

Fibrous calcite characteristics and petroleum potential source rock of Permian carbonate, central Thailand

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Abstract

The outcrop samples of the Permian carbonate in Phetchabun, central Thailand have been studied to determine the characteristics and the occurrence of bedding-parallel calcite fibrous veins. Field occurrence, petrographic study, and geochemical investigations are conducted to interpret the formation mechanism of the veins and to assess petroleum potential in two Permian carbonate rock localities, including Khao Khwang and Nam Duk Formations. Total organic carbon (TOC) and extractable organic matter (EOM) analysis are performed in order to evaluate source rock potential of the samples and pyrolysis. The bedding-parallel fibrous calcite vein is divided into two forms, including beef veins and cone-in-cone structure. Both characters present adjacent parallel growing of fibrous calcite veins to host rock bedding and they are approximately perpendicular to the bedding based on petrography. As the total organic carbon (TOC), extractable organic matter (EOM), and pyrolysis analyses conclude that both the Khao Khwang and the Nam Duk Formations have a capacity to produce hydrocarbons which are mainly gas-types as a dry gas prone source rock.

Keywords: Fibrous calcite, Source rock, Permian Carbonate

1. Introduction

The Khorat plateau area, Thailand has been discovered two commercial gas fields, Nam Phong and Sin Phu Horm and is defined by the regional area about 200,000 square kilometers of Mesozoic (mainly Cretaceous) continental sedimentary rocks of Khorat Group. Petroleum in this plateau have been found within Permian carbonate strata of Pha Nok Khao Formation of Saraburi Group. A petroleum source rock is believed to be from three potential source rocks including 1) Lower Cretaceous Khorat Group, 2) Triassic Huai Hin Lat Formation, and 3) Upper Carboniferous - Upper Permian in Saraburi Group (Racey, 2011). The Upper Carboniferous - Upper Permian succession contain the main source rock for most of the discoveries to date. Potential source rocks in this succession are

both marine shales and micritic limestones and are expected to be regionally extensive throughout the Permian carbonate platforms. The Permian rocks in this region consist of three major elements: the Khao Khwang Platform Formation, the Pha Nok Khao Platform and the Nam Duk Basin located in the west, the east and the middle of the Loei - Phetchabun Fold Belt, respectively. Although, the Permian source rocks from wells and outcrops are suggested to be thermally overmature with peak generation in Late Triassic (Kozar et al., 1992), they are still attractive and have potential for further exploration in central and northern Thailand.

Due to the first discovery of bedding parallel calcite fibrous veins in Thailand which are found in the Permian carbonate platform, including the Khao Khwang Platform and Nam Duk Basin, which could be connected to

worldwide occurrence and interpretation about bedding parallel calcite fibrous veins forming. Generally, fibrous calcite veins parallel to bedding planes are observed in black shales and carbonates with a rich in organic matter and low permeability, and they are divided into two types, including beef vein and cone-in-cone structure (CIC) (Cobbold et al., 2013). These fibrous calcite veins are oriented vertically to sub-vertically, approximately perpendicular to the wall margins of the host rocks as a horizontal parallel bed. The mechanism of formation and growth of fibrous calcite veins is still great controversy with many studies inferring that the occurrence of fibrous calcite relates to hydrocarbon generation due to overpressuring formation (Basson and Viola, 2004). However, Swarbrick et al. (2002) suggested that the mechanical compaction, hydrocarbon generation or a combination of chemical compaction and dehydration of hydrous minerals should be considered as a cause of an overpressuring in sedimentary formation. Within petroleum generation window, if pore pressure exceeds the weight of overburden, creating horizontal fractures, then fibrous calcite veins were formed by displacive growth along overpressured horizons (Marshall, 1982). Furthermore, precipitation of fibrous calcite was mainly derived from connate waters or dissolution of marine carbonates originally in great abundance within shale and mudstone, and partly from decomposition of organic matters (Meng et al., 2017). Therefore, this study aims to describe and characterize the bedding parallel calcite fibrous veins that could be applied for petroleum exploration as an indicator for hydrocarbon generation.

2. Geological Background

The Khao Khwang Formation samples (Tak Fa Formation) were collected from Ban - Pho Sawan, Bueng Sam Phan District, Phetchabun Province and the Nam Duk Formation was sampled along highway 12 (Lomsak - Chumphae) as shown in the Figure 1.

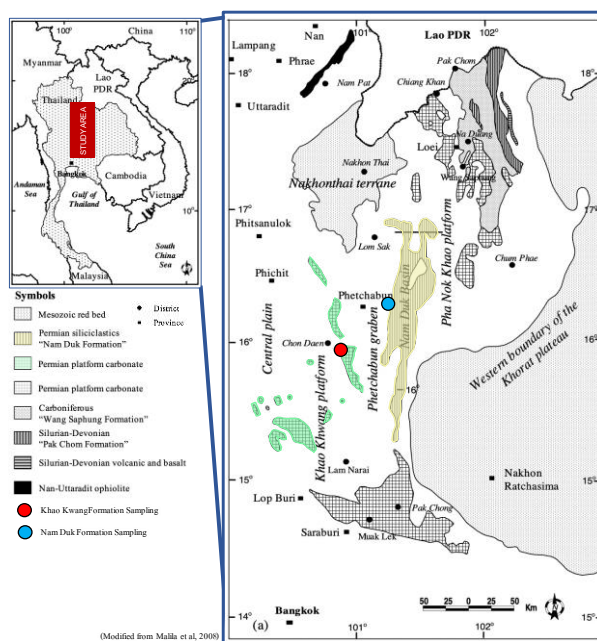


Figure 1. The study areas and sample locations

The Permian carbonate platforms and basin are believed to form during the closure of the Palaeo-Tethys Ocean around the end of Permian to early Triassic responded from collision of plates between the Shan Thai and Indochina plates (Helmcke and Linderberg 1983). As a result, the passive continental margin with an extensive creating carbonate platform is formed along the western rifted margin of the Indochina plate during the early and middle Permian, including Khao Khwang Platform and Pha Nok Khao Platform. Both platforms acted as an extensive distally steepened ramp-like margin which carbonates and siliciclastics accumulated. The Nam Duk Basin was formed in outer part of the Indochina platform on the western boundary which separated the two carbonate platforms including, the Khao Khwang platform in the west and the Pha Nok Khao Platform in the east boundary. The siliciclastics to carbonate rocks dominated in the Nam Duk Basin consist mainly of lime mudstone and carbonate sand turbidites with extensive debris flow around platform as a slope to basin depositional environment (Ueno and Chareontitirat, 2011; Booth and Sattayarak, 2011).

3. Methodology

Fibrous calcite veins and their host rock characterizations were identified from polished slabs and thin sections by a polarized light microscope. Total organic carbon (TOC) and source rock potential analysis were measured from all samples using a rock-eval pyrolysis technique and combined with extractable organic matter (EOM) to evaluate the quantity, quality, and maturity of the rock samples.

4. Result

4.1 Field Observation

The predominant lithology of Khao Khwang Formation rock samples are argillaceous limestone without sedimentary structures that are adjacent to the bedding parallel fibrous calcite veins. In general, the succession in this study area comprises of thick beds limestone (approximately 1 to 50 cm) interbedded with calcareous mudstone to argillaceous limestone as a thin layer (approximately 1 to 10 cm) (Fig. 2). On the other hand, the Nam Duk Formation rock samples are calcareous mudstones that are commonly observed as thin beds with obvious subparallel to parallel laminations and are interbedded with thick beds of sandstone (Fig. 3). The bedding parallel fibrous calcite veins in the Nam Duk sampling location are distributed around 20 meters along the roadcut outcrop, and thickness was found at around 1 to 7 cm from surface of calcareous mudstone. In contrast, the Khao Khwang Formation was sampled from a stream cut outcrop, and the thickness of fibrous calcite veins is around 1 to 5 cm where they align at the top and bottom parts of argillaceous limestone.

4.2 Petrographic Study

Observation under the polarized light microscope shows that the fibrous calcite veins are oriented approximately perpendicular to the bedding at the upper and lower parts of the host rocks in both the Khao Khwang and Nam Duk Formations. The parallel fibrous calcite can be separated into two characteristics, including beef veins and cone-in-cone structures.



Figure 2. Interbedding of limestone and mudstone exposure in the Khao Khwang Formation.

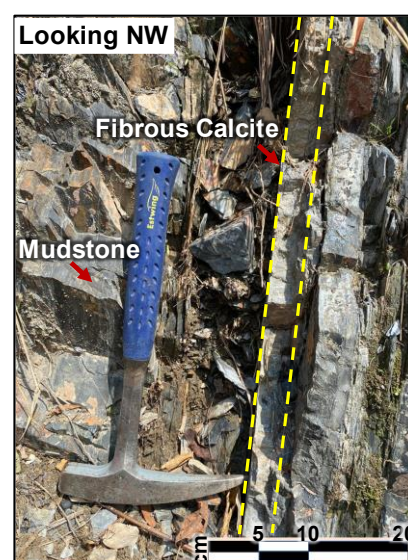


Figure 3. Fibrous calcite vein within calcareous mudstone on the exposure outcrop in the Nam Duk Formation.

4.2.1 Khao Kwang

The cone-in-cone structure (CIC) is a significant structure of this study area. The fibrous calcite crystals commonly associate with solid inclusions, which are generally composed of insoluble mud components, organic matters, and pyrite. Furthermore, cone-in-cone structure layers were connected with a clear fibrous calcite or a beef vein at the base of the cone in some samples. The sinusoid length of the solid inclusions ranges from a few micrometers to about 1.0 centimeter as symmetrical to asymmetrical parabolic lines of sinusoidal

shapes (Fig. 4A, B). On the other hand, the entrapped solid inclusions can also find as a scattering wedge or lenticular shapes. In contrast, this structure in some samples can be found without the solid inclusions. Most of samples, the median suture lines or zones, which are a seed to form fibrous calcite veins, are not apparently to determine the exact growing direction of calcite, but except in the Figure 4C. However, the growth characters of fibrous calcite veins apparently precipitated from the bottom of vein margin where attaches to the host rock matrix toward the top of the vein margin indicating from the gradually changed from equant calcite to fibrous calcite form (Fig. 4B).

4.2.1 Nam Duk Basin

In contrast to the Khao Khwang sample, the fibrous calcite in this study area clearly appears as a beef vein (Fcal) and can be observed as a sharp contact to the host rock surface (Fig. 4D, E). The fibrous calcite crystals have a width at around 0.2 to 1.0 millimeter with twinning. The median suture lines or zones in the samples are not clearly observed but they can be distinctly found in the ND-1 showing an evidence of fibrous calcite growing from the median suture line in the center of veins to the edges of the host rock surfaces or vein margin boundaries (Fig. 4H). Moreover, there are indistinctive to absent of scattered solid inclusions (CIC structure) of the host rock. Nevertheless, the fibrous calcite and matrix rocks in this area were found the interference of quartz and feldspar that may the primary composition from silicate minerals in the matrix of host rock portions to contribute the quartz precipitated with fibrous calcite.

In general, abundant pressure solutions were observed in host rocks both the Khao Khwang and Nam Duk rock samples, such as

stylolite and microstylolite that aligned along the grain boundaries. They are mainly consisted of insoluble mud minerals, organic matters, and pyrite as a wavy or rectangle sutures. However, calcite twinning and interlocking of calcite grains presented as a sutured grain boundary predominantly are noticed that can be suggested to the diagenetic condition in term of physical and chemical controls which should be an effect for their changing (Fig. 4D). On the other hand, pyrite is also prevalent within the host rock matrix in various forms, including euhedral, framboid, and aggregate morphologies (Fig. 4F).

4.3 Quantity of Organic Carbon

4.3.1 Total Organic Carbon (TOC)

The level of TOC richness levels in this study is based on definition of Peters and Cassa (1994). The TOC value for the the Khao Khwang Formation samples range from 0.22 to 0.39 wt.%, with an average of 0.33 wt.%. KK-6 has the lowest TOC value, while KK-1, KK-3 and KK-4 have equivalent value as the highest of TOC value. As a result, these rock samples are fair potential source rocks (0.2 - 0.5 wt.%). For the calcareous mudstone samples from the Nam Duk Formation presented their TOC levels vary from 0.45 to 0.64 wt.%, with an average of 0.56 wt.%. ND-3 has the lowest TOC value and ND-5 has the highest TOC value that they indicated a poor (0.0 - 0.5 wt.%) to fair (0.5 - 1.0 wt.%) petroleum potential of the source rock. On the other hand, the Nam Duk Formation also appear to be higher on average than the TOC values which analyzed from the argillaceous limestone of the Khao Khwang Formation as shown in the Table 1.

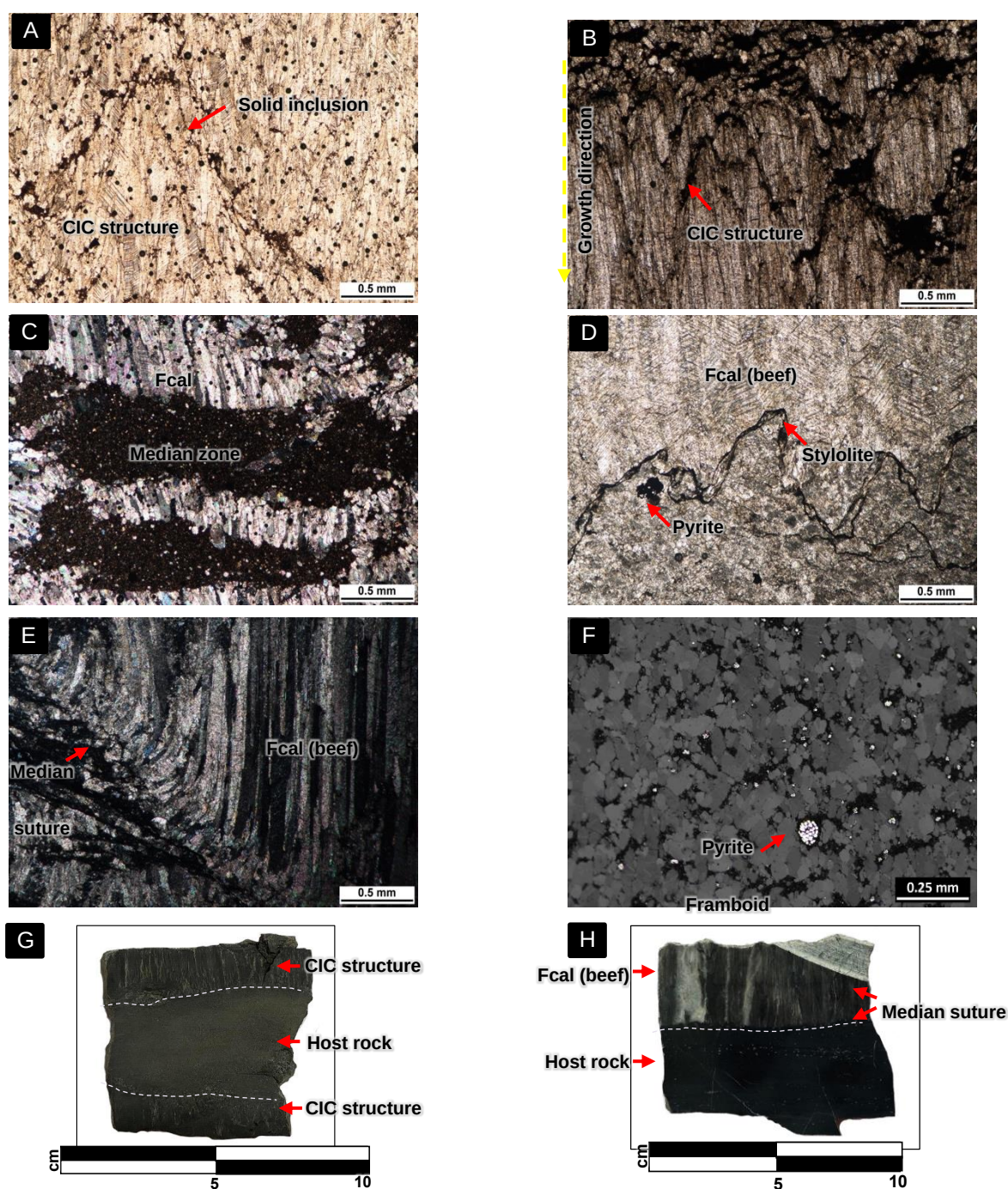


Figure 4. Thin section photomicrographs show the characteristics of the Khao Khwang Formation and the microstructures fibrous calcite veins as follow: (A) cone-in-cone structure with sinusoid solid inclusion; (B) a seam of solid inclusion as continuous parabolic line of solid inclusion, outlined the fibrous calcite as a conical structure; (C) fibrous calcite growth from the median zone compositions; (D) sharp contact between fibrous calcite vein and host rock; (E) long fibrous calcite (beef) precipitating from median suture line; (F) the framboid pyrite generally formed in the clay matrix as in between calcite grains; (G) Polished slab sample of the Khao Kwang formation shows area bedding parallel fibrous calcite veins (CIC) in upper and lower parts of host rocks; (H) Polished slab sample of the Nam Duk Formation shows bedding parallel fibrous calcite veins (beef) on top of host rocks.

4.3.2 Extractable Organic Matter (EOM)

The bitumen contents of the the Khao Khwang Formation samples were extracted as shown in the range of 20 ppm to 220 ppm, with the highest are occurred in the KK-3 sample and the lowest concentration is in the KK-5 sample. The Khao Khwang Formation samples in this research have an average bitumen concentration of 117 ppm. On the other hand, the bitumen contents from Nam Duk Formation ranges between 20 ppm and 100 ppm, with the highest content observed in the ND-4 shale sample and the lowest in the ND-1 shale sample. Additionally, the average of the Nam Duk Formation is 53 ppm. According to Peters and Cassa (1994), the bitumen contents in both formations are represented as a poor potential source rock due to the amount of bitumen less than 500 ppm (Table 1). The combination of TOC and EOM from the Khao Khwang and Nam Duk Formation samples are compared as shown in Figure 5.

4.3.3 Rock-Eval Pyrolysis

The Khao Khwang Formation has an average hydrocarbon yield (S2) of 0.04 mg HC/g rock, with a range of 0.02 to 0.07 mg HC/g rock, the greatest levels were found in the KK-4 (0.07 mg HC/g rock) with highest TOC levels as well. The S2 values of the measured samples from the Nam Duk Formation is in the range of 0.01 to 0.04 mg HC/g rock, averaging 0.03 mg HC/g rock. Therefore, samples from both Formation suggest that they have poor petroleum generation potential based on definition from Peters and Cassa (1994).

4.3.4 Genetic Potential

The hydrocarbon potential of the source rocks is determined by a combination of light hydrocarbon (S1) and hydrocarbon cracking from kerogen (S2) as genetic potential. Argillaceous limestone and calcareous mudstone samples from both study areas are a poor petroleum source rock due to their low genetic potential, below 2 mg HC/g rock, based on Peters and Cassa (1994).

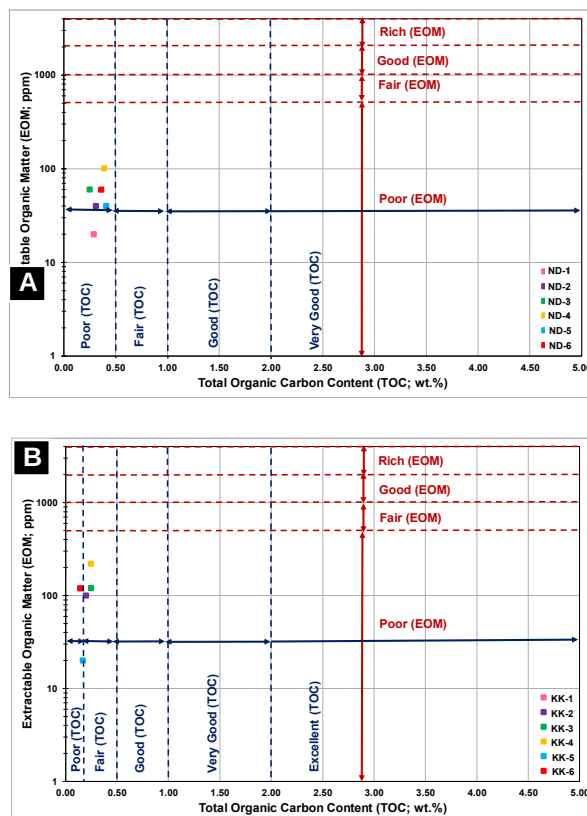


Figure 5. Showing the cross-plot diagrams between extractable organic matter (EOM; ppm) versus total organic carbon content (TOC; wt.%) to indicate potential source rock of (A) the Nam Duk Formation and (B) the Khao Khwang Formation.

4.4 Quality of Organic Carbon

4.4.1 Van-Krevelen diagram

Types of organic matters can be defined by the coherence of pyrolysis parameters and TOC contents for converting to hydrogen index (HI) and oxygen index (OI) contents and used to plot in Pseudo Van-Krevelen diagram. In this study, the pseudo - Van - Krevelen diagram is an unqualified kerogen evaluation in both the Khao Khwang and Nam Duk samples due to low HI. The determination from this diagram suggest that they are kerogens type IV (inert or asphaltenes) (Fig. 6). Moreover, using the standard of Tissot and Welte (1984) can be also implied as kerogen type IV; HI average 12 mg HC/g TOC, ranging from 5 to 18 mg HC/g TOC, and OI average 85 mg CO₂/g TOC, ranging from 59 and 105 mg CO₂/g TOC from the Khao Khwang Formation and HI average 5 mg HC/g TOC, ranging from 3 to 8 mg HC/g TOC, and

OI average 79 mg CO₂/g TOC, ranging from 50 and 133 mg CO₂/g TOC in the Nam Duk Formation.

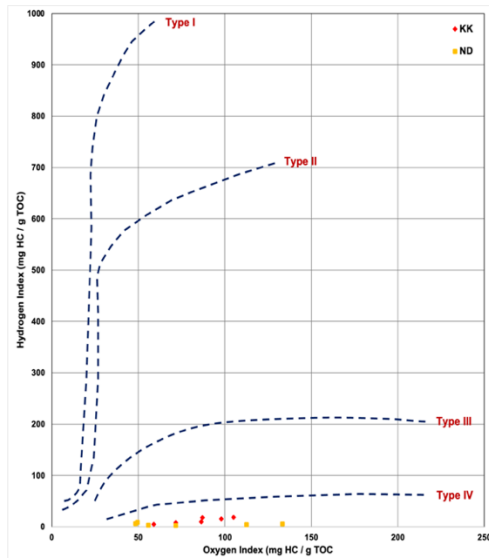


Figure 6. Geochemical correlations between hydrogen index (HI) and oxygen index (OI).

4.5 Thermal Maturation (T-max)

T-max may generally be compared to the production index (PI) to provides source rock maturation level as presented in Figure 7. Samples from both study areas mostly are a thermally immature at present day from the T-max values at below 430 °C, except in the ND-1 sample falling in the zone of oil cracking or gas generation based on 446 °C of T-max and 0.50 of PI value. T-max values vary between 352 and 409 °C in the Khao Khwang Formation samples, while the Nam Duk Formation samples have values from 349 to 446 °C (Table 1). Generally, T-max values of both Formations are less than 430°C with relatively low S2 (lesser than 2.5 mg HC/g TOC). Thus, they are suggested a thermally immaturity, but only ND-1 (446 °C) indicated maturity level at the top of oil window (Figure 8). In contrast, a ranging of production index of both study areas is relatively high when compared to the T-max values. It was inferred that the Khao Khwang

and Nam Duk Formations generally have not reached to the window for oil generation but would have an adequate capacity to produce mainly gaseous hydrocarbon types (Figure 8).

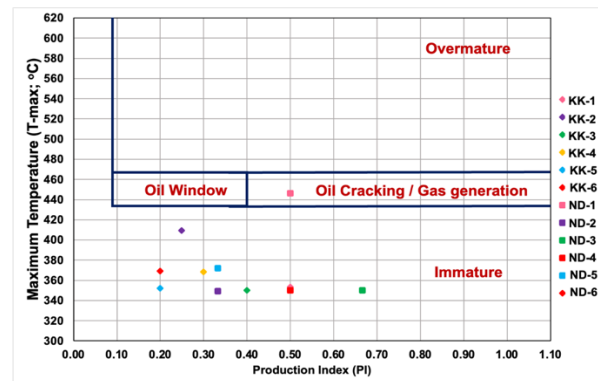


Figure 7. Cross plots between production index (PI) versus maximum pyrolysis temperature (T-max).

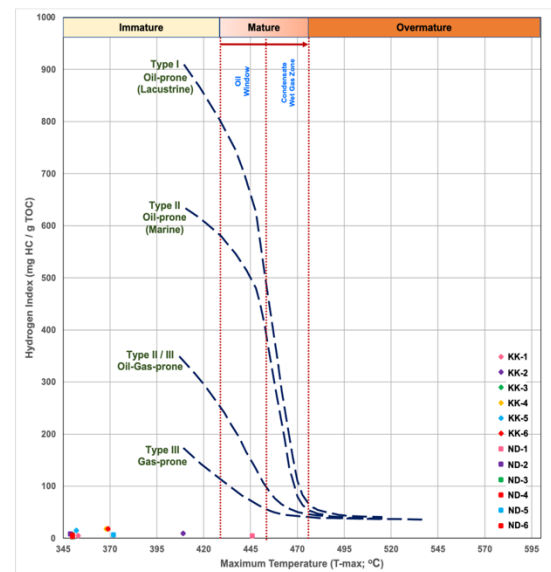


Figure 8 Cross plot between hydrogen index (HI) versus maximum pyrolysis temperature (T-max).

Table 1 Showing all the values as TOC, EOM, Pyrolysis, and indicative indexes.

Samples	TOC (wt.%)	EOM (ppm)	S1	S2	S3	T-max (°C)	HI	OI	PI	Genetic Potential
			(mg HC / g rock)							
KK-1	0.39	100	0.02	0.02	0.23	353	5	59	0.5	0.04
KK-2	0.31	120	0.01	0.03	0.27	409	10	86	0.25	0.04
KK-3	0.39	220	0.02	0.03	0.28	350	8	72	0.4	0.05
KK-4	0.39	120	0.03	0.07	0.34	368	18	87	0.3	0.10
KK-5	0.27	20	0.01	0.04	0.26	352	15	98	0.2	0.05
KK-6	0.22	120	0.01	0.04	0.23	369	18	105	0.2	0.05
ND-1	0.45	20	0.02	0.02	0.51	446	4	113	0.5	0.04
ND-2	0.48	40	0.02	0.04	0.24	349	8	50	0.33	0.06
ND-3	0.39	60	0.02	0.01	0.28	350	3	72	0.67	0.03
ND-4	0.61	100	0.02	0.02	0.34	350	3	56	0.5	0.04
ND-5	0.64	40	0.02	0.04	0.31	372	6	48	0.33	0.06
ND-6	0.56	60	0.03	0.03	0.75	350	5	133	0.5	0.06

Discussion

5.1 Fibrous Calcite Characteristic

According to petrographic study, the Nam Duk Formation samples exhibit good development of beef veins with smooth continuous boundaries of fibrous calcite and low to lack of interference of solid inclusions. On the other hand, the Khao Khwang Formation samples are significantly developed the fibrous calcite as the cone in cone structure with abundant of solid inclusions. However, the median suture zones and lines of both formations are unclear observations or found in a narrow to tight zone can be concluded that the fibrous calcite were growing in consistency rate (Yu et al., 2015). As the different fibrous calcite characteristics can be used for interpreting their growth possibilities as follow:

(1) The existence of a significant cone in cone structure as the sinusoidal shape in the Khao Khwang Formation samples can be signified that the fibrous calcite crystals were formed at a different rate of continuous calcite fibers forming from abundant of solid inclusions presented between conical stackings. These features also suggest that the host rocks were unconsolidated or partially consolidated during the fibrous calcite development (Meng et al., 2017). As a result, this implication can be

referred to the clear fibrous calcite or beef veins within the Nam Duk Formation that might be formed at more consolidated host rocks than the Khao Khwang Formation.

(2) The presenting of sinusoidal solid inclusions in the fibrous calcite veins of the Khao Khwang Formation samples may be the cause of fibrous calcite production in an outward orientation from the solid inclusions or host rock fragments toward the vein walls (Fig. 4C). Therefore, the solid inclusions could indicate that fibrous calcites were precipitated directly from the pore water, which obtained from the carbonate fluids of the host rock surfaces and grew vertically inward during the gradual opening of the vein space (Franks, 1969; Cobbold et al., 2013).

5.2 Potential Hydrocarbon Generation and Source Rock Richness

The TOC contents of the rock samples of the Khao Khwang Formation are considered as fair potential source rocks, on the other hand, the rock samples of the Nam Duk Formation are thus considered as poor to fair potential source rocks. Furthermore, extractable organic matter in both Formations represents as a poor source

rock potential due to their values less than 500 ppm.

However, the S2 values also conclude that the Khao Khwang Formation and Nam Duk Formation are poor, which have various values as less than 2.5 mg HC/g rock and partial agreement with the TOC assessment. As a result, these can be indicated a dry gas - prone source rocks, which are consistent with the determination from the kerogen composition of the samples dominating by gas - prone type kerogen when using the HI versus T-max. The apparent low value of HI could result from increasing maturation and deterioration of kerogen quality, but the correlation between the low HI and OI suggested type IV kerogen higher inertinite contents. However, Tissot and Welte (1984) implied that the inert type IV kerogen can also produce the hydrocarbon type representing some of the gas generations.

As low TOC of these samples can be affected from higher input of terrestrial organic matter and higher oxygenated conditions. In addition, Moore (1985) pointed out that TOC in a gas-bearing source rock usually denotes carbon association with kerogen that is usually too low to be detectable, which can be associated with the interpretation of the kerogen type in the result as gas prone in type III and type IV.

On the other hand, thermal maturations are mostly showed as a non-potential source rock, but possibly have an adequate capacity to produce hydrocarbons, which is mainly gas - type, due to the genetic potential (S1 + S2) and high range production index (PI) values.

6. Conclusion

Bedding-parallel fibrous calcite veins are generally identified in two characteristics including beef veins and cone-in-cone structure and indicate that they continuous growth from

the modified host rock compositions. Both characters present adjacent parallel growing of fibrous calcite veins to host rock bedding and they are approximately perpendicular to the host rock surface. It is assumed that the veins primarily derive carbonates from seawater during diagenesis. As the total organic carbon (TOC), extractable organic matter (EOM), and pyrolysis analyses conclude that both the Khao Khwang and Nam Duk Formations have a capacity to produce hydrocarbons which are mainly gas-types as a dry gas prone source rock.

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References

- Basson, I., and Viola, G., 2004, Passive kimberlite intrusion into actively dilating dyke– fracture arrays: evidence from fibrous calcite veins and extensional fracture cleavage: *Lithos*, v. 76, p. 283–297.
- Booth, J., and Sattayarak, N. 2011. Subsurface Carboniferous-Cretaceous geology of NE Thailand. In: Ridd, M.F, Barber, A.J. & Crow, M.J. (eds.), *The Geology of Thailand*, pp. 185-222. London: The Geological Society.
- Chonglakmani, C. and Sattayarak, N., 1984. Geological map of Thailand on 1: 250,000 scale: sheet Changwat Phetchabun (NE47-16). Department of Mineral Resources, Bangkok.
- Cobbold, P.R., Zanella, A., Rodrigues, N., Loseth., H., 2013. Bedding - parallel fibrous veins (beef and cone-in-cone): worldwide

- occurrence and possible significance in term of fluid overpressure, hydrocarbon generation and mineralization. *Marine and Petroleum Geology*, 43, 1-20.
- Franks, P.C., 1969. Nature, origin, and significance of cone-in-cone structures in the Kiowa Formation (Early Cretaceous), north-central Kansas. *Journal of Sedimentary Research*, 39, 1483-1454.
- Helmcke, D. and Lindenberg, H.-G. (1983) New data on the "Indosinian" orogeny from central Thailand. *Geol. Rundschau*, v. 72, pp. 317 - 328
- Meng, Q., Hooker, J., and Cartwright, J. 2017a. Early over-pressuring in organic-rich shales during burial: evidence from fibrous calcite veins in the Lower Jurassic Shales-with-Beef Member in the Wessex Basin, UK. *Journal of the Geological Society* 174: 869–882.
- Metcalfe, I. 2011. Tectonic framework and Phanerozoic evolution of Sundaland. *Gondwana Research* 19: 3-21.
- Moore, L.V. 1985. Significance of EOM/TOC ratios in identifying possible migration fairways, NPRA, North Slope, Alaska. United States.
- Peters, K.E., and Cassa, M.R. 1994. Applied Source Rock Geochemistry. In *The Petroleum System From Source To Trap*, pp. 93-120.
- Racey, A. 2011. Petroleum geology. In Ridd, M.F., Barber, A.J., and Crow, M.J. (eds.), *The Geology of Thailand*, pp. 351-392. London: The Geological Society.
- Tissot, B., and Welte, D. 1984. *Petroleum formation and occurrence: a new approach to oil and gas exploration*. Springer.
- Ueno, K., and Charoentitirat, T. 2011. Carboniferous In Ridd, M.F., Barber, A.J., and Crow, M.J. (eds.), *The Geology of Thailand*, pp. 71-136. London: The Geological Society.
- Yu, H., Zhou, X.Q., Wang, J.G., Guo, C., Wei H.Y., Chen, D.Z., 2015 The origin of bedding-parallel fibrous calcite veins in the Lower Permian Chihhsia Formation in western Hubei Province, South China. *Science Bulletin*.