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Research Article

Understanding Basin Evolution through Sediment Accumulation Modeling: A Case Study from Malay Basin

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Abstract: Structural and sediment accumulation analysis of available seismic and 10 wells are performed to understand the Cenozoic basin evolution of the south western Malay basin. Structurally, the south western part consists of normal faults, horst and graben geometry. Tenggol fault is the boundary fault between the basinal side and Tenggol arch which penetrated through all Cenozoic sediments. Analysis shows that sediment accumulation rates are high towards basinal side which could be due to the normal faults movement. Rate analysis and 2D modeling explained that sediment accumulation initiated during 33.9 Ma towards the basinal side and could be associated to the activation of Tenggol fault. Sediments of 33.9-25.2 Ma were missing on the tenggol arch and may be arch acted as an erosional surface till 25.2 Ma. Analysis shows that from unit K (25.2-21 Ma) to unit A (6-0 Ma) sediments are found on both tenngol arch and basinal side with the consistent increase in thickness of sediment and accumulation rates towards basinal side. During the basin wide inversion, still sediments accumulated in considerable thickness in the south western part which may be due to less effect of inversion as compare to basin center. After the compression, sediments again deposited with mild tectonic activity or may be reactivation of faults.

Keywords: Basin evolution, fault reactivation, inversion, sediment accumulation, structural analysis

INTRODUCTION

Understanding the formation of sedimentary basins and their evolution is vital for hydrocarbon exploration. Development of a basin is affected by basement subsidence, accumulation of sediments and compaction of rock unit below (Madon, 2007). Basement subsidence factor of any sedimentary rock layer comprises of tectonic forces, loading of water and accumulated sediments (Steckler and Watts, 1978; Watts and Ryan, 1976). For a rift basin, rapid initial tectonic subsidence creates more space for sediment accumulation resulting in the thickening of synrift sediments than post-rift sediments (McKenzie, 1978). The present day sediment thickness indicates paleotectonic conditions which help to understand basin evolution.

With basin initiation, created space start filling with sediments and become compacted with burial depth (Athy, 1930). Behavior of sediment compaction depends on the lithologies, porosity, density, pressure and entrapped fluids (Athy, 1930; Hedberg, 1926). In general, compaction increases with burial depth which creates more space for basin infill and takes part in basin development. Compaction of sediment takes part in accommodation space creation over time.

The Malay basin is a large NW-SE trending trough parallel to the trend of Peninsular Malaysia (Fig. 1a). It is situated in the southern part of the Gulf of Thailand between Vietnam and Peninsular Malaysia (Fig. 1b). The basin is under water of 70-80 m and covers an area of 80,000 km^2 and is filled up to 14 km of sediments (Arshad *et al*., 1995). Towards Northwest the basin merges with Thailand's Pattani trough and southeast ward it merges with the Indonesia's West Natuna Basin.

The aim of this study is to understand the Cenozoic evolution of the south western part of the Malay Basin. The study is based on:

- Structural integration and 2D modeling
- To study the sediment accumulation rates on the Tenggol arch and basinal side. Results based on the analysis of 10 deep wells situated in the south western part of the Malay Basin

Geological setting and stratigraphy: The Malay basin is located at the center of Sundaland and part of

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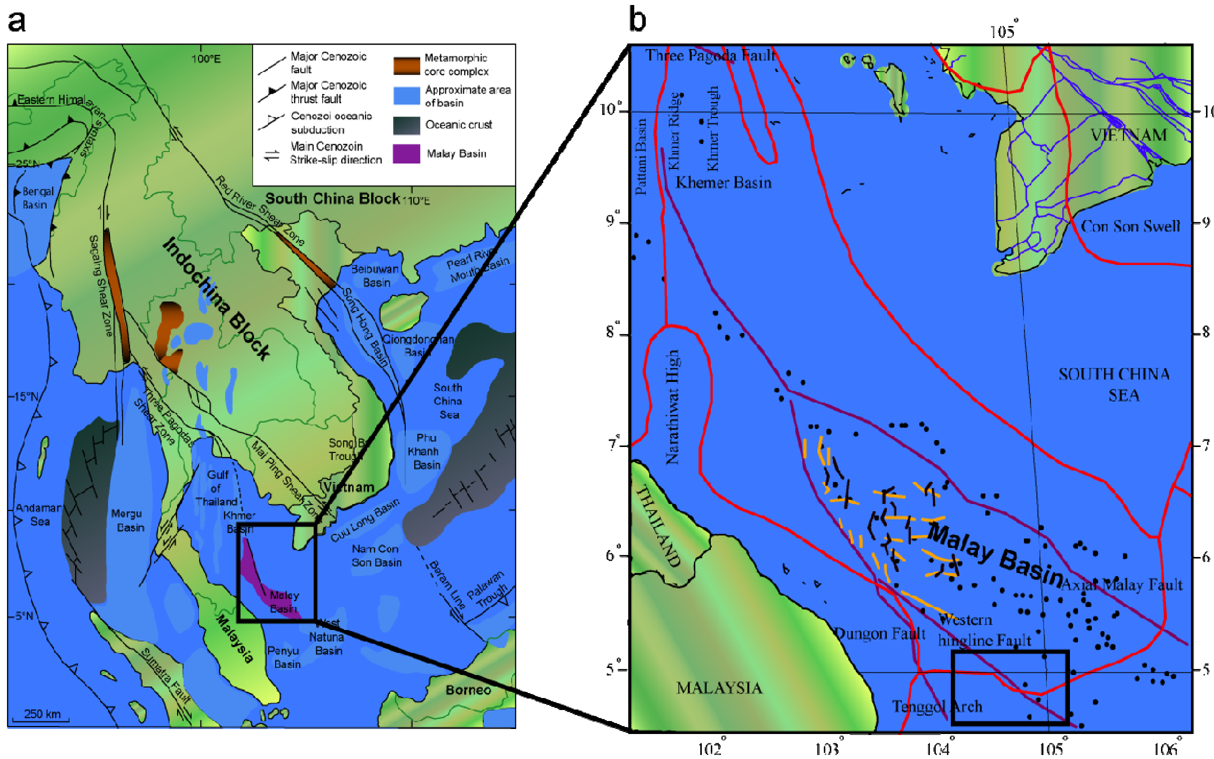

Fig. 1: (a): Location map of the Malay basin with regional tectonic features and basins of South-East Asia (Fyhn *et al*., 2007); (b): Malay basin with major structural features i.e., faults, E-W anticlines etc., also showing diverse exploration activity in the basin (wells/black dots) (Liew, 1994; Ngah *et al*., 1996; Tjia, 1996)
Black box is showing current study area and A-A line demonstrate seismic line location (b)

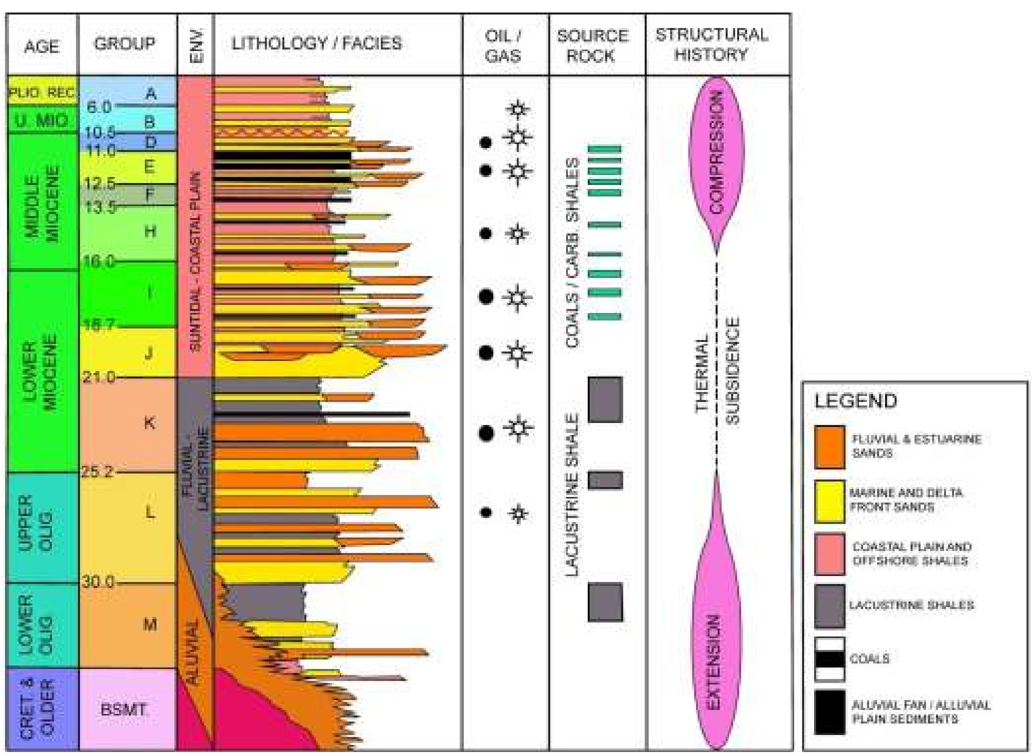

Fig. 2: Stratigraphy of Malay basin form unit A-M, which shows different lithologies with structural history, modified after EPIC (1994) and Petronas (1999)

cratonic core of Southeast Asia (Madon *et al*., 1999a). This intracratonic basin lies close to the boundaries between major tectonic plates. Pacific, Indian, Eurasian and Australian (Fig. 1a). It is one of the deepest basin in the region and is known to have formed during Early Tertiary times. The basin is underlain by pre-tertiary basement of metamorphic, igneous and sedimentary rocks (Madon *et al*., 1999a).

The Malay basin is asymmetrical along its length and in cross section (Madon *et al*., 1999a; Mansor *et al*., 2014). Its south western flank is slightly steeper than its north western flank. Basement faults in the south eastern and central part of Malay basin mostly trend E-W oblique to the overall basin trend. These basement faults appear to have influenced the geometry of compressional anticlines in the Neogene sedimentary fill along the axial Malay fault zone. The south western margin is marked by the western hinge fault, which is a zone of en echelon normal faults.

The large number of tertiary sedimentary basins in South East Asia indicates wide spread extensional tectonism. The basins in Sumatara and Java sea developed by extension during Paleocene-Eocene times, whereas the interior Sunderland basins, like Malay, West Natuna and Thailand basins, formed during the late Eocene to early Oligocene (Fig. 1a).

The Malay basin underwent inversion during the middle-late Miocene. The structural evidence for the basin inversion like compressional anticlines, inverted and uplifted half grabens and reverse throws on the half graben normal faults was described by Tjia (1994a). The intensity of inversion is generally greater at the center than on the flank of the basin. Inversion also increases in the intensity toward the southeast. Basin inversion resulted in the development of large wrench-induced compressional anticlines, mostly within the axial region of the basin. The inversion anticlines then formed over the half grabens by NW-trending dextral shear during the basin inversion phase (Tjia, 1994a).

The Malay basin strata are subdivided informally in to seismo-stratigraphic units. The stratigraphies were derived exclusively on sources from the oil companies working in the area. The oil companies in the Malay basin have subdivided the strata in to units referred to a “groups”. These units are defined based on basin-wide seismic reflectors (Esso, 1985), some of which represent erosional unconformities on the flanks or in the southern part of the basin, which there appears to have be a major inversion during the middle-late Miocene (ASCOPE, 1981). The groups are named according to an alphabetical order, starting with group A, the youngest and ending with group M, the oldest (Fig. 2).

MATERIALS AND METHODS

The study area covers approximately 1000 km^2 in the south western part of the Malay Basin. The analysis consists of 10 exploration wells and two 3D cube data provided by Petronas Carigali Sdn bhd. In addition to seismic data, checkshots, deviation data, well tops and lithological data of each well were also provided. Petrel v.2013 (Schlumberger) was used to performed seismic interpretation, well correlation and time-depth conversion. Seismic-to-well log correlation and integrated to lithostratigraphic data were carried out to provide a framework of interpreted surfaces as well as detailed seismo stratigraphic interpretation in order to understand basin structure and evolution. The interpreted surfaces were then converted to depth from time (msec) by using checkshot function. The depth converted well tops were corrected through well logs by placing them on lithological breaks. Corrected well tops then used to calculate net thickness and further sediment accumulation rates (Van Hinte, 1978). In addition to the seismic horizon, the major bounding faults were mapped on the 2D seismic section.

2D basin modeling also performed on the depth converted seismic section in order to understand the fault influence and sediment accumulation in the south western part of the Malay Basin. For this purpose, PetroMod v.2012 (Schlumerger) was used to digitize the depth section, age assignment and fault assignment to perform the forward modeling.

RESULTS AND DISCUSSION

Structural interpretation: Extensive well and seismic data has been used in order to interpret the study area structurally and stratigraphically. In the south western part of the Malay Basin, horst and graben structure with the normal fault geometry are common. Tenggol fault which separates the tenggol arch from basinal side penetrated through all sedimentary units. Stratigraphic correlation between all ten wells reveals that the unit M (33.9-30 Ma) and L (30-25.2 Ma) are missing on the tenggol (Fig. 3).

Seismic interpretation suggested that the thickness of the sedimentary units are increasing towards the basinal side which may be proposing that the sedimentation activity is higher towards the basinal side as compare to the tenggol arch. Previous workers explained the structural behavior of the Tenggol arch and suggested that the arch is less active as compare to basin center (Madon *et al*., 1999a; Shahar, 2008).

Sediment accumulation rates: In the basinal side, subsidence commenced with the wide spread sedimentation of unit M (33.9 to 30 Ma) during early Oligocene whereas on the tenggol arch the sedimentary units (L and M) are missing over the pre-tertiary basement. Calculated SAR (Sediment Accumulation Rate) for unit M in the basinal side is about 7.8-10.6 cm/ky whereas on the tenggol arch SAR is zero (0) because of no deposition (Table 1). This feature could propose a tectonic activity mainly concerned in the basinal side along the Tenggol fault due to activation

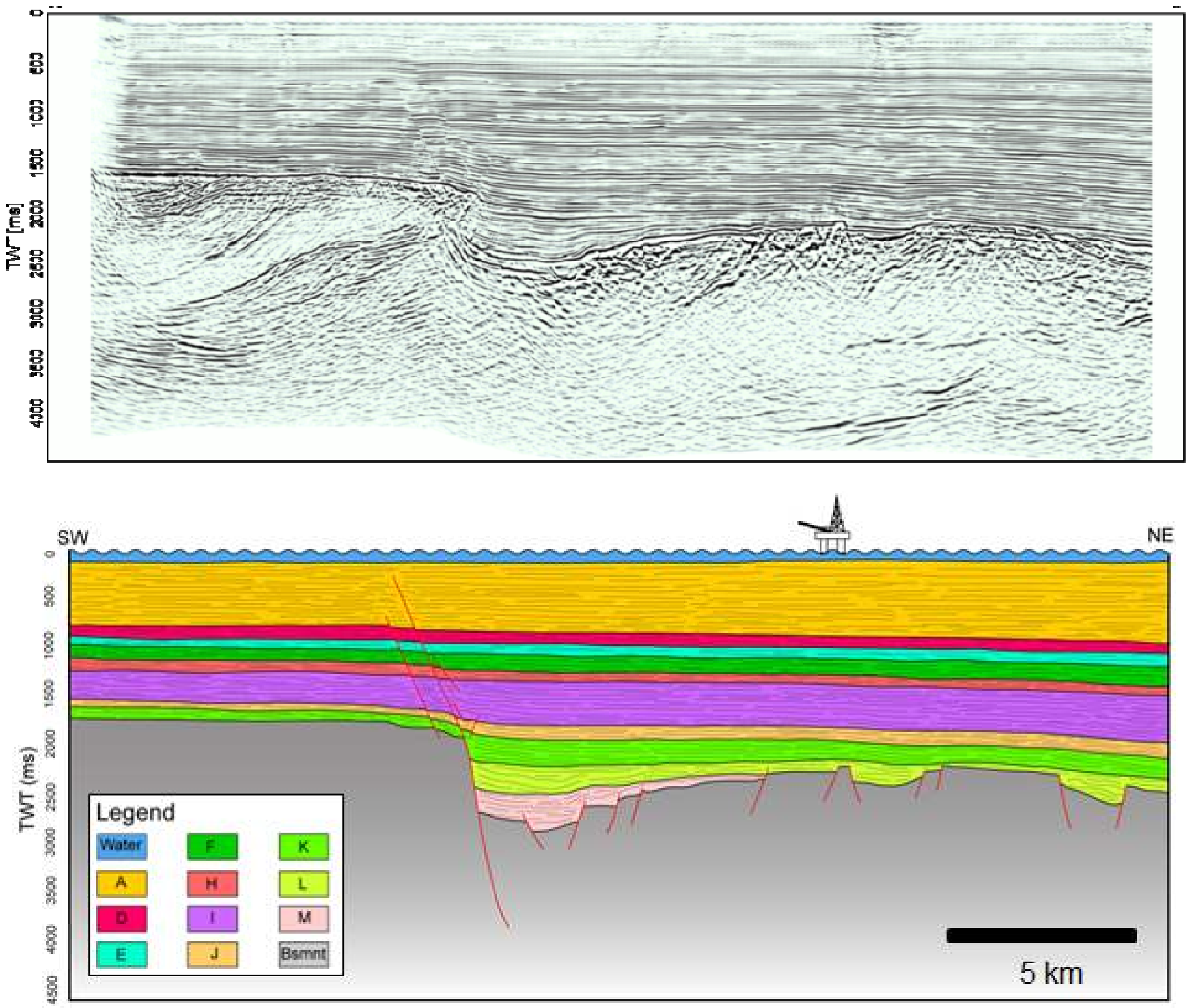

Fig. 3: (a): Raw seismic line; (b): Interpreted seismic section is showing structural geometry of the area and stratigraphic units extend based on the seismic interpretation using available well data (well tops, check shot, well deviation etc.) Horst and graben structure with normal fault geometry are the common features of the study area

Table 1: Sediment accumulation rates (cm/ky) for all ten well situated on the tenggol arch and basinal side in the south western part of the Malay basin

South Western Malay basin	Well	A	D	E	F	H	I	J	K	L	M
Tenggol arch	M-1	2.60	7.00	3.60	11.80	2.73	9.10	2.70	1.74	0.00	0.0
	M-2	3.90	9.00	3.90	11.77	2.37	9.70	3.27	3.97	0.00	0.0
	M-3	3.40	4.80	3.61	11.42	3.27	9.07	3.45	2.50	0.00	0.0
	M-4	4.00	5.95	3.40	11.34	3.74	9.70	3.10	2.36	0.00	0.0
Basinal side	M-5	4.50	6.00	3.60	13.97	2.97	14.97	6.58	9.02	4.74	10.6
	M-6	4.62	6.79	4.20	11.95	4.17	14.50	7.35	7.32	3.12	7.8
	M-7	4.63	6.56	3.90	12.50	4.57	16.01	8.10	8.89	6.60	0.0
	M-8	4.96	8.70	4.60	10.40	4.17	16.20	7.93	7.65	3.03	0.0
	M-9	5.20	9.10	4.80	9.50	4.62	17.03	5.99	7.39	0.68	0.0
	M-10	5.40	7.80	3.90	12.96	5.70	18.60	5.40	7.53	0.76	0.0

whereas on the tenggol arch during this time period probably no subsidence activity. Unit L (30 to 25.2 Ma) deposited during late Oligocene in the basinal side where as its missing on the Tenggol arch, which represents that still the activity is related along the Tenggol fault and no considerable sedimentation activity found on the Tenggol arch. SAR of unit L is around 0.68-6.6 cm/ky which is less than the unit M activity. In the south western part of the Malay Basin the major sediment supply is from Peninsular Malaysia (Morley and Westaway, 2006; Morley, 1998) yet there is no sediment found of Oligocene age (Rupalien to Chatian/33.9-25.2 Ma) on the Tenggol arch which reflects that the basin developed with activation of the

Tenggol fault in the south western part. Another period of subsidence began during late Oligocene to early Miocene through the deposition of unit K (25.2-21 Ma) which is also found on the Tenggol arch but the rate of sediment accumulation are highly variable. From Tenggol arch to basinal side in the south western part of the Malay Basin, the SAR increases as 1.74-3.97 to 7.3-9.02 cm/ky, respectively means the activity is increasing towards basinal side and still the normal faults were active. In comparison between unit L and unit K, the sediment accumulation activity increased during unit K deposition relicts as an alternate behavior of activity. Unit J (21-18.7 Ma) deposited during early Miocene on both basinal side and Tenggol arch, calculated SAR on the Tenggol arch and basinal side are 2.7-3.1 and 5.4-8.1 cm/ky correspondingly which shows a clear increment towards basinal side but the activity is less than unit K subsidence activity. In early Miocene after a tectonically low active period, immense tectonism can be interpreted as SAR are increased abruptly during the deposition of unit I (18.7-16 Ma) whereas on the basinal side the activity became increasing as the SAR on the Tenggol arch and basinal side are 9-9.7 and 14.5-18.6 cm/ky, respectively. Again a low sediment activity recorded during unit H (16-13.5 Ma) deposition in the Middle Miocene, as SAR on the tenggol arch and basinal side are 2.4-3.7 and 2.97-5.7 cm/ky, respectively but the clear increment can be seen towards the basinal side.

Basin inversion during late Miocene effect the rate of sedimentation during the deposition of unit F, E and D. Inversion or compressional tectonics affected the whole basin structural style but the effect of the activity is less in the South western part of the Malay Basin as there are no inverted structure showing in the seismic (Fig. 3). SAR calculation revealed that during the deposition of unit F (13.5-12.5 Ma) the sedimentation activity is also high on basinal side than Tenggol arch in the study area as SAR are from 9.5-14 to 11.4-11.8 cm/ky, respectively. As the inversion activity increased during the deposition of unit E (12.5-11 Ma), the SAR are affected abruptly as compare to unit F, but still SAR are higher towards the basinal side than Tenggol arch as 3.6-4.6 and 3.4-3.9 cm/ky individually. Madon *et al*. (1999a) also argued that the inversion activity was high during the deposition of unit E (12.5-11 Ma).

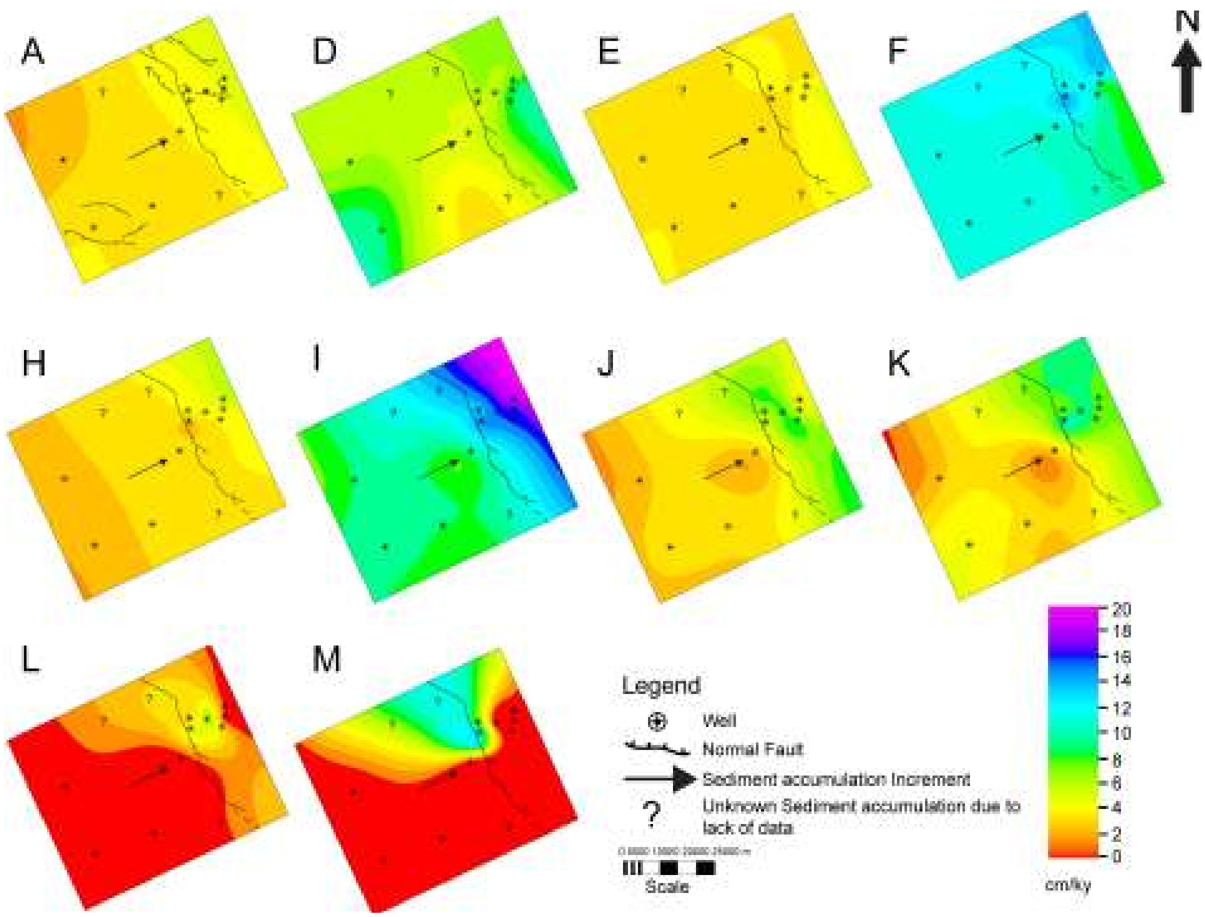

Fig. 4: Calculated Sediment Accumulation Rate (SAR) of each unit (A-M) in every well distributed. Whereas based on SAR for each sedimentary unit is to observe aerial distribution and increment of the activity which help to understand the evolution of the south western part of the Malay basin

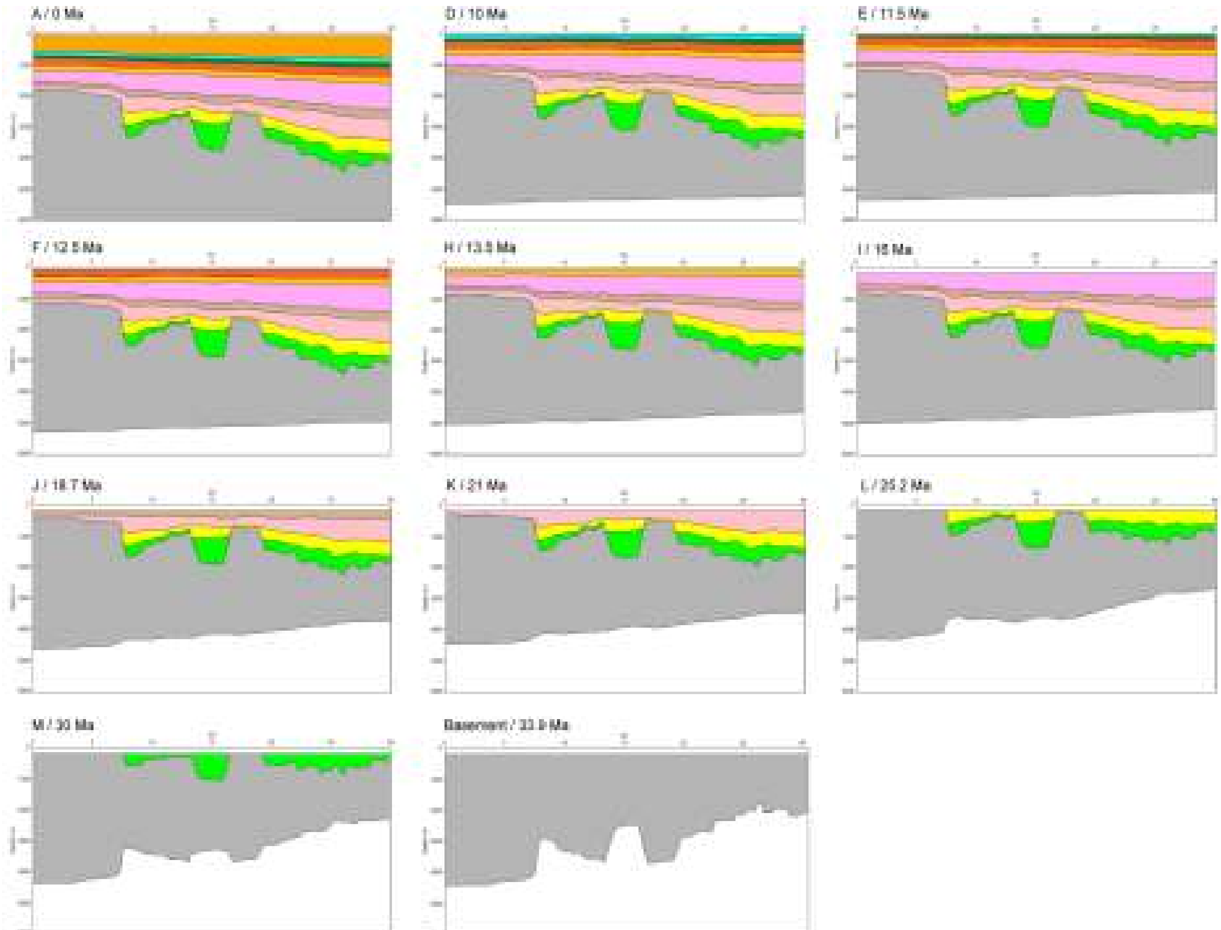

Fig. 5: 2D modeling of the south western part of the Malay basin, to understand the sediment accumulation influenced by fault activation and horst and graben formation

Unit D (11-10 Ma) deposited during probably termination or deliberate inversion, as the SAR are considerably increased as compare to unit E (12.5-11 Ma) where SAR shows significant difference in the wells on the Tenggol arch (4.8-9 cm/ky) and basinal side (6-9.1 cm/ky). Throughout Middle to Late Miocene (Servalian and Tortonian) basin underwent inversion caused by right lateral movement of the axial basement fault reactivated due to plate dynamics (Mansor *et al*., 2014; Tjia, 1994a; Tjia and Liew, 1996).

Unit B (10-6 Ma) is missing in all (10) wells and can be considered as non-deposition, which may be related to inversion or sea level fall. In the central part of the basin sediment (Unit B/10-6 Ma) has been deposited during this time (Madon *et al*., 1999a).

Basin reactivation could be possible with the deposition of unit A (6-0 Ma) with calm tectonism as the SAR are very low but increasing towards basinal side (4.5-5.4 cm/ky) then Tenggol arch (2.6-4 cm/ky). The last phase of basin formation after inversion could be related to fault reactivation and sediment supply. Recently fault activation also found on the onshore Peninsular Malaysia (Tjia, 2010). Basin also experienced marine conditions during this time (Madon *et al*., 1999a; Mansor *et al*., 2014).

Calculated rates of sediment accumulation for each unit in every well are combined and plotted as contour maps in order to observe the distribution of sediment accumulation in the study area (Fig. 4). Since the tertiary evolution of the south western part of the Malay basin initiated during Oligocene, the sedimentary unit deposited until present were showing that the SAR are increasing towards basinal side from the Tenggol arch.

2D sediment accumulation through basin modeling: Interpreted seismic section was converted to depth section to perform 2D basin modeling. Length and depth of the section used for the modeling is 30 and 6 km, respectively. Dating of basement well samples revealed that the Age of pre-tertiary basement in the south western part is cretaceous (Shahar, 2008). Cenozoic development of the south western part of the Malay Basin initiated with the deposition of alluvial sediments of unit M (33.9-30 Ma) influenced with the activation of faults (Fig. 5). While during this time no sedimentation occurred on the tenngol arch and may be it exposed to erosion. Depositional environment changed to fluvial lacustrine and deposited thick lacustrine shales and estuarine sand of unit L (30-25.2 Ma towards the basinal side but still no sedimentation commenced over the tenggol arch. Unit K (25.2-21 Ma) with thick shales and sand deposited towards basinal side whereas the thickness of sediments is less on the tenggol arch. Inferences can be made that the subsidence activity may be related to faults movement which creates enough space to accumulate the sediments. Unit J (21-18.7 Ma), I (18.7-16 Ma), H (16-13.5 Ma), F (13.5-12.5 Ma), E (12.5-11.5 Ma) and D (11.5-10 Ma) deposited under tidal to coastal plain environment, whereas coastal plains, shales, coal and deltaic front sands are commonly associated deposits (Madon *et al*., 1999a; Shahar, 2008). The overall deposition of the sediments is increasing towards the basinal side. Basin experience regional inversion during 13.5 to 12.5 Ma but the effect is very low on the current study area. Whereas unit A (6-0 Ma) deposited during shallow marine conditions with marine clays deposits.

CONCLUSION

The evolution of the south western part of the Malay Basin has been interpreted through the detailed analysis of sediment accumulation rates, structure and 2D modeling. The geometry is mainly controlled by the normal faults which resulted in the formation of horst and graben structure. Tenggol fault penetrated through all cenozoic sediments and separates tenggol arch from basinal side.

Sediment accumulation activity is mainly concentrated towards the basinal side and may be intiated with the activation of tenggol fault (33.9 Ma). The oldest sediments found on the tenggol arch and basinal side are of 25.2 and 33.9 Ma respectively. During 33.9 to 25.2 Ma, no sediments were deposits over the tenggol arch and could be arch acted as an erosional surface. The overall thickness of the sediment is also increasing towards basinal side which reflects that structuraly tenggol arch less active as compare to the basinal side. During the basin wide inversion, still sediments accumulated in considerable thickness which may be due to less effect of inversion in the study area. After the compression, sediments again deposited with mild tectonic activity or may be reactivation of faults.

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