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STRUCTURAL STYLE OF THE SOUTHERN PROVINCE OF WEST SULAWESI FAULT THRUST BELT, AND ITS IMPLICATION FOR HYDROCARBON EXPLORATION, MAKASSAR STRAIT, INDONESIA

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ABSTRACT

Exploration activity in the center of Makassar Strait where the West Sulawesi Fault Thrust Belt (WSFTB) is present is still promising especially after oil discovery under the over pressure zone in Kaluku-1 well.

This paper describes structural interpretations of the southern part of WSFTB (Southern Structural Province (SSP) of Puspita et al., 2005) to identify the structural style and to define the presence of a decollement system which is believed to be a regional seal and roof of vertical migration from active petroleum system and exploration plays.

Two main structural styles are present in the SSP-WSFTB. The fault propagation fold structural style were formed along the SSP, compressed and folded the sediment material above the decollement surface. Supra fault with dextral transform movement chopped the decollement surface and sediment body as compartmentalization in the SSP-WSFTB.

The hydrocarbon charge can get into the supra fault section with en-echelon pattern as the migration pathway in vertical direction to the younger trap. Meanwhile in the intra compartment where the supra fault is not available, the hydrocarbon is still preserved in the older Eocene play system.

INTRODUCTION

The study is situated in the eastern part of North Makassar Basin, in the offshore of western border of Sulawesi Island where the fault thrust belt structures were developed, currently known as West Sulawesi Fault Thrust Belt (WSFTB).

Puspita et al (2005) subdivided the WSFTB into three structural provinces. The provinces are North Structural Province (NSP), Central Structural Province (CSP), and South Structural Province (SSP) (Figure 1).

Nowadays, exploration activity in the North Makassar Basin WSFTB, especially in SSP is challenging. The key success is the crude oil discovery in Kaluku-1 well drilled by ConocoPhillips in 2012 though it is not commercial at present. This well penetrated the decollement over pressure zone which is understood as the northern limb of the south structural province (Satyana, 2015).

The source rock is believed from the lower part of the Eocene sediments which deposited directly above the crust of continental margin in the entire North Makassar Basin (Hall et al. 2009). This is mainly based on 2D and 3D seismic interpretation across the Greater Makassar Strait deepwater area showing tilted fault block structures of many half grabens, grabens, and horsts with NNW-SSE trend respecting the extension mechanism in Makassar Strait (Nur’aini et al, 2005). Hence the Early Eocene sediments filled in the syn-rift lineament structures where the mature shales as the source rocks and the sandstones as the reservoir rocks. These syn-rift sequences were overlain regionally by the transgressive outer neritic to deepwater shales and marls as a widespread, effective top seal for the Early-Middle Eocene syn-rift exploration play in the region.

Based on the geochemical analysis, Kaluku-1 crude oil origin is from the lacustrine source rocks. The oil migrated into the Eocene sandstone reservoir under the decollement fault system which is believed to act as a regional seal structurally in the SSP-WSFTB (Satyana, 2012). Furthermore, the sub decollement play system in Makassar Strait is equivalent with proven petroleum systems onshore West Sulawesi (Doda oil seeps).

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Hence, detailed structural information that covers the area of interest is needed to identify the decollement shape and architecture for further exploration phase. The results will, either to prove the sub-thrust play presence or at least to give the new insight regarding the sub-thrust play concept.

DATA AND METHODS

This paper mainly presents the geophysical hard data acquired during the exploration activities conducted by PTTEP in Makassar Strait. These produce various data from 2D & 3D seismics, Gravity and Magnetic and Sea bed cores.

The set of seismic data which covers part of the area of interest forms the main data in this study. More than 4500 km of 2D seismic and 1000 sqkm of 3D seismic data have been utilized for structural interpretation purposes.

The geochemical data from sea bed cores and published literatures of the geochemical analysis in the area e.g. micro-seep data from west Sulawesi offshore and Kaluku-1 well are also integrated to support the petroleum system concept.

The specific gravity data from internal study is integrated to support seismic interpretation. The gravity analysis data along the western part of Sulawesi border is functioned to control and validate the regional widespread of the structural style of both lateral and vertical distribution, and is also utilized for seismic interpretation guidance.

The methodology used in this paper includes the data observation, conventional seismic interpretation, balanced cross-section, and palinspatic fault restoration. Further data integration and analysis are used to prove the presence of sub-thrust play concept or to indicate a new concept for this area of interest for the success of further exploration.

RESULTS

Seismic Interpretation

The sets of available seismic sections are structurally interpreted to define the structural style and fault characteristic along the SSP-WSFTB.

From the gravity models, the high density body (2.72 g/cc) was identified as a highly compacted sediment material along the SSP in WSFTB which is interpreted as highly folded and compacted sediment above the decollement surface which received pressure and force during the deformation period. Following this hypothesis, the gravity model successfully indicates the decollement surface along the SSP- WSFB as a giant cup of material sediment which is highly folded and faulted (Figure 2).

The results are shown in (Figures 3-5). In these seismic lines, the fault propagation fold is consistently developed along the SSP-WSFTB with divers structural component intensity from the north to the south. The northern part of SSP is more intensively folded compared to the southern corner.

The intensity of the fault propagation fold in the northern part is higher compared to that in the southern corner of the SSP-WSFTB due to the un-uniform movement from the decollement surface along the SSP-WSFTB. Hence, the mass sediments above the decollement surface also impacted the heterogeneous movement stages. Because of the heterogeneous movements, the material sediments above the decollement surface ~~is~~ have been compartmentalized by the transform (supra) faults as the implication of the compressional forces from the eastern part of the collision (Sulu Spears).

The southern area is comprised more folds than faults, and the decollement is detaching on the syn-rift -post-rift unconformity. There is some evidence for the inversion here, but it does not look like the inversional structures connected to the shallower folds. The southern area is more reminiscence of a gravity slide detachment similar to that in the West Kutai area.

This observation is in-line with the study of stress distribution which was previously conducted in West Sulawesi onshore. The study suggested a counter-clockwise movement of the South Sulawesi micro block derived by the tectonic collision impact of the Sulu Spear movement from the east. This movement gives a bigger radial distance in the far position compared to the closest position from the axis of rotation.

The seismic line which crosses SSP-WSFTB in NNE-SSW direction shows the mega cup of mass material sediment which is bounded by decollement surface. This section also reflected the zone of supra fault as a dimmed asymmetrical fold shape with axial surface buckle to the north (in the north SSP) and to the south (in the south SSP) (Figure 6).

Another indication to support this hypothesis is the discontinuous front deformation structure folded in the western part border of the decollement zone of the SSP-WSFTB. The anticline trend is separate from en-echelon parallel line in NW-SE direction in the form of compartmentalized structure shown in the Miocene time structural map (Figure 7).

Structural Analysis

Seismic structural interpretation results bring current situated figure of structural style along SSP-WSFTB. The structural style which developed is a "fault propagation fold" in the shape of a bow arc toward the front deformation border. This structure is also clearly reflected in the sea bed topography map. The mechanism is consistent in each line of seismic on W-E direction which is relatively perpendicular dip of thrust fault along the SSP. Even though, the intensity of the fold propagation decreases to the south.

To simplify, this architecture leads us to imagine about mega cup of sediment which is compressed above the decollement surface known before as SSP-WSFTB. The mega cup sediment above the decollement surface is chopped by transform fault with en-echelon pattern in NW-SE direction. This separation built the compartmentalization of SSP-WSFTB. Further, the transform fault presented is called as a supra fault. This fault system enabled vertical migration of hydrocarbon to follow the weak zone and passing the decollement surface as regional seal. The shapes of structural style that were developed in the SSP area are presented in (Figure 8).

The Riedel shear ellipsoid is applied to identify the stress force which worked and formed the current structural style component recorded in the SSP-WSFTB.

From the alignment, the "dextral stress ellipsoid" component matched with the structural composition in the area of interest. The ellipsoid model showed the thrust fault in the N-S trend, folds in the N-S trend, and the dextral strike-slip fault in the NW-SE trends as presented in (Figure 9). For further discussion, a reading material published by Sylvester (1988) is used to interpret the structure mechanism.

For a further step, the simple balance cross section and palinspastic reconstruction are applied for selected seismic lines in the southernmost location to get the validation of interpretation and give other information from an un-deformed perspective. As the initiation work, 5 (five) horizons were interpreted above the decollement surface which will be used for the unrestored work as a stratigraphy markers.

The balanced cross-section is presented and shows that the length of horizon in SSP-WSFTB in the southernmost line is on average longer by around 8-9 km than the current deformed position. It also identified that the average thickness of sagging sediment of the 1st horizon to 3rd horizon is around 500 ms (millisecond). Meanwhile the 4th horizon and 5th horizon are gradually thicker to the east, close to Sulawesi islands. The thickness of sediment in horizon 4 and horizon 5 in the easternmost are around 1500 ms (Figure 10).

In line with the balanced cross-section results, the palinspastic models show the unrestored condition from the 5 lines in the section for the Pliocene through Mid-Miocene horizons which lies above the decollement surface (Figure 11).

Exploration Implication

The set of folds above decollement surface developed along the deformation stages during Neogene times are considered as the upside potential in this area. A number of wells penetrated the fault propagation fold play failed to discover hydrocarbons. The post drill analysis concludes that the failure may occur due to the absence of reservoir targets at the proposed well location. Another possibility is related to the opportunity of hydrocarbon migration to charge this play from the Eocene lacustrine mature source rock.

The key of charging process to the fault propagation fold play depends on the kitchen location, and how the hydrocarbons could migrate in to these closed systems. Even though, some micro seep biomarker sample from the seabed around SSP area and oil discovery from Kaluku-1 well proven the source rock within this area is already in the mature stage.

The biomarker analysis of micro seep samples from the sea bed core in the area indicated that the source rock is from marine environment. Based on current knowledge, the formation which contains the marine source rock should be positioned above the decollement surface (Satyana, 2012).

From the internal piston coring study in 2012 concluded that the samples from the area contain the alkanes-gasses and other interstitial gas which increases due to the deepest sample of seabed sediment cores. The Bernard Plot of gas composition of selected gas samples show that the samples plotted in the thermogenic gas range. The samples of gas did not contain an evidence of microbial alteration of the isotopic composition (oxidization) of methane, or molecular fractionation during gas migration or by hydrate formation. Hence, the gas sample composition possibly represents a very mature, overcooked gas which migrated from the deeper part.

The geochemical analysis of oil sample from below the decollement surface in Kaluku-1 well shows a high levels of normal alkanes with very low of sulfur content (< 0.1%) and also moderate wax content which indicates the oil sample is sourced from shallow lacustrine systems (Satyana, 2015).

The hydrocarbon is still preserved below the decollement surface. The decollement surface is believed to act as the regional seal which holds the vertical migration into the Neogene reservoirs upward.

After carefully defining and mapping of the surface of decollement, we can figure out the supra faults as part of the transform mechanism. These faults separated the material above decollement surface into several compartments. This situation opens up an opportunity of vertical migration for hydrocarbons to charge the Neogene reservoirs above the decollement surface.

Further, the exploration can be focused on definition of petroleum system components in each compartment in detail. The structural traps seismically are present in the sub decollement surface and above the decollement surface with the supra fault which possibly as the vertical migration pathway in the SSP.

CONCLUSION

The conclusions of the overall observation and interpretation of SSP-WSFTB:

(1) The structural style which developed in South Structural Province (SSP) – West Sulawesi Fault Thrust Belt (WSFTB) is a “fault propagation fold”. This structure is also clearly reflected in the sea bed topography map. The mechanism is consistent in each line of seismic on W-E direction which shows relatively perpendicular dip of thrust fault along the SSP. The intensity of the fold propagation decreases to the south.

(2) The SSP architecture leads us to imagine about mega cup of sediment which compressed above the decollement surface. The mega cup sediment above the decollement surface is chopped and separated by transform fault with en-echelon pattern in NW-SE direction as a dextral movement called as a supra fault.

(3) The hydrocarbon charge conceptually enters into the supra fault section with en-echelon pattern as the migration pathway in vertical direction to the fault propagation fold trap. Meanwhile in the intra part where the supra fault is not available, the hydrocarbon is still preserved in the older Eocene section below the decollement surface.

(4) Exploration can be focused on definition of petroleum system components in each compartment in detail. The structural traps seismically are present in the sub decollement surface and above the decollement surface with the supra fault which possibly as the vertical migration pathway in the SSP.

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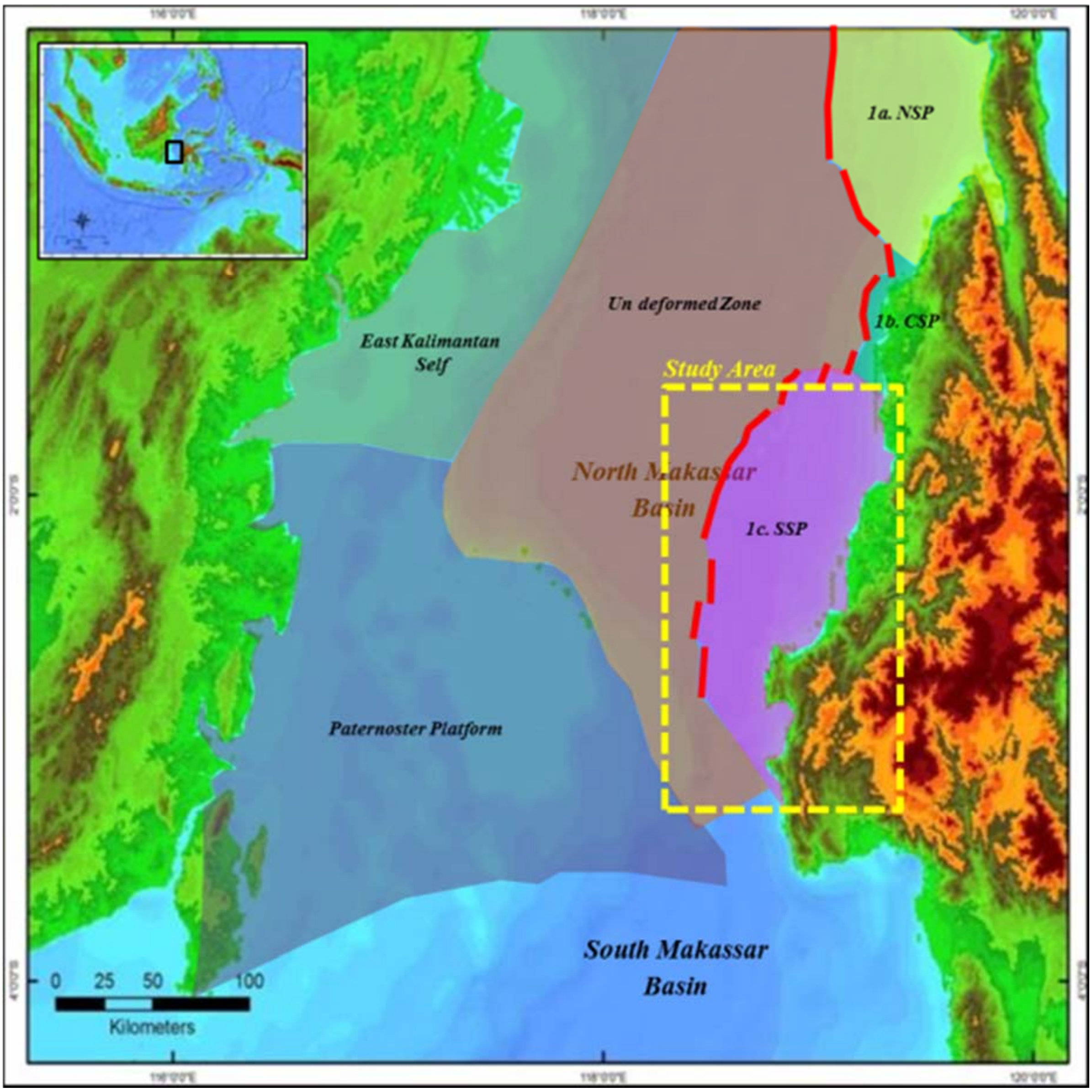

Figure 1 - Makassar Strait regional structural province; showing the South Structural Province (SSP) in West Sulawesi Fault Thrust Belt-WSFTB (After Puspita et al, 2005).

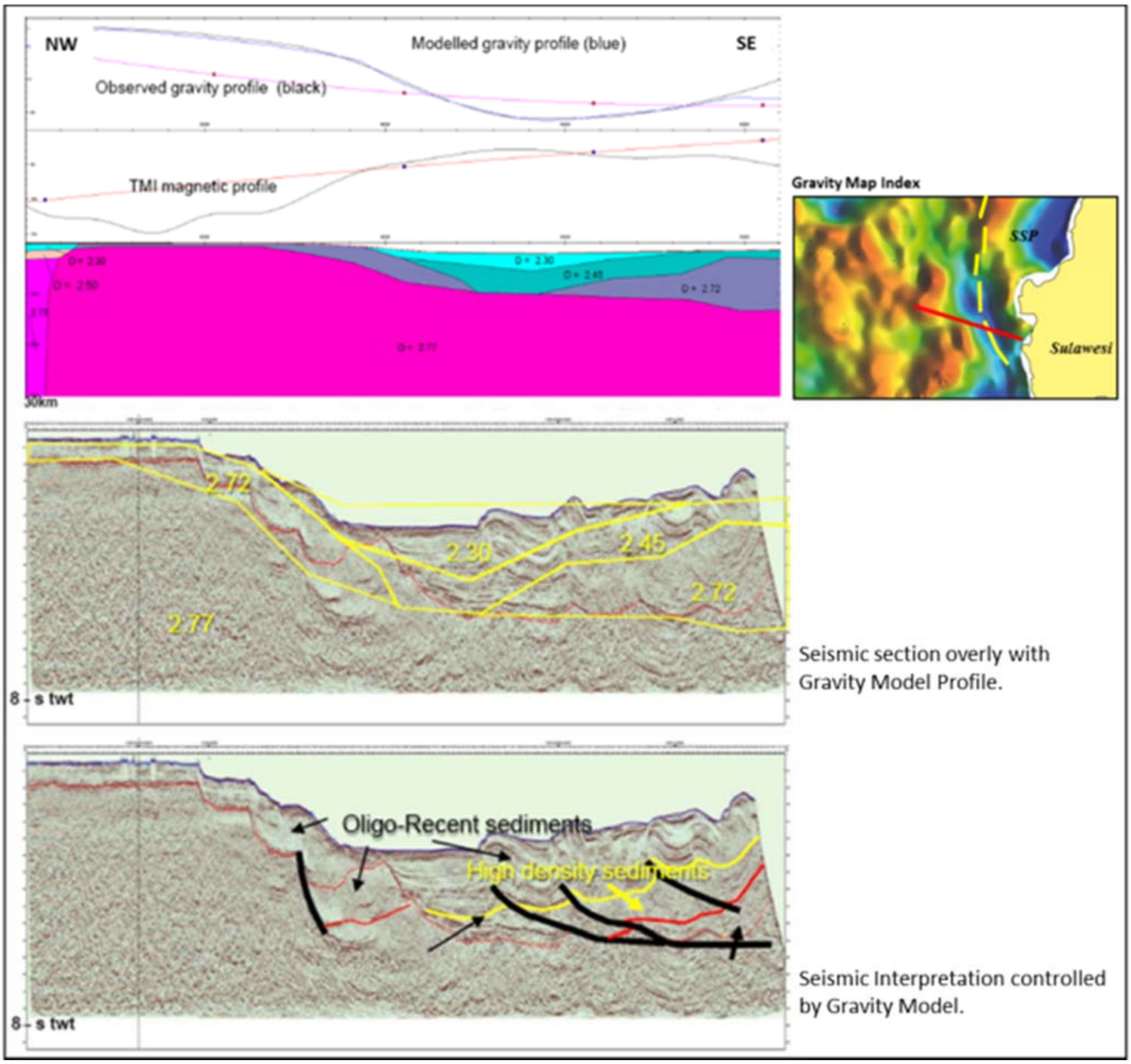

Figure 2 - Gravity model in selected seismic line showing the high density sediment body in the southernmost of SSP-WSFTB. This will be used as a guidance for decollement interpretation.

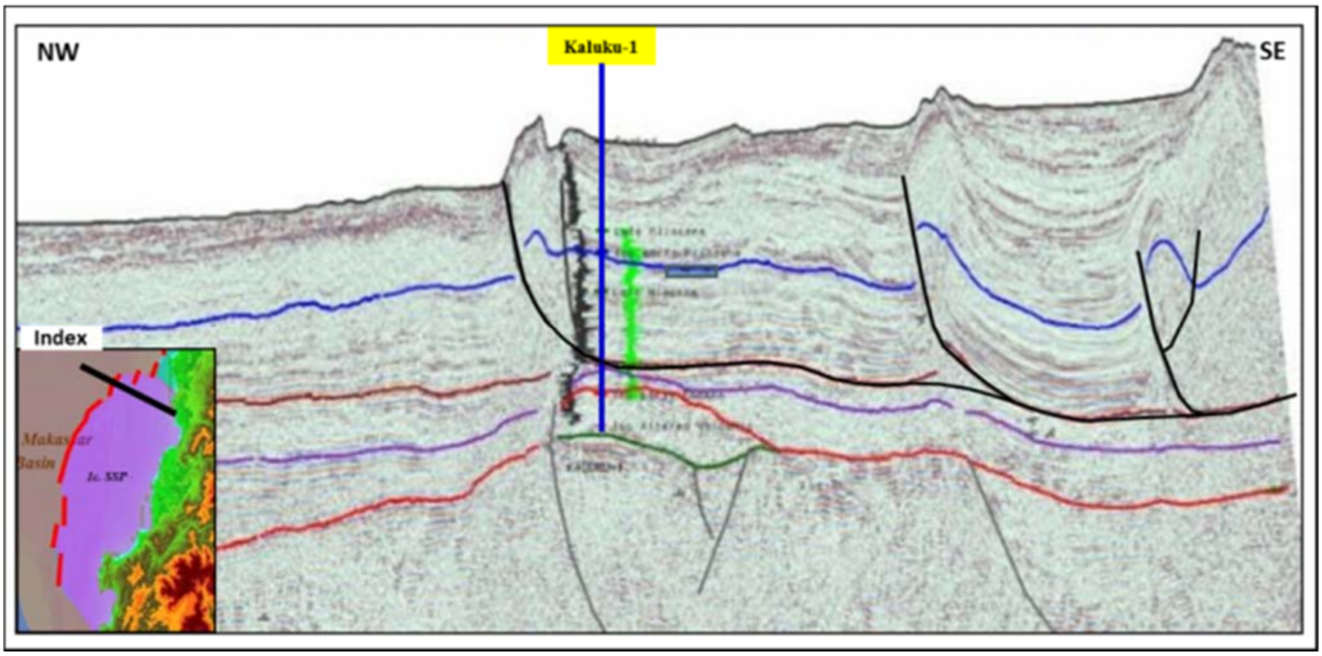

Figure 3 - Seismic section across Kaluku-1 well penetrated the decollement surface in the northern most of the South Structural Province of the West Sulawesi Fault Thrust Belt (Satyana, 2015).

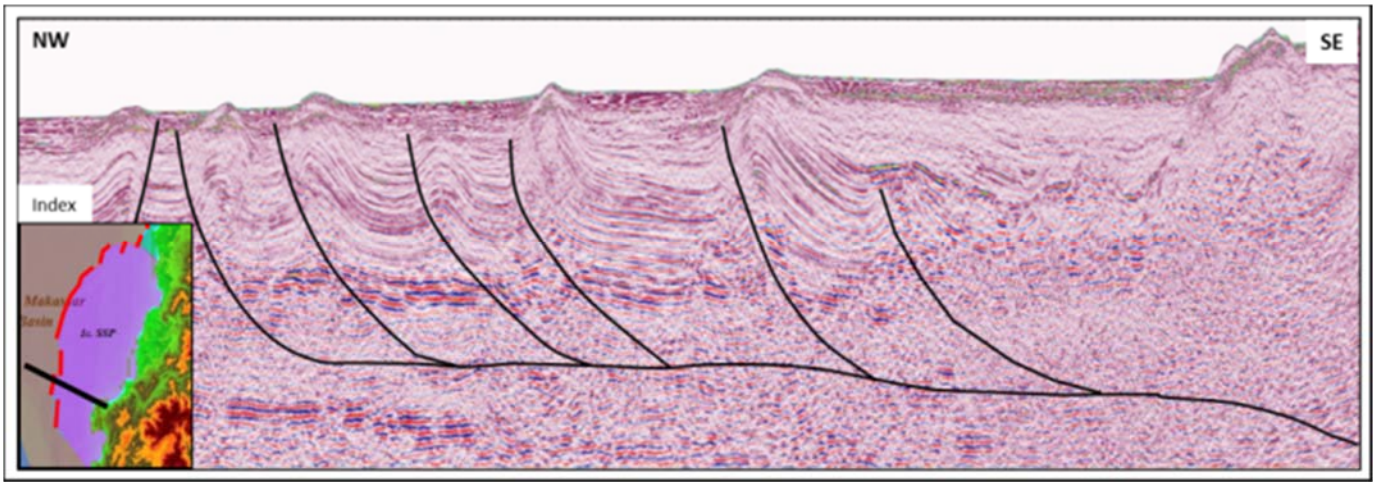

Figure 4 - Seismic section showing the fault propagation fold in the center of the South Structural Province (SSP).

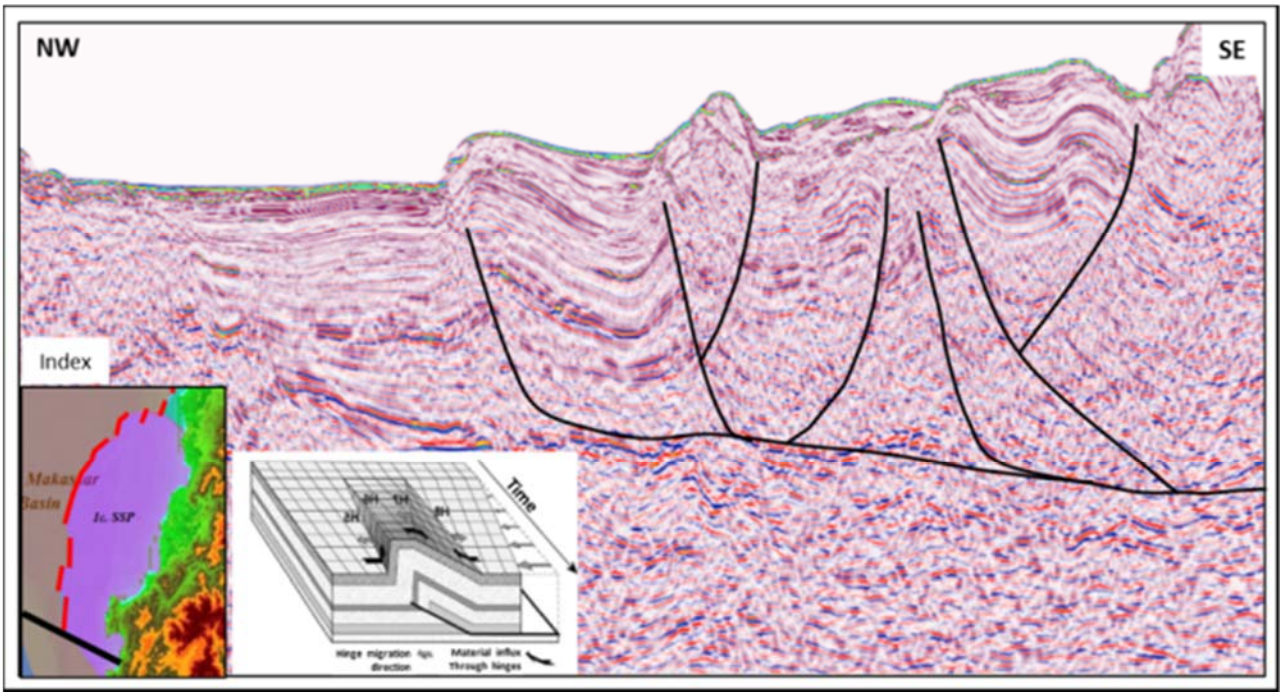

Figure 5 - Seismic section showing the fault propagation fold in the southernmost part of the South Structural Province (SSP).

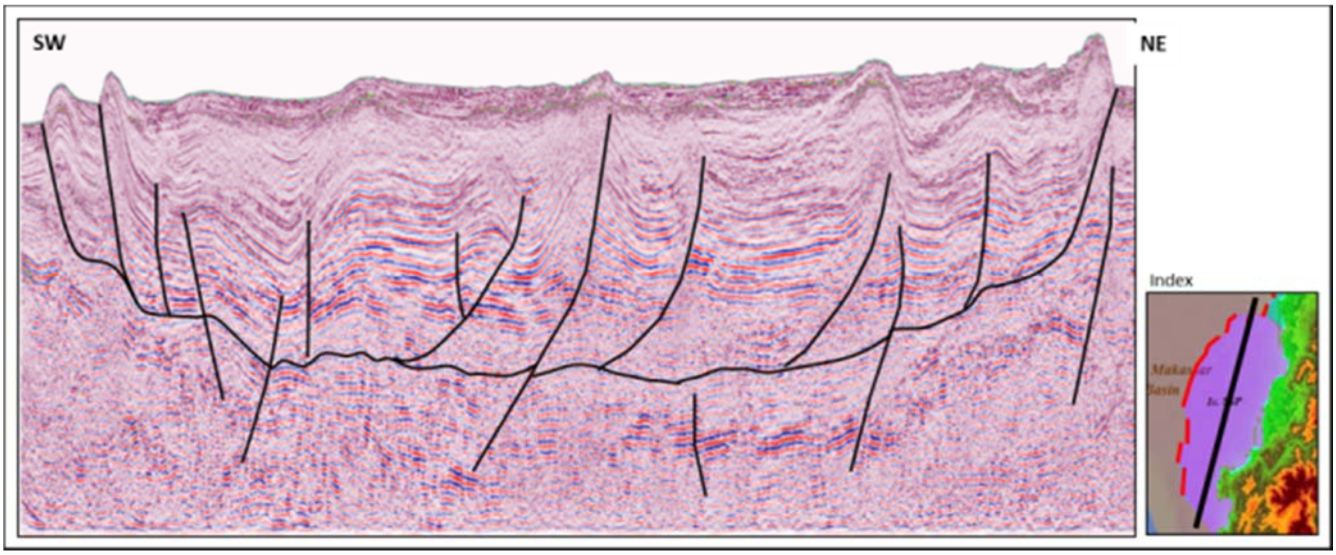

Figure 6 - Seismic section across ~~of~~ the mega cup sediment materials above decollement surface in South Structural Province (SSP) in N-S direction.

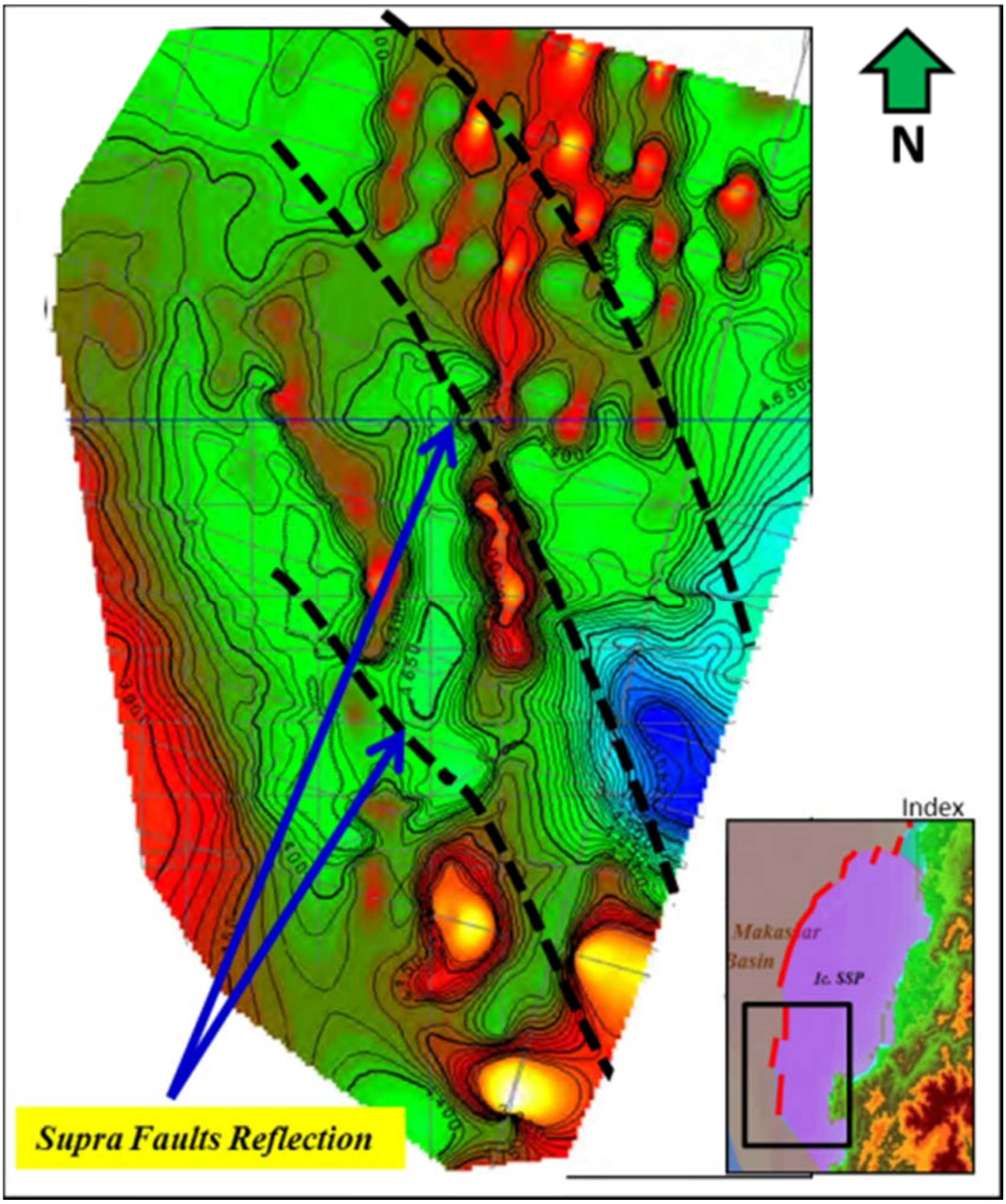

Figure 7 - Time-structure map on the Top Miocene horizon, showing the distribution of fold and en echelon fault.

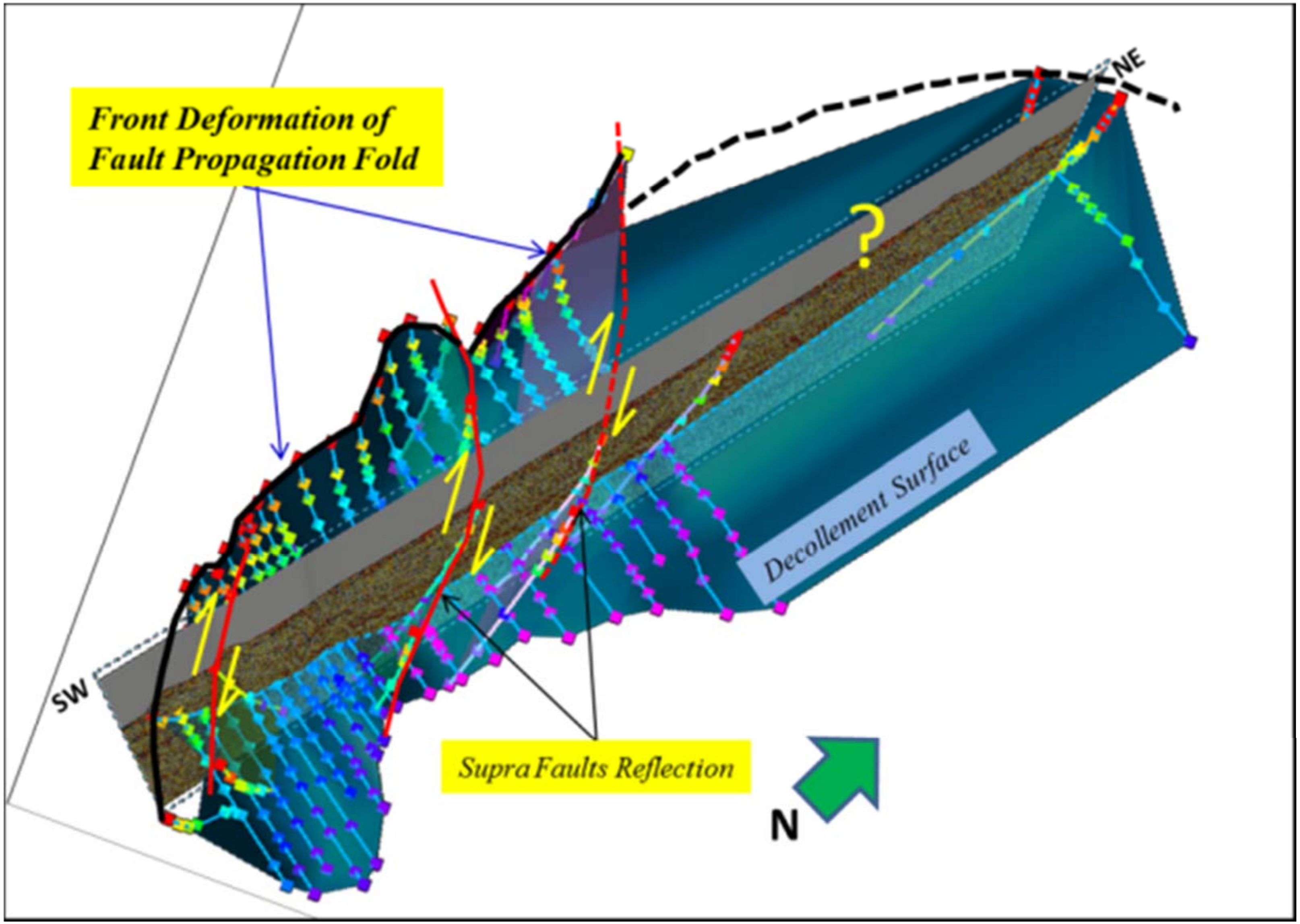

Figure 8 - Decollement Surface Architecture in South Structural Province (SSP-WSFTB)

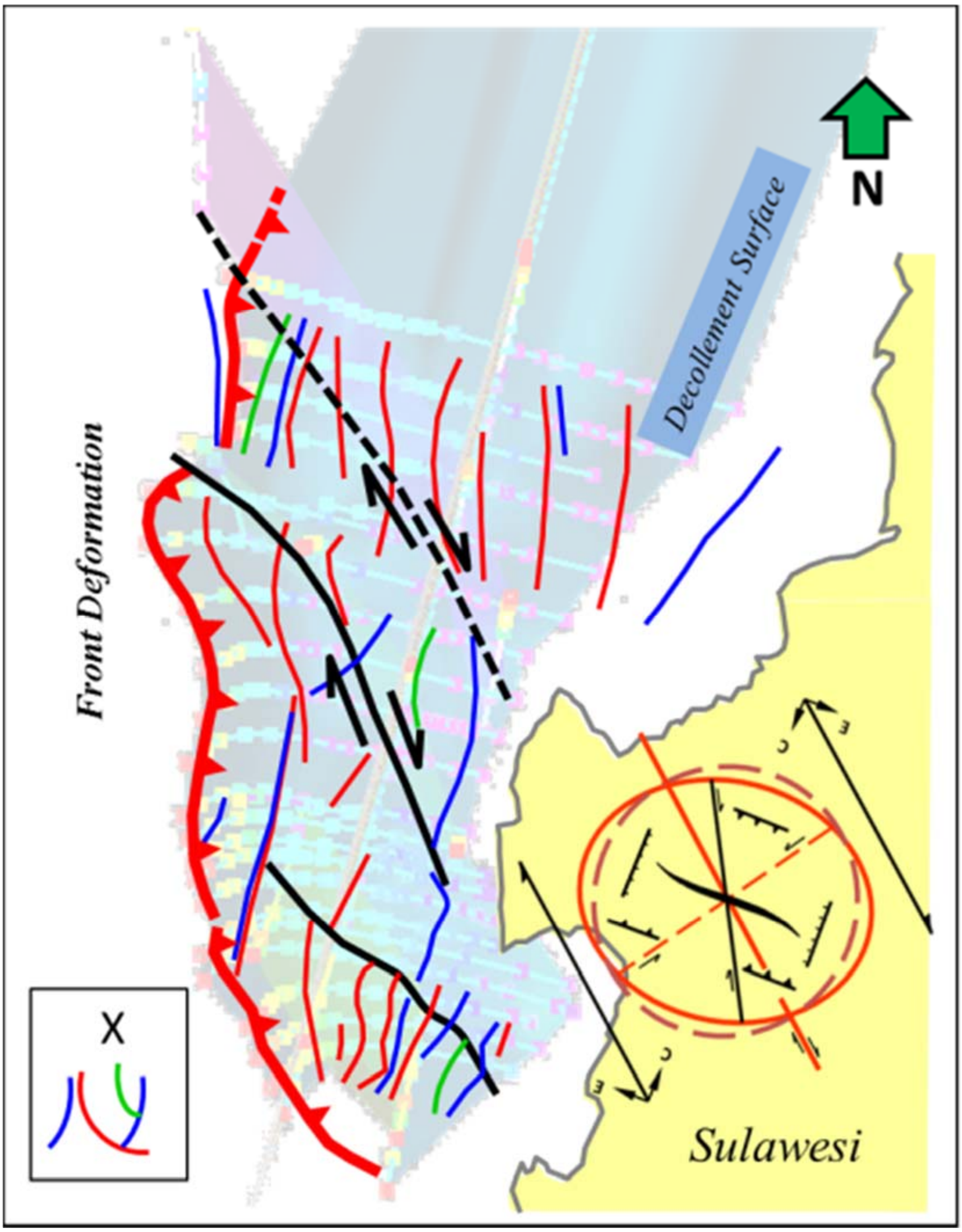

Figure 9 - Structural style analysis and comparing with Riedel shear model shown the supra fault reflecting the dextral movement.

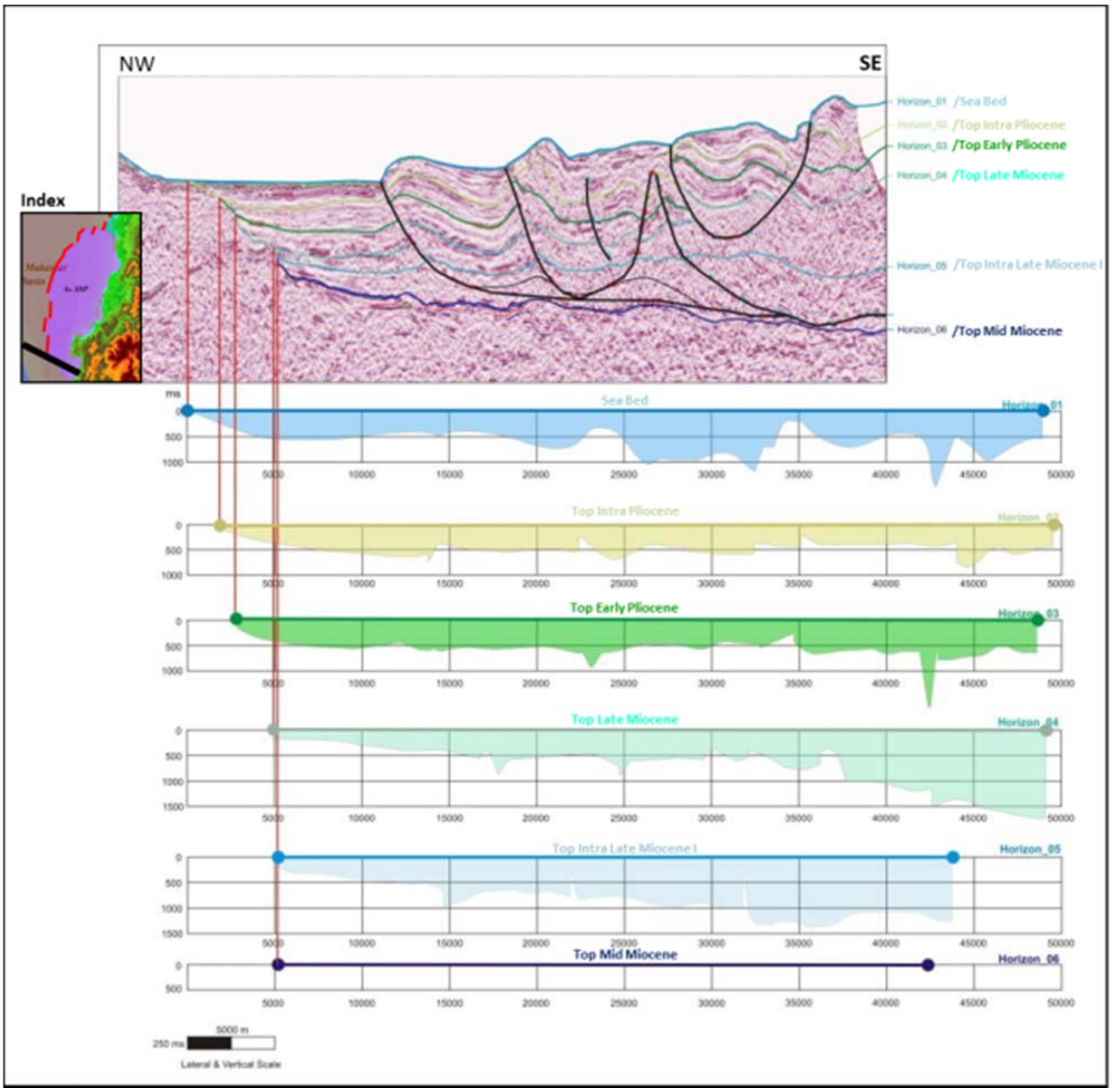

Figure 10 - Section Analysis of selected seismic line in the southernmost SSP-WSFTB.

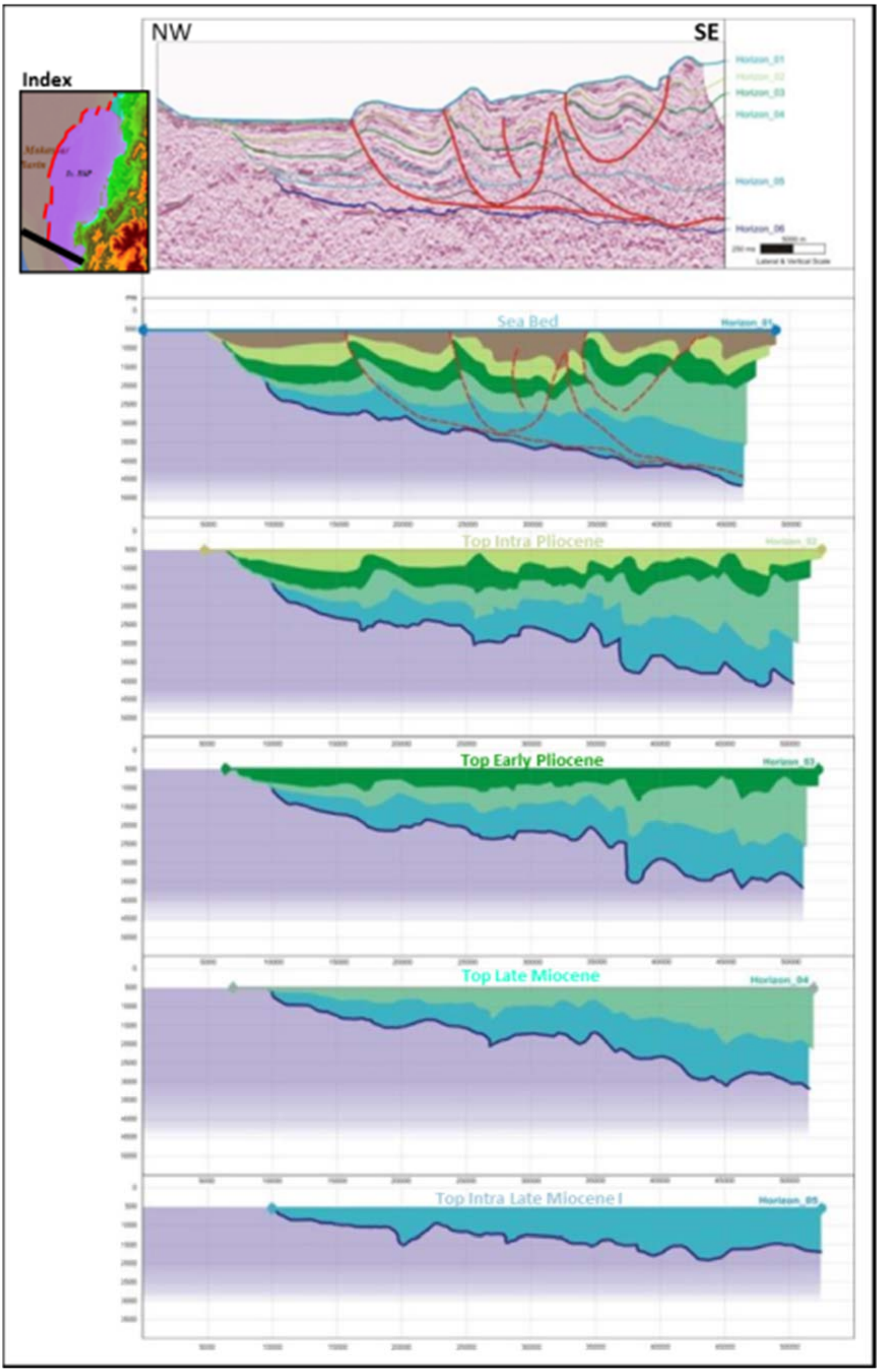

Figure 11 - Palinspastic of selected seismic line in the southernmost of SSP-WSFTB.