POROPERM CONTROLS IN AN "ORDOVICIAN" FRACTURED CARBONATE RESERVOIR IN THE SUPHANBURI BASIN, WESTERN THAILAND: USING A COMBINATION OF CUTTINGS, ISOTOPES AND FMI

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Abstract

Fractured carbonate reservoir is a new hydrocarbon target in the "A area," which is located in the north-western part of the Suphanburi basin, western Thailand. Based on study of cutting chip samples from this newly recognized basement reservoir interval in well A-01, this producing zone be an interval of fractured and brecciated marble. It is not made up of Ordovician limestone, as was previously inferred. This study uses a combination of petrographic analysis, XRD analysis and carbon-oxygen isotope analysis, combined with image log (FMI or CMI) reinterpretation. Implications, in terms of reservoir quality, are discussed and relationships between subsurface and outcrop are defined. Reservoir-hosting fractured marbles show a dominant NNE-SSW fracture direction, which is directly related to a measured minor fracture trend seen in outcrop. C-O isotope crossplots define three trends, related to increasing metamorphic grade and subsequent uplift. Trend 1 is a lower temperature burial trend representing a set of deep meteoric fluids contaminating marbles located near fissures in the very early stages of Paleogene uplift. Trend 2 is an older trend than trend 1 and is tied to increasing burial tem-peratures of the late mesogenetic burial or metamorphic realm. Trend 3 is the youngest, and is related to entry of typical (soil-gas enriched) telogenetic fluids during Tertiary-age uplift. Trend 3 samples are associated with the development of reservoir-grade secondary porosity. In terms of total rock volume, trend 2 dominates the rock fluid signature. This suggests that the likelihood of porosity storage and permeability in the rock matrix is very low. Productive storage will be found in uplift-related solution-enhanced fissures or late-stage fractures and fault-related breccia haloes.

Keywords: Fractured Carbonate, Metamorphic, Marble, Fault Breccia, Late Mesogenetic

1. Introduction

The key characteristic for hydrocarbon exploration in the Suphanburi basin were established by BP in the 1980s (O'Leary and Hill, 1989). Later, PTTEP explored the western side of the Suphanburi basin and this work provided further details of the interaction between structure and sedimentation in the vicinity of the boundary fault of the basin (Ronghe and Surarat, 2002). The main reservoir target is Unit D, which was deposited in a Tertiary fluvio-lacustrine environment (Figure 1 and 3).

In March 2015, well A-01 was drilled, and it can be justified as oil well as it recovered 6.8 mTV from a Tertiary clastic reservoir, but it also recovered 14.0 mTV from a deeper fractured carbonate reservoir. The latter was a secondary target, which until well A-01 had no proven hydrocarbon potential in the "A area" of the basin. The initial interpretation of the intersected carbonate was tied nearby carbonate outcrops mapped by the DMR as Ordovician limestone (PTTEP, 2015). These outcrops are currently being studied by Bunpitaksakul (2016). He has clearly shown that these outcrops are composed of high-grade metamorphics, mostly marbles, and are not Ordovician limestones. The distance between well A-01 and the outcrop study area is approximately 10 km. (Figure 1). It is likely that the carbonate reservoir intersected in well A-01 is a metamorphosed carbonate.

Therefore, this study focus on the "basement" carbonate interval, first intersected at 2000 – 2400 mTMD. To better define the nature and likely poroperm distribution in this "basement" carbonate interval, this study integrates the results of petrography, XRD, image log (FMI or CMI) and carbon-oxygen isotope and compares the observations with the results of Bunpitaksakul's (2016) outcrop study.

Metamorphics are unusual reservoir rocks and so before discussing the main body of research some of the features that typify metamorphic successions will be summarized. A protolith typically possesses a set of rock properties and mineralogies that are different from the rock into which it evolves. The original rock may be a limestone or dolomite, with evaporates, or interlayered with sands and shales.

After regional metamorphism, typically driven by subduction and continent-continent collision, the end product of a once dominantly a carbonate body of rock is a series of calcic, sodic and magnesium aluminosilicates, calc-silicates and marbles with local possible zones of potassic enrichment (Warren, 2016)

The diagenetic terms eogenetic, mesogenetic and telogenetic used in this report follow the usage of Choquette and Pray (1970) and imply early marine-influenced, burial and uplift-related pore waters, respectively. However, as these rocks are highly metamorphosed, telogenesis (uplift-related) is the most relevant term in terms of any diagenetic discussion. Meta morphism has largely obliterated eogenetic and early to mid mesogenetic textures. The term late mesogenesis, as used in this study, encompasses the metamorphic burial realm.

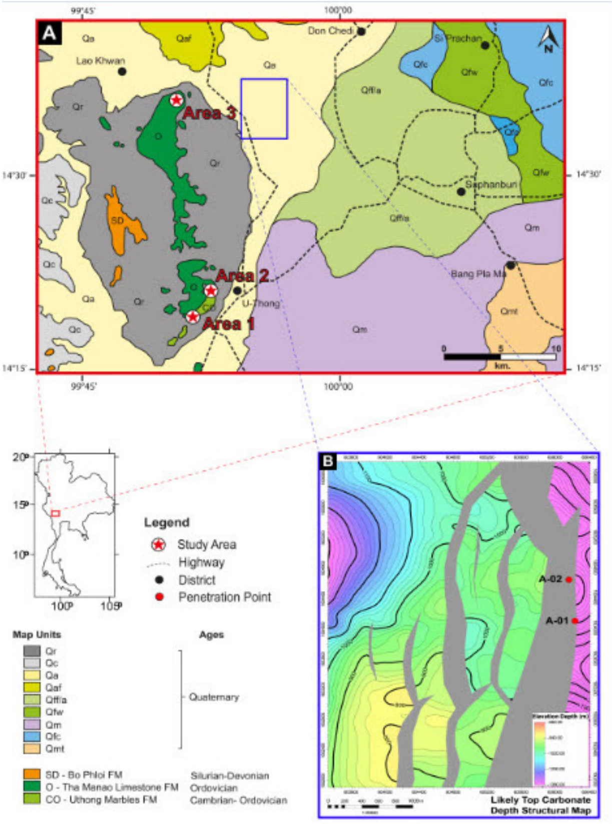


Figure 1 A) Geological map in Suphanburi Province, Thailand (DMR, 2014b) with outcrop study locations (areas 1, 2 and 3) by Bunpitaksakul, 2016. B) Likely top carbonate depth structural map (PTTEP, 2016) with well A-01 and A-02 location in subsurface study area (area A) approximately 10 kilometers distances from outcrop study area.

2. Regional Tectonic Setting and Stratigraphy

During its tectonic evolution Thailand formerly consisted of two continental terrains, the Shan-Thai and Indochina (Figure 2A). They were welded together by a collision that occurred in the Triassic and Permian periods (Bunopas, 1992; Mantajit, 1997). Convergence and collision of Shan Thai block in the West and the Indosinian block in the East played drove eastward subduction and underthrusting during the late Paleozoic-early Mesozoic. This collision resulted in a fold thrust belt that is tied to an event known as the Indosinian Orogeny (F. Hirsch et al., 2006; Kaewkongkaew et al., 2013).

Subsequent development of the Suphanburi basin is controlled by two main east-dipping fault systems, a low-angle boundary fault system (LABFS) that controls the western sub-basin and a high angle boundary fault system (HABFS) that controls the main Suphanburi basin. Structurally, the Suphanburi basin is a N-S oriented basin that lies between the Mae Ping fault zone and the Three Pagodas fault zone (Figure 2B; (Morley, 2006). Up to 30 Ma, both faults zones underwent significant sinistral displacement during the Eocene-Oligocene (Lacassin et al., 1997). Since 30 Ma the fault zones have undergone minor episodic dextral displacement. However, this dextral displacement does not appear to have strongly interacted with the rift basin development and basin activity appears to have been largely independent of the strike-slip fault zones (Smith et al., 2007). Figure 3 summarizes the relevant basin stratigraphy.

Based on geological map of Suphanburi province by DMR (2014, Figure 1), basement in the study area in ascending order consists of Cambrian-Ordovician metamorphic rocks, and Ordovician limestones beneath a Quaternary sediment cover (Table 1). The Cambrian-Ordovician metamorphic rock is assigned to the Uthong Marble, which is dominantly a white marble with sugary and foliated textures, occasional dolomite, quartz schists and mica schists. The Ordovician limestone or Tha Ma Nao Formation is typically gray to dark gray and made of thick beds of massive limestone interbedded with claystone. This limestone can possibly be recrystallized to marble and greenish gray calc-silicates with foliated textures. The Quaternary cover is considered to be made up of alluvial fan delta deposits consisting of sandstone interbedded with claystone, siltstone interbedded with nodular limestone, gravel and sand (DMR, 2014a, b).

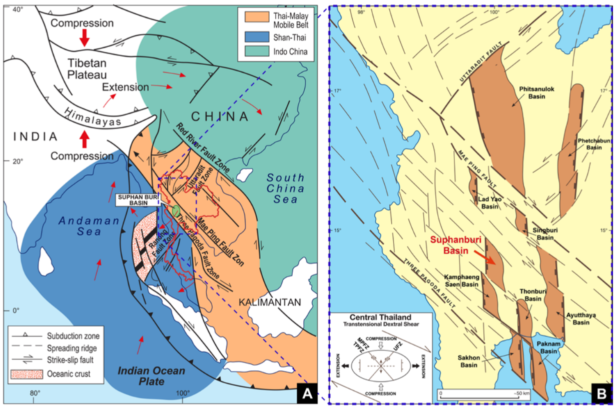


Figure 2 A) The Indochina continental block was extruded to the southeast during India-Asia collision, with movement of the Indochina continental block relative to the Shan-Thai continental block accommodated by strike-slip along the Thai-Malay Mobile Belt (Polachan et al., 1991). B) Regional Suphanburi basin location related to tectonic element showing the development of north trending pull-apart basins between the Three Pagodas and Mae Ping dextral strike-slip faults (Polachan and Sattayarak, 1989).

The stratigraphy of the Khao Wong and Khao Phu Thong areas, which are located along western part of Suphanburi basin was modified Bunpitaksakul (2016). The Tha Ma Nao limestone, as shown in Figure 1, is now known to be absent in the outcrop area (incorrectly mapped by the DMR). Instead, outcrops are tentatively considered equivalent to the Uthong Marble but, as yet, there are no age determinations on the outcrop lithologies proving a Cambrian-Ordovician age. Bunpitaksakul (2016) has shown that all the carbonate outcrops along the western margin of the Suphanburi basin are dominated by variably-mylonitic marbles with equigranular textures, foliations, augens and porphyroclastic structures, along with rare fault breccia (Table 1).

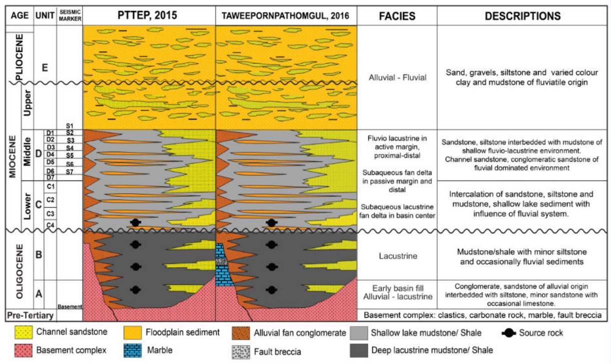


Figure 3 Stratigraphic column of Suphanburi basin, after PTTEP, 2015; the results of this study add Pre-Tertiary units of marble and rare fault breccia haloes (in the northwestern part of basin) to the generalized basement legend.

AGE	DMR, 2014				BUNPITAKSAKUL, 2016		
	GROUP	FORMATION	DESCRIPTIONS		AGE	FORMATION	DESCRIPTIONS
QUATERNARY			Alluvial fan, sandstone interbedded claystone, siltstone interbedded limestone nodule, gravel and sand.				
ORDOVICIAN	Thung Song	Tha Ma Nao Limestone	Thick bed to massive limestone, recystallized to marble and laminated calc-silicate.		Age Unknown	Likely Uthong Marble equa-valent	Mylonitic marble with equigranular texture, foliated, augen and porphyroclastic texture are common, occasional mica schist, rarely fault breccia.
CAMBRIAN - ORDOVICIAN		Uthong Marble	Marble with sugary texture, quartz schist, mica schist, occasional dolomite.				

Table 1 Stratigraphic column of Suphanburi Province in the vicinity of the study area; comparison between DMR, 2014 and Bunpitaksakul, 2016.

3. Data Available and Analytical Techniques

This study is focus on reservoir quality in the "basement" carbonate reservoir in term of porosity and permeability, which in "area A" are overprinted by metamorphism, rock-fluid evolution and fracture orientations as well as by possible telogenetic effects related to Tertiary uplift. Well A-01 is an exploration well with the prime aim of investigating hydrocarbon potential in S1.5, S3, S5 and S6 reservoirs levels in the "A area". It is located in the L53/43 concession. The well was drilled in order to penetrate into sediments associated with the major western boundary fault of the Suphanburi basin. The wireline log evaluation of this well by PTTEP petrophysicists defined an unexpected 14 m oil column in a zone with 5-14% porosity, located in a fractured carbonate "basement" reservoir interval.

A total of 40 intervals of cuttings were bagged from 2000.0 to 2400.0 mTMD in main carbonate section and some 50 cutting samples collected for this study were classified into 12 lithotypes based on color, crystal characteristics and intensity of HCl reaction. Representative cuttings were submitted for thin section analysis (see below). Equivalent texture-aware lithotype samples were crushed to analyze for δ^{13}Carbon-δ^{18}Oxygen (C-O) stable isotope values. The isotope samples are mainly collected from calcite crystal and matrix that were expected to be representative of calcite veins, calcite-filled fractures, and limestone or marble matrices. Isotope-equivalent samples were separated into 10 thin-sections composed of 47 cutting chip samples for detailed petrographic analysis. Each textural sample was made up of 2-3 cutting chips showing the same lithotype under initial binocular microscope study. Rock texture and mineral presence are considered be responses to diagenesis or metamorphic phase and relevant indicators of variations in term of pressure, temperature and shear stress associated with tectonic activity. XRD analysis was performed on 10 lithotypes (with no acid reaction) to test mineral compositions determined in thin section study and to assign appropriate rock names. In terms of wireline data, the studied Compact Micro-Imager (CMI) log interval in well A-01 totals 487.4 m from 2038.8 - 2526.2 mTMD. This study focuses on the carbonate interval at 2038.8 – 2400.0 mTMD. Raw CMI data (DLIS format) were loaded into the Interactive Petrophysics® software package and were reinterpreted in order to better define structural trends and to better classify possible metamorphic rock types. This was done by comparing CMI features with core plug image data from well A-02, which was drilled approximately 500 m from well A-01 (Figure 1). Well A-02 ran CMI from 1855.0 – 2540.0 mTMD and collected 19 core plugs.

4. Petrographic Analysis

Petrographic analysis was performed on 47 samples of cuttings loaded in quadrant sectors in 10 thin sections. The microscale-texture and mineral compositions were first defined by using a binocular microscope at the time of sample collection in the PTTEP core storage facility and layout laboratory. This was done prior to thin-section manufacture and was very useful for controlling cutting lithotype sampling that would ultimately lead to a better understanding the metamorphic stage, pore system evolution and rock type classification and so give more reliable comparisons with the relevant isotope values.

Examples of microscale binocular-thin section textures with notation which relates to subsequent isotope plot (Figure 14) are shown in Figures 4-8. Photomicrographs of white crystalline calcite cutting chips from 2030 - 2040 m interval (Figure 4) are made up of small single calcite crystals with tiny cleavage faces. Isotope values plotted in Figure 14 imply these chips are likely related to marble contamination via deep meteoric fluid entry in the early stages of Paleogene uplift (as identified by Bunpitaksakul, 2016).

Photomicrographs of gray cutting chips from 2030 - 2040 m interval (Figure 5b) show small recrystallized grains of calcite and calcite veinlet crosscuts which capture the isotopic signal of decreasing temperature related to an uplift event and fluid mixing in calcite filled fractures (Figure 14). Photomicrographs of yellow calcite cutting chips from 2020 - 2030 m interval (Figure 5c) show foliatied textures in calcite, indicating shear stress on the rock prior to an uplift event with recrystallisation of calcite and quartz intergrowth into vugs that reduced porosity. Later, the isotope plot points are related to this sample, it is highly likely that some of the calcite recrystallisation was post metamorphic and occurred in the early stages of uplift.

Figure 5b-5c are from cuttings samples that show evidence of meteoric mixing trend or a telogenetic stage in isotope determination plotted in Figure 14.

Photomicrographs of white calcite with red staining, as well as white calcite and quartz cutting chips from 2340 - 2350 m, 2290 - 2300 m and 2110 - 2120 m intervals, respectively (Figure 6d-6f). The samples illustrate calcite with well-developed crosscutting twin cleavages, heteroblastic textures, with calcite and quartz crystals having sutured boundary shapes. Together these lithological observations suggest a limestone protolith was recrystallized into marble with quartz vein intergrowths at somewhat higher temperatures. These samples represent the lower temperature end of the late mesogenesis/metamorphic stage.

Photomicrographs of black cutting chips from 2110 - 2120 m intervals (Figure 7) showing cross-cutting microfractures that cut transect the rock and filled by recrystallized calcite and quartz that obliterated any remaining porosity at the higher temperature end of the late mesogenesis stage (Figure 14).

Some microscale-textures seen this subsurface cuttings study can be related to textures documented by outcrop study. For example, calcite and quartz crystals with heteroblastic textures in the subsurface are similar to marble textures in Bunpitaksakul's (2016) outcrop study (Figure 8a). Both represent rock matrix intersections that are highly metamorphosed. Interestingly, prismatic calcite crystal meshworks as seen in very high temperature calcite veins in outcrop are not seen in the subsurface samples. These meshwork features make up less than 0.0001% of the rock volume in outcrop, so sampling them using subsurface cuttings is very unlikely. They likely indicate hot, out-of-sequence, hydrothermal fluids hosted in veins that crosscut the high grade metamorphics of the late mesogenetic stage (Figure 8b).

5. Compact Micro-Imager (CMI) Reinterpretation

CMI data interval in well A-01 from 2038.8 - 2526.2 mTMD has already been interpreted by Weatherford (Kloos and Razlan, 2015), with a guiding model of Ordovician limestone in the basement interval. This study has reinterpreted the same CMI data but with a more realistic focus on carbonate interval at 2038.8 – 2400.0 mTMD as a series of metamorphosed marbles. In order to better identify metamorphic rock features the CMI DLIS files were loaded in Interactive Petrophysics® (IP) software. Outputs were viewed as static or dynamic images and to map orientations of features sine waves were fitted to observed bed boundaries, fractures, and other geologic features, as show the in detailed

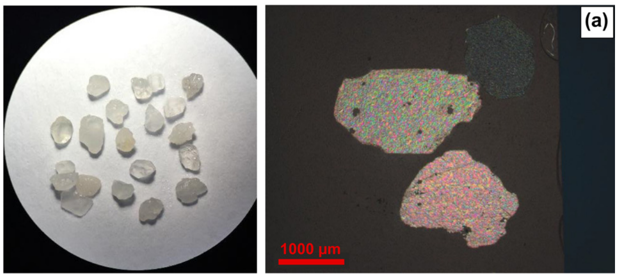


Figure 4 Photomicrograph of cutting chips of white crystalline calcite at 2030 m, possibly representing the entry of early Paleogene deeply-circulating fluid, as seen in the C-O stable isotope plot (a) calcite crystal with tiny cleavage (see notation in Figure 14).

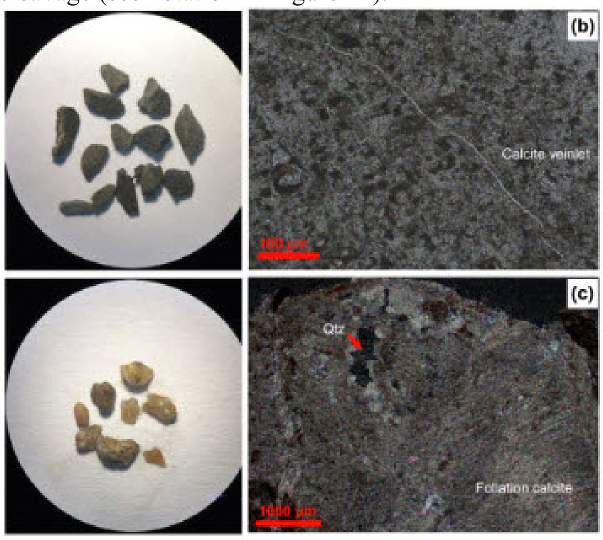


Figure 5 Photomicrograph of cutting chips of matrix at 2030 m and yellow calcite at 2020 m representing meteoric mixing trend features as seen in C-O stable isotope plot seen in Figure 14 (b) smaller calcite crystals with crosscutting calcite veinlet (c) calcite with foliation texture crosscutting vein fill and quartz intergrowths.

descriptions summarized in figure 9.

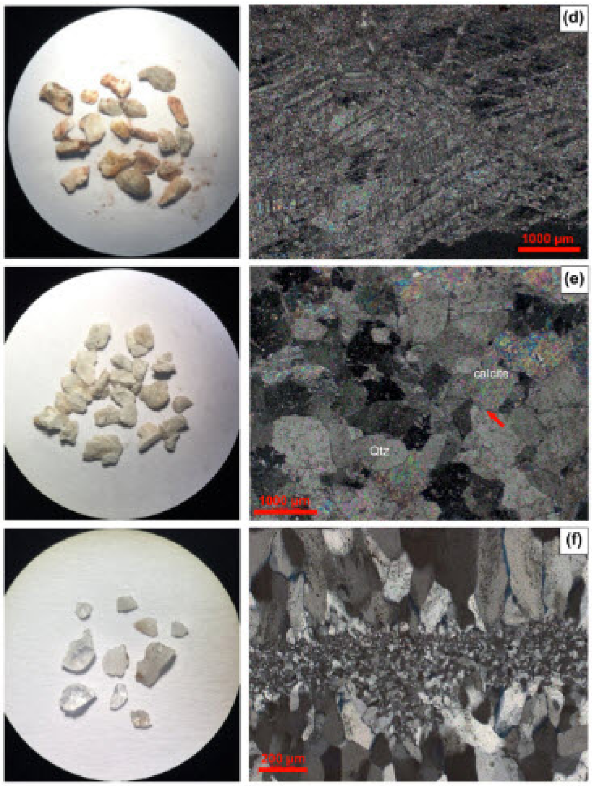


Figure 6 Photomicrograph of cutting chips of marble at 2340 m, 2290 m and quartz at 2110 m representing late mesogenetic stage features corresponding to high temperature values in C-O stable isotope plot in Figure 14. (d) Calcite with crosscutting twin cleavages (e) Heteroblastic, mortar texture, with calcite crystals having sutured boundary outlines indicative of high temperature suturing. (f) Quartz intergrowths possibly related to cooling hydrothermal fluids.

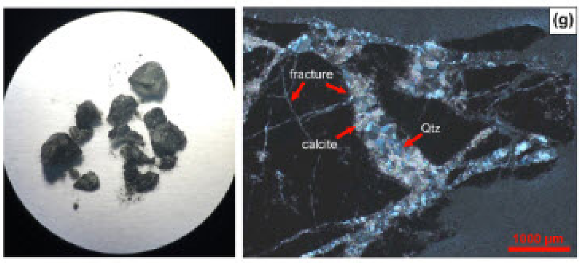


Figure 7 Photomicrograph of cutting chips of matrix with veinlets at 2110 m representing late mesogenesis stage features

A natural fracture is classified as either a resistive fracture or conductive fracture. In a water based mud a conductive fracture will be highly conductive relative to the background

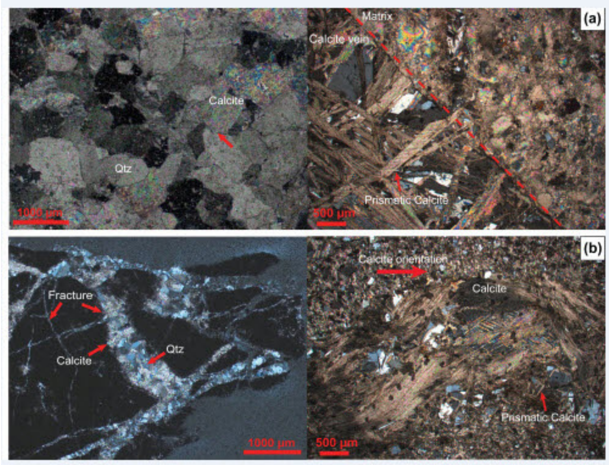


Figure 8 Photomicrographs of samples from subsurface (left side of both a and b) and outcrop (right side of both a and b) representing higher temperature rock types and metamorphic stages. (a) Sutured boundary shape of calcite crystal and quartz represent recrystallized calcite in low grade metamorphism of late mesogenesis stage. (b) Cross-cutting calcite-filled fractures (left) and prismatic calcite crystal meshworks seen in high temperature calcite veins in outcrop but not in subsurface. These meshwork features make up less than 0.0001% of the rock volume in outcrop, so sampling using subsurface cuttings is very unlikely. They likely indicate hot out-of-sequence hydrothermal fluids in the high grade metamorphic late mesogenetic stage.

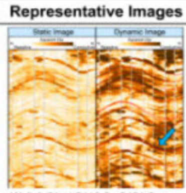
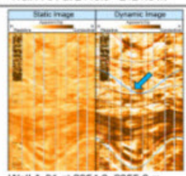
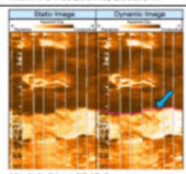
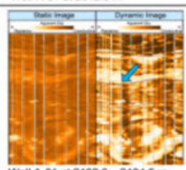
Classification	Representative Images	Description	Symbol
Conductive fracture	 Well A-01 at 2119.0 - 2121.0 m	Moderately to very steeply dipping, irregular to planar, dark colored (less resistive compared to host rock) features that are discordant to layering fabrics. Fracture traces are continuous and discontinuous around borehole. May be either, open or healed fractures.	
Resistive fracture	 Well A-01 at 2054.0, 2055.0 m	Moderately to very steeply dipping, irregular to planar, bright colored (more resistive compared to host rock) features that are discordant to layering fabrics. Fracture trace is continuous around borehole. May be closed (quartz or calcite filled) or cemented mineralized fractures.	
Bed boundary	 Well A-01 at 2042.0 m	Sharp boundary associated with a change in rock fabric. The possible cause for such developed surface is related to a possible change in metamorphism process.	
Layering	 Well A-01 at 2102.0 – 2104.5 m	Planar or irregular layering surface as well as dark colored (conductive) features used as an indicator of structural dip. The very steep rock fabric within the meta-sediment sequence is interpreted to be representing banding/foliation. Possible banded marble.	

Figure 9 CMI classification and symbols for interpretation used in this study.

matrix (and so will appear dark on the image). Fractures that are mineralized with a more resistive mineral such as quartz and calcite will be resistive and show light as colors along the fracture trace on images log and suggest a closed fracture. In contrast, conductive or low resistivity fractures will show as a darker color because of mud fill in the crack and it usually has higher angle or is different than the foliation or other features of the metamorphic layers.

The results of the reinterpreted data with respect to fracture orientation are illustrated as rose diagrams (Figure 10). Overall fractures interpretations done in this study in well A-01 comprise a total 193 data points. The major fracture orientation in well A-01 define a NNE-SSW strike trend with mean 354°, with NW-SE as a minor trend (Figure 10a). Resistive fractures were strike trend with mean 22° (Figure 10b). The conductive fractures were identified by 189 data points and show a major fracture orientation that is a NNE-SSW strike trend with mean 353° and NW-SE is a minor trend (Figure 10c). The conductive fractures were identified by 189 data points and show a major fracture orientation that is a NNE-SSW strike trend with mean 353° and NW-SE is a minor trend (Figure 10c). This major trend corresponds to structural trend of Suphanburi basin which show an overall N-S trend and in the western part of the basin are controlled by an east dipping low-angle fault system. When compared to the fracture trend measured from calcite veins, joints and fractures in outcrop (Bunpitaksakul, 2016) the outcrop shows a major NW-SE trend direction with a 321° mean strike. This is similar to the minor fracture trend in this subsurface study (Figure 11). However, outcrop also has NE-SW trend but there is a limitation of outcrops of walls in the quarries with appropriate orientations to see this fracture intersection, therefore there is a relative lack of data points in the quarries allowing measurement of a NE-SW trend.

To better compare image log and core observations, the CMI interval 1855.0 – 2524.0 mTMD and 19 core plug description and photos from well A-02 were integrated with the current CMI study in well A-0. Well A-02 is approximately 500 m distant from well A-01. A core plug collected at 1890.5 m in Well A-02 is described as a likely fault breccia (medium to dark grey, medium brown, grey, clear quartz grained, transparent-translucent, medium to coarse grained, pebble, angular to sub-angular, sub-spherical to spherical, poorly sorted, argillaceous matrix, calcareous cement, hard, poor visible porosity, moderately to strong calcareous) CMI from this depth is similar to that seen in well A-01 at 2190.0 – 2220.0 mTMD interval. In addition; microscale-textures in cuttings from this depth in well A-01 show recrystallized calcite which might be caused by both wells drilling through a major fault (Figure 12). At a depth of 2190 m in well A-02 the core plug lithology was described as marble (predominantly milky white, off white, occasionally very pale orange, predominantly moderate hard to hard, occasionally brittle, predominantly sub-blocky to blocky, sub-platy, occasionally recrystallized to form marble, moderately to strong calcareous), Most of well A-01 shows similar CMI features to the CMI seen across the marble interval in well A-02 and microscale-texture of cuttings from marbles

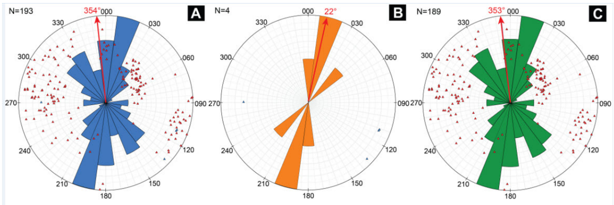


Figure 10 Strike Rose diagram (A) All fractures, shows a dominant NNE-SSW trend (354° mean strike) (B) Resistive fracture show NNE-SSW trend (22° mean strike) (C) Conductive fracture show NNE-SSW trend (353° mean strike)

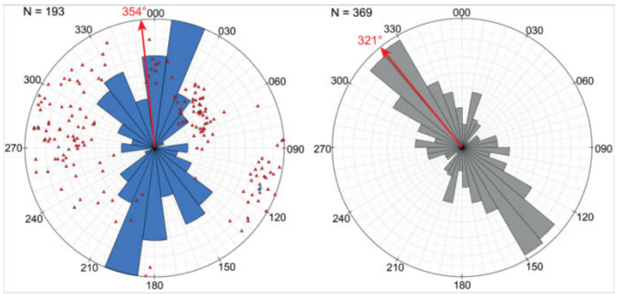


Figure 11 Strike rose diagram fractures of subsurface (left) and outcrop study (right; from Bunpitaksakul, 2016).

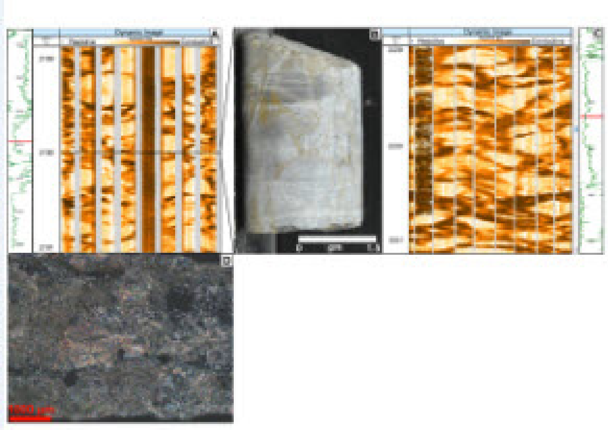


Figure 12 (A) Image log and (B) core plug photo showing fault breccia at 1890.5 m in well A-02, which are relevant to image log features in well A-01 (C) and (D) photomicrograph of cutting chips of 2190.0 – 2200.0 m interval in well a-01 showing recrystallized calcite crystals of a limestone clast.

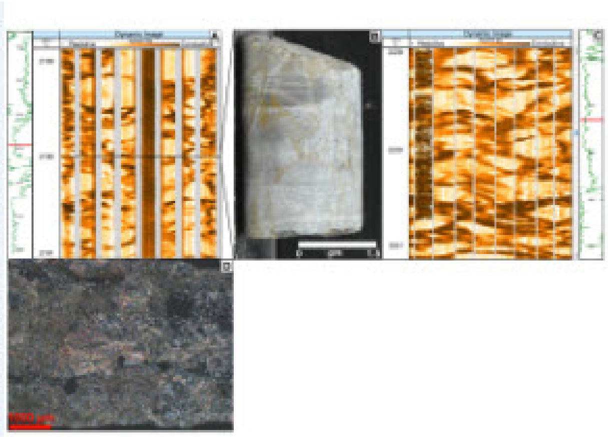


Figure 13 (A) Image log and (B) core plug photo showing recrystallized limestone or marble at 2190.0 m in well A-02 which are relevant to image log features in well A-01 (C) and (D) photomicrograph of cutting chips of 2220.0 – 2230.0 m interval in well A-01 showing recrystallized crystals of calcite and metamorphic foliation typical of marble.

in well A-01 show recrystallized crystals of calcite and foliated textures indicative of metamorphosed carbonate (Figure 13).

6. Stable Isotope Analysis

The twelve lithotypes of cutting samples were classified into rock types as various marbles and grouped into five lithotypes, based on microscale-texture, mineral composition, CMI features and C-O stable isotope result. Outcrops were compared to subsurface study results, including rock crush characteristics from outcrop samples used to compare to cutting samples.

There are three obvious plot fields in the stable isotope values collected in this study. When overlaid with stable isotope data measured in outcrop five plotfields can be seen (Figures 14 and 15). In Figure 14 the designations a – g in the various plotfieds correspond to the designated descriptions in Figures 4 – 7.

When subsurface C-O plots are tied back to rock types seen in cuttings there are three obvious covariant trends (Figure 14) The first trend, made up of few samples of crystalline calcite have -7 to -9 $\delta^{18}O$ values along with +3 to +4 $\delta^{13}C$ values (shaded green in Figure 14). This interval indicates contamination of the metamorphic matrix by the entry of very early telogenetic fluid, driven by the Paleogene event (Bunpitaksakul, 2016). These oxygen isotope values indicate temperatures that cooler, are not metamorphic and do not lie on the main meteoric mixing trend (shaded yellow in Figure 14). They are tentatively interpreted as having negative carbon values from bicarbonate that has experienced catagenesis or methanogenesis.

The second trend, encompassing most of the cuttings samples including calcite, quartz and matrix all have oxygen values more negative than -12‰ $\delta^{18}O$ and range from -13 to -23‰. These values C-O plot with $\delta^{13}C$ values ranging from -5 to +2‰. The oxygen values lie well to the left of an oxygen value of -12‰ considered to define the point in fluid–exchange temperature burial curves that defines the end of rock matrix fluid exchange in the passive margin burial realm in central Thailand (Warren et al., 2016; Warren et al., 2014). The increasingly negative oxygen values from -7 to -23 $\delta^{18}O$ represent increasing thermal evolution of the basement and relate to intense metamorphism in orogenesis. Overall, this covariant plot field show the fractured basement carbonate rock in study area was already been metamorphosed to marble during the late mesogenesis stage. This will be discussed further when these results are compared with isotopes values from the outcrop study of Bunpitaksakul (2016).

The third trend (colored purple), is defined by only two samples, with carbon values around -25‰ on the δ13C axis, along with increased δ18O values (-12 to -13‰) compared to the typical marble. Compared to marble, it indicates a calcite precipitated at some time after the Shan Thai block and Indosinian block collided. It is perhaps tied to the entry of organic-entraining (catagenic) fluids or hydrocarbons. This signature was not recognised in the work of Bunpitaksakul (2016).

7. Is the Subsureface Isotope Result Related to the Outcrop Isotope Result?

From the integrated data rock typing, thin sections of cutting chips are now interpreted as mostly marble in well A-01 and are very similar to marbles sampled in outcrop study by Bunpitaksakul (2016). A comparison of C-O isotope plot between subsurface data and outcrop data of Suphanburi basin is illustrated as Figure 15.

Overall, isotope results from the two regions show considerable overlap and most plot points relate to calcites crystallized in the metamorphic realm. But the C-O plot field from outcrop samples show better definition of two plot fields not obvious in Figure 14 There is an additional high temperature field with $\delta^{18}O$ values ranging up to -31‰ (shaded pink) and a yellow shaded plot field defined by a meteoric mixing curve with a lower set of $\delta^{13}C$ values around -10‰ measured in speleothems.

The more negative oxygen values in outcrop (pink shade) are indicative of higher thermal rock fluid evolution. Many of the samples from outcrop that have the most negative oxygen value were taken from narrow calcite and quartzose vein fills that constitute less than 0.0001% of the rock volume in the exposed quarry area (Figure 12b). These vein fills are tentatively interpreted as out-of-sequence hydrothermal fluids, with fluid entry perhaps related to the movement of the Three Pagoda and Mae Ping faults (Nazrul, 2015; Bunpitaksakul, 2016). The likelihood of sampling these high-temperature calcite veins in a set of cuttings is very low. So, these more negative values are not seen in subsurface data set. Rather, the more volumetrically significant marble values overlap well between the subsurface and outcrop data plotfields; most of them occupy the $\delta^{18}O$ value range -13 to -23‰, which is expected as sample come from similar metamorphic terrains in both outcrop and the subsurface, perhaps with a slight higher metamorphic grade in the outcrops west of the subsurface study area.

There is a distinct meteoric-mixing trajectory in the outcrop (shaded yellow and defined by Bunpitaksakul, 2016). Only two data values from the subsurface plot in this field, so it is not so obvious in the subsurface dataset (Figure 15). The yellow plotfield encompasses calcite cements formed in later uplift from shallow meteoric fluids that are relatively cool (more positive oxygen) with significant soil gas (negative carbon) (outline by purple shaded polygon in Figure 15).

Both the yellow and purple shaded plot fields encompass isotope values that are considered related to fluid entry driven by the Paleogene event, with the dominant meteoric uplift trend (shaded yellow) showing dominantly negative $\delta^{13}C$ value down to -10‰, along a range of $\delta^{18}O$ values from -7 to -13‰ and representing shallow phreatic meteoric mixing. Without more isotopic study of the hydrocarbon emplacement timing and modes of source rock the catagenic separation for the two most negative carbon values (purple shading) in the dataset can only be inferred not proved.

8. Broader Comparison to Other Fractured Basement Carbonate Reservoirs in Thailand

This section compares Suphanburi data with data from Phuhorm field, which is located in the western part of the Khorat Plateau basin, between Kon Kaen and Udon Thani provinces, north-eastern Thailand, at the northern edge of the Indochina block. The fracture analysis from image logs in Phuhorm shows the same major fracture orientation, namely a NE-SW direction (Promsen, 2016). This may be related to regional tectonic evolution of Thailand; i.e., the Shan Thai block and the Indosinian block are convergent

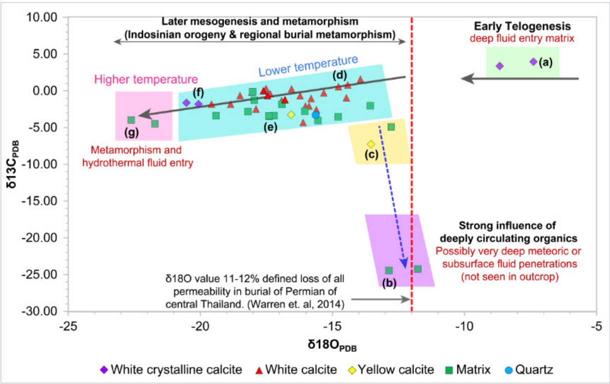


Figure 14 Carbon-Oxygen stable isotope cross plot integrating the sample classification well A-01. It integrates all available data and defines three main trends dominated by temperatures related to calcite crystals formed in the metamorphism stage; the green polygon is a cooler trend related to fluid contamination, light blue indicates the elevated temperature of late mesogenetic (metamorphic) stage and the purple polygon indicates catagenic fluids. The descriptors (a-g) relate to petrographic analysis illustrated in figures 8-11.

and their collision caused a widespread clockwise rotation of Southeast Asia during the late Paleozoic-early Mesozoic. This resulted in N-S trending half grabens or graben rift basin and a NE-SW array of fault splays over much of Thailand. The Khorat Plateau forms a part of the Indochina plate and is bounded by major Tertiary strike-slip faults. It contains two fold belts; the N-S trending Loei-Phetchabun fold belt in the western area and NW-SE trending Phu Phan range in the central part (Glumglomjit, 2010).

Most of oxygen isotope values from Phuhorm field show values less negative than -12‰ (Promsen, 2016). Oxygen values from Suphanburi field are far more negative than in the Phuhorm field, as it has rock textures that are metamorphic. The Permian limestone and dolomite basement reservoirs of Phuhorm field are not metamorphosed, yet show the same Paleogene overprint as seen in the Suphanburi basement carbonates.

9. Conclusions

The fractured carbonate reservoir of well A-01 has been metamorphosed to a marble and shows metamorphic lithotypes very similar to mylonitic marbles seen in outcrop located some 10 km west of well A-01. The major fracture trend is NNE-SSW in the well and is considered to indicate responses to the stress field created by the Himalayan (Paleogene) event, driven by the collision of India with Eurasia. A similar NNE-SSW trend is seen as the minor fracture trend, measured from calcite veins, joints and fractures, in the nearby outcrop study of Bunpitaksakul (2016).

In addition, comparison of microscale-textures from thin section analysis of cuttings from the well A-01 and associated stable isotope plotfields show both subsurface data and outcrop data outline the same thermal regime for the marbles and ties to the regional metamorphic realm. But outcrop data also show hot out-of-sequence hydrothermal fluids in rare calcite meshwork veins that crosscut the outcrops of high grade metamorphics (late mesogenetic stage rocks). These hot vein fills are thought to be related to the deeply penetrating Paleogene movement of the Three Pagoda fault system. Similar calcites were not sampled in the cuttings collected in this, but are thought to be present in the subsurface, but at such low levels (<0.0001% of rock volume in outcrop) they were not captured in any of the isotope 50 analyses run for this report.

The Paleogene event overprint in the subsurface of the Suphanburi basin is defined by the NNE-SSW fracture trend mapped in CMI and two isotope trends in cutting. Both isotope trends are related to fluid cooling and meteoric mixing, driven by ongoing uplift and increasing exposure to meteoric waters. One isotope trend indicates a stronger catagenic signal in very early stage of uplift and meteoric influence (possibly from oxidised organic matter in graphitic schists or deep methanogenesis). The other uplift-related isotope trend overlaps similar measurement in speleothem-influenced samples from outcrop (Bunpitaksakul, 2016). It indicates a cooling trend in the oxygen values, tied to somewhat less negative carbon isotope values, and represents shallow meteoric mixing in the presence of bicarbonate influenced by soil gas.

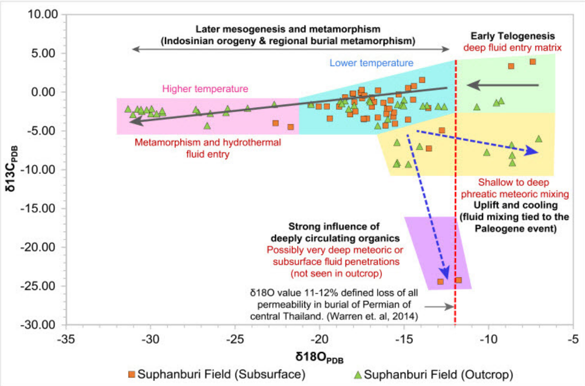


Figure 15 Carbon-Oxygen stable isotope crossplot combining subsurface data (this study) and outcrop data (Bunpitaksakul, 2016) shows that most of subsurface plot points define the late mesogenesis (metamorphic) stage (indicated by light blue polygon). Some of outcrop data also shows much more negative oxygen values indicative of much higher temperatures from samples typically captured in late stage vein cements. These more negative values are indicative of "out-of-sequence" hydrothermal fluid entry (pink polygon; Bunpitaksakul, 2016). There are two other trends, both showing more negative carbon values. One is only seen in the subsurface data and likely indicates a stronger catagenic or organic matter influence in very early stage of meteoric influence. It possibly comes from oxidised organic matter in graphitic schists or deep methanogenesis (purple polygon). The other plot field is characterized by somewhat less negative carbon isotope values from calcites precipitated from shallower meteoric waters (yellow polygon). This meteoric trend is much more obvious in outcrop where speleothem-influenced regions can be identified and directly sampled. The plot region indicated by green shading is thought to relate to fluid contamination of marble with calcites precipitated from fluids entering in the very early stage of uplift driven by the Paleogene event.

A combination of isotope and CMI analysis shows that matrix porosity and permeability is not present in the metamorphic carbonates sampled by well A-01. Rather, there are two possibilities for hydrocarbon storage in those parts of the sequence where isotope signatures in cuttings indicate a predominance of metamorphics in the well, namely; 1) fractures crosscutting a metamorphic marble host, in this situation there is little or no matrix storage, 2) Interclast storage hydrocarbon in a metamorphic-lithoclast breccia (located at the base of the Tertiary section). Type 2 storage occurs between eroded carbonate clasts, it is a type of sedimentary deposit likely near fault scarps and would have derived from erosion of uplifted metamorphic basement and been deposited in the early stage rift stage basin edge sediments. Type 2 likely has greater storage volumes per unit rock volume compared to type 1. Therefore, lithoclast breccia intervals are the more interesting carbonate reservoir target and would tend to occur in down-dip proximity to basement cutting faults. Hydraulic fracturing in directional wells, drilled orthogonal to the Paleogene fracture trend (NNE-SSW) would likely improve recovery levels in Type 1) reservoir.

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