STRUCTURAL RECONSTRUCTION OF NW SABAH: THE PREPARATION AND IMPORTANT STEPS IN RESTORATION FOR ONSHORE AND OFFSHORE DATA

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ABSTRACT

One of the ways to study and understand the history of deformation and structural evolution of an area is by using the structural reconstruction technique based on the outcrops and seismic data. The objectives of this paper are to study the reconstruction processes and determine suitable algorithms for restoration of structures in an extensional and compressional regime. Structural reconstruction is tested to understand the evolution of the Kudat Peninsula, which eventually will illustrate the pre-deform condition of the area prior to the structuring and deformation events. The reconstruction process involves the importing of input and parameter, determining the section trace, digitizing the structures from the cross-sections, creating the polygons, data allocation and restoring the section using the best method provided in Move software. Both onshore and offshore cross-sections are used in section reconstruction and later developed into a kinematic model to represents the deformation history of the area. Fault Parallel Flow (FPF), Simple Shear (SS) and Trishear algorithms are suitable methods for the restoration of the structures in the Kudat Peninsula and its offshore.

Keywords: Kudat Peninsula, Move software, kinematic model, outcrops, seismic data

INTRODUCTION

Northern Sabah had undergone three major episodes of deformation [1] consisting of sedimentary and igneous rocks of Early Cretaceous to Pliocene age, has experienced three major episodes of deformation associated with NW-SE and N-S oriented compressions. The earliest episode deformed and uplifted an oceanic basement (Chert-Spilite Formation that is believed to occur due to rifting and the subduction of the Proto South China Sea beneath Sabah. Tectonic compressions produced from the opening of the South China Sea during Oligocene to Middle Miocene [2] and [3] had intensely imbricated and deformed Northern Sabah including Kudat Peninsula [4]. Kudat Peninsula nowadays exhibits a complex structural style with the presence of folds, refolded folds, and faults [1], [5]-[6]consisting of sedimentary and igneous rocks of Early Cretaceous to Pliocene age, has experienced three major episodes of deformation associated with NW-SE and N-S oriented compressions. The earliest episode deformed and uplifted an oceanic basement (Chert-Spilite Formation as a result of these continuous tectonic compressions. These structures can be observed clearly in each member of the Kudat Formation referred to as Tajau, Sikuati and Gomantong Member [7]. Poor age control of Kudat Formation makes it difficult to determine the exact timing of the structuring and deformation [8] consisting of sedimentary and igneous rocks of Early Cretaceous to Pliocene in age, has undergone several episodes of deformation, the earliest episode of deformation which was responsible for the deformation and uplift of the basement rock (chert-spilite formation.

Uncertainties arise regarding the geological evolution and the deformation episodes of Kudat Peninsula as the structures had evolved through a continuous deformation. Structural reconstruction is applied purposely to study the geological deformation process, structural evolution, and assessment of the hydrocarbon play. The study of [9] had adapted section restoration in assessing the hydrocarbon play of Nile Delta, meanwhile [10] had used this method to demonstrate the forces involve in the deformation of Baram Delta in Sarawak. However, this paper focuses on the application of structural reconstruction in improving the understanding of the structural history and structural evolution of this area. The objectives of this paper are to study the reconstruction process and determine the suitable algorithms for the structural restoration of the study area.

The section restoration method is implemented to investigate the reconstruction process and the suitable algorithms for the tectonic setting of the Kudat Peninsula. Generally, there are seven algorithms used in section balancing and restoration [11] and linear transformation equations produce homogeneous strain. Most existing restorations use linear transformations, and many assume simple shear strain, a special case of linear transformation. Linear transformations (such as simple shear which are the Simple Shear, Fault Parallel Flow, Rigid Body Analysis, Fault bend Fold, Detachment Fold, Fault Propagation Fold, and Trishear. Each algorithm is used in specific conditions depending on the tectonic settings. Balanced and restorable cross-sections honouring all the data are constructed to analyze the pre-deformed setting of rocks and rock behaviour during the deformation in the related tectonic setting. Accuracy of the structural data collected and interpreted will generate a more logical and acceptable restoration result [12].

ESSENTIAL DATA AND RESTORATION PROCESS

Kinematic models of the Kudat Peninsula and its offshore are constructed based on the geological cross-sections. The development of geological cross-sections for onshore and offshore of the Kudat Peninsula are based on field recording of the strike and dip and seismic interpretation. Geological fieldwork was conducted to find the possible outcrops along the onshore acquisition lines. A total of ten (10) outcrops descriptions on the lithology and strike/dip measurements of beddings, faults and folds were observed. Complimenting these data are the seismic line acquired in the onshore of Kudat Peninsula for the detail subsurface interpretation. Section construction and balancing involve five (5) basic steps that are importing the input and parameter required, determining the section trace, digitizing the structures from the cross-sections and creating the polygons, data allocation, and restoring the section using the best method. The simplified workflow of the process of developing the kinematic model of the Kudat Peninsula and the transition zone using the available data is shown in Figure 1. The results and discussion shared in this paper are based on the onshore seismic line, herein mentioned as Line K9 and offshore transition line, herein mentioned as TL6.

Development of the kinematic models

The orientation of the sections was determined based on the trace orientation suggested by the Move software and the orientation of the seismic line. All the horizons, structures and lithological units in the geological cross-section were digitized into a 2D kinematic section in the software, followed by the creation of polygons. The creation of polygons in the seismic section represents the sections to be restored [13]. Once the polygons are fully created, the physical rock properties and stratigraphic input were assigned to each unit. The rock properties values were obtained from laboratory analysis, where sandstone samples collected were further analyzed for rock properties analysis such as porosity, permeability, density, Poisson's ratio, and Young modulus. The results of this analysis are presented in Table 1.

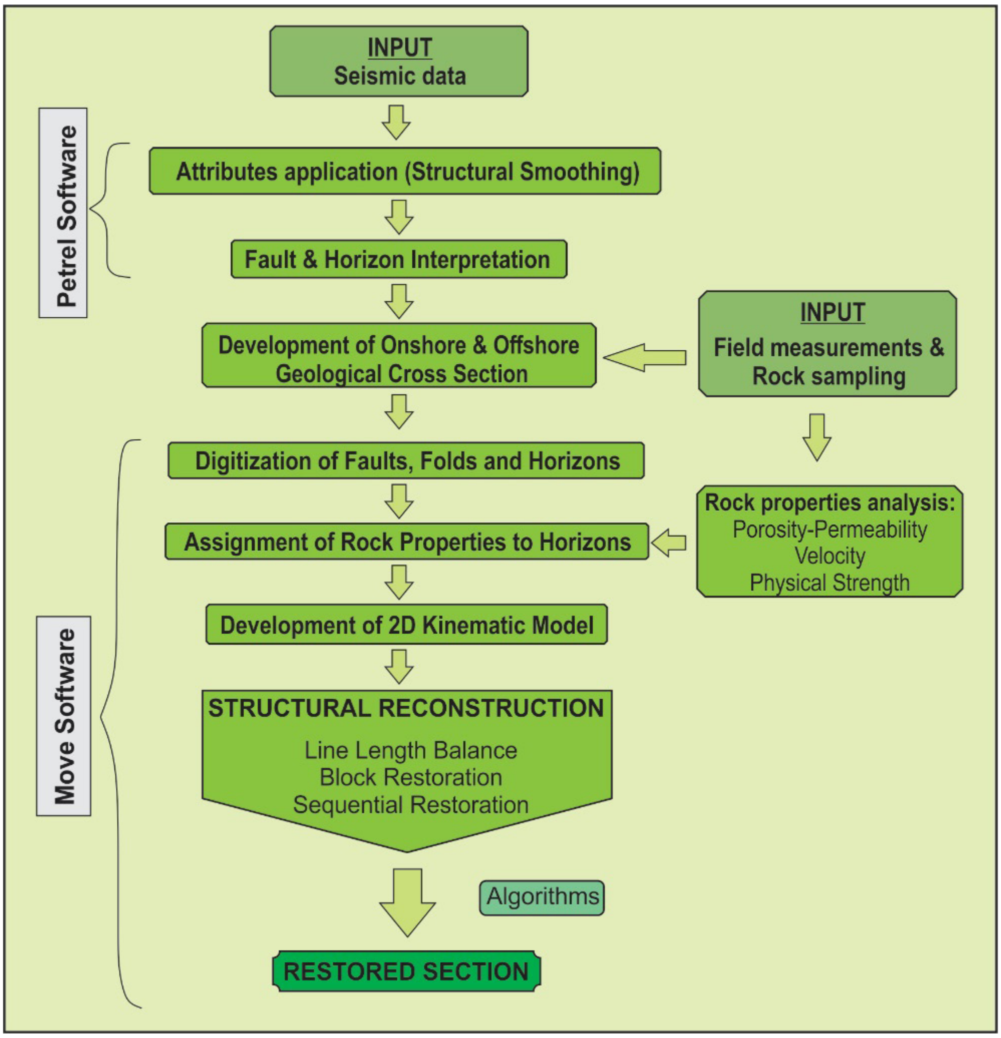

Figure 1 The reconstruction process of Kudat Peninsula from onshore and offshore data

Table 1 Physical properties of Gomantong, Sikuati and Tajau Members of Kudat Formation

Physical Properties	Porosity (%)	Permeability (mD)	Density (g/cm^3)	Velocity, Vp (m/s^{-1})	Poisson Ratio, v	Young Modulus (N/m^2)
Gomantong	8.114	0.691	2.376	3308	3.49×10^{-001}	1.11×10^{7}
Sikuati	14.518	0.758	2.279	1349	1.13×10^{-001}	2.068×10^{6}
Tajau	1.00	0.002	2.447	2330	2.31×10^{-001}	6.940×10^{6}

Once an accurate cross-section is established, the structures present in the geological units were reconstructed until the section was restored to its undeformed condition. The reconstruction process of both onshore and offshore kinematic model begins with the youngest to the oldest units or structures until the restored models represent the pre-deform geometry of the basin using the best-suited algorithms. The section was restored until it becomes balanced. A balanced cross-section is both viable and admissible [14]. These results are hopefully to explain and improve the understanding of the deformation history and structural evolution of the Kudat Peninsula.

Techniques and Algorithms

Section balancing and structural restoration reveal the depositional structures or features at a particular time. Move software provides a fully digital environment for structures and uses algorithms for section balancing. Four (4) algorithms were tested to identify the suitable techniques for the restoration of the complex geology of the northern Kudat, which are the Fault Parallel Flow (FPF), Simple Shear (SS), Fault Bend Fold (FBF) and Trishear (Table 2). Incorrect use of the techniques in restoration of these structures will form artefacts such as bending and undulating. Artefacts and distortions from flattening processes can significantly mislead interpreter if not recognized [15].

suitable trace orientations were suggested by the software by honouring the field readings. Seismic line K9 was used as a supporting data for subsurface structural interpretation for the deep-seated faults and stratigraphic boundaries. Figure 2 is the geological map of Kudat shows the location of seismic line K9 and transition line TL6. The hypothetical cross-section of line K9 that cut through Tajau Member, Mélange zone, and Sikuati Member in the northern part of the peninsula as shown in Figure 3A.

Selected transition line TL6 was interpreted to study stratigraphy and structural style of the offshore province, which was further used to establish a cross-section for structural restoration purposes. A higher signal to noise ratio of offshore seismic data produced a better cross-section. The TL6 is oriented WSW- ENE located in the transition zone on the west coast of the peninsula. The cross-section of the transition zone was constructed based on seismic interpretation of the transition line and followed the orientation of the seismic line. The seismic reflectors in TL6 show the same characteristics with the reflectors of onshore Kudat Formation, particularly at the bottom unit that

Table 2 The algorithms that are suitable for restoring the structures in Kudat Peninsula and the transition zone. The move-on-fault algorithms are SS, FPF, and Trishear while the unfolding algorithm involves Line Length technique.

Algorithms	Description of the algorithm
Fault Parallel Flow (FPF)	The most applicable for the restoration of thrust faults as it works by moving the hanging wall beds through an analogue of laminar particulate flow over a fault surface [16]. This theory is based on the principle of Particulate Laminar Flow developed by [17] and [18]. FPF algorithm suit best in the modelling hanging wall in a compressional environment, such as the movement of fault in a fold-thrust belt.
Simple Shear (SS)	The work of [19, 20, 21] had contributed to the development of the Simple Shear algorithm. SS models the relationship of the fault geometry and the hanging wall deformation. This algorithm is suitable in an extension tectonic setting for structures that developed on listric fault and growth fault. Simple Shear allows multiple movements in both the slip and the throw along the fault [22]. Normal fault or oblique fault is commonly restored using the SS algorithm.
Fault Bend Fold (FBF)	FBF works best to model the kinematic development of a complex thrust system geometries [23]. This algorithm allows the amount of hanging wall displacement to be controlled following the geometry of the fault as the fold is parallel to the fault.
Trishear	It works on deformed beds in a triangular shear zone where the magnitude of the slip varied from top to bottom.

Construction of the 2D kinematic section of onshore and offshore of Kudat Peninsula

Structural measurements from ten (10) outcrops lying along seismic line K9 are used to develop the cross-section of the line. For the onshore section, the horizons were constructed based on the dip data recorded. Based on the stereonet analysis, the most referred to as Ophiolite Basement rock. Figure 3B shows the cross-section of TL6 in the offshore of the Kudat Peninsula. The geology of Unit B, Unit C, and Unit E overlying basement rock are correlated to the onshore formation of the Kudat Formation, Bongaya Formation and Timohing Formation, respectively.

STRUCTURAL RESTORATION

Restoration and balancing of Seismic Line K9

Kudat Peninsula lies in an extensional and compressional regime where the commonly found structures are normal faults and reverse faults. Fault

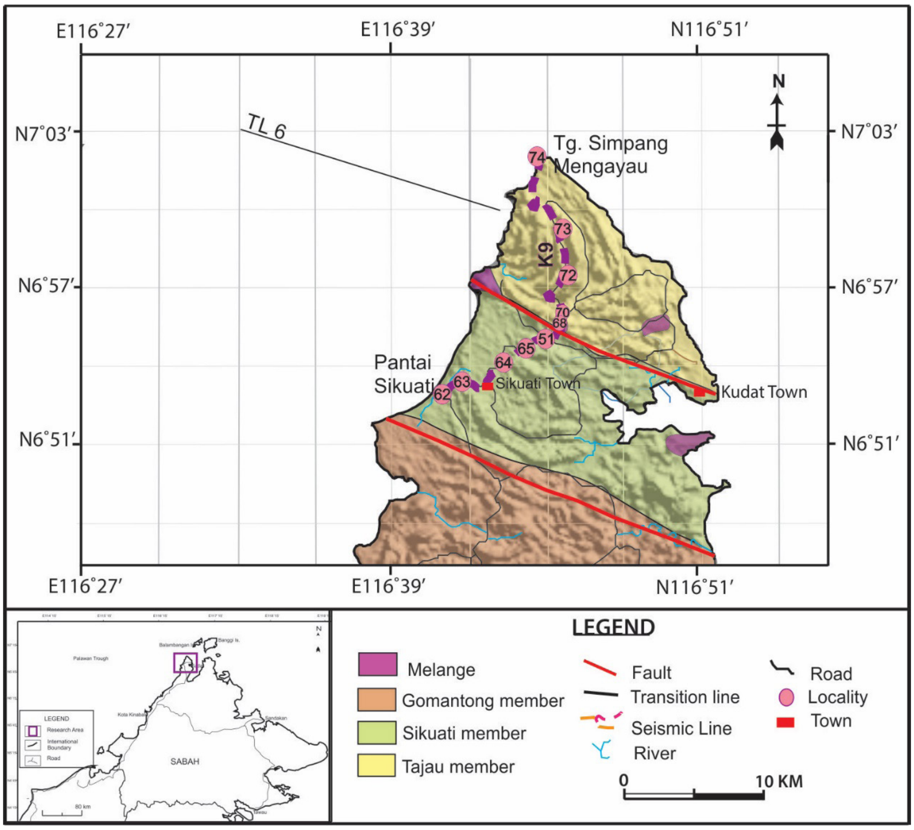

Figure 2 Geological map of the northern Kudat Peninsula showing the distribution of Kudat Formation Members as well as the location of the localities, onshore and offshore seismic lines. The Ophiolite Basement lies underneath Kudat Formation.

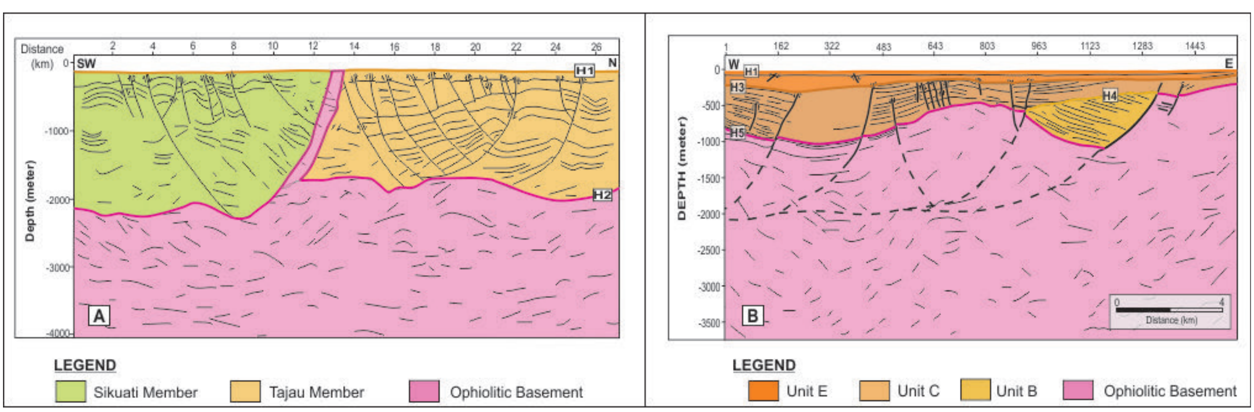

Figure 3 A) Cross-section of seismic line K9 in the northern part of Kudat Peninsula; B) Offshore cross-section of transition line TL6 offshore of Kudat Peninsula.

displacements can be observed on Fault 1, which had displaced Horizon 3 (H3) and Horizon 4 (H4) in Tajau Member. The movements created by the youngest set of normal fault forms a triangular zone of shear. Four move-on-fault techniques: FBF, FPF, SS, and Trishear, have been tested on this fault. Balancing a cross-section starts with the removal of the youngest structure present in the area, referred to as Fault 1. The reconstruction involves fault displacement restoration of antithetic fault in a domino fault system which had locally faulted the strata in the upper part of Kudat Formation as presented in the box in Figure 4. The fault displacement was observed between the strata in the hanging wall and the footwall, varying between 40 m to 50 m.

fault. Fault 1 was formed in relation to the reverse movement of the major fault adjacent to it. As the major reverse fault continues to displaced, Fault 1 was formed branching from the major fault. It works by the movement of beds in the hanging wall through an analogue of laminar particulate flow over a fault surface [24], where the footwall remains unchanged. The most applicable algorithm for the restoration of Fault 1 is the Trishear algorithm. The seismic interpretation shows that Fault 1 was formed as a conjugate fault in a triangular shear zone. This algorithm works best to restore the deformed beds in a triangular shear zone. With the FPF and Trishear technique, H4 and H5, as well as H2, H3 and H4 of

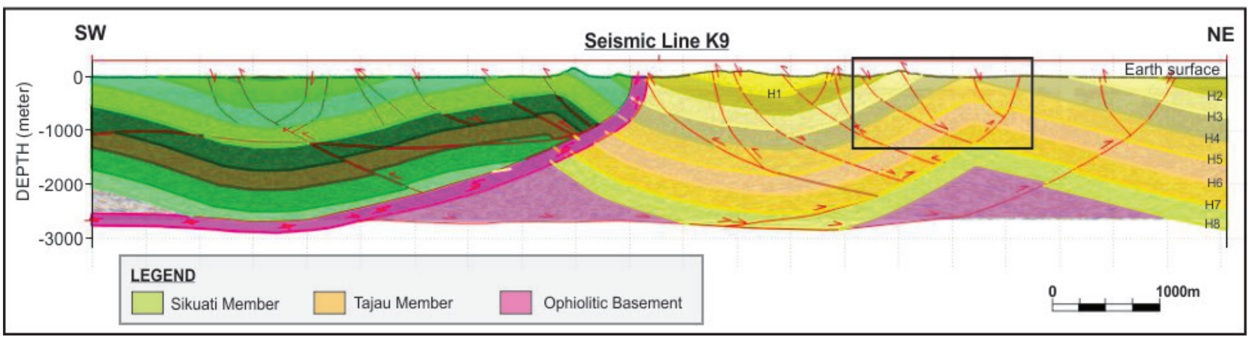

Figure 4 Digitized geological cross-section of seismic line K9 made up of Sikuati member, Melange unit, and Tajau member. Restoration of fault displacement in the boxed area of Tajau member.

Figure 5 shows a small section of line K9 from depth 0 m to 1200 m. The displacement on Fault 1 (F1) was removed using four move-on-fault techniques. Based on the fault restoration, FBF and SS fault removal method had resulted in excessive bedding displacement as artificial bending formed above the faults (Figure 5A and 5B). FBF is usually associated with the folding of strata due to the reverse fault movement over ramp surface, in response to the tectonic compression. Meanwhile, the SS method works best in reconstructing the listric fault, where the dipping angle of the faults decreases with depth.

In this case, FPF and Trishear are suitable algorithms that can be used to restore an antithetic normal

Fault 1 and Fault 2 matched in both hanging wall and footwall (Figure 5C to 5F) after the restoration process.

Restoration of TL6 offshore of Kudat Peninsula

Similar procedures and methods were applied to the fault in the transition zone. The seismic interpretation suggested there are six (6) horizons marked as H1 to H6 as shown in Figure 6. Figure 7 shows a small section of line TL6 in depth from 0 m to 1000 m below sea level. Step 1 of reconstruction involves the removal of fault displacement of a normal fault presented in the box in Figure 6. FPF, FBF, SS and Trishear techniques had been tested to H4 in the hanging wall of Fault 3 (F3).

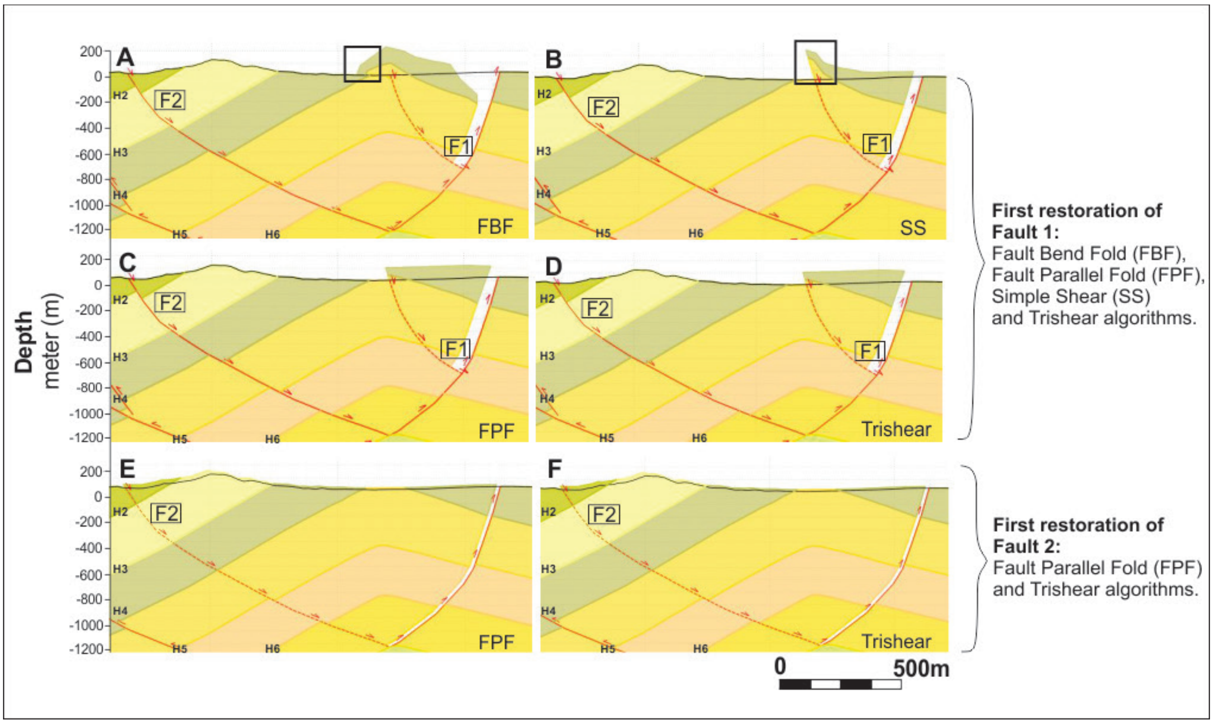

Figure 5 A small part of seismic line K9. Several algorithms were tested on Fault 1 and Fault 2 (a normal fault). After the first restoration of Fault 1 using FBF and SS, artefacts occurred as shown in the box. C to F is the restoration of Fault 1 (F1) and Fault 2 (F2) using FPF and Trishear; these techniques had matched the horizon in the footwall and hanging wall of both faults.

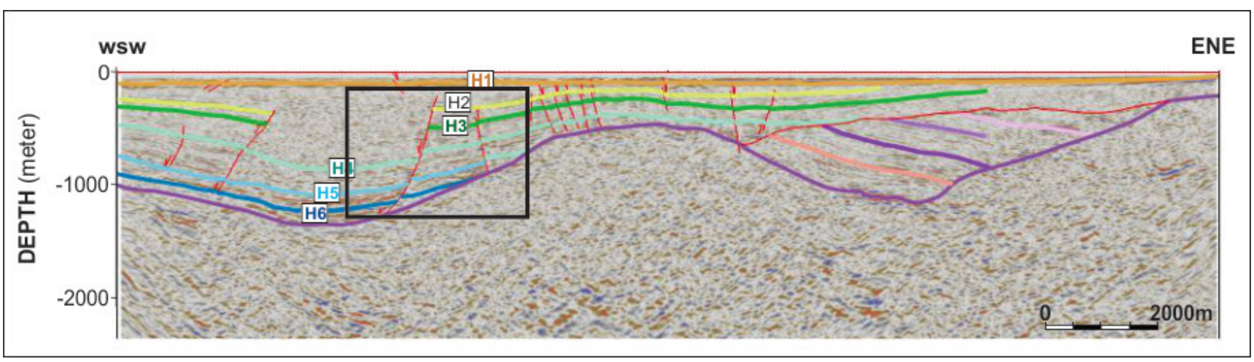

Figure 6 Seismic interpretation of transition line TL6 based on structural characteristics from WSW to ENE. H1 to H6 represents the horizons of unit A.

Fault 3 (F3) interpreted as a normal fault that had displaced the horizon in the hanging wall with the average displacement produced ranges from 30 m to 60 m. Reconstruction of Fault 3 (F3) using the FBF and Trishear method had resulted in the formation of undulating features, which could be explained as a hilly topography. Excessive removal of the fault displacement had failed to restore and match H4 on both hanging wall and footwall (Figure 7A and 7B). Section balancing was unsuccessful due to the unsuitable use of algorithms with the condition of the tectonic setting of TL6. FBF and Trishear methods are applicable in restoring faults in a ramp-related fault and triangular shear zone. Incorrect use of the techniques in the reconstruction of these structures will produce artefacts such as bending and undulating.

The horizons on the hanging wall had undergone a planar fault movement along with the curving geometry of the fault plane. FPF and SS restoration had successfully balanced the horizons by matching the H4 in the hanging wall with the H4 in the footwall in the same topographic level (Figure 7C and 7D). Both of these algorithms work best in restoring the deformed beds in the hanging wall with respect to the geometry of the fault. These algorithms were used to reconstruct all the faults present in the transition zone until the section completely restored. A complete and successful restoration requires a balanced section and it is defined by two rules [25]. The first rule is ensuring the geometry is valid by measuring the bed length as the length needs to be consistent. The second rule is the only limited suited structures can exist in a specific geological environment.

CONCLUSIONS

Structural reconstruction of onshore and offshore cross-sections of the Kudat Peninsula was conducted using Move software. Cross-sections balancing is a technique available to study and analyzed the pre-deformed setting of rocks and rock behaviour during the deformation in a particular tectonic setting. Four move-on-fault algorithms involving Fault Bend Fold (FBF), Fault Parallel Flow (FPF), Simple Shear (SS), and Trishear were applied to remove fault displacement in seismic line K9 and TL6. FPF and Trishear algorithms are identified as the suitable method for the restoration of the faults in onshore of the peninsula while FPF and SS algorithms had successfully removed the fault displacement and matched the horizon in the hanging wall to the footwall in TL6. The suitability of

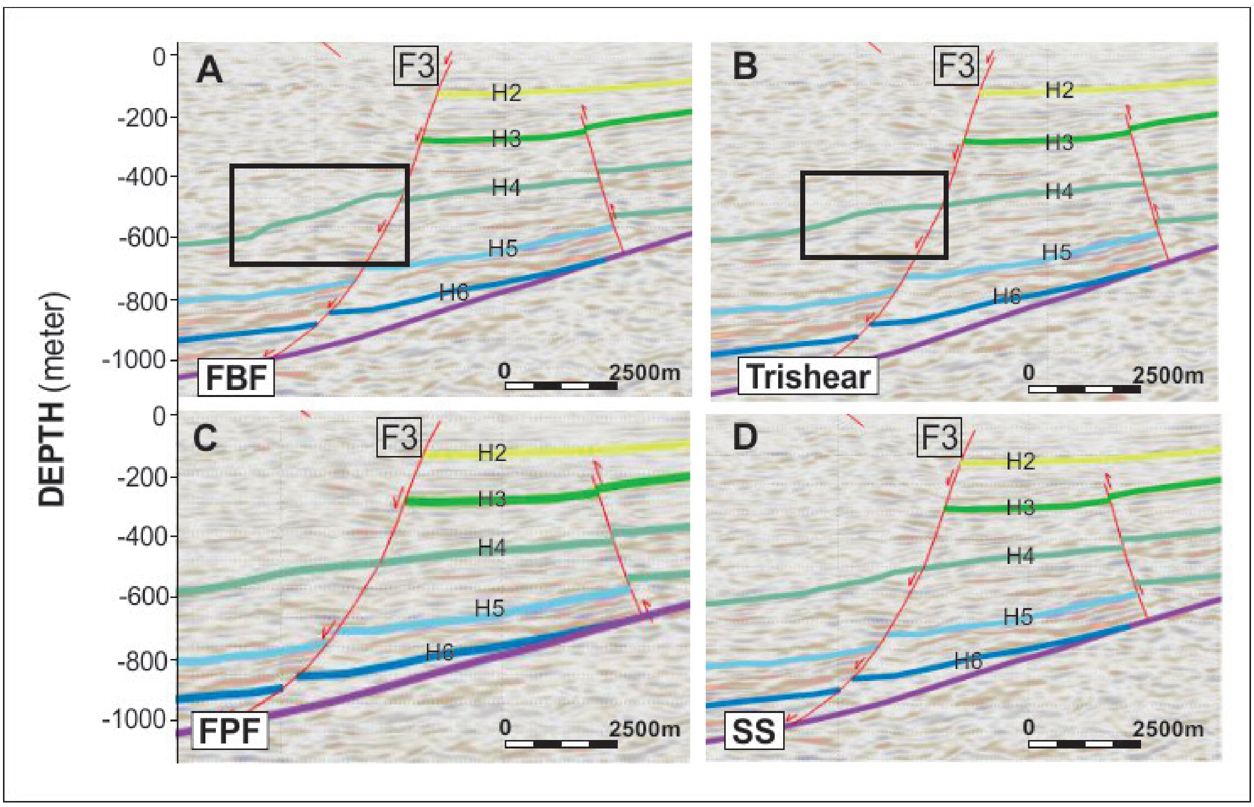

Figure 7 A small section of interpreted TL6 offshore of Kudat Peninsula. FBF, Trishear, FPF, and SS restoration techniques were applied on H4 of Fault 3 (F3) and the results are from 7A to 7D. Boxes in A and B are the undulating topography formed after the restoration of H4 using FBF and Trishear.

these techniques is determined based on the tectonic setting and rock behaviour of the rock units. Structural reconstruction is practical in a way to improve the understanding of the deformation history, structural evolution of an area and is expected to show the timing of structuring.

ACKNOWLEDGEMENT

We would like to show gratitude to Malaysian Petroleum Management (MPM), PETRONAS, for providing the seismic data for the research. The academic software used is MOVE Software from Petroleum Exploration Limited (PETEX), cultivated by the Academic Software Initiatives (ASI). The financial support for this study provided by the Yayasan Universiti Teknologi PETRONAS (YUTP) Grant 0153AA-E71.

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