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Outcrop Analogue for Basement Exploration in Songkhla Basin, Gulf of Thailand

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Abstract

This study focuses on the lithological and structural variations in the pre-Cenozoic rocks of the Songkhla and Phatthalung areas, likely constituting the basement rocks of the offshore Songkhla Basin, where subsurface exploration is limited by seismic resolution. The methodology employed includes field studies and digital outcrop analysis to determine the relationships and patterns of bedding planes, fractures, and folding. Four lithological facies are defined: 1) Sandstone-dominated facies, 2) Shale-dominated facies, 3) Chert facies, and 4) Granite. The fold analysis indicates contraction varying from WNW-ESE to NW-SE. The dominant fracture patterns align with the NW direction, running subparallel to the maximum horizontal stress and perpendicular to the fold axis. Conversely, secondary fracture patterns appear in the NE-SW direction. At the outcrop scale, fracture characterization indicates that open fractures predominantly occur in coarse-grained and poorly sorted sandstone, chert—especially in the forelimb zone—and granite. In contrast, finer sediments and sedimentary rocks adjacent to the granite are typically clay-filled or filled with quartz veins and veinlets. The results are expected to enhance the understanding of the geology at a sub-seismic scale of the pre-Cenozoic fractured basement potential in the Songkhla Basin.

Keywords: Songkhla Basin, basement rocks, outcrop analog, fracture, fold

1. Introduction

Pre-Cenozoic rocks in the Gulf of Thailand have been studied for their basement potential based on 3D seismic data in petroleum basins, such as the South Pattani Basin (Gusti & Ferguson, 2022) and the Western Basin (Saifulizan, 2019). These basement rocks include sedimentary, meta-sedimentary, extrusive, and intrusive igneous rocks (Polachan et al., 1991; Doust and Sumner, 2007; Morley & Racey, 2011). However, seismic resolution limits the mapping of natural fractures that affect reservoir quality on a sub-meter scale, particularly in zones with multiple tectonic deformations and a lack of core data.

The Songkhla Basin is a Cenozoic basin in the Gulf of Thailand that is bounded to the west and south by the coastal areas of the Phatthalung, Songkhla, and Pattani provinces of southern Thailand (Figure 1). The basin's basement rocks are expected to extend southward following the regional tectonic trend (Ridd, 2013; Kamata, 2014). Outcrop exposures near the shore, therefore, provide opportunities for basement study in the Songkhla Basin and adjacent basins aligned along the same tectonic trend.

This paper presents the results of an outcrop study in the Phatthalung and Songkhla areas, with a discussion on the lithological and structural variations of the pre-Cenozoic rocks, and provides implications for fracture development in the basement rocks of the Songkhla Basin.

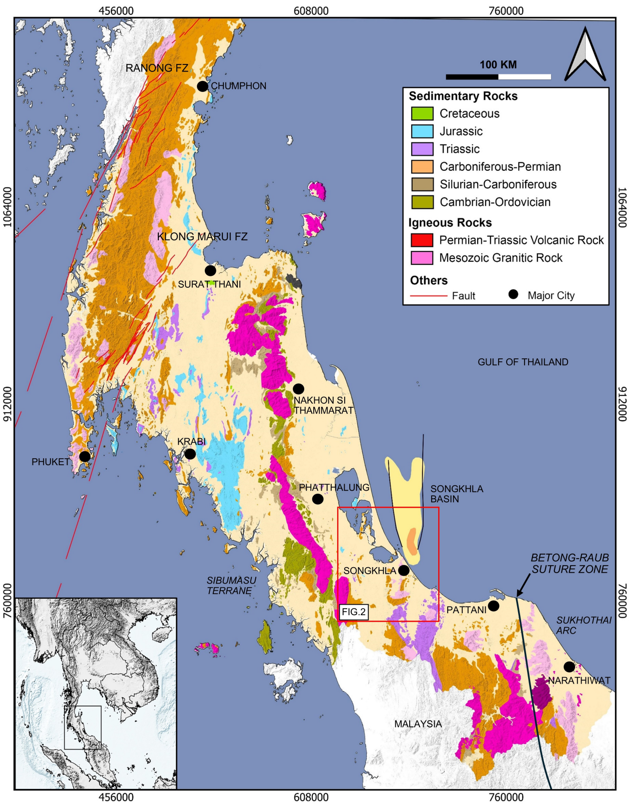

Figure 1 Geological map of southern peninsular Thailand and location of the Songkhla Basin in the Gulf of Thailand (adapted from DMR, 2014). The red box indicates the study area.

2. Study Area

The study areas encompass multiple outcrops at both quarries and road cuts in Songkhla and Phatthalung provinces, which are included in the Sibumasu terrane (see Figure 2). All outcrop localities can be accessed by car.

In the Songkhla area, outcrops and quarries are aligned along Highways 42 and 43, which run east to west. These highways provide opportunities for observing lithological and structural variations across the regional north-south striking compressional axis and the axis of the Songkhla Basin.

Triassic granite and its fractures are studied and measured in the Wang Phai quarry south of Highway 43. This quarry provides an understanding of the fracture pattern associated with the post-collision of the Sibumasu terrane.

In the Phatthalung area, only one large, abandoned quarry is studied, which is located on the easternmost side of Koh Nang Kham Island. It is roughly 59 km from downtown Hat Yai. This quarry highlights thrusts and folds of chert and mudstone beds on quarry faces at different angles. Structural features in this locality represent syn-collision deformation of the eastern continental slope of the Sibumasu terrane.

3. Stratigraphic Framework

The stratigraphy of the Patthalung and Songkhla area has been extensively studied (Sashida et al., 2002; Kamata, 2009; Ridd, 2013), revealing a complex geological history spanning from the Carboniferous to the Triassic period.

The Carboniferous Yaha Formation (Muenlek et al. 1985) comprises clastic rocks exposed in the Yaha District, Yala Province, and extends to Saba Yoi, Na Thawi, and Sadao Districts of

Songkhla Province, as well as Pattani and Phatthalung Provinces. The formation, approximately 400-450 meters thick, consists of six members: a massive quarzitic sandstone member, an interbedded mudstone and sandstone member, a well-bedded dark grey sandstone member, a tuffaceous sandstone intercalated with mudstone member, a chert member with Early Carboniferous radiolarians, and an evenly bedded shale and sandstone member. The age of the formation is supported by late Tournaisian conodonts and Early Carboniferous radiolarian assemblages reported from various locations within the formation (Sashida et al., 2002).

Grant-Mackie et al. (1980) reported that the marine Triassic sequences in the Songkhla area resemble those of the Lampang Group in northern Thailand, except they lack volcanogenic components and contain abundant conglomerate. The informal name Na Thawi Formation was applied to most of the Triassic rocks in the Songkhla region. This formation is characterized by a thin-bedded turbidite sequence with a fold axis trending north-south in the so-called Payang Syncline. Fossils of *Daonella* sp. (Ladinian-Carnian) were found approximately 60 km south of Songkhla, to the west of the syncline. The Khao Mi Kiat Conglomerate consists of poorly sorted clasts up to small cobble size of quartzites, with current bedding indicating a northward flow direction. This conglomerate is likely the basal conglomerate of the Triassic rocks.

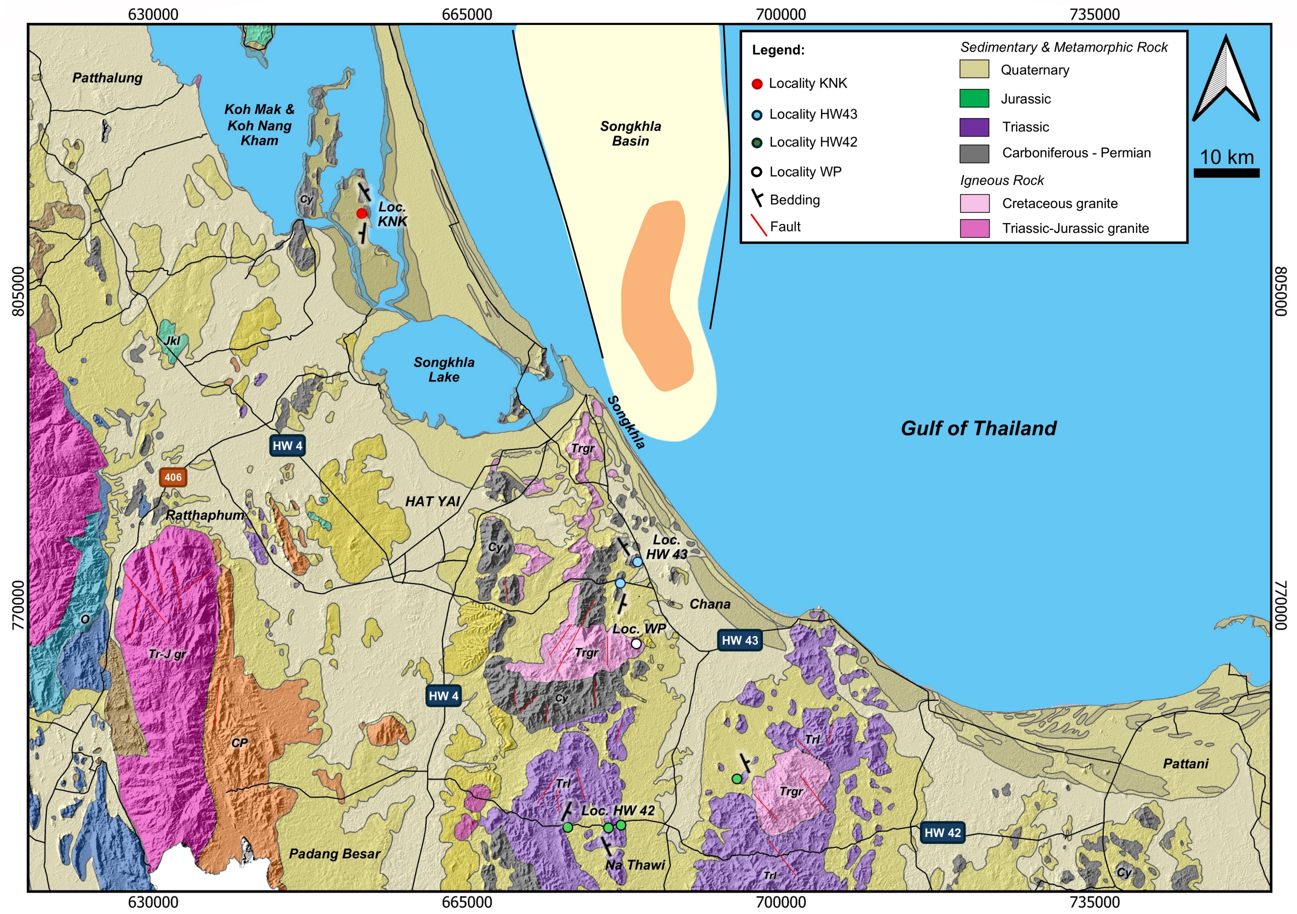

Figure 2 Geological map of Phatthalung, Songkhla, and Pattani provinces showing lithological

distributions in the study area and highway network (adapted from DMR, 2007). Outcrop localities are also present (colored dots) with representative bedding orientations.

Kamata et al. (2014) conducted a more focused study on radiolarian chert and shale cropping out 20 km WNW of Hat Yai. They identified laminated Middle Permian shale, becoming increasingly siliceous upwards, and found well-bedded radiolarian chert of the Middle Triassic age in nearby sections. They distinguished two types of charts based on the fineness of terrigenous components and the presence or absence of calcareous tests: Type 1 (pelagic origin) and Type 2 (hemipelagic origin). In the Hat Yai area, only Type 2 cherts were found, leading to the interpretation that these rocks were deposited on the eastern continental slope of Sibumasu and subsequently thrust westwards, ending up near shallow-marine carbonate platforms and continental-shelf terrigenous clastics (Ratburi Limestone/Chaiburi Formation and Kaeng Krachan Group).

In Songkhla province, two north-south trending granite ranges are present: the western and eastern ranges. This granite is considered to be the central belt (Pongsapich et al., 1983; Charusiri et al., 1993). The Geological Project Research team (1979) designated the western range as the Wang Pha pluton and the eastern range, which extends into the northern part of Malaysia, as the Songkhla pluton. These granites have intruded the surrounding Paleozoic and Triassic sedimentary rocks, causing thermal metamorphism that transformed these rocks into quartzite, metasiltstone, and hornfels. The granites primarily consist of coarse-grained porphyritic biotite granite, with some occurrences of fine-to-medium-grained muscovite-biotite granite. The landscape is also marked by pegmatite, aplite, and quartz veins of varying widths that fill fractures either in the granites or in the sedimentary rocks.

4. Methodology

Outcrops were systematically mapped in April 2024, with geological information meticulously documented through photographs, sketches, structural orientation measurements, and sample collection for laboratory analysis.

An unmanned aerial vehicle (UAV) is used to take photos of outcrops in the quarries to create a Digital Outcrop Model (DOM). Coordinates, elevation, thickness, bedding, and fracture planes are quantitatively measured using VRGeoscience Limited's VRGS software (Figure 3).

At each measurement station, comprehensive geological data were recorded, including rock type, lithology, sedimentary structures, bedding and fracture styles, fault planes with slicken line orientations, sense of movement, joints, veins, and folds. Detailed fracture data were also documented. These measurements were integral to determining the deformation characteristics of the outcrops.

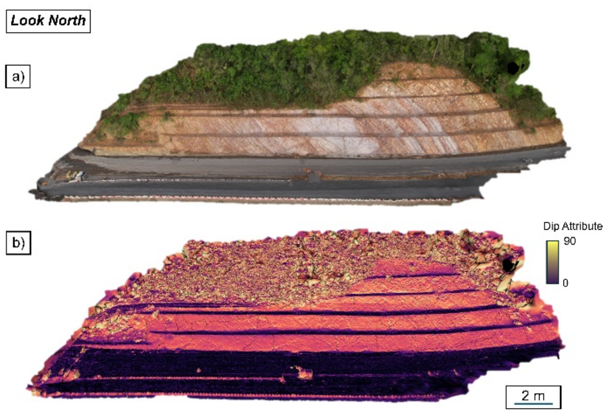

Figure 3 An example of a digital outcrop model of the Koh Nang Kham quarry face that was

later used to measure the orientation of the outcrop using VRGS software. a) 3D modeling photograph. b) 3D modeling with dip attribute.

5. Results

The pre-Cenozoic rocks in the study area can be grouped into three units based on their dominant lithology: clastic sedimentary rocks, chert formation, and granite. All units are named and described below, followed by structural variations along highways 42 and 43 and in the Koh Nang Kham and Wang Phai quarries.

5.1 Lithological units

5.1.1 Na Thawi Clastic Formation

In the study area, the rock unit exhibits a rhythmic alternation of sandstone and shale or mudstone, with thicknesses ranging from 100 to 250 meters. The sandstone, which is prominent throughout the unit, is medium- to coarse-grained and generally poorly sorted. It consists of quartz, chert, and volcanic rock fragments, which are typically subangular to subrounded and possess moderate to high sphericity. The interstitial matrix of the sandstone includes silt-sized quartz and clay. Feldspars within the sandstone appear as white spots and are often completely altered, primarily to clay minerals and sericite.

The sandstone beds, which vary in thickness from 0.2 to 1 meter, are interbedded with thin-bedded shale. The argillaceous rocks within the formation are predominantly shale and mudstone, with minor occurrences of siliceous shale. When fresh, these rocks display a dark grey color, transitioning to pale grey upon weathering. The shale is well-laminated, with layers ranging from 1 centimeter to 0.5 meter in thickness.

5.1.2 Chert Formation

In the designated study area, a stratigraphic sequence is observed where well-bedded chert from the Middle Triassic, which includes radiolarians, is found lying above laminated shale from the Permian period that also contains radiolarians. The Permian shale is composed of a variety of interlayered rocks: brown shale, yellowish-brown silty shale, and dark brown or black shale that features calcareous nodules. The presence of dark-colored shale with calcareous nodules in this sequence suggests a correlation with ammonoid-bearing Permian shale that has been identified in other geographical regions (Fujikawa et al., 2005). Notably, the uppermost section of this shale unit is siliceous and is interspersed with layers of chert similar to the bedded chert of the Middle Triassic.

5.1.3 Wang Phai Pluton

The granite in this area has a phaneritic texture with a typically felsic color. It displayed many cracked voids and high alteration degrees (feldspar turned to yellowish-brown color). In general, it is composed of abundant coarse-grained quartz, plagioclase, and alkali-feldspar. Mafic mineral biotite grains show a dark brownish-green to black color, according to the observation under the polarizing microscope. It’s composed of quartz, plagioclase alkali-felspar, biotite, and very rare hornblende. The grained size of quartz is approximately 0.2 to 0. 9 mm. Plagioclase is approximately 0.3 to 1.2 mm, alkali feldspar is approximately 0.3 to 1 mm, and biotite is approximately 0.1 to 0.5 mm. Most of the feldspar grains were altered to sericite (sericitization).

5.2 Structural variations

5.2.1 Highway 42

Three road-cut outcrops and two quarries along Highway 42 were examined. The primary lithology observed consists of medium-bedded volcaniclastic sandstone interbedded with minor laminar to thin-bedded mudstone. The main geological structure in this section shows an eastward dip direction of the bedding planes, with strikes mostly in the NNE to NNW directions. Sedimentary structures, such as convolute bedding, indicate normal bedding. Most faults in this section are thrust faults trending NE-SW and dipping towards the SE. Regarding fold analysis, the maximum horizontal stress is oriented in the NNW-SSE direction, averaging N30W.

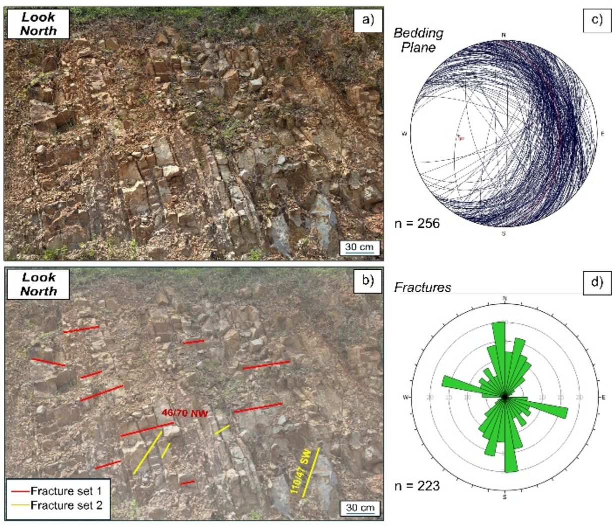

Figure 4 Fracture pattern at Highway 42. a) outcrop photograph. b) line drawing of the outcrop. c) stereographic plot shows bedding orientation in NNE-NNW direction, N=256. d) rose diagram illustrating fracture orientation, primary fracture set (set 1) trends NNW-SSE to NNE-SSW. The secondary fracture set (set 2) trends WNW-ESE, N=223.

Various fractures are present. Most of these fractures are filled with quartz veins or veinlets. Open fractures are rarely observed. The primary fracture set (set 1) trends NNW-SSE to NNE-SSW (set 1A). The secondary fracture set (set 2) trends WNW-ESE (Figure 4). The fracture patterns show that set 2 fractures terminate at set 1. Sheared fractures are infrequent. Some slicken sides, indicating right lateral movement, can be found trending NE-SW. These sheared fractures are more prominent in softer formations. Fracture spacing ranges from 3 to 15 cm. However, this may be uncertain in highly weathered, soft formations. Non-systematic fractures, which develop locally, are not considered further in this study.

5.2.2 Highway 43

Along Highway 43, most outcrops are located in abandoned quarries. The lithology of this section is almost the same as that along Highway 42, as mentioned above. However, there are differences in the finer formations, which are slightly metamorphosed to meta-shale or slate, likely due to contact metamorphism caused by nearby granite bodies. Index minerals or clear contact zones cannot be observed in the field.

Most of the bedding planes follow the regional structure, striking NNE to NNW and dipping mainly towards the east. Folding is observed, particularly in the shrine quarry (lower blue colored dot in Figure 2), where both limbs are oriented in the almost N-S direction but dips to the east and west. The axial plane strikes in the NNE-SSW direction (average N3E/9SE), similar to the Koh Nang Kham folded ribbon chert section. The maximum horizontal stress in the WNW-ESE direction (N85W on average). Faults in this area are challenging to observe due to significant weathering. However, normal faults can be observed at the shrine quarry, trending NE-SW with a dip angle of 30 degrees towards the west.

Sheared fractures, visible as slicken sides, are predominantly observed in the slate quarry. Two sets of measurements for these fractures are N60E/40SE and N10W/30SW, likely caused by right-lateral strike-slip faulting. Three fracture sets are measured as follows: Set 1 trend in the NE-SW direction, subparallel to the bedding strike. Set 2 trends in the NW-SE direction. These fractures are orthogonal to each other. The fracture pattern indicated that fracture set 2 terminates at set 1. Set 3 trends in the NW-SE direction (Figure 5).

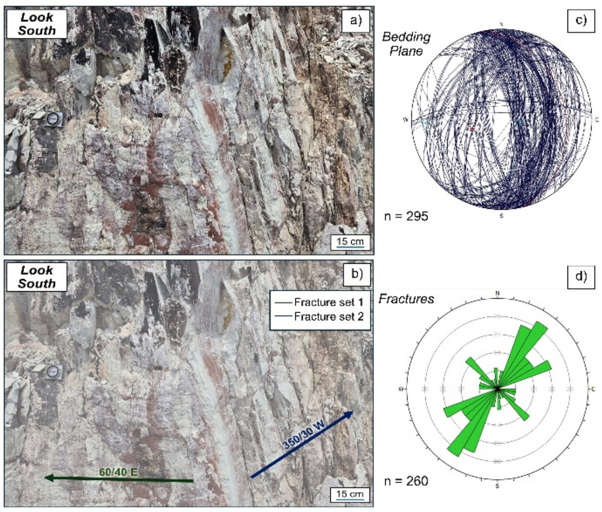

Figure 5 Fracture pattern at Highway 43. a) outcrop photograph. b) line drawing of the outcrop. c) stereographic plot shows bedding orientation in NNE-NNW direction, N=295. d) rose diagram illustrating fracture orientation, set 1 trend in the NE-SW direction, subparallel to the bedding strike. Set 2 trend in the NW-SE direction, N=260.

5.2.3 Koh Nang Kham Quarry

The studied rock units are located in a large quarry in the easternmost region of Nang Kam Island, Pak Phayun District, Phatthalung Province. The lower part of the studied stratigraphic sequence comprises white mudstone, which is overlain by chert layers. The white mudstone is dense and fine-grained, exhibiting very thick beds. The light grey chert occurs in thin layers, approximately 1-5 centimeters thick, interspersed with clay seams. The thickness of the chert layers increases to approximately 3-10 centimeters towards the top.

The bedding orientation varies from NW-SE to NE-SW, caused by the strong folding of ribbon chert interbedded with siliceous shale. The orientation of the rock layers changes from approximately N20W/50NE to N30E/40NW. The fractures in this study area are related to folding. The axial plane strikes in the NNE-SSW direction, similar to the Highway 43 section. The maximum horizontal stress in the WNW-ESE direction (N80W on average).

Fractures are associated with strong folding events. On the forelimb, where the strain is higher, fractures tend to be longer, exhibit wider apertures, and are more densely packed, indicating high intensity. Conversely, as one moves away from the forelimb, the fractures become less intense, shorter, and less frequent.

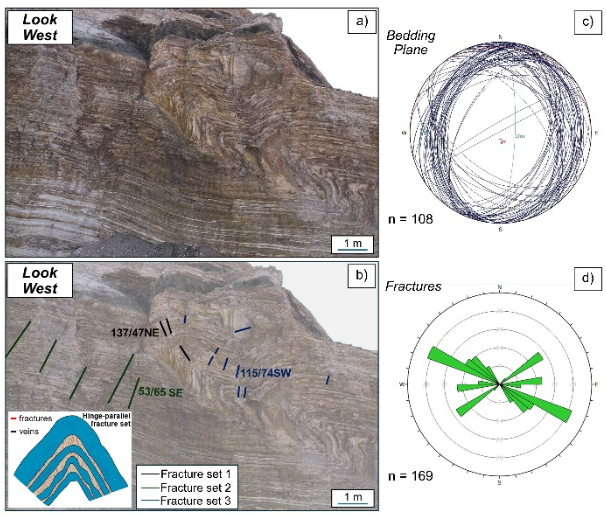

Figure 6 Fracture pattern at the Koh Nang Kham abandoned quarry. a) outcrop photograph. b) line drawing of the outcrop. c) The stereographic plot shows bedding

orientation in both NE and NW directions, N=108. d) rose diagram illustrating fracture orientation, set 1 trend in the WNW-ESE direction, set 2 in the NE-SW direction, N=169.

Three distinct sets of fractures have been identified: Set 1 trends in the WNW-ESE direction, set 2 in the NE-SW direction, and is noted to terminate at intersections with Set 1, and Set 3 trends in the E-W direction (Figure 6). Open fractures are particularly prominent at the forelimb of the folds. Additionally, the chert and siliceous rocks present have developed conchoidal fractures, which are irregular and non-systematic, leading to their exclusion from further consideration in this study.

5.2.4 Wang Phai Granite Quarry

The Wang Phai granite is predominantly composed of biotite granite. In the bench, cut and clear fracture patterns are visible, although some are disrupted by the effects of blasting.

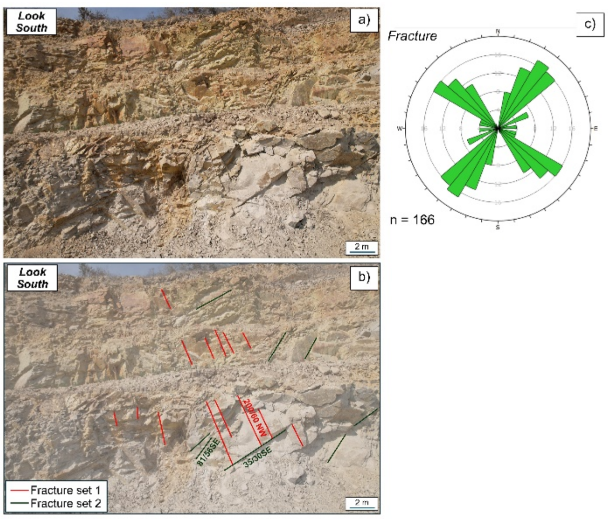

Figure 7 Fracture pattern at the Wang Phai granite quarry. a) outcrop photograph. b) line drawing of the outcrop. c) rose diagram illustrating fracture orientation, set 1 trend in the WNW-ESE direction, set 2 in the NE-SW direction, N=166.

Two distinct sets of fractures have been identified: Set 1, trending in the WNW-ESE direction, and Set 2, trending in the NE-SW direction but noted to terminate at intersections with Set 1 (Figure 7).

Open fractures are dominant in the area. Additionally, some fractures curve due to the effects of blasting; these non-systematic, locally developed fractures are not considered further in this study.

6. Interpretation and Discussion

6.1 Lithological facies and structural characteristics

This section aims to document the key lithological facies based on outcrop studies and to provide structural characteristics for basement exploration in the Songkhla Basin. Figure 8 shows a summary of structural analysis results. The four dominant facies are presented as follows:

A: Sandstone Dominated Facies

Most fractures in the sandstone are filled by quartz veins and veinlets, potentially during the deformation stage or influenced by nearby granite bodies. However, stylolite and some open fractures are present in volcaniclastic sandstone and greywacke, which are poorly sorted and contain smaller amounts of fine-grained interbedded material.

The maximum horizontal stress from fold analysis is indicated in the NW-SE direction. Fractures are oriented in the N-S and WNW-ESE directions, subparallel to maximum compression. However, these fractures are likely unrelated to the folding episode. Instead, it appears that the fractures developed due to subsequent deformation following the collision of the Sibumasu and Indochina terranes.

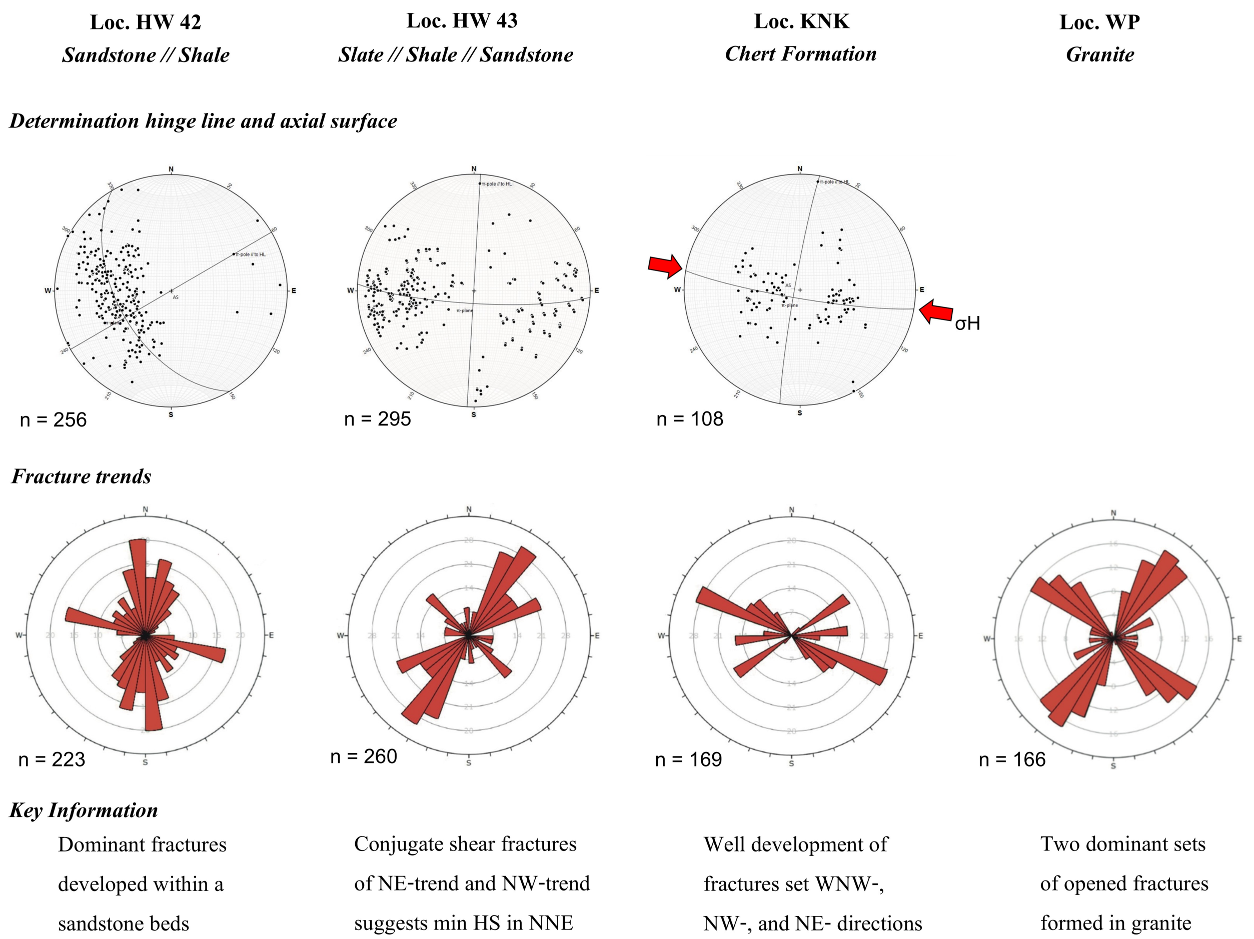

Figure 8 Summary of structural analysis results of the four dominant facies. (above) Stereonet plots of the pole (dip/dip direction), displaying the maximum horizontal stress direction from fold analysis. (below) Rose diagrams showing fractures. The hinge line and axial surface determinations, along with fracture trends, are illustrated in stereographic plots accompanied by key information.

B: Shale Dominated Facies

Most fractures within the finer-grained facies are self-filled or exhibit clay smearing. These fractures predominantly develop along the orientation of fissility, with minor occurrences perpendicular to this direction. Quartz veins-filled fractures are observed significantly in the dark gray sandstone and greywacke. However, the presence of numerous conchoidal fractures or sun-crack structures disrupts the existing fractures, resulting in locally curved fracture patterns. The maximum horizontal stress cannot be determined precisely due to the strong deformation of soft-sedimentary rocks, which have developed folds in various directions. The fractures are mainly oriented in the NE-SW direction, with minor fractures in the NW-

SE direction. This may indicate that the maximum horizontal stress has changed from E-W to either NE-SW or NW-SE.

C: Chert Facies

The fracturing of this formation is associated with the pronounced folding of chert intercalated within siliceous shale. The majority of the fractures are located on the forelimb and exhibit extensive spacing of open fractures resulting from significant strain. Some of these open fractures remain unfilled, while others are infilled with clay materials or have undergone sulfur formation, possibly due to the presence of blackish shale.

The fractures in this area are likely related to the folding episode. The maximum horizontal stress is oriented in the WNW-ESE direction. The main fractures are approximately parallel to the direction of contraction and have formed opening fractures that remain unfilled by minerals. These results may reflect fractures formed during the closure of Paleotethys, as indicated by the lithology and fold analysis.

D: Granite

In the study area, the granite exhibits less exfoliation. Generally, fractures within this granite remain open and rarely display pegmatite and quartz veins that cut through the granite bodies. Nevertheless, these fractures often contain sulfur crystals, likely resulting from the alteration of sulfide-rich minerals. However, this alteration does not significantly affect the open spaces within the granite. The granite in this area is generally associated with a late collision event. The main fracture features are oriented in two directions: NE-SW and NW-SE, which may have formed after the collision event. This probably suggests that the maximum horizontal stress shifted from E-W to NE-SW.

6.2 Relationship of fractures to tectonic history

As discussed previously, the pre-Cenozoic sedimentary structural trends exhibit fold structures elongated primarily in an NE-SW to N-S direction. The variation in fold trends suggests slight alterations in the stress patterns, accompanied by variable strain.

The fracture trend of chert facies is likely related to the folding episode and aligns with the maximum horizontal stress during the pre-Cenozoic collision event. The fracture trends of sand-dominated, shale-dominated, and granite lithological facies, oriented from NNW-SSE to NE-SW, possibly formed after WNW-ESE compression and may have also developed due to the post-Cenozoic event.

The observed deformation and fracture patterns indicate a phase of WNW-ESE to NW-SE compression. This study interprets these findings as a consequence of the collision between the Sibumasu and Indochina terranes, occurring no earlier than the post-Middle Triassic period, as inferred from the radiolarian age of chert formation.

During the Cenozoic, E-W extension led to the formation of N-S trending normal faults following the compression of the pre-Cenozoic rocks in a WNW-ESE direction. These faults generated basins oriented north-south, where Cenozoic fluvial-lacustrine sediments accumulated, laying down with angular unconformity above the older

Mesozoic basement rocks (Kaewkor et al., 2015).

6.3 Implication to subsurface

Considering the fracture evolution and tectonic history, the fractured sandstones and chert formations have been identified as potential basement reservoir rocks. Hydrocarbons are believed to have migrated from depocenters and accumulated in these formations, creating buried hill plays in the subsurface. Fracture reservoirs enhance fluid flow significantly by increasing porosity and permeability. However, careful study of clay-rich units is essential, as they can act either as seals, preventing leakage, or as pathways for migration.

Gusti & Ferguson (2022) proposed a characterization of the fractured basement reservoir in the South Pattani Basin, situated in the northeastern part of the Songkhla Basin. The primary lithology consists of crystalline rocks. They utilized ant tracking technology for seismic interpretation to propose fracture trends, predominantly in the N-S to NE-SW direction, with minor NW-SE directions. These trends are closely related to the fracture patterns observed in the Wang Phai granite analog outcrop discussed in this study.

To improve the prediction of fracture systems, it is recommended to integrate outcrop analogs with future subsurface data.

7. Conclusion

This study integrates fieldwork and digital outcrop analysis to investigate the fractured basement reservoir potential of the pre-Cenozoic basement rocks in the Songkhla basin. The analysis focused on bedding orientation, fracture patterns, folding, and related structures. The results indicate that the fracture patterns and fold analysis suggest a WNW-ESE to NW-SE compression. The primary fracture trends developed in the NW direction, sub-parallel to the maximum horizontal stress and perpendicular to the fold axial plane (Figure 8). In contrast, the minor fracture trends developed in the NE-SW direction, parallel to the fold axis.

Fracture characterization at the outcrop level revealed that open fractures are dominant in coarse-grained, poorly sorted sandstone, chert, particularly in the forelimb zone, and granite. Finer sediments and sedimentary rocks adjacent to the granite are either self-filled or filled with quartz veins and veinlets. Outcrop analogs and structural variations of the pre-Cenozoic basement rocks are crucial for understanding subsurface geology, especially in areas with limited seismic resolution and lacking core data. Comparing outcrop analog data with subsurface data is essential for understanding fracture patterns and improving the prediction of fracture systems.

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