Structural Analysis of Northwest Sabah Basin by 2D Reconstruction of Seismic Sections

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Abstract

The tectonic evolution of thrust-fold belt and thrust sheet zone in Northwest Sabah basin was described based on balanced reconstruction of seismic sections representing Mid-Miocene to Recent deposits. The study area is located at the center of a wide crustal deformational zone bordered by the Sunda Shelf on the northeast, Sulu Sea in the southwest and the South China Sea in the northwest. Balancing cross section can be applied after the deformed geological structure geometry is accurately determined from seismic sections and 7 seismic stratigraphic unit from 15 Ma until Recent is consecutively restored. There are four steps involved in retro-deformation processes beginning with removing all faults displacements followed by unfolding the folds, isostasy correction and finally the removal of each compacted layer parts or decomposition. Wider fold wavelengths with least thrust faults were observed from south to north in the seismic sections ranging from 12 to 4 km with an average of about 7 km, while smaller fold wavelengths and more thrust faults were observed in the north based on the same seismic sections. In general, the reconstructed cross sections revealed compressional tectonic deformation activity as shown by shortening strain trending NW-SE. Measurement of total shortening shows that thrust fold belt is imbalance by an exceeds of 14.7 km and more active compared to thrust sheet zone which has only 0.9 km. Results of the study also indicate facies destruction due to shortening which is decreasing towards Pliocene or younger deposits.

Keywords: 2D Reconstruction, NW Sabah Basin, 2D Seismic Profiles, Retro-deformation

1. Introduction

NW Sabah Basin, which is also generally known as Sabah-Brunei basin, Northwest Borneo basin or Baram-Balabac basin proposed by Cullen (2010) is bordered in its east-west to major part of the North Sarawak Basin. These two basins are separated by a steep slope sea bed of West Baram lineament which is connected to NW-SE trending Tinjar strike slip fault (Mazlan Madon, 1999; Tan & Lamy, 1990)

Sabah Basin is a trench associated basin or sometimes is called as fore-arc basin (Levell 1987). Based on previous gravity, depositional history and sequence stratigraphy studies, this basin is expanding as a foreland basin followed by collision of continents below the South China Sea and West Sabah (Hazebroek et al. 1994; Noor Azim Ibrahim 1994; Milsom et al. 1997). Sabah basin is also formed by thinning of continental crust layer due to dispersion of South China Sea (Tjia & Mohd Idrus Ismail, 1994).

The Sabah Basin is considered as a compressional dynamic tectonic zone of northwest-southeast trend. There are some variations in previous study on the tectonic activity of Sabah basin where Abdul Manaf & Wong (1995), Mohd Idrus et al. (1995) and Hamilton (1979) reported that the study area was in passive condition without any earth movement and

seafloor spreading during early Eocene. But this hypothesis was rejected due to the discovery of highly compressional deformation in the Miocene to recent sedimentary rocks as well as evidence from tensional movements measurement by global positioning system (GPS) technique (Ingram et al. 2004; Simons et al. 2007; King et al. 2010).

King et al. (2010) used 2D Dynel computer software for structural reconstruction of Southern Sabah Basin only. Results of their study show a decrease in crustal shortening towards the north into Baram Delta. The subject of crustal mobility and the mechanism to enhance the formation of Sabah Basin is still under discussion until today. It is hoped that the study of structural reconstruction based on seismic data and well in the area of thrust fold belt and thrust sheet by using latest 2DMOVE computer software would resolve some of the problems. In this study we used the same technique to propose some crustal restoration and reconstruction by using seismically derived cross sections or profiles in the thrust fold and thrust sheet zones.

The analysis is hoped to optimize the use of seismic sections in increasing the understanding related to the tectonic mechanism that is controlling the formation of folds and thrust faults

in the study area by using 2DMOVE computer software.

1.1. Geological Setting

Sabah Basin constitutes of 85% marine or offshore deposits towards the South China Sea while the rest covered along the west coast of western Sabah and north of western Sarawak. The basin is about 350 km length and 140 km width trending along northeast-southwest covering an area of about 47075 km squares with thickness of about 10 km of mostly Tertiary siliciclastic sediments (CCOP, 1991)

Bol & Hoorn (1980) studied the structural style across NW Sabah continent and basically found out that the structural style along northwest to southeast was dominated by compressional deformation with minor early tensional stage. In some of the area, the structural pattern was dominated by tensional activity with some compressional effect. The third structural style was mainly compressional with thrust belt due to gravitational sliding and subduction or both.

Tan & Lamy (1990) and Hazebroek et al. (1994) has identified six structural regions namely Inboard Belt, Outboard Belt, Sabah Trough, Dangerous Ground, Thrust Sheet Zone and active delta (Baram Delta) thrust-fold based on the structural style differences and depositional history. The study area covers the whole region of geologically complex tectonic structure of NW Sabah Basin (Fig. 1).

In terms of depositional history, the siliciclastic sediment of shelf slope was deposited pro-gradationally towards the sea during early Miocene after the early phase of deep sea deposition. The depositional processes were interrupted by several episodes of tectonic activities leading to formation of regional unconformities which have been used to divide the Sabah basin into several stages. These stages were separated by major unconformities resulted from tectonic movements and uplifted towards the southeast near the basin boundary.

The most major regional unconformity in the study area is the deep regional unconformity (DRU) which is separating the underlying post-mid Miocene deep marine rock sequence from the top mid Miocene to Quaternary slope-shelf sediments.

2. Methodology

A total of 10 seismic sections basically representing nine sequence boundaries divide the Quaternary sediment overlying the basement. These seismic sections were then traced and divided into 2DMOVE polygonal shapes for structural interpretation and fold types classification. Sequences 1 to 6 represent post-rift Mid-Miocene episodes while sequences 7 and 8 represent depositional units formed during the rifting processes taken place in lower Miocene. These sequences (7 and 8) are also both considered to be the top surface of shale basement or the base of thrust faults (Fig. 2) as refer to previous work by Akhmal Sidek et al. (2015).

Cross section restoration or sometime known as retro-deformation process is carried out for reconstructing the formation of structural geometry deformation or to bring back the original sedimentary layers before they are being deformed by tectonic process. The reconstruction process includes removing the effect of faulting and folding. There are four sequential algorithms involved in the retro-deformational processes to generate the algorithmic cross sectional model resulting from the deformational phases. The algorithmic sequence begins with removing the faults displacement, unfolding of folds, isostatic correction and lastly is removing the layer which has been compacted by compression during the deformation to its original position (de-compaction).
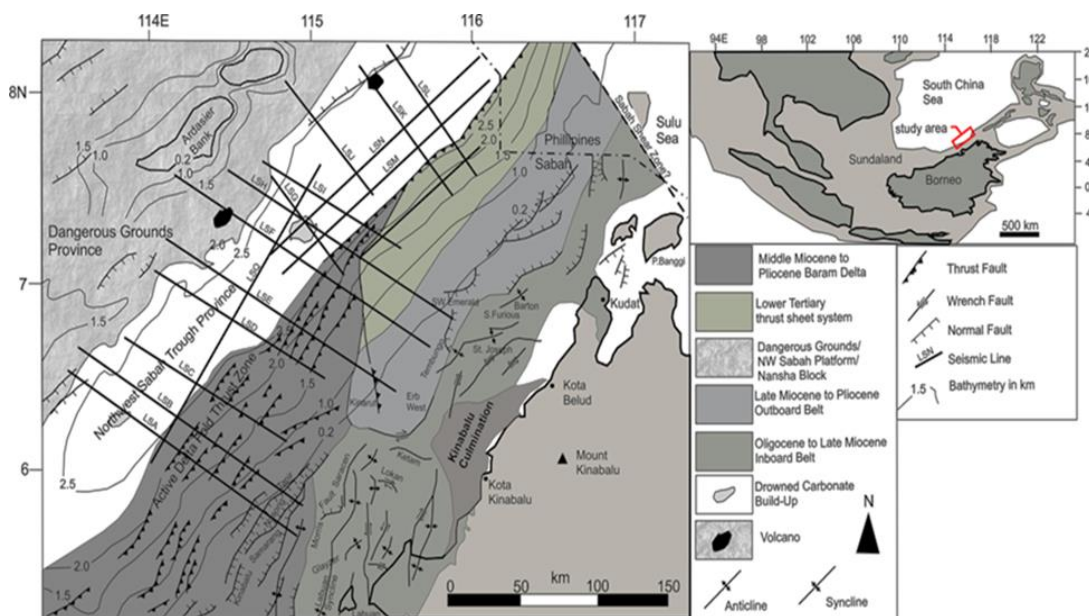

Fig.1. Tectono-stratigraphic provinces of Sabah Basin and location of seismic lines. (After Hutchison, 2004)

The assumption made during the processes is no input and output movement must originate from the sedimentary layer during the tectonic deformation (Midland Valley 2012). The correct algorithm is determined by the horizon mechanic of each layer and the boundary situation. Nevertheless, the restored model is not necessarily representing the correct pre-deformed geometry or the structural evolution movement. Suitable algorithmic model selection in the study is concentrated to tri-sheared technique for fault shift algorithm while the sliding technique is used in the algorithm for unfolding the folds. These techniques are particularly used to resolve both types of tectonic regimes represented by compressional thrust-fold belt and tensional inboard belt observed in northwest Sabah basin.

The measurement for isostasy correction depends on the loading dimension acted upon the sediment layer plus the rigidness of lithospheric. In this respect the elastic thickness has to be assumed as fixed and constant in time and space even though it has different lithospheric rigidity (Watts & Talwani, 1974) The elastic thickness value (Te) and the average wavelength (λ) is about 8 km and 6 km respectively (Braitenberg et al. 2004). These parameter values are used in general for subduction analysis in South China Sea and the values are constant for the whole process of kinematic model development. Parameters used for isostasy modelling in this study are given in Table 1.

Table 1. Parameters for 2DMOVE kinematic modelling in NW Sabah Basin.

Layer model unit	Bulk density, kg/m^3	Young Modulus, GPa
U1 (Late Pliocene-recent)	2.24	1.12
U2 (Early Pliocene)	2.28	1.90
U3 (Late Miocene)	2.30	2.11
U4 (Mid-Miocene)	2.34	2.35
U5 (Mid-Miocene)	2.37	2.50
U6 (Early Miocene)	2.40	2.85
Sea water	1.03	-
Mantle	3.33	-

Kinematic model in this study is a kind of inverse modeling since its purpose is to analyze retro-deformational process involving thrust fold and normal fault structures. It is also meant for predicting fault development, kinematic analysis and layer length in designing the pre-deformed structural architecture. Kinematic modelling analysis in this study is carried out with the aim of measuring the percentage and rate of layer model total shortening. Shortening percentage represents qualitative value of compressional tectonic process experienced by the area.

2DMOVE is used in kinematic model development for geometrical interpretation in line

with the geological concept. All seismic sections in SEGY format were imported into the software for analysis involving five complete stages. In stage 1, structural geometry or faults positions, footwall and hanging wall blocks were identified from the seismic sections. Selection of fault shifting algorithm by tri-shear technique is carried out in the following stage 2 and clearing the fault shift by downward movement along the dip direction is accomplished in stage 3. Selection of algorithm for unfolding the fold by flexural slip technique, completing the restoration process for upper section and calculation of shortening length are carried out in stage 4.

Finally, the restored upper section is cleared from the model for de-compaction process and isostasy correction in stage 5. Shortening percentage is calculated after the fault shifting algorithm and fold unfolding for every layer section or balanced restoration is completed. The equations for the shortening percentage length is L = Pin1 – Pin2 where L is the distance in meter between Pin1 and Pin 2. Pin 1 is fixed while Pin 2 is moved during the restoration process. The difference in length ΔL = L (Final) – L (Initial) where L (Final) is the section length after restoration and L (Initial) is the length before restoration. The equation for calculating the total of shortening percentage is $\Sigma \Delta L = \Delta Lu1 + \Delta Lu2 + \ldots + \Delta Lu5$, where ΔLu is the difference in length of each section.

The uncertainty for each shortening magnitude calculation is about 15 % considering the uncertainty in seismic depth-time conversion, error in horizon picking during the interpretation and uncertainty in the restoration processes.

3. Result

Structural fold in the study area are closely related to thrust faulting and classified as gentle to open. It can be observed in many seismic sections within thrust fold belt and only few in Sabah Trough as well as in thrust plate. Maximum and minimum fold wavelengths in the NW Sabah Basin is 12 km and 4 km respectively.

The maximum fold wavelength is observed in the south of study area along seismic line LSD while the minimum fold wavelength is observed in seismic line LSL located in the north of study area.

Average fold wavelength is about 7 km and the fold type is considered as low angle based on its size calculated between fold wings. The calculated average value is not very far different from what has been reported by Morley et al. (2011). They found that the average fold wavelength in NW Borneo is about 10 km.
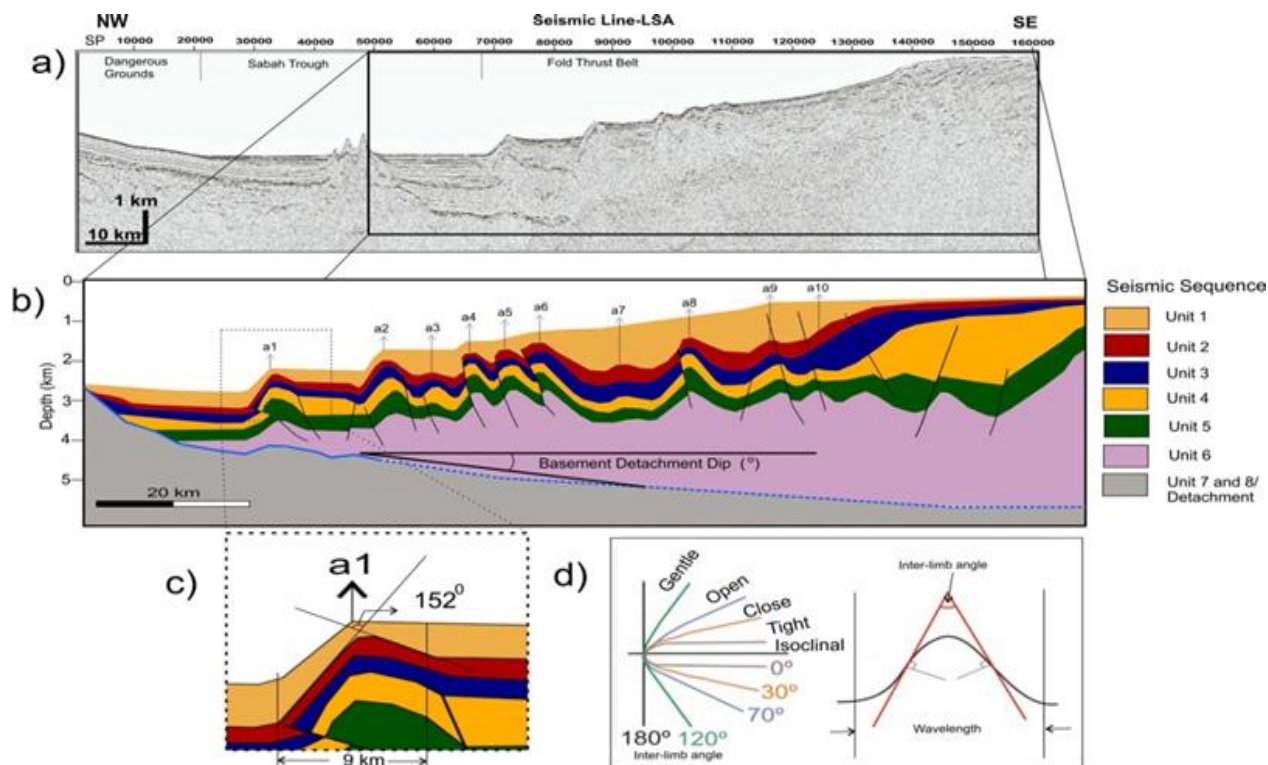
Fig. 2. Example of seismic section (a) polygonal model and sequences (b) determination of inter-limb angle and fold
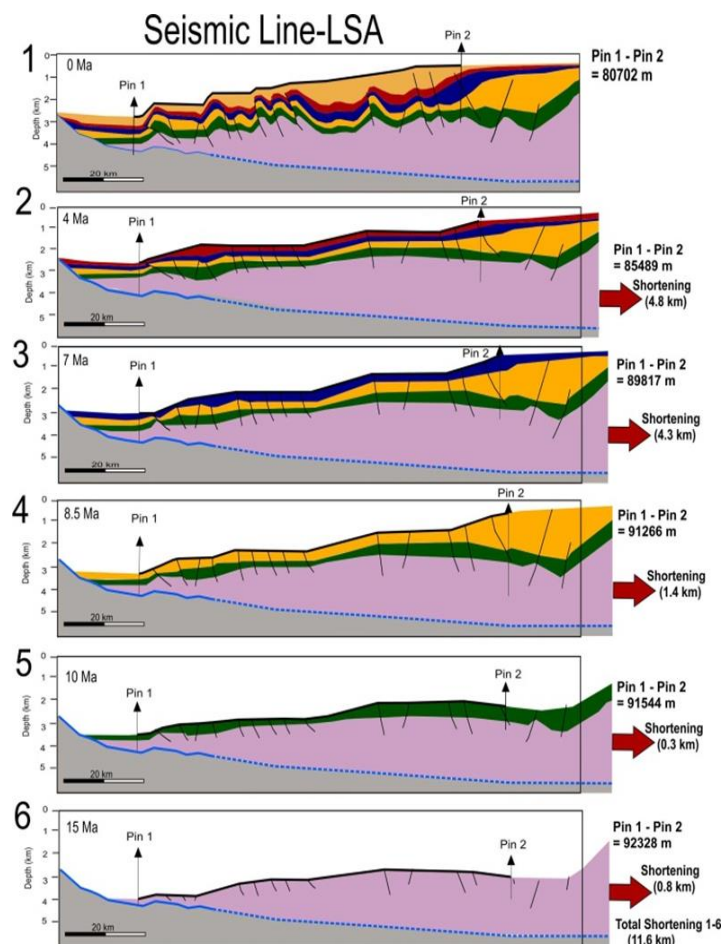

Fig.3. Schematic cross section traced from seismic line LSA representing south of study area illustrating structural restoration from mid-Miocene (6) to Recent (1).wavelength (c) fold type classifications (d).

The restoration processes began with layer unit of recent to Mid-Miocene in age (15 Ma) numbered as 1 representing the youngest age to 6 for the oldest one. Fig.s 3 to 5 are examples of kinematic models representing south to north of the study area.
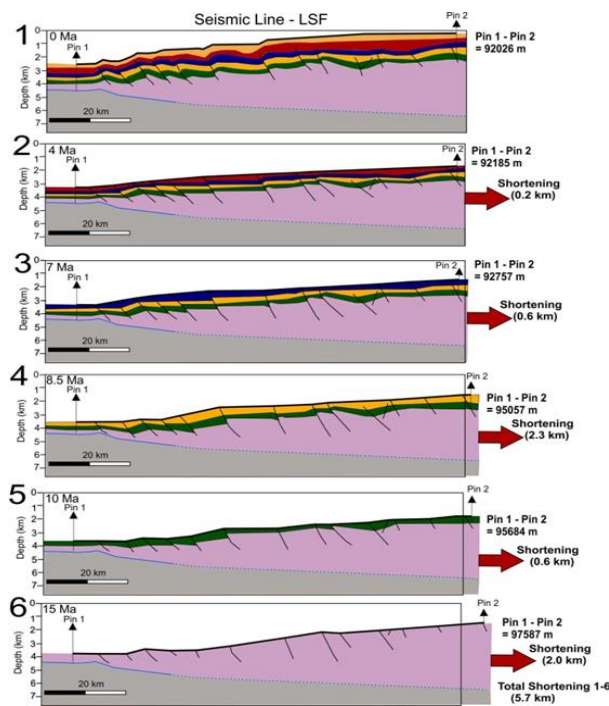

Fig. 4. Schematic kinematic model for seismic line LSF representing the center of study area.
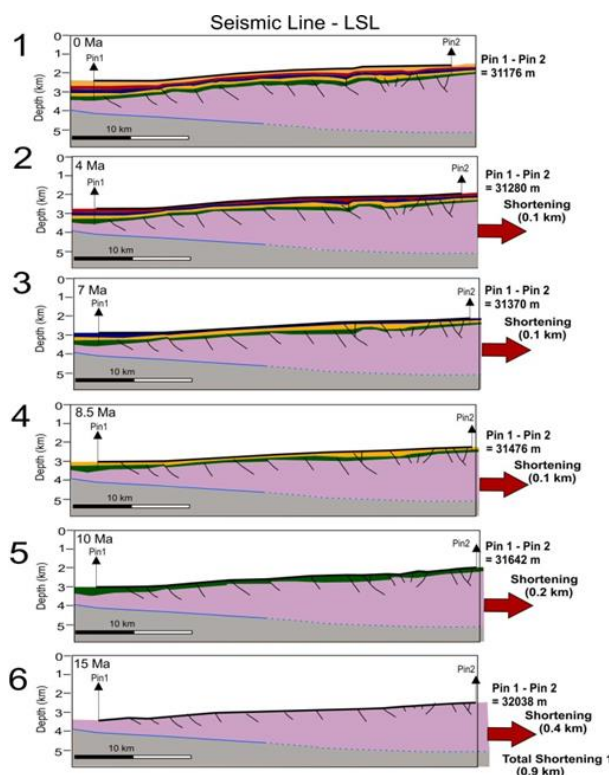

Fig. 5. Schematic kinematic model for seismic line LSL representing north of study area.

Overall, the restored cross sections show compressional deformation tectonic activities displayed by shortening strain that striking from northwest to southeast. This deformation is interpreted to be related to thrust faulting activities within thrust-fold belt and all normal faults in the shelf slope.

4. Discussion

Thrust faults in the study area were originated from compressional tectonic while all the normal faults were from tensional zone. Based on total shortening calculation, structures in deep water northwest Sabah basin is dominated by compressional activity. The value of total shortening percentage is calculated along 230 km length from seismic line LSA to LSL as shown in Fig. 6.

The plotted curves include uncertainty limit with total shortening length of 0.9 km to 14.7 km. The curves also record the age of each reconstructed layer unit during the formation of sequence stratigraphy unit 6 to unit 1. The lowest value of total shortening (0.9 km) is observed in the north along seismic line LSL while the highest value (14.7 km) is calculated in the south along seismic line LSB. Length of total shortening is found increasing from 11.6 km in south seismic line (LSA) to 14.7 km in northern seismic line (LSB) and then decreased again to 6.5 km along seismic line LSC. The significant decrease in total shortening in seismic line LSC may probably be due to error during the seismic interpretation process. Most likely the complete image of thrust fault structures were failed to be identified due to the quality of available seismic sections.

Total shortening is increased from 7.7 km along seismic line LSD to 9.4 km along seismic line LSE and then started to decrease towards the north from 5.7 km in LSF to 3.6 km along seismic line LSH. A very small total shortening of 3.2 km is observed in seismic line LSI, 1.6 km along LSK and eventually the shortest shortening of 0.9 km is observed in seismic line LSL.

The major shortening with a magnitude of about 14.4 km was observed in restoring unit 3 along seismic line LSB (Fig. 6). It can be interpreted as due to thick sediment supply from the continental shelf into the slope occurs during 7 to 8.5 Ma (million years) in the southern part of the study area. The rate of shortening is relatively decreasing in 15 Ma to recent.

Fig. 7 shows the difference rate of total thrust-fold belt by previous researchers and in this study. Hesse et al. (2010) reported similar study in structural restoration based on a total of 6 seismic sections in the same thrust-fold belt. Four of the seismic sections overlapped with LSA, LSB, LSD and LSF and in conclusion they divided the sections into 5 sedimentary sequences as opposed to 7 sequences that found in this study.
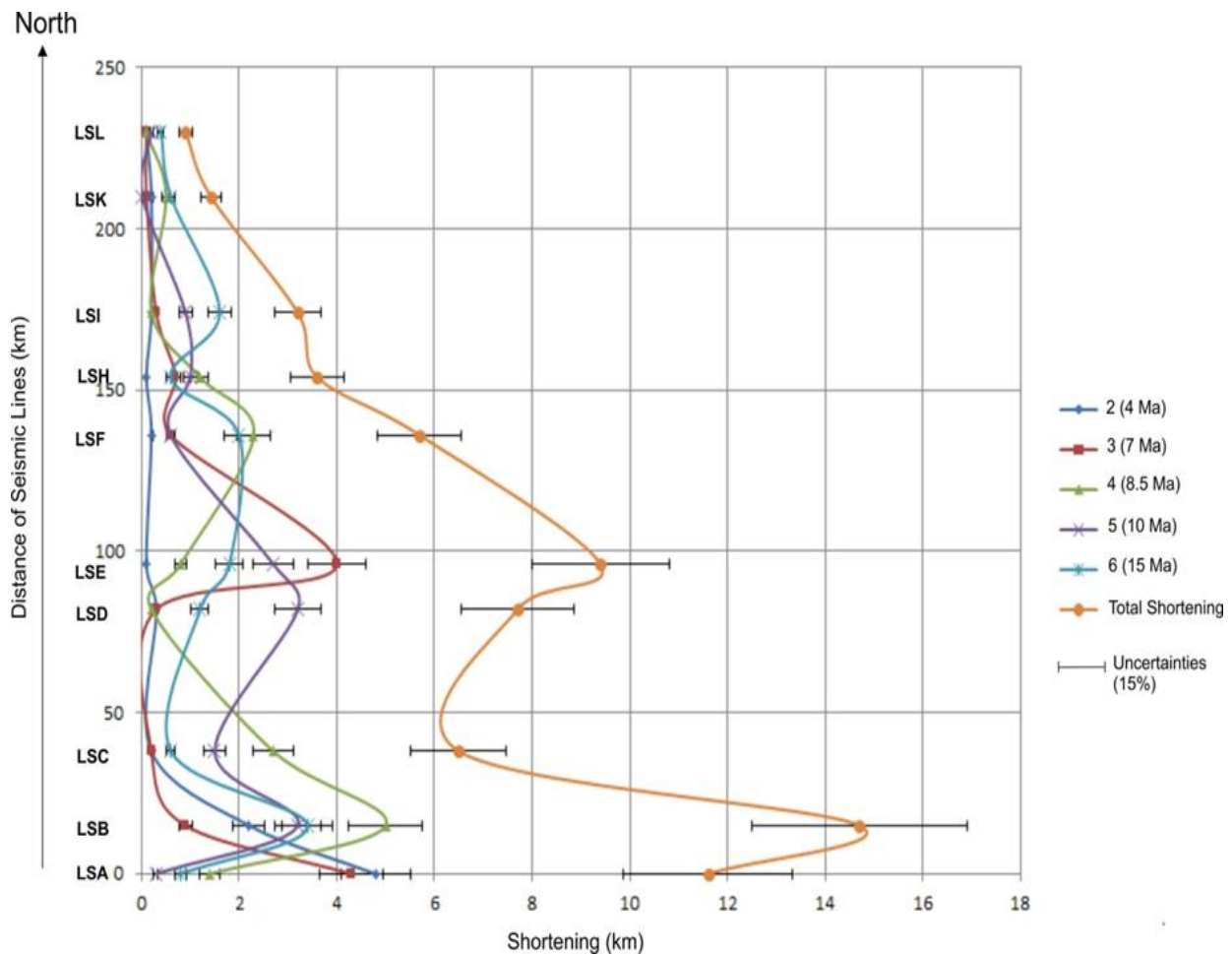
Fig. 6. Curves showing the shortening values against distance of seismic lines with uncertainties bars from mid-Miocene (15 Ma) until Pliocene (4 Ma).

Hesse et al. (2010) also observed crustal total shortening (8-13 km) in the thrust-fold belt from recent to Miocene. Shortening of about 5 to 7 km for each layer was observed in recent to Pliocene unit sequence while a much smaller shortening of 2-4 km was observed in the Early to Late Pliocene sequences. A shortening of approximately 3 km was calculated in layer sequence of early Pliocene to Miocene in age. In general, the rate of shortening in sedimentary sequence is found decreasing from older towards younger. Basically their findings are not so much in difference from the results of this study where the major shortening was reported in the southwest particularly along seismic line LSB.

Based on seismic line positions, major tectonic compression was towards NW-SE which is almost similar to what was reported by King et al.(2010) that obtained the tectonic trend by investigating a total of about 200 wells in Baram thrust-fold belt and in some part of Sabah Basin thrust-fold.

5. Conclusion

The seismic cross sections used in the structural reconstruction of the study area are considered as effective for estimating the rate of crustal

shortening. The tectonic compressional activity which is considered as the main factor to cause the shortening and destroying the sedimentary depositional facies from parallel to chaotic seismic facies as observed in several seismic sections within the thrust-fold belt and thrust sheet.

The values of total shortening measured in thrust-fold belt and thrust sheet zones indicate that both areas are not in equilibrium and had different rate of tectonic intensities. Exceeding balanced about 0.9 km and 14.7 km lengths were observed in crustal shortening of thrust-fold belt and thrust sheet zone both representing compressional area.

This study is only completed if the value of crustal shortening is also measured from seismic lines representing the extensional zones located in shallow bathymetry (<200 m) area of Sabah Basin. The reconstruction system is balanced when the rate of crustal shortening observed in compressional and extensional zones are equal. Higher rate of crustal shortening indicates higher degree of compressional tectonic suffered by that particular crustal area resulting to formation of many thrust fault structures.
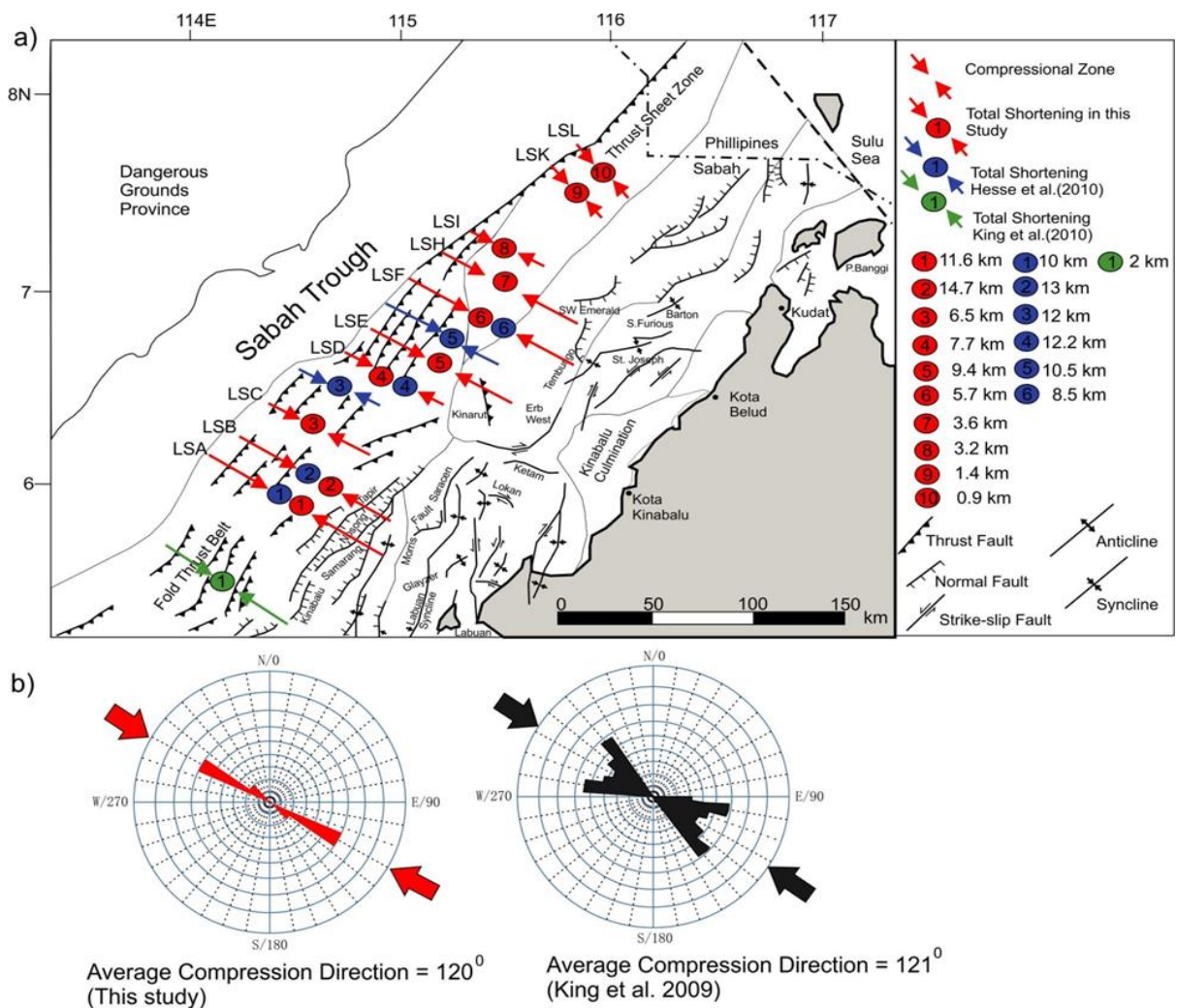
Fig.7. Comparison of structural reconstruction results by previous researchers and in this study. Comparison based on seismic lines (a) and comparison based on rose diagrams (b).

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