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Characterization of naturally fractured basement reservoir and its play concept, South Pattani Basin, Gulf of Thailand

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Abstract: Structural development and complex basin forming mechanism in Pattani Basin may have formed naturally fractured basement reservoirs. The basement of the South Pattani Basin is poorly understood, as a result of low seismic resolution in its deeper part and lack of wells that reach the basement. Hence, seismic interpretation may improve the understanding of South Pattani Basin basement fracture systems. This paper aims to investigate the geological and seismic characteristics of the fractured basement reservoir, identify the relation between basin evolution and fracture network and development, and proposed a play concept for naturally fractured basement reservoir. Seismic attributes exhibit prominent N-S fault and fracture trends in the study area. Three basement high areas revealed that open fractures distribution identified using seismic ant-tracking technology has good correlation with regional maximum horizontal stress direction (N-S), but the intra-basement (central) area exhibits strong alignment with pre-existing fabrics (NW-SE). Open fracture networks in Zone A and B developed around major fault swarm features. Integrated qualitative and quantitative seismic analysis suggests that the three basement high areas have the potential for fractured basement reservoirs, with a complex fracture configuration and development due to poly-phase deformations.

Keywords: Fractured basement reservoir, Pattani Basin, Bu Do Granite, Pre-Tertiary

INTRODUCTION

Fractured basement reservoir is becoming one of the key plays for future hydrocarbon exploration. Understanding fractured basement reservoirs is important as they give a chance to find missed or yet-to-be-found hydrocarbon fields in southeast Asia. South East (SE) Asia petroleum geology is characterized by a long history of hydrocarbon exploration in Tertiary sedimentary basins underneath its shallow shelf seas. For instance, in the Pattani Basin, the Tertiary sedimentary sequences have been extensively explored and produced hydrocarbon whereas in the deeper parts, where the basement rocks and the early syn-rift sequences lie, are still relatively unexplored. The Pre-Tertiary rocks in South Pattani Basin leave many questions regarding their composition, structural inheritance, and the tectonic setting.

The potential fractured basement reservoirs in Pattani Basin are likely to be found in buried hill structures and consisting of amalgamated Pre-Tertiary rocks (granite, meta-sediments, carbonates, and red beds). Hydrocarbon accumulations has been discovered in these types of fractured basement reservoir in adjacent parts of SE Asia (e.g., Bach-Ho and White Tiger field in Cuu Long Basin, Vietnam and Anding, Malay Basin, Malaysia) (Cuong & Warren, 2009; Ngoc & Quan, 2010; Huy *et al.*, 2012; Fun *et al.*, 2014; Vo Thanh *et al.*, 2019). With more recent data, information, and technology, fractured basements reservoirs still have the potential for storing large undiscovered hydrocarbon resources if the complexity in subsurface fractured reservoir characterization can be solved.

The Pattani Basin occupies an area of approximately 15000 km^2 in the southern part of the Gulf of Thailand. The study area is a part of South Pattani Basin where the main producing reservoirs occur in the Tertiary sedimentary sequences. This basin is limited by Narathiwat High in the eastern side and bounded by Ko Kra Ridge on the western side while in the southern part it is delimited by Malaysia terrane (Figure 1).

This study aimed to investigate the fracture network and the associated structural features in the basement highs in the South Pattani Basin. In addition, this paper characterized and modelled the distribution of natural fractures and provides a better understanding of a fractured basement play concept and its exploration potential.

GEOLOGICAL SETTING

Tectonic framework

The Pattani Basin is the longest and deepest basin in the Gulf of Thailand, with approximately 7.5 km (3.75 s) of sediments in the deepest part (Figure 1). It is characterized as

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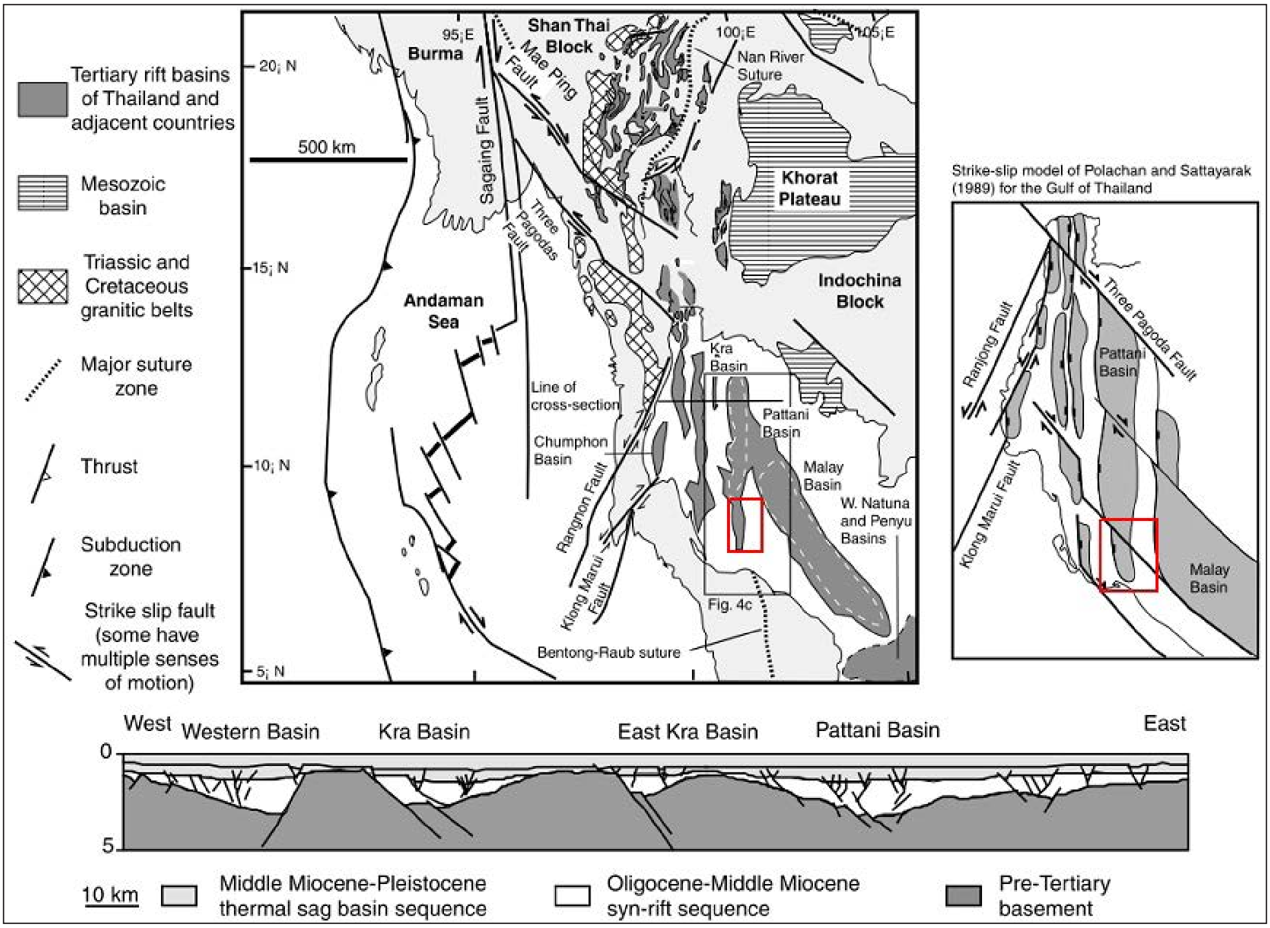


Figure 1: Tectonic map of Gulf of Thailand area and the geological setting of the Pattani Basin (Watcharanantakul & Morley, 2000). (left) Regional tectonic map of western South East Asia showing the rift basin of Thailand in dark grey, (right) showing the zoom in Pattani Basin and its major structural product, (below) regional cross-section of the northern Gulf of Thailand, red rectangles are showing the study area.

a rift basin with a N-S−oriented structural fabric. Structurally, Pattani Basin is divided into three parts; northern, central, and southern parts which are bounded by strike-slip faults (Morley & Racey, 2011). The study area is located in the South Pattani Basin, adjacent to Narathiwat High to the east. The western part of the basin is bounded by Ko Kra Ridge. South Pattani Basin is an asymmetrical basin where the depocenter lies in the western part of the basin and gets shallower towards the east (Morley *et al.*, 2004).

The Pattani Basin is approximately over 270 km long and approximately 100 km wide (Watcharanantakul & Morley, 2000; Morley & Racey, 2011). The initial extension in the Pattani Basin was previously proposed to have occurred during the Late Oligocene (Regan *et al.*, 1976) but recent studies identified that the extension continued from Late Eocene to Late Oligocene. The initial rift in South Pattani Basin started during Late Oligocene to the Early Miocene, with the basin-bounding faults which are interpreted as linked normal faults rather than the strike-slip faults of the typical escape tectonics model (Morley & Charusiri, 2011). An alternative explanation of the forming of Pattani Basin is closely related to the tectonic escape process of the Eurasian Plate during the Indian-Eurasian collision, it creates a strike-slip rift basin that has a parallel direction with the major tectonic movement (Morley *et al.*, 2001; Morley & Charusiri, 2011).

The Pattani Basin is filled with a Tertiary sedimentary section approximately 8500 m thick which lies above a basement of Pre-Tertiary rocks that continue from surrounding Pre-Tertiary basement highs (Watcharanantakul & Morley, 2000). Based on the onshore geology, the basement of Pattani Basin is divided into five elements: 1) Precambrian crystalline basement, 2) highly folded and foliated rocks consisting of greenschist grade meta-sediments of Lower Palaeozoic age, 3) Perm-Triassic suture belt, created by a collision between the Shan-Thai and Continental blocks, 4) the Indosinian orogen as a product of subduction of oceanic crust beneath the Indosinian craton and closure of one arm of the neo-Tethys, and 5) Late Cretaceous – Early Tertiary granite intrusions along Burmese border and peninsula Thailand as a result of the subduction of Indian Plate beneath western Burma Plate which became the source of sediments in the Pattani Basin

(Watcharanantakul & Morley, 2000; Morley & Racey, 2011). In this basin, the pre-existing rock fabrics in the basement high are covered by Tertiary sediments sequences.

The South Pattani Basin is probably the deepest rift basin in the Gulf of Thailand. This basin experienced super-deep subsidence during post-rift sediment loading (Morley & Westaway, 2006). There are three main tectonic events in the study area that influences the basement, which are:

a. Pre-Tertiary plutonism: N-S (Watcharanantakul & Morley, 2000; Charusiri & Pum-Im, 2009).
b. Rifting phase – the initiation of the Pattani Basin: Initial rifting during Early Tertiary with a dominant NW-SE alignment of sedimentary facies belts changed to N-S in the Miocene due to rotational of the extensional stress field (Regan *et al.*, 1976; Watcharanantakul & Morley, 2000; Morley *et al.*, 2004; Morley & Charusiri, 2011; Morley & Racey, 2011; Phoosongsee *et al.*, 2019).
c. The Post-rift phase: (Jardine, 1997; Morley *et al.*, 2004; Charusiri & Pum-Im, 2009; Morley & Racey, 2011).

Regional stratigraphy

The South Pattani Basin lies above pre-Tertiary igneous rock as its basement. The igneous rock is equivalent to Merah Granite / Bu Do Granite (Trgrmr/bd) and the outcrop analog of Merah Granite yfound exposed at Narathiwat Province, Thailand. The granite is Triassic in age and characterised as grey coloured, strongly foliated with NNW-NNE strike with steeply dipping (60° to 80°) towards the ENE to ESE directions (The Malaysian-Thai Working Group, 2012). Bu Do Granite forms a north-south lineament of high elevation trending, occupying Pattani Province in the east coast to Yala and Narathiwat Provinces in the southern part nearby the Malaysia-Thailand border (The Malaysian-Thai Working Group, 2012).

In the South Pattani Basin, Tertiary sedimentary sequences deposited unconformably above the basement rock. The Tertiary sedimentary sequences in Pattani Basin consist of 5 sequences based on the integration between well-log, seismic and core description (Morley & Racey, 2011) (Figure 2). The five Tertiary sequences in South Pattani Basin have a typical rift basin character and were derived from multiple sources in the north, east, and west directions (Morley & Racey, 2011) (Figure 3).

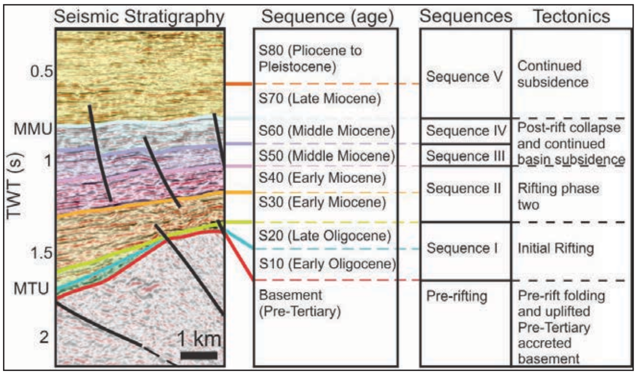


Figure 2: Seismic stratigraphic framework of the study area, showing the main interpreted seismic reflection events.

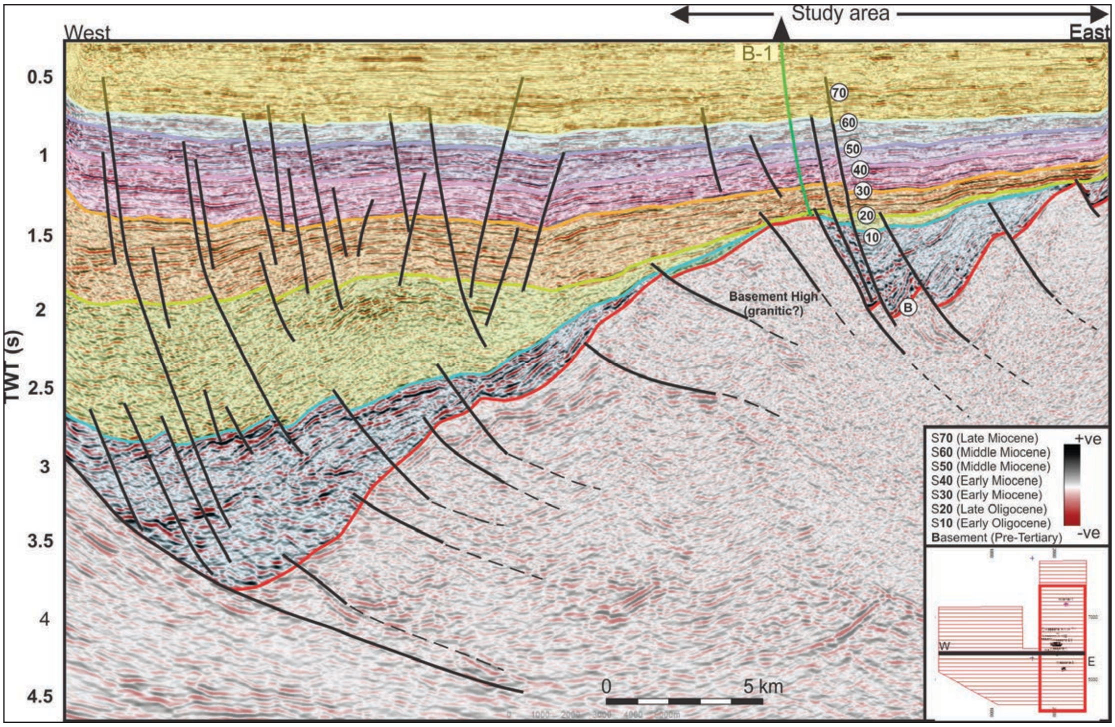


Figure 3: Geoseismic cross-section through the study area in the South Pattani Basin showing the sedimentary sequences and the faults.

Sequence I is the poorly known part which is the Late Eocene – Oligocene initial syn-rift section which consists of alluvial fans, fluvial-deltaic sequences and lacustrine deposits in the upper part of this sequences during Late Oligocene to Early Miocene (Morley & Racey, 2011). Based on the seismic section (Figures 2 and 3) from South Pattani Basin, Sequence I is located at a small graben and shows proximal alluvial-fan wedges seismic reflection geometries and lateral continued reflection of lacustrine shales (Jardine, 1997).

The transition from Sequence I to Sequence II can be seen by two distinctive channel characteristics. Sequence I has complex meandering channel belt while in Sequence II the channel belts are relatively narrow (Phoosongsee *et al.*, 2019). Sequence II is a rifting phase two section which consists of fluvial to lower delta plain deposits of Early to Middle Miocene age. On seismic, its Lower Red-bed unit is observed to onlap onto Sequence I and is overlain conformably by Sequence III (Morley & Racey, 2011). Above Sequence III, known as the Middle Miocene Upper Grey Beds unit, which is associated with a transgressive phase of fluvial deltaic to marginal marine deposits, there is a disconformity that is marked as Middle Miocene unconformity (Morley & Racey, 2011). Sequence III is overlain unconformably by Sequence IV.

Sequence IV, or Middle to Late Miocene Upper Red-beds unit (Figure 2), is a fluvial-deltaic sand stacked point bars during a regression phase which created a fluvial floodplain environment (Morley & Racey, 2011). The uppermost sequence, Sequence V marks the onset of transgressive marginal marine deposits in the Late Miocene to the Recent age, and consists of coals and predominantly unconsolidated claystone (Morley & Racey, 2011). This sequence contains terrestrial dominated Type III and Type II kerogens and are known to have generated gas/condensate and minor oil (Jardine, 1997).

METHODOLOGY

This study focused on 3D seismic interpretation combined with various seismic attributes analysis using Petrel software by Schlumberger at the top of the basement horizon, which is indicated by a decrease in acoustic impedance. Horizon picking was done at a regular interval of 40 in crossline and 20 in inline with more detail in complex basement areas. The inline sections cut across the basin strike. Five seismic attributes (Root Mean Square (RMS) amplitude, average energy, mean amplitude, sweetness, and variance) were generated to characterize and delineate potentially fractured zone. Horizon probe combined with time slice was used to display the 3D geometry and model the characteristics of the seismic attribute of fractured zones on the basement highs. Structural attributes (ant-track) were generated to capture potential open fractures area in the basement highs. The output of high ant-track attributes and amplitude attributes were combined to extract potential open fractures zone (Gaafar & Najm, 2014; Kee *et al.*, 2017).

RESULTS

Intra-basement seismic reflection and seismic facies

Based on seismic reflection characteristics, several seismic facies were recognised within the Pre-Tertiary basement. The reflection characteristics were divided into four seismic facies according to their reflection distribution, relation, and orientation.

Seismic facies SF1

Seismic facies SF1 (Figure 4A) is identified by fairly continuous reflection above the top of the basement horizon with subparallel continuous reflections in the upper part of intra basement reflections which gently dip towards the west (<20°). It has moderate to high amplitude reflection range. It occurs in the upper part of basement high and is located around well B-1 area (Figure 2, 3). The pre-existing fabrics have varying orientation which indicates several factors for example, faults linkage; overprinting structures; poly-phase deformation, and rock rheology, that control the rifting mechanism in South Pattani Basin (Morley & Charusiri, 2011).

Seismic facies SF2

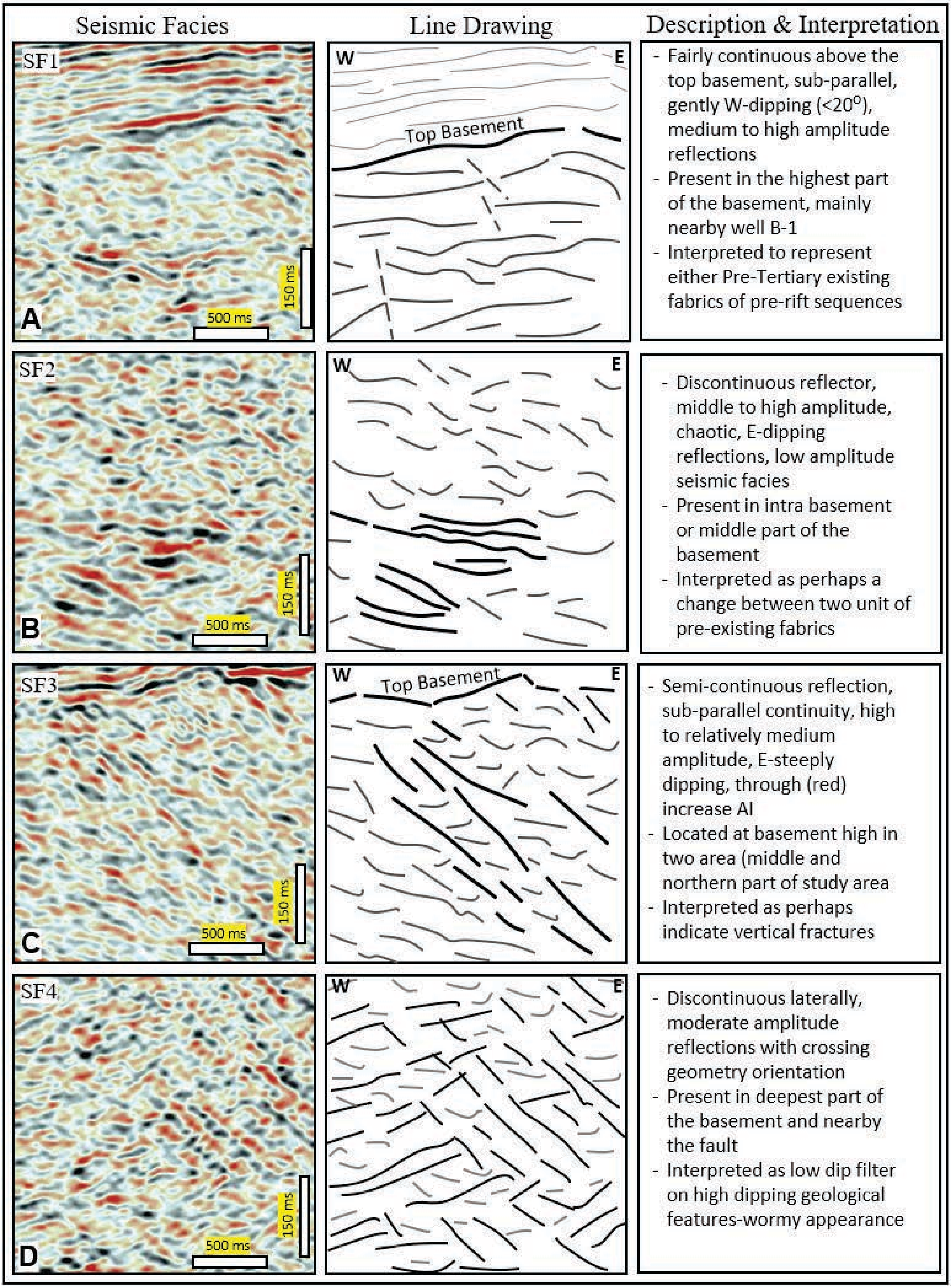
Seismic facies SF2 is characterized by discontinuous reflectors with moderate to high amplitudes despite chaotic reflection patterns. The reflections dip gently towards the east and have low amplitude and high frequencies (Figure 4B). The facies is present in the central part of the basement high area. It is interpreted as two different pre-existing fabrics of possible inheritance of granitoid intrusions in the basement areas (Watcharanantakul & Morley, 2000; Morley & Charusiri, 2011).

Seismic facies SF3

Seismic facies SF3 is categorized by semi-continuous reflection near the unconformity between overlying sediment and basement top while in the basement area, there is sub-parallel reflector continuity with medium to relatively high amplitude (Figure 4C). The intra basement reflection has steep dipping towards the east geometry and is noted by an increase in acoustic impedance (red colour). It is located at the two observed basements highs in the study area which are in the middle and in the northern side of the basin. The steeply dipping reflector is interpreted as due to the pre-existing fabric in the basement area and it indicates lithological discontinuity that might be potential as fractured basement reservoir. Their influence of pre-existing fabrics on rift structural style provides a very complex fault linkage pattern and also fractures distribution (Morley & Charusiri, 2011).

Seismic facies SF4

Seismic facies SF4 is observed by discontinuous reflection laterally with moderate amplitude reflections



Description & Interpretation

- Fairly continuous above the top basement, sub-parallel, gently W-dipping (<20°), medium to high amplitude reflections
- Present in the highest part of the basement, mainly nearby well B-1
- Interpreted to represent either Pre-Tertiary existing fabrics of pre-rift sequences

- Discontinuous reflector, middle to high amplitude, chaotic, E-dipping reflections, low amplitude seismic facies
- Present in intra basement or middle part of the basement
- Interpreted as perhaps a change between two unit of pre-existing fabrics

- Semi-continuous reflection, sub-parallel continuity, high to relatively medium amplitude, E-steeply dipping, through (red) increase AI
- Located at basement high in two area (middle and northern part of study area
- Interpreted as perhaps indicate vertical fractures

- Discontinuous laterally, moderate amplitude reflections with crossing geometry orientation
- Present in deepest part of the basement and nearby the fault
- Interpreted as low dip filter on high dipping geological features-wormy appearance

Figure 4: Seismic facies characteristic, and interpretation of the crystalline basement seismic facies (SF1-SF4) (A-D) identified in 3D-seismic data along the eastern area of South Pattani Basin, Gulf of Thailand.

within crossing orientation geometry (Figure 4D). SF4 is present at the deepest part of the basement area and nearby faults. The crossing geometry of the seismic reflection is interpreted as perhaps contraction between two pre-existing fabrics in the basement area. Besides, it also occurs nearby the survey edge. There may also be a seismic processing effect where a low dipping filter is applied to high dipping geological events.

Lateral or vertical termination of seismic reflections and sudden change of seismic facies are considered as boundaries between different basement units. Crystalline basement 3-D geometry and structural architecture can be reconstructed by identifying the spatial relationship (Lenhart *et al.*, 2019). Different characters of seismic reflection are representing the basement or pre-tertiary rocks that are controlled by pre-Tertiary rock fabrics.

Faults in basement

Numerous faults have been identified in the study area. The structural style is rift basin which consists of synthetic and antithetic fault sets. Synthetic normal faults cut from the basement into Tertiary overlying sedimentary strata. However, there are several faults observed in the top of the basement section which are low angle eastwards dipping. The major faults in the study area or synthetic faults are dipping towards the east while the antithetic faults are dipping towards the west direction. Fault interpretation was done by interpreting three compared seismic volumes: basic seismic volume, dip-illuminator volume attributes, and structural-oriented-filtered-volume attributes (Figure 5).

Faults in the basement area were interpreted by tracing moderate to steeply dipping reflectors. The faults in the Pre-Tertiary rocks, which are represent by the steeply dipping

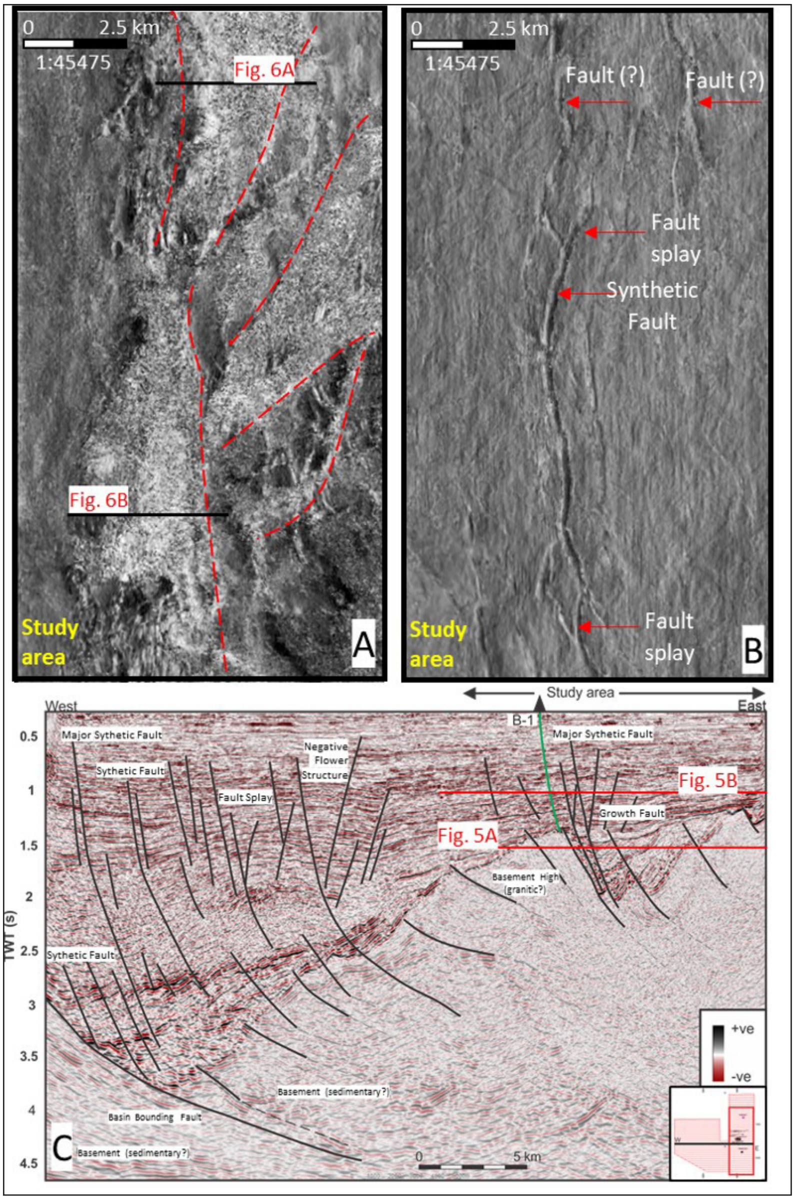


Figure 5: Interpretation of faults in study area based on 3D seismic. (A) showing dip-illuminator attribute at time-slice 1544s which cut basement rock, (B) showing the time-slice at 1010s or at syn-rift sequence, (C) Fault Picking at XL 5836 showing the Top of Basement.

reflector, are related to the reactivation of pre-existing fabrics during initial extension or rifting (Morley *et al.*, 2004). The main direction of fault sets in the basement horizon is north-south trending with dipping towards the east. A normal fault located at the centre of the study area is identified as the major synthetic fault.

Identification of faults in basement

Intra-basement reflections are poorly imaged in the deeper >1000 ms Two Way Time (TWT) of the basement rocks while at the shallow basement rocks, the reflections are well-imaged >100 ms TWT. The crystalline basement has a generally chaotic reflection. The most prominent seismic features in the intra-basement are medium-to-high amplitude, continuous to semi-continuous, and discontinuous, with steeply east-dipping (50° to 70°) reflections. There are three types of intra-basement fault seismic reflections which are; continuous reflections, semi-continuous reflections and discontinuous reflections (Figure 6C, D, and E).

Type A features consist of a circa 1 km-wide zone of steeply dipping (50° to 60°) high amplitude reflection (Figure 6C). The type A reflections are defined by a peak-trough-peak wave pattern and also a single peak wave. The seismic character within this package changes laterally, from high amplitude continuous reflection at the western side to continuous reflection low amplitude at the eastern side. Type A reflections typically offset Top Basement horizon (Figure 6A).

Type B is represented by steeply dipping (60° to 70°) amplitude reflection and have a close lateral spacing of 500 m

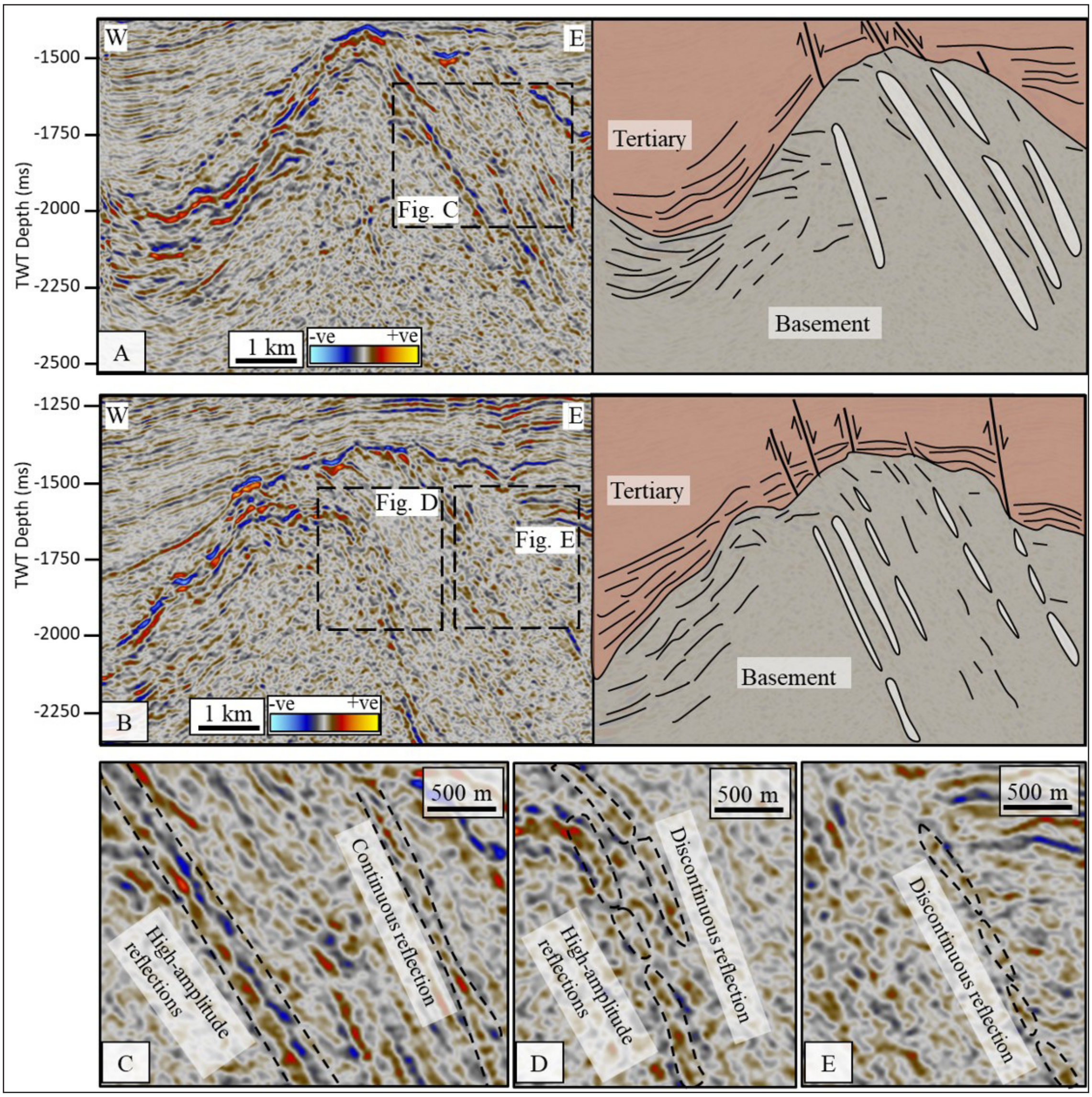


Figure 6: Uninterpreted seismic profiles and interpreted sections delineating the key characteristic of intra-basement reflections, (A & B) seismic section oriented perpendicular to the major fault in two locations (Fig. 5), (C) showing continuous reflection, (D) close-up of high-amplitude of discontinuous reflection, (E) close-up of discontinuous reflection towards sedimentary layer in the eastern side.

(Figure 6D). The reflection is defined by a peak (red colour) wave. Seismic reflections are vertically discontinuous and semi-continuous from the Top Basement down to the 3000 ms survey depth. Type B reflections have high amplitude reflection and decrease with depth. Type B reflections are truncated by the Top Basement unconformity.

Type C has similar characteristics to Type B, but the reflections are discontinuous to semi-continuous and weaker at the basement boundaries towards sedimentary sequences (Figure 6E). The reflections are vertically segmented and have relatively low amplitudes. Type C reflections typically offset Top Basement. This type of reflection can be found in the non-conformity between basement high and tertiary sedimentary sequence on the eastern side of the major fault.

Basement faults and basement fracture development

The structural evolution in Pattani Basin was controlled by rifting as the main basin-forming process. The basin began to form in the Late Oligocene by initial rifting that continued to the Early Miocene. Extensional faults are the dominant products of rifting. Our kinematic analysis found that the maximum stress is vertical with north-south maximum horizontal stress component, except for local deviations (Figure 7). In general, the maximum horizontal stress in Pattani Basin is dominantly north-south trending, sub-parallel to the strike of major extensional faults (Tingay *et al.*, 2009).

In the study area, ten faults have been identified from the interpretation of the seismic volume (Figure 7). Out of the 10, seven faults were selected for kinematic analysis using fault properties for inferring maximum horizontal stress (SHmax). The measured fault properties include strike and dip, and pitch as slip indicator (Table 1). Based on the kinematic analysis, the maximum horizontal stress direction is N-S direction.

The faults are divided into three zones: Zone A, Zone B, and Zone C (Figure 8). Fault 1 and Fault 7 are located in Zone B in the central area. Fault 6 and Fault 2 are located in Zone A and act as basin-bounding faults. Fault

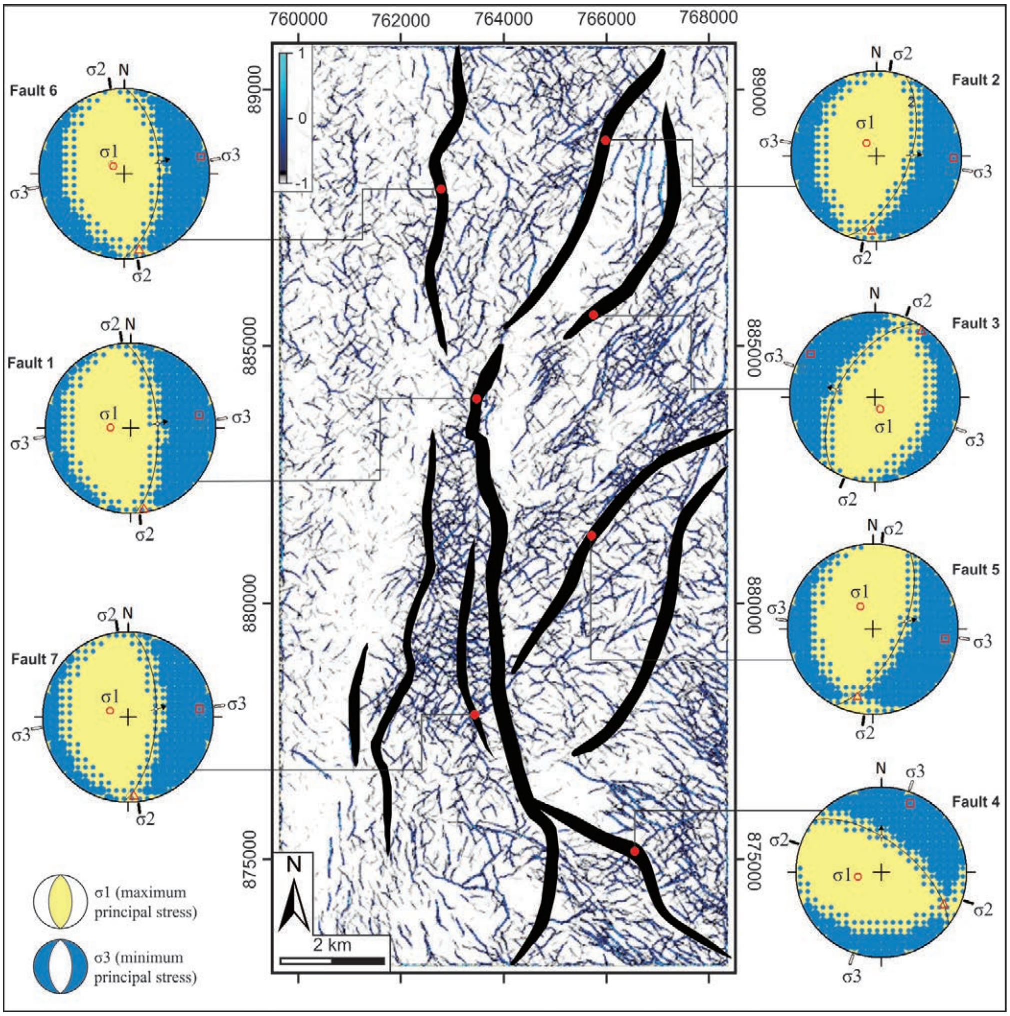


Figure 7: Kinematic analysis of faults and its implication to fracture development. The beach ball shows stress inversion from fault properties (strike, dip, and pitch). Fine black-to-blue lines between the major faults are the result of ant-tracking.

Table 1: Faults properties measurements at the study area.

No.	Fault Name	Strike (N….°E)	Dip (….°)	Pitch (….°)	SHmax
1.	Fault 1	357	64	87	Maximum horizontal stress is N356°E – N176°E where it is N-S trending
2.	Fault 2	020	58	78	Maximum horizontal stress is N004°E – N184°E, where it is N-S trending, deviated to NNE
3.	Fault 3	210	54	79	Maximum horizontal stress is N013°E – N193°E where it is NNE-SSW trending
4.	Fault 4	308	61	69	Maximum horizontal stress is N283°E – N103°E where it is WNW-ESE trending
5.	Fault 5	026	63	70	Maximum horizontal stress is N003°E – N183°E where it is N-S trending
6.	Fault 6	001	56	79	Maximum horizontal stress is N354°E – N174°E where it is N-S trending
7.	Fault 7	003	63	81	Fault 7 has strike N003°E with dipping 63° and pitch 81°. Maximum horizontal stress is N354°E – N174°E where it is N-S trending

3 and Fault 5 are located at Zone C where they also act as basement high boundaries. Fault 5 and Fault 4 are located in the downthrown area of Fault 1 and dips to the east.

Fault 1 is the largest fault that has been identified in the study area. It dips steeply towards the east at 64° and it has pitch of 87° that implies the maximum stress is vertical (Figure 7). Fault 7 is synthetic to, and has similar characteristics as, Fault 1. Fault 1 and Fault 7 seem to be controlling the fracture distribution in Zone B. The distribution of fractures in the basement high crest is probably due to opening mode from vertical stress.

Fracture development in Zone A and C are not as extensive as in Zone B. The fracture orientation in Zone B is different from the other two zones possibly because of highly deformed area, thus the pre-existing structures become open together with normal faulting process.

The seven faults described above are classified as normal-slip faults (Rickard, 1972; Ragan, 2009). The dominant movement is dip-slip movement (dip ± 80° and pitch >60°). N-S is the maximum horizontal stress direction while the minimum horizontal stress direction is E-W. The north-south faults and fractures cut the older rock fabrics which trend in the north-northwest–south-southwest direction.

Fracture distribution

Open fractures in the South Pattani Basin have characteristic orientation and density. The main orientation of the fractures is in north-south and northeast-southwest directions. The identified directions were generated by tectonic transport which parallels to the fracture orientations. The collision between India and Eurasian Plate plays an important role in the north-south tectonic transport (“escape”) of Eurasian Plate (Morley *et al.*, 2001). During that process, as compensation of the collision, there is a releasing (extensional) stress mechanism which causes the formation of the Pattani Basin.

The delineation of open fracture in seismic interpretation was done by grouping fracture sets that have parallel orientation to maximum horizontal stress of the South Pattani Basin. Regional maximum horizontal stress was used for open fracture characterization due to most of drilled well did not reach the top of the basement horizon. Based on the analysis, the open fracture orientation at the basement horizon is dominated by N-S trend between the azimuth 345° - 015° (Figure 8). Qualitatively, the open fracture distribution at the basement horizon is low to moderate on the flank of the basement high and moderate on the crest of the basement high. Areas nearby the major fault are highly fractured and may have potential as a naturally fractured basement reservoir.

Quantitatively, the number of open fractures identified after the filtering process is 449. Based on statistical analysis, the open fractures showed N-S dominant trend, as the following details:

a. Zone A has two main fracture orientations: N-S (N350°E – N010°E) and NNE (N010°E – N020°E). The mean strike and dip from all 131 open fractures is N005°E/75°.
b. Zone B has two main fracture orientations: N-S (N350°E – N010°E) and NNW (N340°E – N350°E). The mean strike and dip from all 228 open fractures is N356°E/72°.
c. Zone B has two main fracture orientations: NW (N030°E – N40°E) and NE-SW (N020°E – N030°E). The mean strike and dip from all 90 open fractures is N026° E/77°. This zone has different trending than the other two zones. The difference is due to this basement high is controlled by pre-existing fabrics that lie in the basement horizon which has NE-SW trending. The pre-

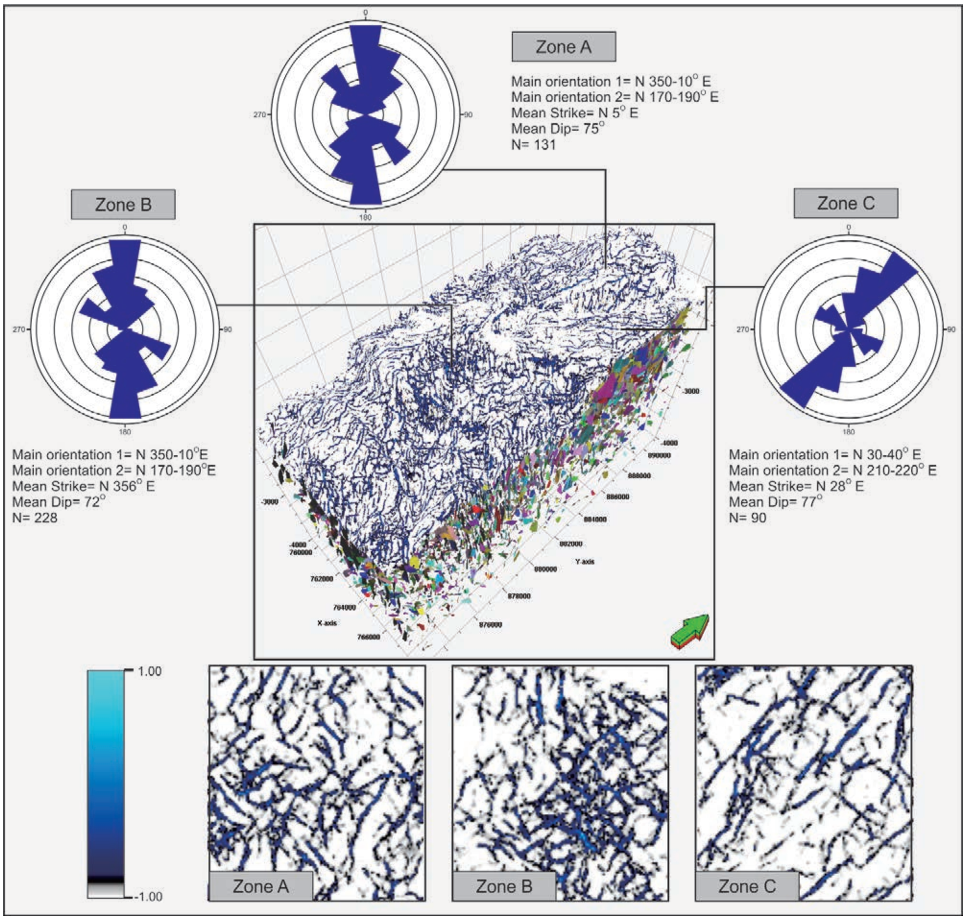


Figure 8: 3D geometrical model of naturally open fractured basement reservoir based on ant-track extracted seismic attribute, rose diagrams are showing dominant fracture orientation and statistical analysis based on regional stress filtering.

existing fabrics of oblique faults are less active during the recent period due to a rotation of the extensional stress field in the Miocene to N-S trending.

Seismic attributes

Fractured basement reservoir zones in South Pattani basin are unique. The north fractured basement reservoir (FBR) area shows the high value of amplitude attributes (RMS amplitude, mean amplitude, sweetness and average energy). In contrast, the structural attributes show fractured areas. The anomaly might be caused by fractures with a fill that is mapped in the amplitude attributes. The western FBR area exhibits a similar result of the structural attributes where fractures accumulated in the crest of basement high. The amplitude attributes play a crucial role in the open fracture's potential. The amplitude attributes are low which indicate areas of open fractures. The NE-SW trending effects the potential open fractures occurrence. The east FBR area is controlled by a deflection of local stress caused by the open fractures that are not in N-S direction but are in a NE-SW direction. The ant-track result shows the fractures align parallel to the nearby normal faults. The amplitude attributes marked the fractures are open.

Structural evolution of South Pattani Basin is controlled by rifting tectonic that caused the development of normal faults (Charusiri & Pum-Im, 2009; Morley & Charusiri, 2011). Amplitude based seismic attributes showed different behaviour of fractured, non-fractured and non-potential fractured zones. Using ant-track and variance attributes, a high probability of open fractures occurrence is located nearby the major faults and at the basement highs crest. The eastern side of west FBR area, coloured by dominantly purple, promises a high potential fractures area. The eastern FBR area dominated by blue colour as closed fractures.

DISCUSSION

Fracture productivity analysis

Fracture productivity chart is an important and useful technique to help understand the faults and fractures behaviour observed in 3-D seismic data, by bridging the gap between the well bores with knowledge of tectonics and structural geology. Fracture productivity in basement horizons are mainly controlled by the faults and fractures behaviour. The fracture productivity analysis was done by using fracture productivity chart (Figure 9) (Sagita *et al.*, 2008).

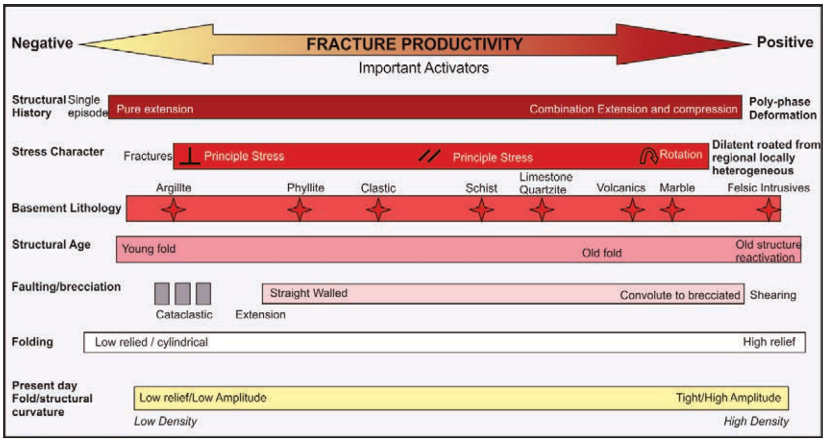


Figure 9: Fracture productivity chart (Sagita *et al.*, 2008). Overal, fractured basement reservoir in South Pattani Basin felt in positive fracture productivity values.

We found that fracture productivity chart result depicts critical elements of fracture systems in our study area. The results scored from negative or less positive fracture attributes (left) to positive or potential/possibly fracture attributes (right), several key aspects had been made:

a. The basement high has experienced poly-phase deformation since the Pre-Tertiary uplift, initial rifting to the post-rift phase which leads to the positive value of fracture productivity (Regan *et al.*, 1976; Watcharanantakul & Morley, 2000; Charusiri *et al.*, 2002; Morley *et al.*, 2004; Charusiri & Pum-Im, 2009; Morley & Charusiri, 2011).

b. Early Miocene structural rotation is extremely important which change the fractures trend from NW-SE to N-S (Lockhart *et al.*, 1997; Morley *et al.*, 2004).

c. The fracture in the basement high in the study area is identified as mostly fractured and might be weathered igneous rocks which is granite as felsic intrusives and is equivalent to Merah Granite/ Bu Do Granite (Trgrmr/bd) (The Malaysian-Thai Working Group, 2012).

d. Structural age in South Pattani Basin is the reactivation of pre-existing of pre-tertiary fabrics (Morley *et al.*, 2004; Charusiri & Pum-Im, 2009).

e. Present-day structural curvature left the basement high as a high relief area with highly fractured rock (Morley *et al.*, 2004; The Malaysian-Thai Working Group, 2012). Faults and fractures in basement high are also observed in the 3-D seismic data by applying ant-track attribute (Gusti, 2021).

The study area is four-way dipping basement highs structures which are probably intensely fractured, as indicated by the seismic interpretation. Fracture behaviour in the basement highs observed as a positive and potential to be a hydrocarbon reservoir. The important factors contributing to the formation of fractured reservoir such as tectonic setting, structural geology aspect and petrology are showing positive fracture productivity. While all important activators are showing positive remarks, the subsurface condition is not as easy as the conceptual framework, so it still needs a well that reaches the intra-basement to prove the concept.

South Pattani Basin fractured basement reservoir (FBR) - conceptual model and play concept

A conceptual model of naturally fractured basement reservoir (FBR) is presented in Figure 10. Fracture basement reservoir conceptual model consists of fault core, inner fault zone and outer fault zone. Simplified anatomy of fault rocks consist of pseudo-matrix and fault zone rocks. Continuous and sub-continuous seismic reflectors were used as a principal idea of the fracture appearance in the basement section. The north-south direction is the major tectonic stresses and inferred as the trend of tectonic transport. The fracture attitudes are parallel and sub-parallel to the major fault zones which becomes the core of the rupture zone.

The FBR conceptual model was built by using volume crop from 3-D seismic data at basement high area. The

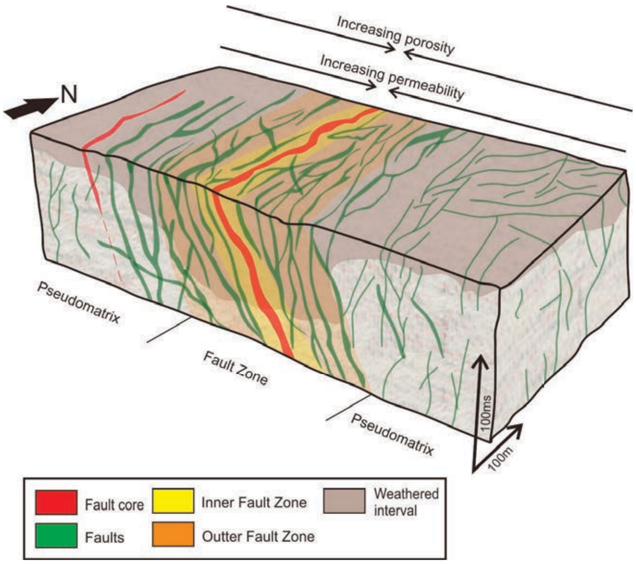


Figure 10: Conceptual model of naturally fractured basement reservoir within the basement high in Area B. The fracture distribution is divided into three zones: (1) an Inner Fault Zone; (2) an Outer Fault Zone (both are characterized by a Fault Damaged Zone); and (3) Pseudo-matrix. Fault Zones represent the seismic-scale faults where pseudo-matrix includes the sub-seismic-scale faults and protolith.

characteristic of each conceptual model zone change through distance from fault plane. Fault damage zone is composed of fault core or slip surface and the surrounding volume of brittlely deformed wall rock (Fossen, 2010). The surrounding area of the fault core divided into two zones; inner fault zone and outer fault zone. The inner fault zone is characterized by highly deformed area close to the slip surface while the outer fault zone is moderate to far from the slip surface or fault core (Richard H. Groshong, 2006; Fossen, 2010).

The Pre-Tertiary rocks in South Pattani Basin consist of amalgamated igneous (felsic intrusive), meta-sediment and metamorphic rocks (The Malaysian-Thai Working Group, 2012). The most imperative one is the igneous rocks (felsic intrusive). Based on the seismic reflector in the study area, it indicates highly fractured and possibly weathered igneous rocks although no well has reached the basement horizon to prove the interpretation. The basement rocks in the study area might have similar lithologic characteristic with Bach Ho granite except for Bach Ho field experience inversion tectonics that creates wide damage zone and flexural fractures (Cuong & Warren, 2009), whereas in the South Pattani basin super-deep subsidence (Morley & Westaway, 2006) plays an important role to faults and fractures distribution.

The fault core in the model represented the major normal fault in the study area where the inner and outer fault zone is the surrounding damage zone (eastern and western side of the major fault). Porosity and permeability might increase towards the fault core. Fault damage zone range around 250 meters from the fault core or slip surface to the eastern and western side respectively.

Fracture basement reservoir generating mechanism is unique in every field. For example, in White Tiger Field in Cuu Long Basin, the major controlling mechanism is multi-phase deformation (extension, compression, shear and wrenches) (Cuong & Warren, 2009; Huy *et al.*, 2012), while in South Pattani Basin, fractured basement reservoir potential might be closely related to the pre-existing fabrics and overprinting of Tertiary tectonic activity (Morley *et al.*, 2004; Charusiri & Pum-Im, 2009).

Furthermore, fractured basement reservoir play concepts in South Pattani Basin (Figure 11) consist of syn-rift sequences as source rocks, basement highs as reservoirs and post-rift sequence as a regional seal. S10 and S20 or well-known as Sequence I which deposited during Early to Late Oligocene in the lacustrine environment provide a rich organic material as source rocks. This early syn-rift deposit was onlapping towards the flank of basement highs. The onlap itself next becomes the migration point into the fractured reservoir in basement highs (Figure 11). Primary migration and oil expulsion started at Early Oligocene to Late Oligocene (Watcharanantakul & Morley, 2000) while secondary migration began at Early Miocene (Jardine, 1997). Reservoir rocks are the fractured felsic intrusive rocks. The rocks are fractured granite of Merah Granite / Bu Do Granite (Trgrmr/bd). In the subsurface, the configuration of open fractures features is highly controlled by the fault system. Potential open fractures are N-S and NNE-SSW trending based on ant-track attributes. Low amplitude response (average energy, RMS amplitude, and mean amplitude) in faults area (high-value ant-track)

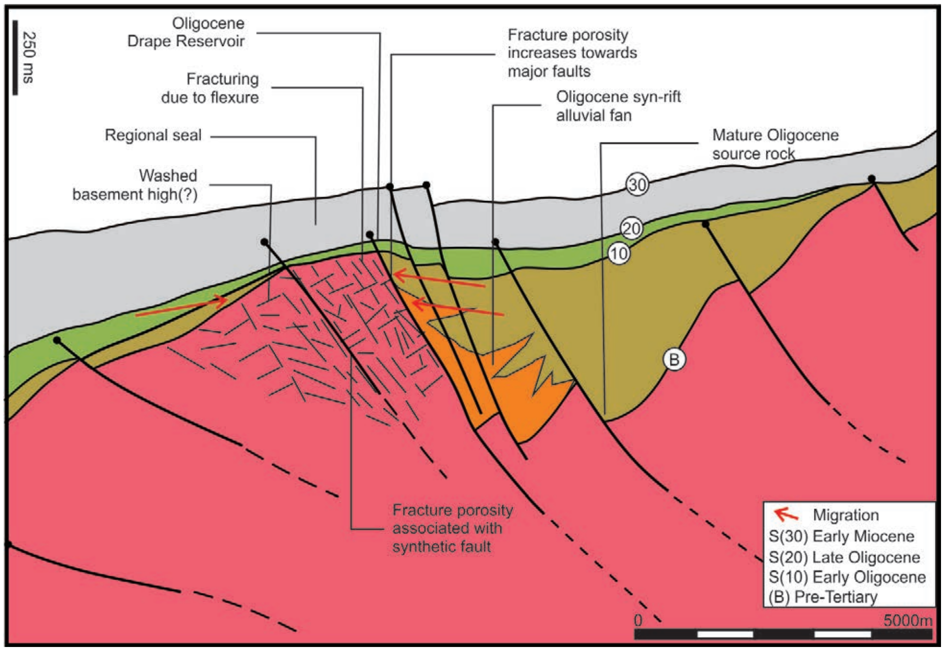


Figure 11: Two-dimensional play concept model of naturally fractured basement reservoir for South Pattani Basin. Potential basement high reservoir is marked with pink color with overprinting dashed lines. S10 is the main source rock, red arrows show the direction of migration and the grey layer act as regional seal.

indicate the occurrence of porous zone basement rocks (Gusti, 2021). The thick claystone maintains laterally vertical overburden pressure to keep the hydrocarbons in the fractured basement reservoir. An analogue for the FBR play concept in the South Pattani Basin may be found in the North Sea especially UK and Norwegian rift margin fractured basement (Bonter & Trice, 2019; Trice *et al.*, 2019). The fractures generated from footwall upfaulting as a consequence of normal faulting during rift phase and later exhumed. The fractured style in South Pattani Basin was quite surprising and suggests that it was controlled by the distribution of pre-existing fabrics.

CONCLUSIONS

A new play in the South Pattani Basin is conceptualized, wherein the Pre-Tertiary basement rock form the reservoirs due to fractures. The rifting mechanism and pre-existing fabrics controlled the fracture development. Rifting during the Oligocene towards the east created north-south striking open fractures. The fractures experienced poly-phase deformation. Middle to Late Middle Miocene deformation caused rotation in tectonic transport direction and change in regional stress regime. The normal faults are characterised by a north-south trend with dips approximately 60° to 70° which are the product of dominant vertical stress. The north-south structures cut through north-northwest and north-northeast striking structures, and enhanced permeability. Fractured basement reservoir potential in South Pattani Basin relies on overlying and onlapping syn-rift deposit of Sequence I which is a lacustrine sediment which provided the initial expulsion from Latest Oligocene to Early Miocene. Hydrocarbon charge direction is possible horizontally via the flanks of the basement high or even vertical on crestal area itself. Thus, the play concept, showed that fracture configurations and networks were complex and sufficiently connected to act as a reservoir for hydrocarbon.

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AUTHOR CONTRIBUTIONS

UKG conceptualized and managed data curation, methodology, analysis, investigation, software, interpretation of the result (structural geology, stratigraphy and seismic attributes), writing of original draft, writing after review and editing. AF analysed, conceptualized, methodology, interpretation of results, software, supervision, validation and helped to draft the manuscript. All authors reviewed the results and approved the final manuscript.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare that are relevant to the content and material of this article.

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