:*
Received 28th Oct. 2024
Revised 10th Feb. 2025
Accepted 5th Mar. 2025

*Keywords:*
Faul seal analysis,
Geological restoration,
Hydrocarbon column height,
Migration,
Throw.

ABSTRACT

*Cross-fault sealing analysis is commonly done by direct and indirect assessments. The former evaluates fault sealing capacity by analyzing MICP (Mercury injection capillary pressure) of samples taken directly from fault zones, which is easy for surface-exposing faults, but difficult to carry out for subsurface fields. The latter method indirectly evaluates cross-fault sealing capacity by establishing a relationship(s) of Buoyancy pressure (BP) or Across fault differential pressure (AFDP) /or Across fault pressure difference (AFPD) with properties of fault plane such as Shale-Gouge-Ratio (SGR) and will be applied for this study. Each fault with a SGR value (higher than the sealing vs non-sealing cut-off) can hold a certain maximum AFDP value related to a maximum hydrocarbon column, and the fault will start leaking if the actual hydrocarbon in formation exceeds the maximum limit. The study's purpose is to evaluate fault F2 seal capacity and its influence on oil and gas migration of the Miocene-Oligocene fault-bounded VS structure in block 16-1/15, Cuu Long basin, offshore Vietnam. Seismic and petrophysical data are used to build a 3D structural framework and stratigraphy model in the VS structure and adjacent areas. The authors will use parameters such as age, fault throw, Vshale (volume of shale), lithology, bed thickness, burial depth history, fluid density, and pressures... for fault seal analysis. Maximum hydrocarbon column height estimation can be held by fault F2 using the empirical relationship between threshold pressure and SGR (Shale Gouge Ratio), combined with the petroleum system model result from previous studies to evaluate fault F2's influence on hydrocarbon migration into the VS structure, therefore helping to assess the hydrocarbon potential in undrilled structures in further exploration plan.*



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DOI: 10.46326/JMES.2025.66(2).07

## 1. Introduction

The fault seal capacity evaluation according to the 3D model for the structures in SH5 (Lower Miocene), SH7 (Oligocene C) and SH8 (Oligocene D) sediments to serve the assessment hydrocarbon potential in the VS area and reduce the risk for further exploration - appraisal work in block 16-1/15, Cuu Long basin. The analogs from the drilled structures will also be used to extrapolate and reduce uncertainties for the undrilled structures. VS prospect is a 3 way-closure structure, bounded by fault F2 in the study area. This research aims to determine the seal capacity of the bounding fault F2, identify potential leak points/ weak points on the fault F2 plane; estimate the theoretical maximum HC column height that can be held by the fault; and restore the activation history of this fault to evaluate the relationship between sealing capacity and migration through time, also help to analyse the hydrocarbon potential in the VS structure.

## 2. Geological setting

Block 16-1/15 is located in the southwestern part of the Cuu Long Basin, offshore of the Vietnamese continental shelf. Its geological development history is closely tied to the characteristics of the basin. The comprehensive stratigraphic column of the Cuu Long Basin and the tectonic map of the region are depicted in Figures 1a and b, with the VS study area situated to the east of Block 16-1/15 (Figure 1b) (Schmidt et al., 2019).

In terms of stratigraphic characteristics, starting from the oldest to the youngest, the studied area comprises Pre-Tertiary basement and Kainozoic sedimentary deposits, as shown in Figure 1a. The basement rocks in Block 16-1/15 mainly consist of Type S granite, including biotite and two-mica granites, as well as Type I granite granodiorite containing hornblende and biotite. The Kainozoic sedimentary deposits encompass sedimentary formations ranging in age from the Eocene epoch to the present and are divided into five stratigraphic units. In the seismic section, the geological formations are elaborately interpreted corresponding to the reflection layers from SHB, SH11, SH10, SH8, SH7, SH5, SH3, SH2, and SH1 (Figure 1a).

The tectonic evolution of the studied area can be divided into three main periods: pre-rift period, rift (extensional) period leading to basin formation from the Eocene to the late Oligocene, and late Oligocene to early Miocene compression and thermal subsidence (Nguyen, 2007; Schmidt et al., 2019; Lee et al., 2001; Tuan et al., 2021; Fyhn et al., 2009).

The petroleum system in the Block 16-1/15 area has been demonstrated by hydrocarbon discoveries, most notably the VS discovery. The oil-bearing reservoirs have been found in the Miocene interval (BI.1 & BI.2 corresponding to SH3 & SH5), the Oligocene interval (C & D corresponding to SH7 & SH8), and the basement interval (SH-B). The gas-bearing reservoirs have been discovered in the Oligocene E & D intervals. This study primarily focuses on the sedimentary deposits from SH5 to SH8 (Figure 2, Figure 3) (Dam & Quang, 2015; Bojesen-Koefoed et al., 2009).

## 3. Methodology

In this paper, we use an interpreted seismic section to make section analysis and a balanced cross-section. Then, we combined previous petroleum system modeling results and fault seal analysis results to evaluate the target fault and its influence on oil and gas migration.

Second, we use Slip Tendency as a parameter to evaluate Fault reactivation potential. Faults that have been critically stressed or reactivated following hydrocarbon charge are more likely to act as conduits for fluid flow (Sibson, 1994). Consequently, a fault prone to reactivation may provide a poor baffle to flow despite having favourable juxtaposition and membrane seals. Stress Analysis calculates the effective shear and normal stresses acting on a 3D surface for a user-defined triaxial stress state. The resultant values can be combined with pore pressure changes to quantify the reactivation potential of a fault. In total, six parameters can be applied in Move to evaluate the probability of fault reactivation and seal breach. Slip Tendency is often the most commonly applied parameter in fault seal analysis (Morris et al., 1996; Mildren et al., 2005).

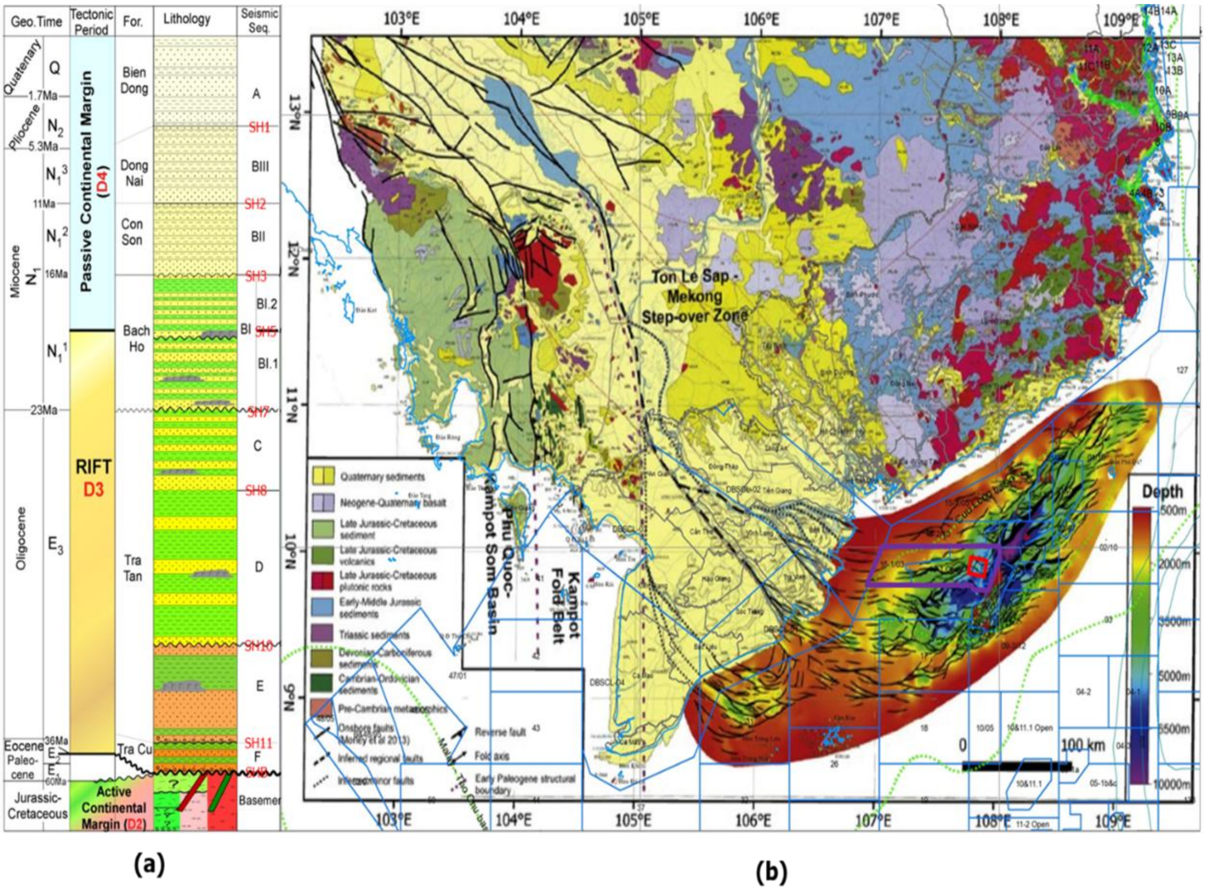



*Figure 2. The general stratigraphic column (a) and the structural map with major structural components (b) of the Cuu Long basin. The study area is red box highlighted in block 16-1/15 (purple line).*

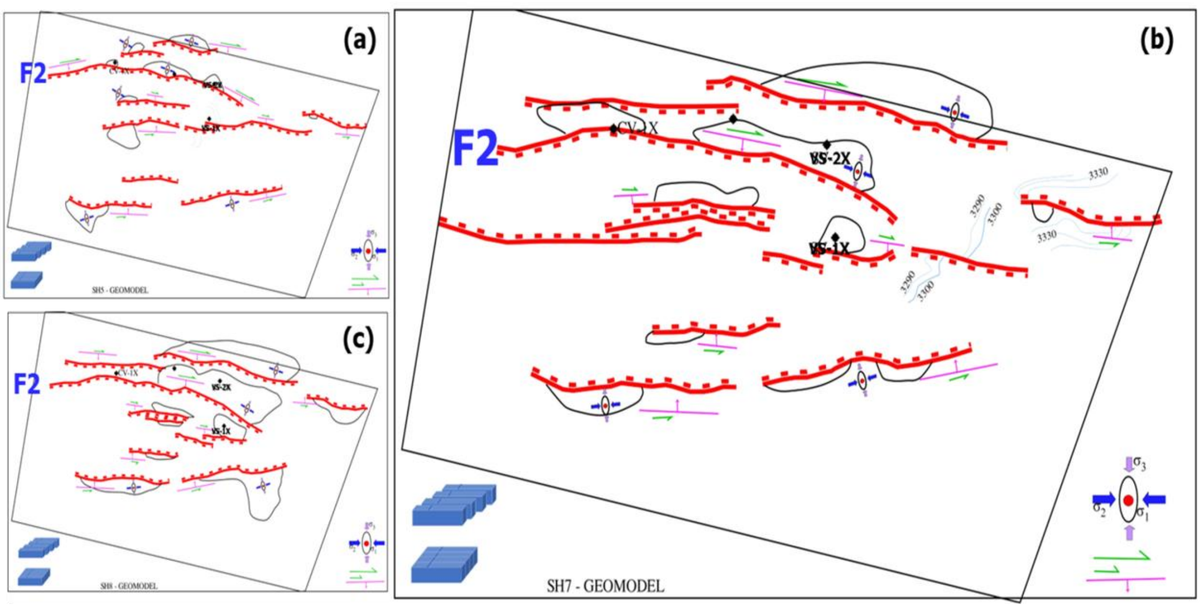



*Figure 2. Fault F2 location on geomodel map of the VS area: a-based on the SH5 map; b- based on the SH7 map and c- based on the SH8 map.*

Slip Tendency is the ratio of effective shear stress (T) to normal stress (σn). Greater values indicate a higher slip tendency and, therefore, a higher probability of fault reactivation. The calibration process suggests the critical value of 0.6, above this value, a fault will slip, thus breaching the seal and providing a potential conduit for fluid flow (Cotesta et al., 2007) (Figure 4).

Nowadays, there are two commonly used methods worldwide to assess the sealing capability of faults. The first method is a direct approach that involves evaluating the sealing capacity of faults by sampling from fault zones and conducting studies on pressure (MICP - Mercury injection capillary pressure) and mineral analysis. This method can be easily implemented if mines or outcrops are exposed on the surface. However, the challenge when applying this method to underground mines occurs due to insufficient data or a lack of core samples from fault zones for estimating the sealing capability.

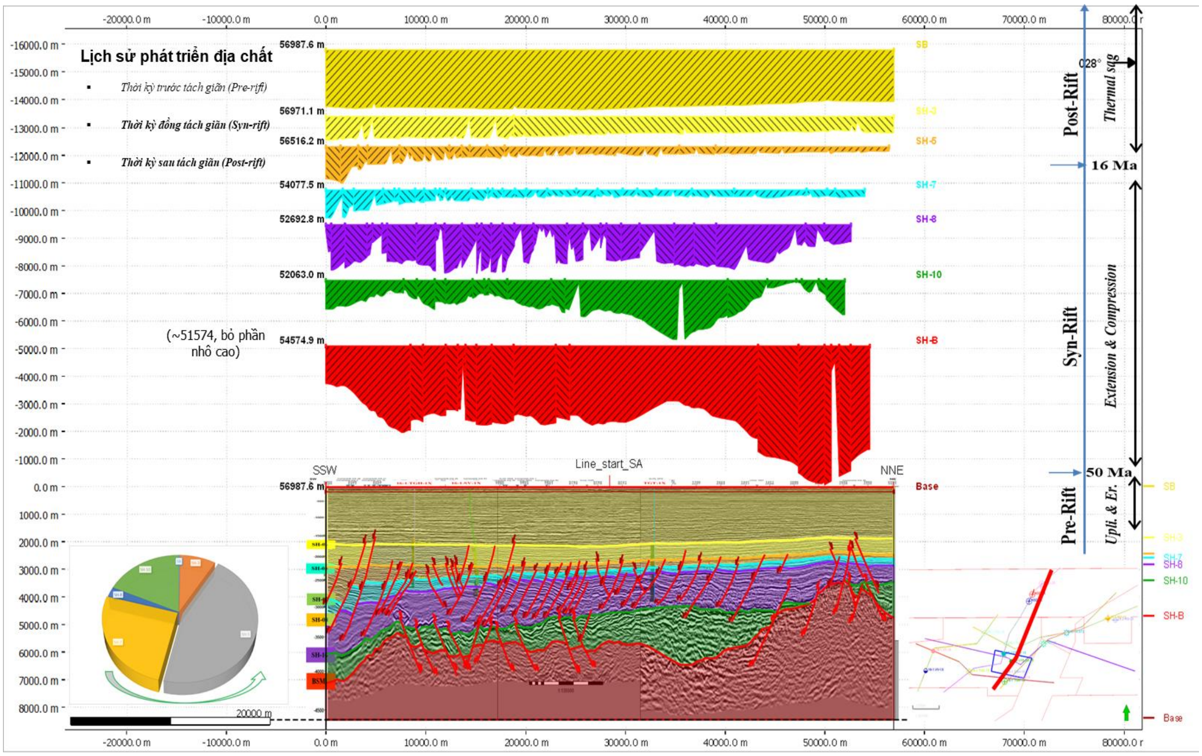
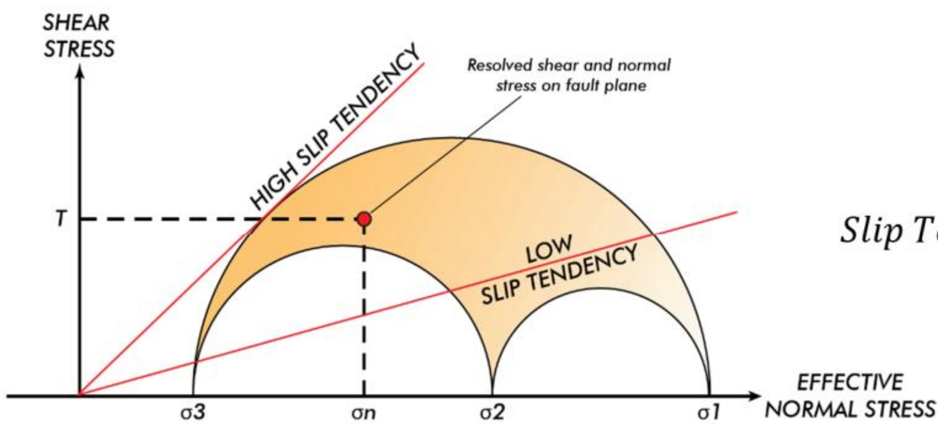


*Figure 3. Section analysis through study area.*




$$Slip\ Tendency = \frac{T}{\sigma n}$$

*Figure 4. Mohr circle illustrating the calculation of Slip tendency. The red point represents the resolved stress on one triangle of a fault mesh surface.*

Therefore, the second method, which is the most widely used for assessing fault sealing, is indirect. This method establishes a relationship between pressure (Bp - Bouyancy pressure/AFDP - Across fault difference pressure) and sealing properties on fault surfaces, such as SGR (Shale Gouge Ratio), in different reservoirs under the same geological conditions (Yielding et al., 2010; Yielding, 2015; Bretan et al., 2003; Lindsay et al., 1993; Fulljames et al., 1997). The distribution of pressure and SGR values from all fields in the area will fall below a defined threshold (seal & non-seal). This report will use the second method to assess the sealing capability of faults, with the research steps illustrated in Figure 5. More details of these methods are represented in our previous paper (Hung et al., 2023).

## 4. Fault seal analysis for F2 and its influence on oil and gas migration

The research results on the fault sealing properties include two parts: 3D Vcl model, 3D lithological model, and extracted attributes (displacement amplitude, shale gouge ratio, clay smear potential, estimated maximum hydrocarbon column height, etc.) of each fault in the study area.

The model is built based on input data including three wells (VS-1X, VS-2X, CV-1X), reservoir correlations, structural maps (SH3, SH3_Intra ... SH8_Intra1), and fault system (53 stick faults) that includes 11 selected faults for assessing their sealing potential. Instead of using a layered cake sand-shale model like some previous studies, a fabric distribution model (lithological model) is constructed for two facies (sand/shale) defined by a cut-off criterion of shale content (Vshale <50%). The facies distribution model is oriented based on seismic attribute information. The distribution model of shale content (Vshale) is constructed with orientation derived from the facies model. The model's results are reliably evaluated using the available input data for fault sealing assessment.

Fault F2 is located in the northern part of the 150 km$^2$ VS area. It is a fault with a length of over 10 km, trending in the NNW-SSE direction and dipping towards the ENE with an average angle of 48 degrees, ranging from 30 to 60 degrees (Figure 6). The fault exhibits the maximum throw of 186 m at the SH8 level, approximately 132 m at SH7, around 70 m at SH5, and 20m at SH3 (Figure 7).

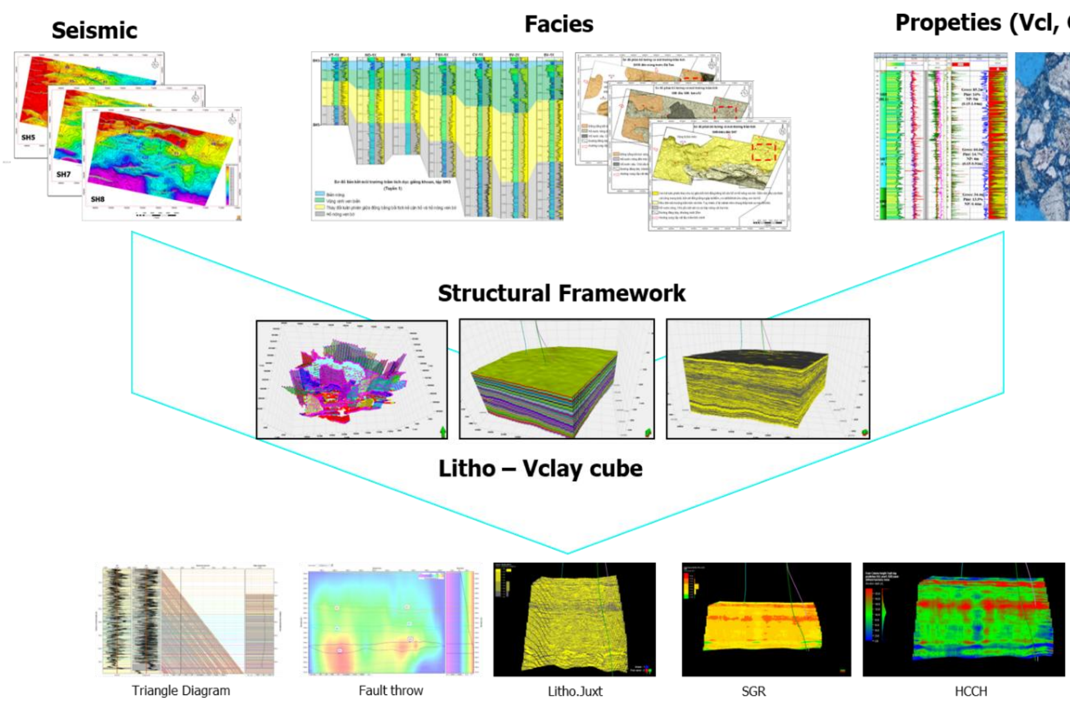



*Figure 5. Workflow for fault seal analysis.*

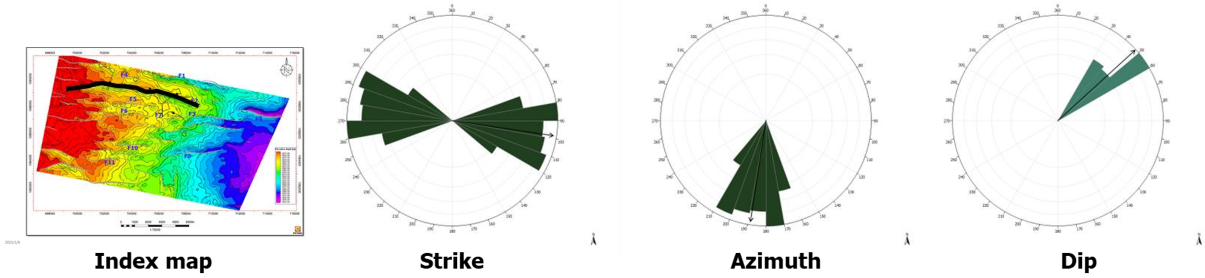



*Figure 6. Strike, dip and azimuth of fault F2.*

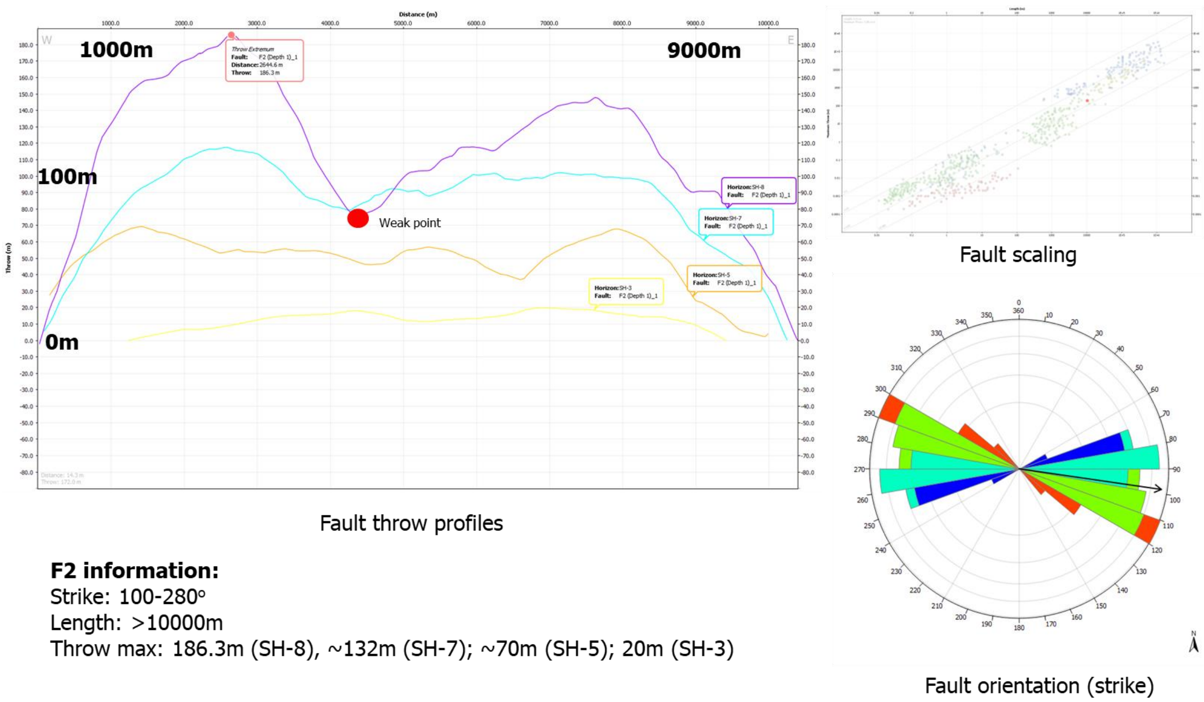



*Figure 7. Fault throw profiles of fault F2.*

This fault is of significant importance in the research area, dividing the footwall where wells CV-1X and VS-2X are located from the hanging wall where well VS-1X is situated.

The characteristics such as throw, lithological juxtaposition, shale gouge ratio (SGR), and estimated maximum sealing height of fault F2 are illustrated in Figure 9.

Based on the cross-sections and isopach maps of the study area, the following characteristics can be observed:

The normal faults are symmetric and syn-rift in nature. Based on section analysis and well data, there are variations in lithological changes and sedimentation rates. The center of the depocenter changes over the area. There are differences in thickness between the two fault wings. Therefore, the presence of symmetric syn-rift normal faults poses a challenge in fault seal studies for the research area, impacting the selection of methods and approaches for structural modeling.

The results of the 1D Triangle Diagram for well CV-1X show that for a minimum throw of approximately 20 m, the majority of depth intervals from SH3 to SH7 exhibit SGR values greater than 0.2. In this case, the fault near the CV-1X area, utilizing lithological characteristics derived from this well, demonstrates good sealing potential. To ensure complete sealing from top to bottom, a throw exceeding 186 m is required (Figure 8a).

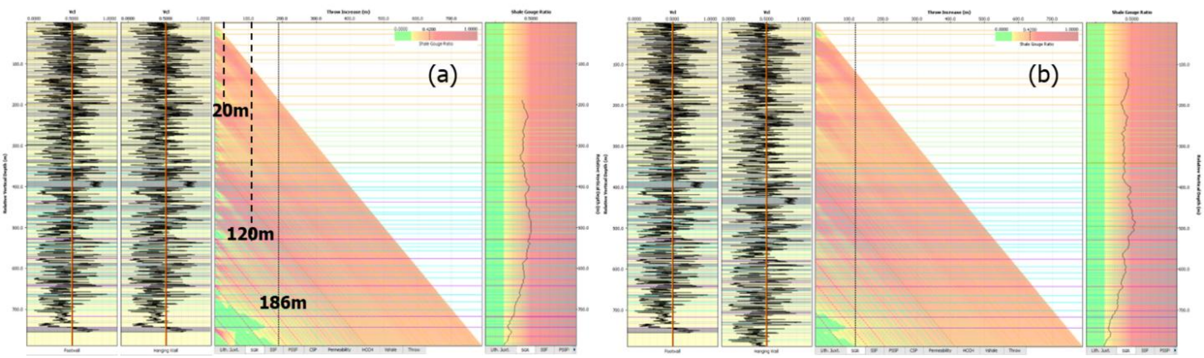



*Figure 8. 1D Triangle Diagram showing the relationship between SGR and vertical throw at well CV-1X: (a) without hanging wall growth; (b) with 10% hanging wall growth.*

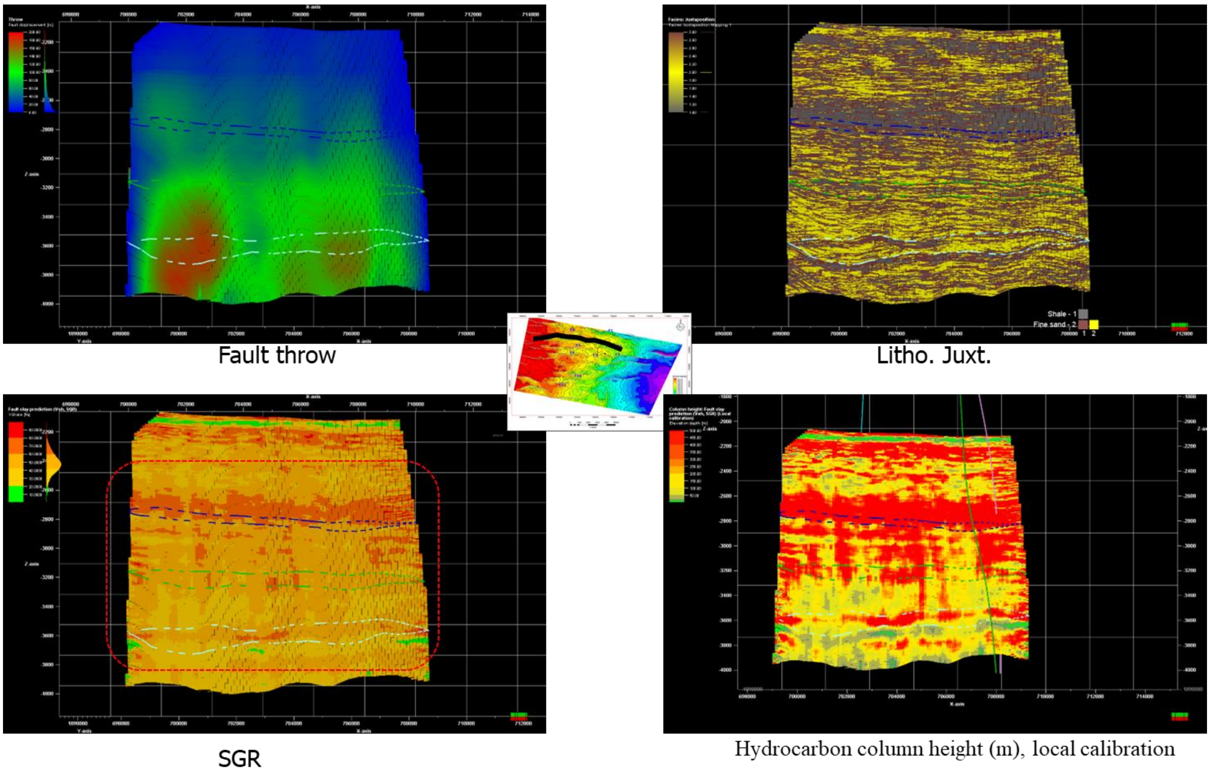



*Figure 9. Fault throw, lithological juxtaposition, SGR and hydrocarbon column height parameters on F2 fault plain.*

If additional factors such as growth faults are considered, the majority of depth intervals from SH3 to SH7 still exhibit SGR values greater than 0.2. Consequently, the faults near the CV-1X area, utilizing lithological characteristics from this well, retain good sealing potential. To achieve complete sealing from top to bottom, a throw exceeding 120 m is necessary (Figure 8b).

The research results on the sealing properties of the faults in the VS area have provided detailed information on the fault characteristics and parameters such as throw, displacement, fault juxtaposition, SGR, and maximum hydrocarbon column height for the selected 11 faults as mentioned in a previous paper (Hung et al., 2023).

Of particular importance, in the research area, there are three drilled wells located on both sides of the F2 fault. The study findings have demonstrated that the F2 fault exhibits good sealing potential in most of the geological intervals it intersects. This aligns well with the pressure differential information obtained from the pressure data of the wells in the study area. Furthermore, it increases the reliability in predicting the properties of the faults in areas with closed structures intersected by faults but lacking drilled wells, serving as a basis for selecting future exploration locations.

The F2 fault: The detailed information of the F2 fault is provided in Table 1. However, further research on the F2 fault indicates that it not only acts as an effective seal currently but also likely played a sealing role in the past (Figures 10 to 14). This is supported by the following observations:

The F2 fault is syn-rift and synsedimentary from the SH8_intra to SH5 intervals, extending into the SH3 interval, which corresponds to the overall tectonic context of the Cuu Long Basin during the syn-rift deposition of Oligocene to Early Miocene sediments.

The displacement amplitude increases progressively from SH3 to SH8, max throw from 20 m (SH3) to 183 m (SH8).

*Table 1. Parameters of fault F2 (N- normal, G- growth).*

| Features | Unit | Zone/Note | Faults |
|---|---|---|---|
| **Fault** | | | **F2** |
| **Strike** | degree | | **100-280** |
| **Azimuth** | degree | | 190 |
| **Dip** | degree | range | 30-60 |
| **Dip** | degree | Mean | 48 |
| **Length** | m | | **10000** |
| **Fault Type** | | | N, G |
| **Max Throw** | m | SH3-SH5 | **20** |
| **SGR** | % | | 30-80 |
| **Possible HC Column (m) can be hold by Fault** | m | | **31.9-469** |
| **Max Throw** | m | SH5-SH7 | **70** |
| **SSF** | Value | | **<4** |
| **SGR** | % | | 30-75 |
| **Possible HC Column (m) can be hold by Fault** | m | | **31.9-438** |
| **Max Throw** | m | SH7-SH8 | **132** |
| **SSF** | Value | | **<4** |
| **SGR** | % | | 24-72 |
| **Possible HC Column (m) can be hold by Fault** | m | | **16.5-410** |
| **Max Throw** | m | SH8_SH8_intra1 | **186.3** |
| **SSF** | Value | | **<4** |
| **SGR** | % | | 10-70 |
| **Possible HC Column (m) can be hold by Fault** | m | | **3.5-406** |

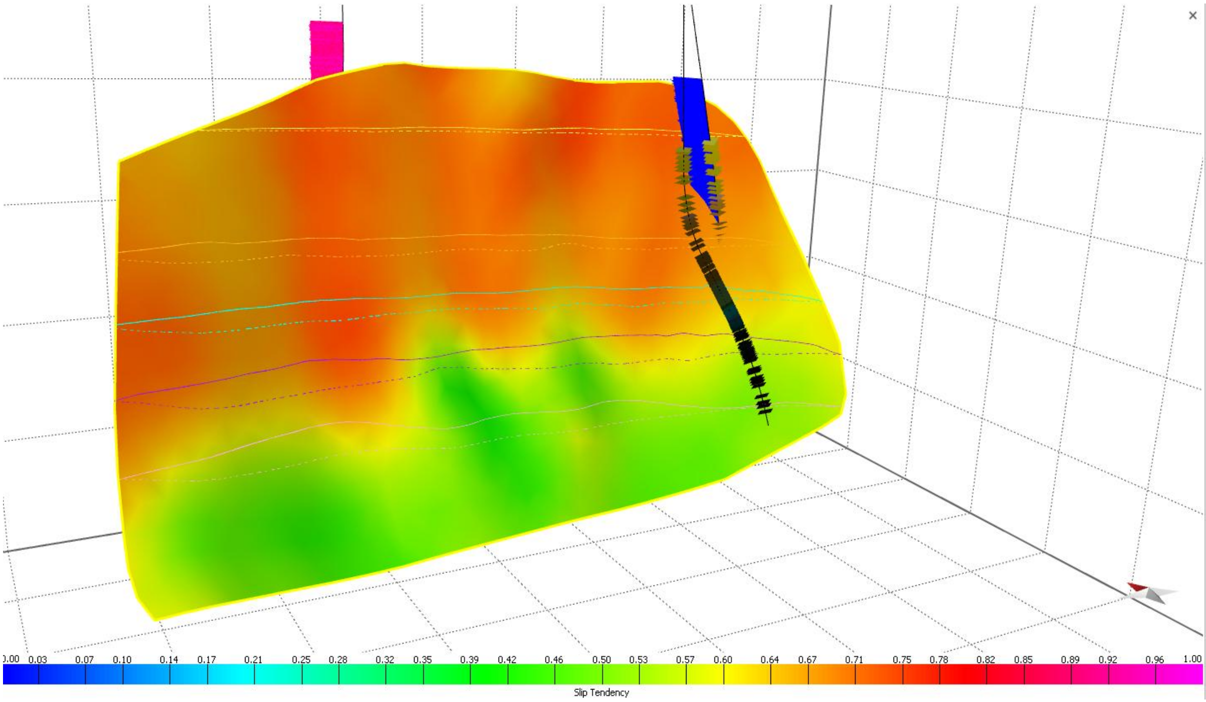



*Figure 10. Slip tendency of fault F2.*

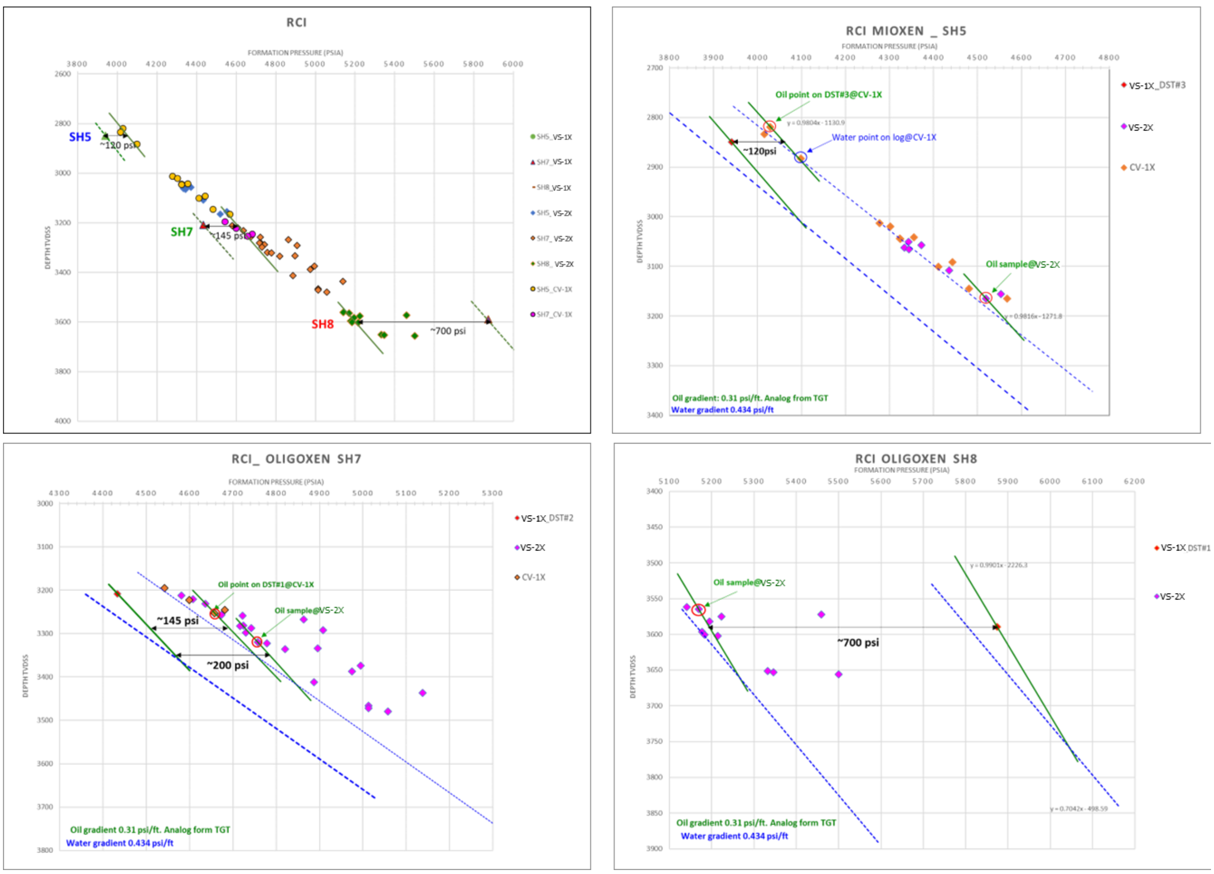



*Figure 11. The pressure data from wells CV-1X (RCI), VS-1X (DST), and VS-2X (RCI).*

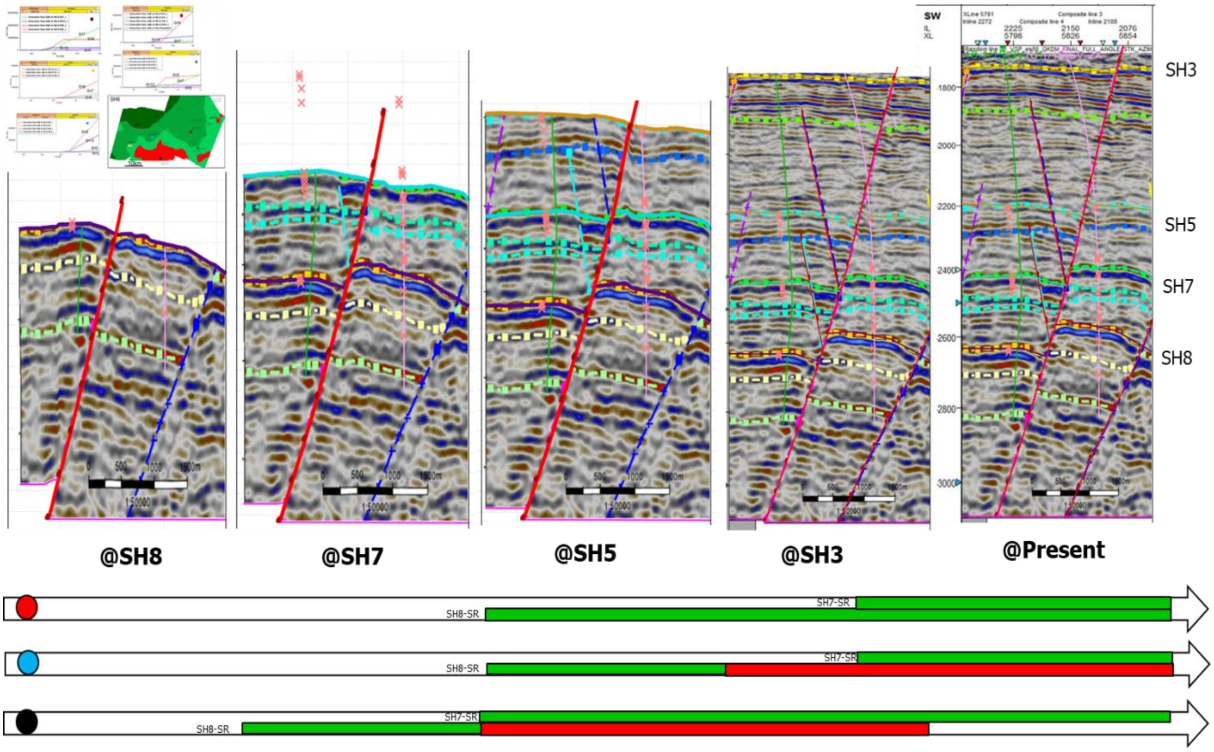



*Figure 12. Balanced cross section for fault F2 (red fault) with migration timing (red- black and blue dot are locations on top left index map).*

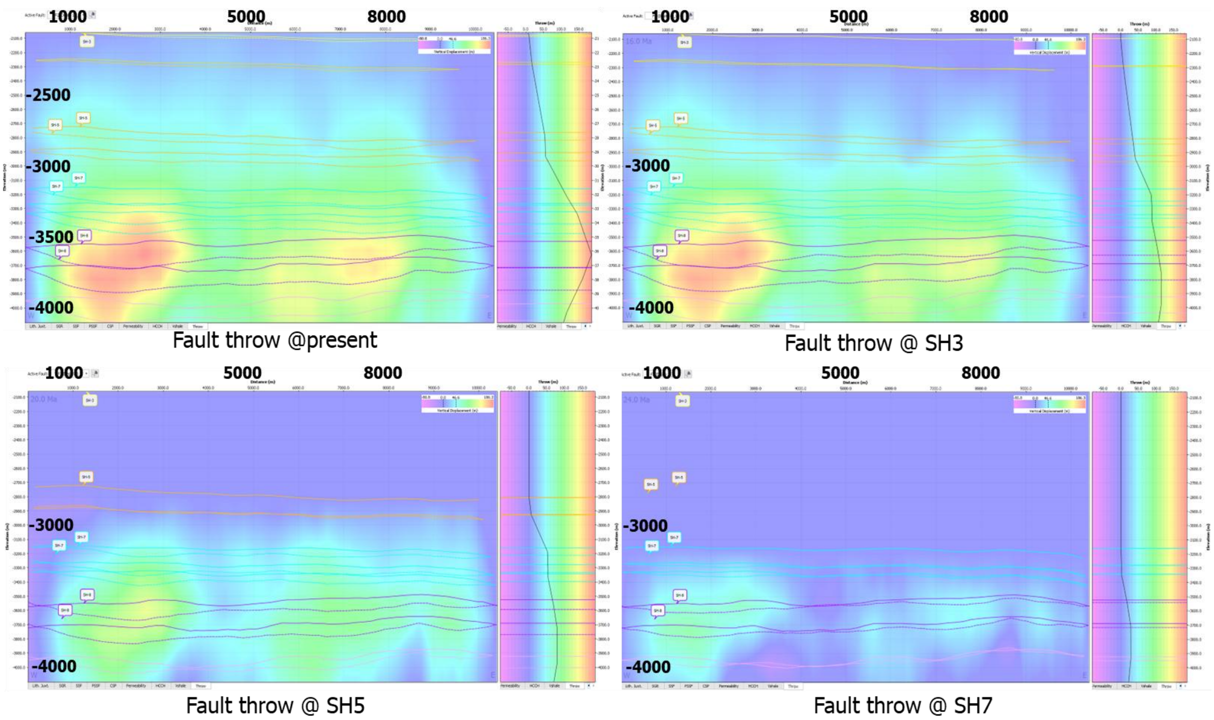



*Figure 13. The vertical displacement restoration through periods of fault F2.*

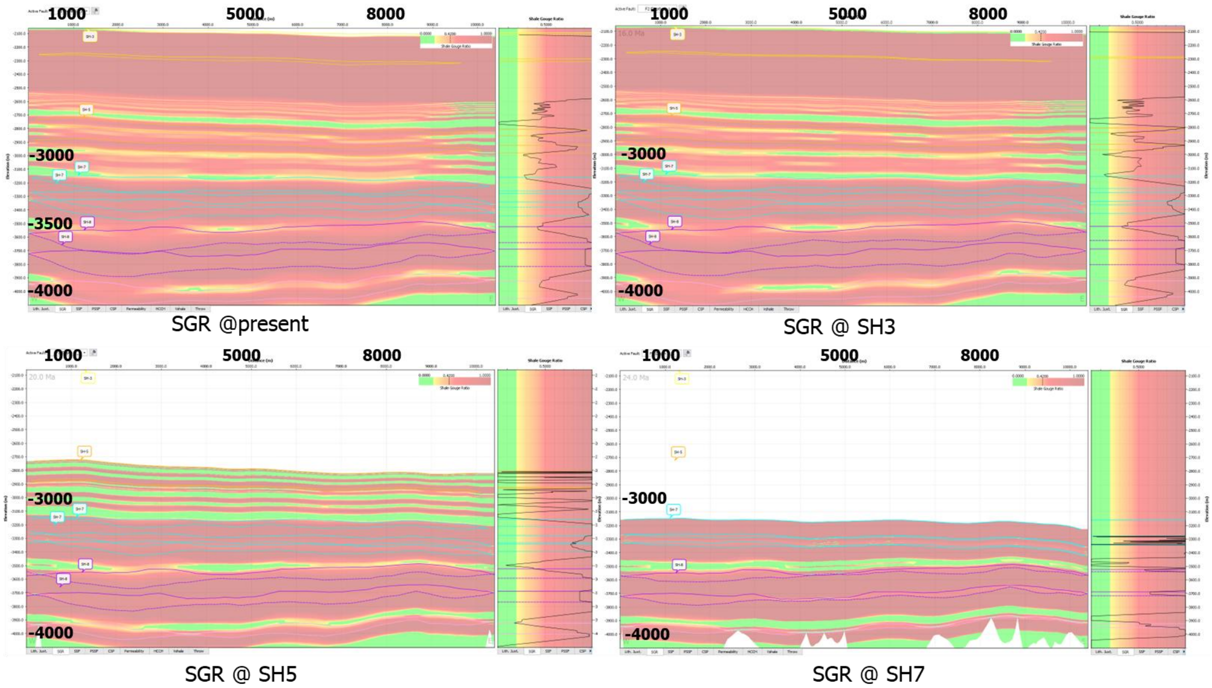



*Figure 14. The SGR restoration through periods of fault F2.*

In addition to characterizing the fault properties, the history of F2 fault activity, as inferred from throw, lithological juxtaposition, SGR, and SSF values (using the advanced layercake method), indicates that the fault provides a good seal along most fault surfaces, with a prevalent SGR value exceeding 0.2, except for a few tip points and weak points <0.2 (Figure 14).

Restoration of the fault history based on throw displacement (Figure 13) and SGR (Figure 14) reveals that the F2 fault had the potential for a relatively good seal in the past, depending on each stage.

There are several locations with slip tendency values greater than 0.6, indicating potential slip, reactivation, and providing fluid migration pathways (Moeck et al., 2009). Therefore, these factors influence the sealing capability of the fault in the hanging wall. The parameters (azimuth, dip, slip tendency, etc.) suggest multiple reactivations of the fault, which may lead to hydrocarbon escape in the hanging wall or diffusive migration (Figure 10). In general, the F2 fault, as well as other syn-rift faults formed during the extensional phase, may act as barriers to hydrocarbon migration. The F2 fault and other large-displacement faults likely acted as early seals before the generation and migration of hydrocarbons from deeper depocenters. Therefore, further research on fault seal is needed for this area. Additionally, the stronger compression on the hanging wall and the reactivation of these large faults could be one of the causes of hydrocarbon escape or diffusion in the hanging wall of major faults in the study area.

## 5. Discussion & Conclusion

The fault is located in the north of the VS area with its length of ~10 km, WNW-ESE strike and an average 48 deg dipping to SSW. The fault has a maximum throw of 186 m in SH8_intra, reducing to 70 m in SH5 and to ~20 m in SH3. The fault has segmented the Soi Vang discovery into the upthrown with CV-1X & VS-2X wells and the downthrown with VS-1X wells. Throw, estimated SGR and estimated maximum hydrocarbon column height along the fault plane are presented. The throw profile in the SH8 unit suggests the fault would be possibly merged from two segments; however, a denoted "weak point" would be at minimum risk as its throw of some 70 m with SGR of more than 20%.

The F2 fault was interpreted as a syn-depositional growth fault with SGR estimated as more than 20% indicating it is a sealing fault that can hold hydrocarbon columns down to the structural spills. The pressure data suggests a fault hold pressure difference of some 110-150 psi between the two flanks, proving its good sealing capacity as per fault seal analysis.

The F2 fault was most active during deposition of SH8 and reduced its activity toward deposition of the SH3 unit, which is aligned with the Oligocene to early Miocene syn-rift phase in the Cuu Long basin. This discussion is focused on the F2 fault using structural software to restore the throw of the fault at various times, from SH8 to SH3:

In recent, throw profiles, SGR and SSF, especially pressure data, suggest the fault has good cross-fault sealing capacity.

Restored fault throw and its related SGR suggest that the fault would still with good sealing capacity during SH7, SH5 & SH3 times. This perhaps has reduced hydrocarbon migration, both vertically and horizontally, and favored hydrocarbon accumulations within the closure.

However, a present-day Slip Tendency shows several locations along the fault plane with values of more than 0.6. It would suggest these locations would have been slipped, reactivated several times, and favored movements of hydrocarbons upward, which in contrary to the sealing capacity estimated by restored throw and its related SGR.

With no references or calibrations of restored fault throw (and its related SGR) and Slip Tendency within the Cuu Long basin, the above results need to be carefully reviewed and/or applied for any further works.

## Acknowledgments

The authors would like to express their sincere gratitude to VietsoPetro & PVEP-ITC for providing the most favorable conditions to complete this study.

## Contributions of authors

Thanh Van Nguyen - data curration, assessment and interpretation, original draft writing; Hung Viet Nguyen - conceptualization, supervision, reviewing and editing; Son Xuan Pham - conceptualization, supervision, reviewing and editing; Tam Minh Nguyen - structural interpretation, data curration; Quang Dinh Doan - structural framework and facies model building, data curration; Lap Quoc Lai - reviewing and editing.

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