Mapping of the Complex Western Boundary Fault System Using Seismic Attributes, Pattani Basin, Gulf of Thailand

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Abstract

The Pattani Basin is known to be a N-S trending extensional half-graben rift basin in the Gulf of Thailand. Seismic data from a study area in the South Pattani Basin show evidences of oblique-slip deformation forming a flower structure. The method used in interpreting the faults is known as the Automatic Fault Extraction (AFE) method, which extracts faults from fault probability seismic attribute calculated using the Ant-Tracking algorithm. The method is proven to be effective in producing interpreted fault sticks/planes with less personal bias compared to manual fault interpretation and is effective in connecting faults that are hard-linked or conjugated. Like the application of seismic attributes extraction for stratigraphy, the AFE method has weaknesses associated with 3D seismic data quality. Striations are also observed in the fault planes made by the AFE method. This is a unique fault character that has yet to be published. The method is recognized to potentially aid in unearthing fault information that has been lying dormant in the seismic data, such as fault sense of motion and fault damage zone heterogeneity characterization.

Keywords: AFE, fault striations, fault damage zone

1. Introduction

The research area is located in the western margin of the South Pattani basin in the Gulf of Thailand. Many of the hydrocarbon fields in the Pattani Basin (Funan, Satun, Erawan etc.), are highly faulted while exploration plays are fault-related. As such, detailed fault mapping is an important routine but time-consuming part of seismic interpretation. The ultimate goal of fault interpretation is to create interpreted fault sticks/planes that accurately represent seismic faults observed in the 3D seismic data.

The AFE method has been commended for achieving highly detailed mapping of faults while reducing interpretation time (Pedersen et al, 2004). This experimental project tested the effectiveness of the AFE method in the given 3D seismic data within a complex faulted area, to determine its advantages against the conventional manual line-by-line seismic interpretation method.

2. Methodology

In seismic data, a fault is represented as reflection cut-off and changes in amplitude of reflection character. These are characteristics of Non-reflective faults (Non-RFs) which can be Negative amplitude reflection fault (Neg-RFs) observed in the project seismic data (Figure 1). and Positive amplitude reflection fault (Pos-RFs) present in the project seismic data are fault reflections. Some of these imaged faults are observed to have changing polarities. The basin-bounding fault consists of Non-RFs and Neg-RFs while the major synthetic fault composes of all three mentioned seismic fault types.

A slightly different process of creating fault interpretation sticks/planes is used for different seismic faults in this project (Figure 2). Fault imaging is not necessary for Pos- and Neg-RFs because they have been imaged in the original seismic data. Applying the Variance (Edge) on them would result in the zero-crossings to be imaged as they are where the highest variance is found. This can cause the reflective faults to be extracted from the wrong location, if used.

In this project, noise is seismic signal that can contribute to the creation of fault patches that do not represent faults. This includes stratigraphic edges (eg. channels), acquisition footprints and edges of shadow zones which are present in the seismic data. Data conditioning, fault enhancement and fault probability attributes are complementary steps applied to lessen the inclusion of noise when fault patches are extracted. Fault patches are small surfaces of faults that have to be merged before they are converted into interpreted fault sticks/planes.

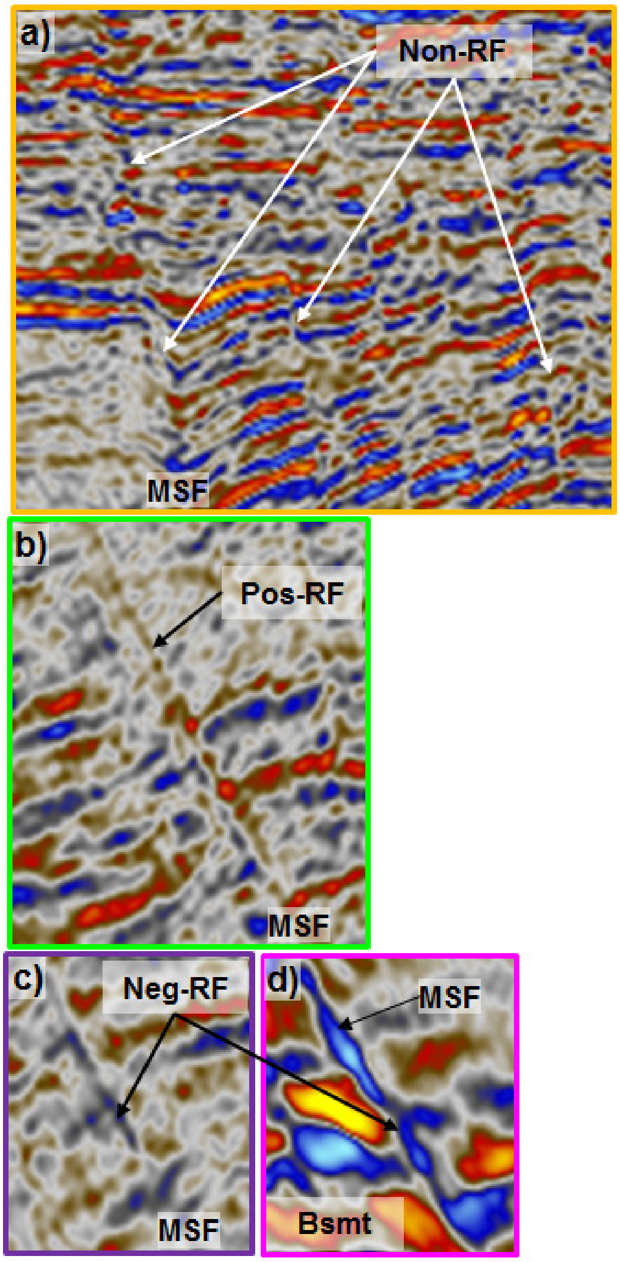

Figure 1: Example of different seismic faults along the MSF. a) Non-reflective fault (Non-RF). b) Positive amplitude reflection faults (Pos-RF). c) Negative amplitude reflection faults (Neg-RF). MSF= major synthetic fault, Bsmt= basement.

Fault patches are created using the AFE method. In AFE, fault patches are extracted from the Ant-Tracking attribute volume (Figure 3-a). Fault patches are generated along trends of the highest value in the Ant-Tracking. AFE patches (Figure 3-b) that belong to the same fault are identified and merged (Figure 3-c) to ideally form one fault patch to represent a single fault. Lone fault patches are regarded as extracted from noise and are not included although there are some possibly from small faults/fractures.

When fault patches merging is completed, they can be converted to fault sticks/planes.

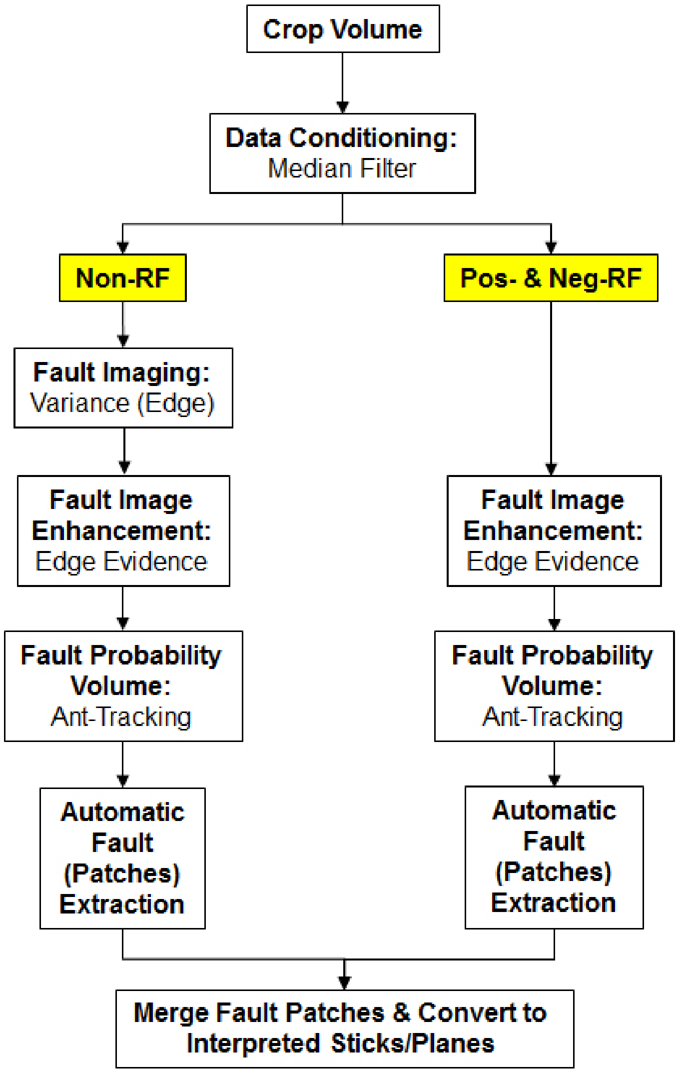

Figure 2: AFE workflow.

3. AFE Method Effectiveness

The AFE method is effective in picking major faults as they appear as high values in the Ant-Tracking Fault Probability volume. Fault patches belonging to the same fault planes can be easily identified (Figure 3-a) for merging. This is extremely helpful in highly faulted areas as it eliminates the effort and time in connecting the right faults between seismic lines when interpreted manually. However, the AFE method also has weaknesses.

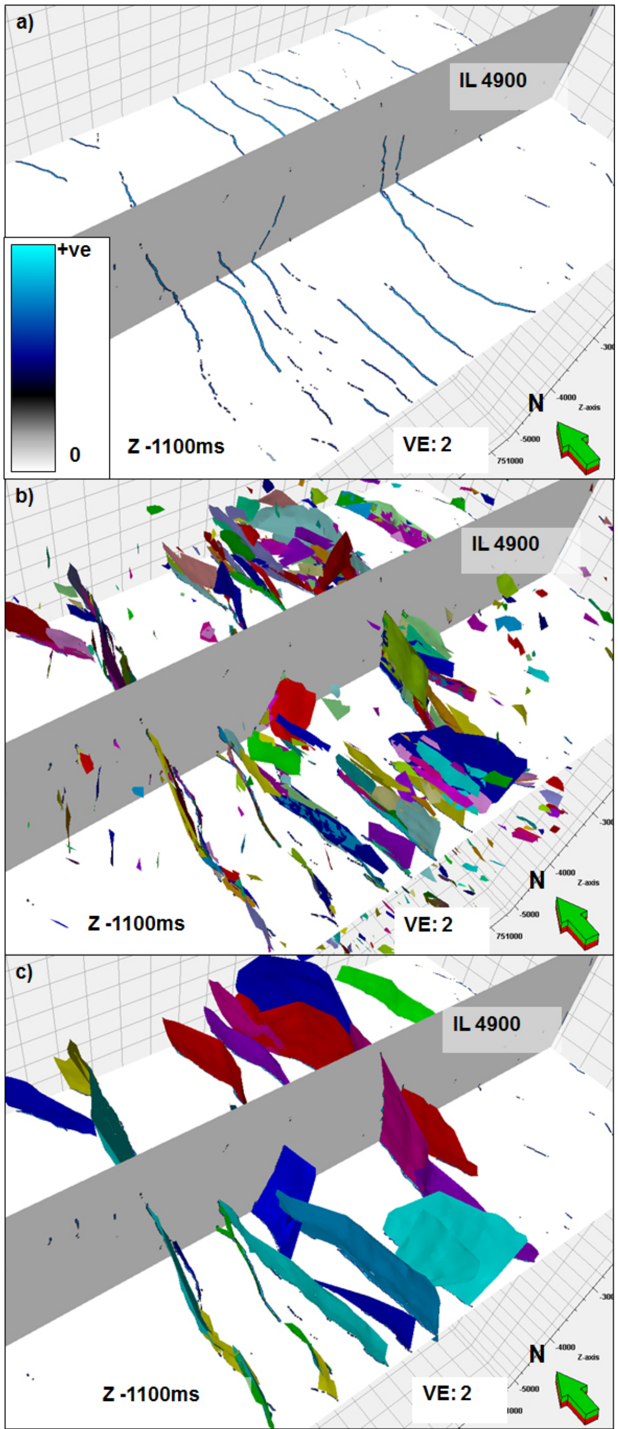

Figure 3: a) Non-RF Ant-tracking volume. b) Fault patches extracted from the Ant-tracking volume. C) Merged Non-RF fault patches.

The Non-RFs are only imaged in intervals of high reflectivity (Figure 4) whereas Pos- and Neg-RFs were only enhanced where reflectivity is strong. As such, this method is not effective for Non-RF where reflectivity is low such as shale-rich intervals and shadow zones under gas sands. For Pos- and Neg-RFs, the AFE method becomes less effective if the amplitude along the fault becomes dim. Although discontinuous fault patches can be merged to improve a particular fault's continuity, its tips cannot be extended. The extension of the fault tips can be done after the fault patches are converted into interpreted fault sticks/planes. This is done by manually lengthening them by moving the fault stick nodes or adding more fault sticks.

4. Mappable Fault Relationships

Hard- and soft-linked and conjugated faults are effectively extracted using the AFE method. Figure 5 shows some examples of hard- and soft-linked and conjugate faults in the project area. As AFE faults can be shorter than seen in the original seismic data, it is recommended that soft-linked faults be verified against original seismic data.

5. Striations on Fault Planes

Striations are detected on reflective faults' merged patches (Figure 6). Striations azimuth on different faults have different directions. These are interpreted to be large-scale linear grooves made on fault planes when fault blocks slide against each other. Striations seen in outcrops are used as evidence of the sense of movement of the last fault reactivation.

If these seismic fault plane grooves are proof of fault sense of motion, then the basin-bounding and major synthetic faults are oblique-slip faults. Assuming the striations are from the last reactivation of the basin-bounding and major synthetic faults which involves a normal dip-slip component, the NW-SE trending basin-bounding fault is a sinistral transtensional fault. Using the same assumption, the near N-S trending major synthetic fault is a dextral transtensional fault, with a very small strike-slip displacement component.

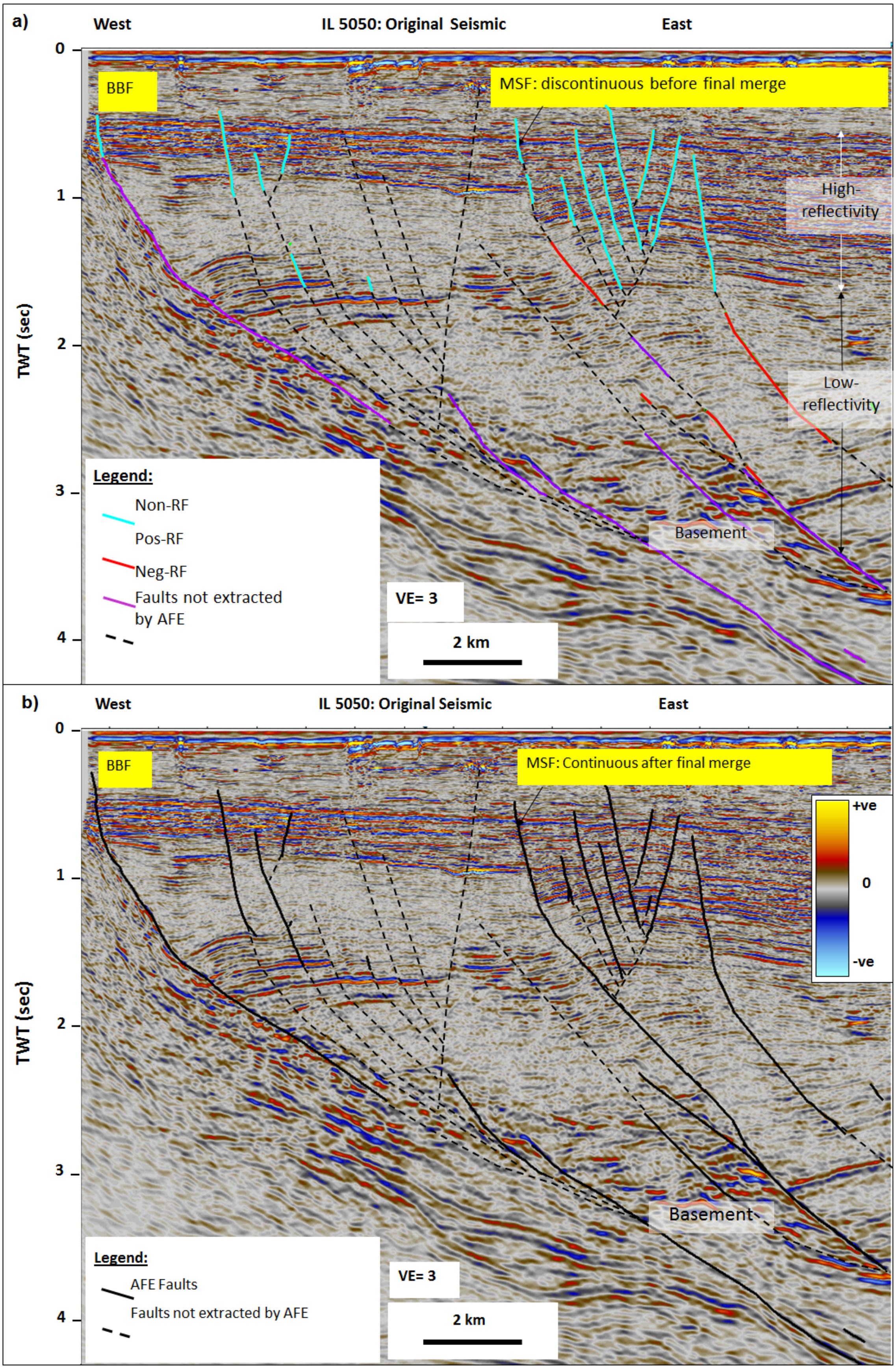

Figure 4: a) AFE faults have a discontinuity problem which can be, b) improved with a final merge of all the patches extracted from different seismic fault types. BBF= basin-bounding fault, MSF= major synthetic fault.

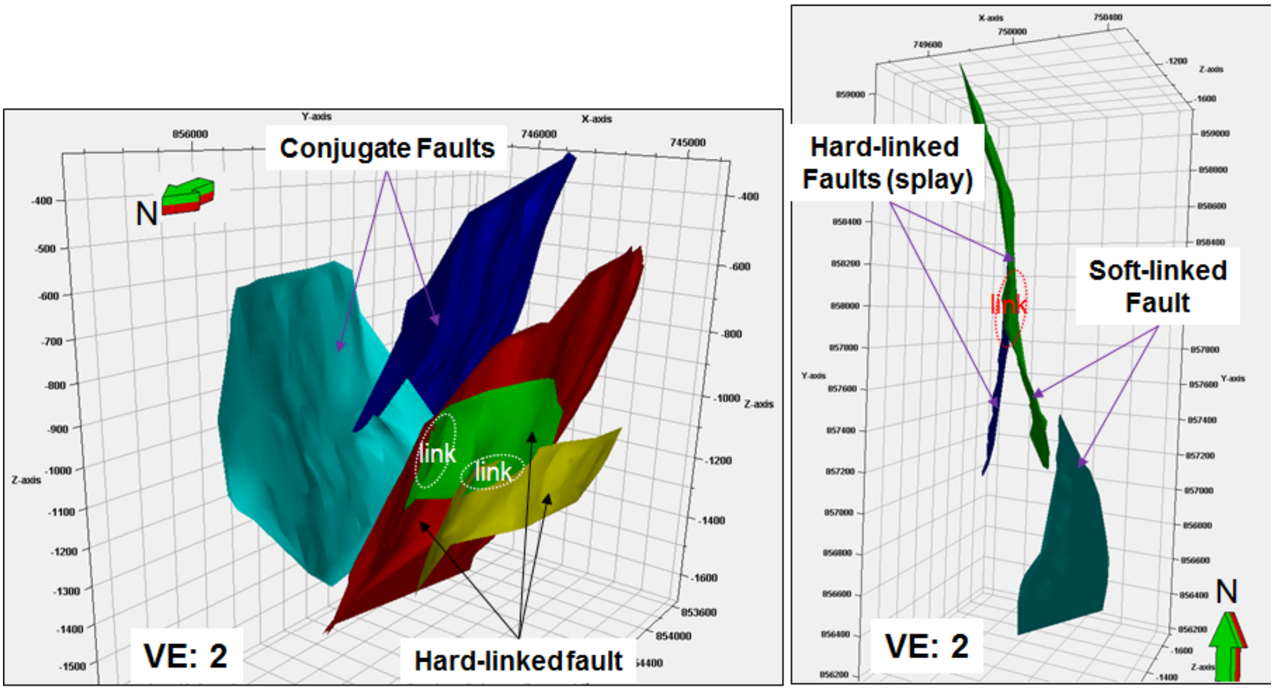

Figure 5: Examples of mapped fault relationships driven by data.

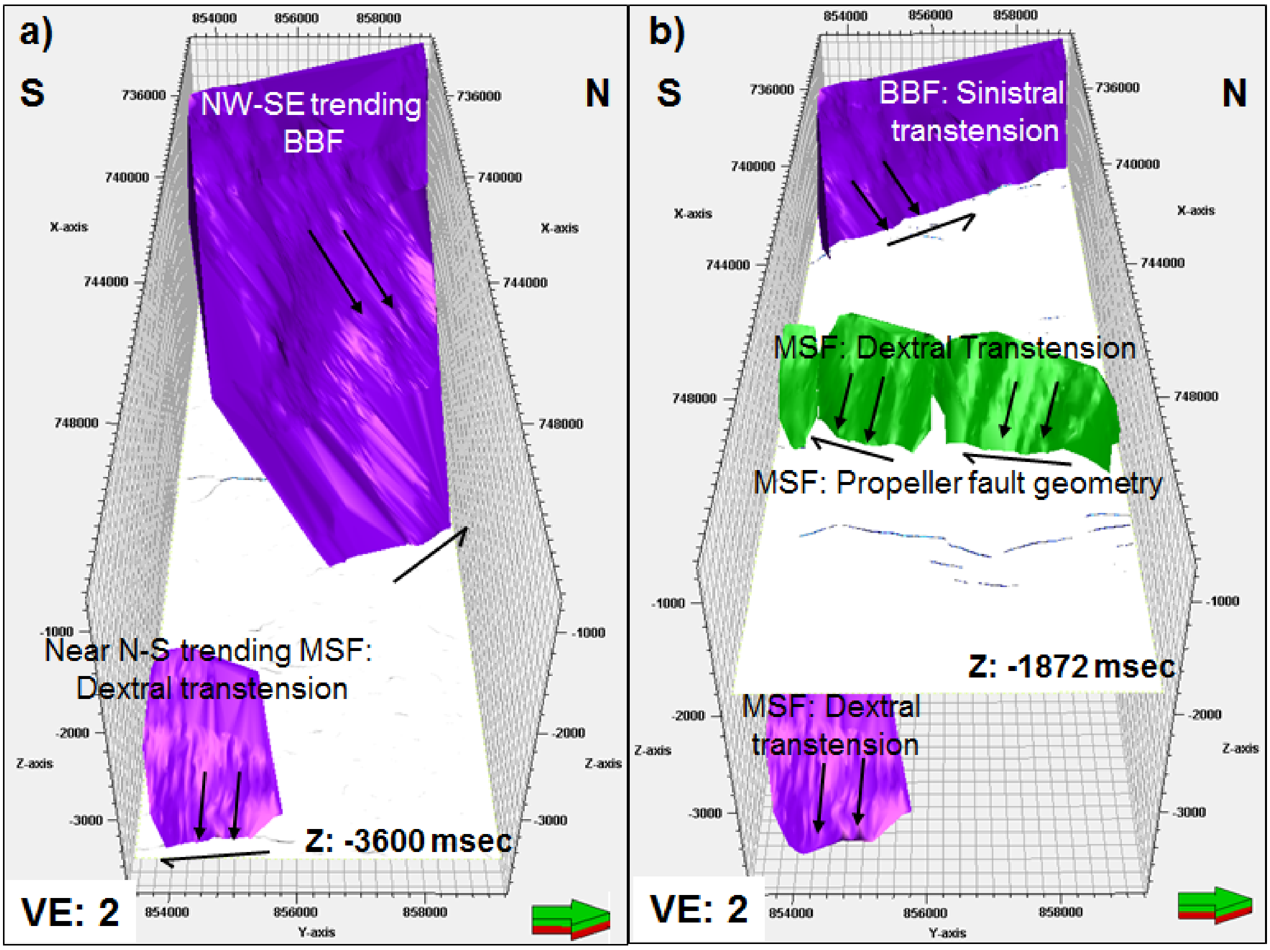

Figure 6: Large-scale striations observed on merged extracted reflective fault patches. BBF= basin-bounding fault, MSF= major synthetic fault.

However, the implications of the striations are in disagreement with the Charusiri et al (2002) model where it states that after the Indian-Asian collision, NW-SE trending faults should have a dextral strike-slip movement component. Palinspastic reconstruction that includes fault block rotation might resolve the conflicting interpretations based on observed seismic fault striations. Other possible explanations are the striations are geological features not produced by fault blocks movement, artifacts from the methodology or the Charusiri et al (2002) model needs to be revisited.

The AFE method of mapping faults brought out striations on seismic fault reflections that has yet to be reported. This fault feature would have continued to be unnoticed had the reflective faults been interpreted manually, which produces smoothed surfaces. A better understanding of the true nature of reflective fault plane striations can be achieved in future studies in different basins.

6. Fault Damage Zone Characterization

Section of faults that juxtapose Tertiary sediments against the pre-Tertiary Basement is observed to have a strong negative amplitude. This is seen in the basin-bounding fault as well as the major synthetic fault.

Within the Tertiary section, the major synthetic fault in particular is found to display changing polarity along its reflective fault section. The reflective section of the major synthetic fault is also observed to be cutting through low bedding reflectivity seismic facies package and changes to become non-reflective in high bedding reflectivity seismic facies package (Figure 4). The low bedding reflectivity seismic facies package is interpreted as a shaly section while the high bedding reflectivity seismic facies package is interpreted as a sand-shale interbedded section.

Immediate to the fault plane/core is a zone of damaged host rocks known as the fault damage zone characterized by deformations bands, shear fractures and joints. In a siliciclastic basin, deformation bands only affect porous rocks such as sandstone and siltstone. There are four types of deformation bands, classified by deformation mechanisms. Phyllosilicate and especially cataclastic bands reduce porosity and permeability, while disaggregation bands alter host rock porosity and permeability minimally unless aided by dissolution or cementation (Fossen *et al,* 2007).

As the reflective section of the major synthetic fault cuts through the low bedding reflectivity zone, assumed to be a shale-rich zone, it is assumed that phyllosilicate bands that reduce porosity are probably the more prevalent deformation bands there. This essentially means that the major synthetic fault reflection could represent a “layer” of rock with denser and higher velocity rock properties (higher acoustic impedance) than the host rocks, as a result of reduced porosities mostly by “shale-smear” deformation bands.

Fault reflections occur where there is rock properties heterogeneity. These heterogeneities may be related to a change in rock mineralogy, volume of pores within the rock, fluid type within the pores. In addition, Dutta (2002) associated high shale content in fault gouge sealing faults with pressure build-up on one side of a fault. This results in differential compaction between fault blocks and the undercompacted (overpressured) fault block has lower velocities. This concept appears applicable to the major synthetic fault.

The Lower Miocene section of the South Pattani Basin has mild overpressures (Racey, 2011). Overpressure is common in synrift growth faulting sedimentation due to constant replenishment of accommodation space. If sedimentation rates are high, fresh sediments are not given enough time to dewater, to normalize pore pressure with overburden pressure. This is especially true in shaley intervals where pore fluids are trapped by effective shale top seals. The trapped pore fluid and constantly subsiding basin creates a higher-than-normal pore pressure at depth. When overpressured undercompacted host rocks juxtapose against a denser and higher velocity “layer” of shale smeared fault damage zone, the lateral heterogeneity should produce reflections.

As the major synthetic fault also cuts into known hydrocarbon source intervals, Units I, II & III, overpressure could also be caused by migration of hydrocarbon into "pockets" in the fault zone that are relatively porous. Therefore, one possible explanation for the major synthetic fault's changing reflection polarity is heterogeneity along the fault zone. Another consideration is that gas significantly reduces bulk density and velocity in rocks. This fluid effect is another possible explanation for the changing reflection polarity in the major synthetic fault. A last possible explanation is that fault reflectivity is an effect of high angle reflection, which can happen when reflectors at dipped higher than 30°.

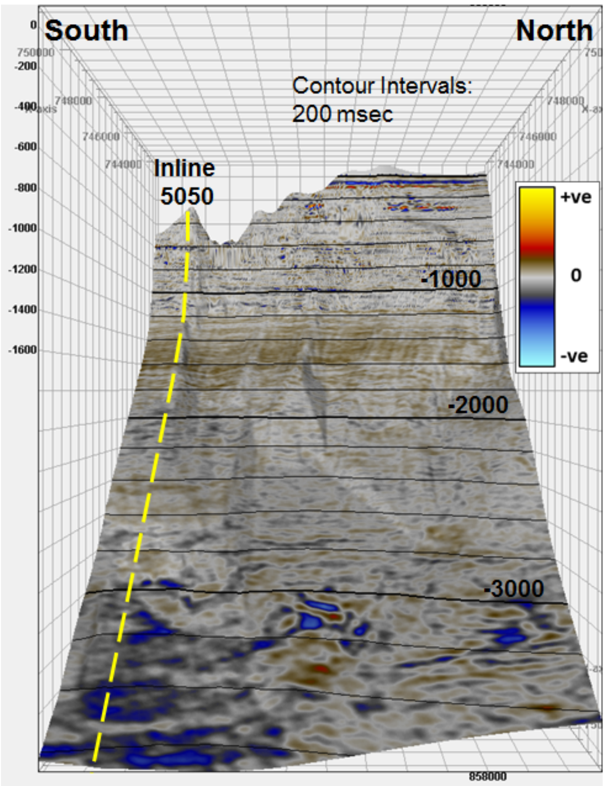

Figure 7: 3D view of the major synthetic fault surface with extracted seismic amplitudes.

Well data is needed to verify those possible explanations. Otherwise, the amplitude distribution of the major synthetic fault surface in 3D view shown in Figure 7 as an indicator for tight (negative amplitudes) or relatively porous (positive amplitudes) areas zone that can be filled with gas (also positive amplitudes) within a fault zone is only a possible interpretation. All seismic images have the possibility of being mere artifacts.

The ability to characterize seismic fault damage zones has enormous benefits in the overpressured South Pattani Basin for safer across-fault drilling operations. If sealing sections of faults can be determined from non-sealing ones, hydrocarbon fault-seal risk assessment can also be done with better certainty. Seismic fault zone characterization could assist in hydrocarbon migration studies where faults are concerned. More attention is needed for the study in fault damage zone geology and its seismic imaging in the future.

7. Flower Structure and Rollover Anticline

The anticline bounded by the major synthetic fault (Figure 8), is one of two anticlines in the study area. There are evidences of abrupt thickness and facies variation across the major synthetic fault and inconsistent vertical fault displacement. The fault is also basement-involved and splayed at a tilted fault block margin, which forms localized basement relief. As such, it is interpreted that the anticline is part of a positive flower structure that formed at a restraining fault bend.

The localized basement relief is very likely the Principal Displacement Zone (PDZ) of the flower structure. The association between basement ridges with flower structures has also been observed by Mansor et al (2014) in the adjacent Malay Basin, although the basement ridges were not specifically termed PDZs.

As the South Pattani Basin is a rift basin, growth fault sedimentation is present and thus, rollover anticlines can be present as well. An antiform is created when a growth fault is reactivated and sediments on the hangingwall block loses support from the footwall block and collapses under its own weight. When sediments near the growth fault collapses, a mini wedge-shaped accommodation space is created that can be filled-in by newer sediments. The wedge-shaped accommodation space can become a river valley or alluvial plain where sand deposition is concentrated. As such, rollover anticlines do not just provide structural trap for hydrocarbon but also potentially thicker stacked reservoirs.

The basin-bounding fault is a growth fault. The antiform observed at the downthrown side of the basin-bounding fault might be a rollover anticline which may also have flower structure overprints as there are indications that the basin-bounding fault could be part of another flower structure. The basin-bounding fault and other faults appear to splay from a localized basement relief.

The AFE method produced quicker mapping results than expected. The time saved afforded time for the unplanned structural geology analysis.

8. Conclusion

The AFE method is highly recommended for fault interpretations with less personal bias. It can assist in providing an independent dataset for the interpretation of deformation regime and basin evolution. This method decreases the uncertainty of fault-bounded hydrocarbon trap size mapping. It has proven to be effective in detailed mapping of hard- and soft-linked and conjugated faults.

Additionally, the AFE method can potentially aid in unearthing fault information that has been lying dormant in the seismic data. New fault information observed in this study could be fault zone imaging and fault plane striations. Fault zone heterogeneity imaging could be used for the study of overpressure, fault seal and hydrocarbon migration. Fault plane striations can be used for observing the sense of movement of the last fault reactivation and improve structural geology knowledge-base. This can be used in any structural deformation regime. Generating and quality-checking each seismic attributes volume for fault extraction is time-intensive, but the identified best parameters can be reused many times over in different parts of the same seismic survey for quick results. As the quality of the AFE faults are controlled by

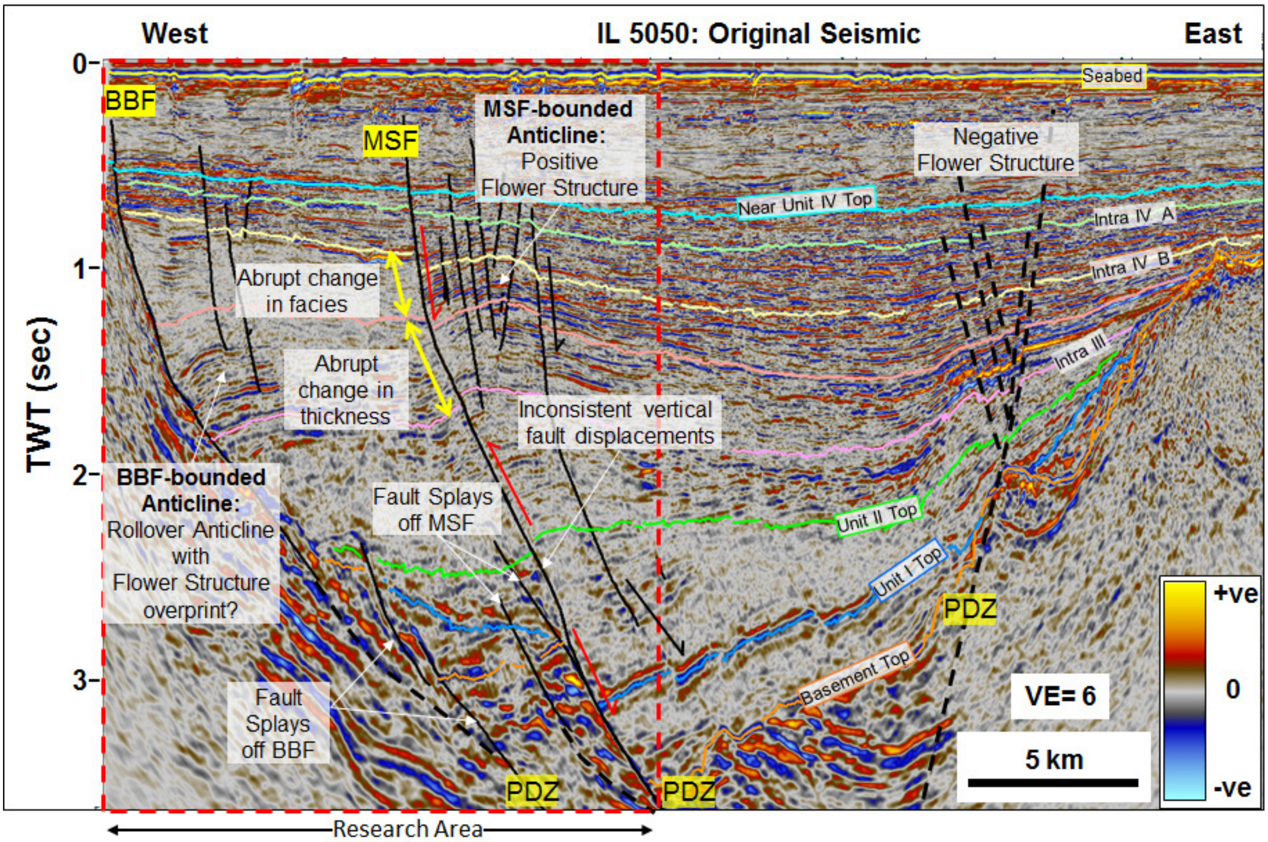

Figure 8: Indications of Flower Structures and Rollover Anticline. BBF= basin-bounding fault, MSF= major synthetic fault, PDZ= principal displacement zone.

the quality of the original seismic data, seismic data should be acquired optimally to bring out faults in seismic. It is also important to maximize the removal of acquisition artifacts and correctly migrate the data to restore energy back into fault and gas shadow zones in seismic processing. Stratigraphic noise can be removed with the workflow used.

9. References

Charusiri, P., Daorerk, V., Archibald, D., Hisada, K. & Ampaiwan, T., 2002. Geotectonic evolution of Thailand: A new synthesis. Journal of the Geological Society of Thaailand, no. 1, p. 1-20.

Dutta, N. C., 2002. Geopressure prediction using seismic data: Current status and the road ahead, Geophysics, 67(6), p. 2012-2041.

Fossen, H., Schultz, R. A., Shipton, Z. K. & Mair, K., 2007. Deformation bands in sandstone: a review, Journal of the Geological Society, London, v. 164, 2007, p. 755-769.

Mansor, M. D., A. Rahman, A. H, Menier, D & Pubellier, M., 2014. Structural evolution of Malay Basin, its link to Sunda Block tectonics, Marine and Petroleum Geology, v. 58, Part B, p. 736-748

Pedersen, S. I., Skov, T., Randen, T. & Sønneland, L., 2004. Automatic Fault Extraction Using Artificial Ants, in Iske, A. & Randen, T. (eds.), Mathematical Methods and Modelling in Hydrocarbon Exploration and Production, volume 7 of Mathematics in Industry, Berlin, Heidelberg, New York, Springer, 2005, p. 107-116.

Racey, A., 2011. Petroleum Geology, in Ridd, M.F., Baeber, A.J. & Crow, M.J., eds., The Geology of Thailand, London, Geological Society, p. 351-392.