DEPOSITIONAL AND DIAGENETIC CHARACTER OF CARBONATE SEDIMENTS AT THE LEVEL OF A BASEMENT HIGH, OFFSHORE THAILAND: A NEW EXPLORATION PARADIGM FOR THE REGION?

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Abstract

Is it possible to have a Tertiary-age carbonate reservoir in the Pattani Basin? This has long been an unanswered question. Especially when it is compared to other Tertiary Basins in similar tectonic settings across South East Asia, where there are many producing fields hosted in Tertiary reef limestones. So, this question was thought to have been finally answered, when a subsurface section that encompassed sediments above a basement high in the central Pattani Basin, Gulf of Thailand, was shown to 1) possess massive limestone characteristics in wireline logs and, 2) was located in a region where 2D seismic indicate geometries similar to that of a carbonate build-up. However, both seismic and wireline are indirect methods; the final answer is thought to lie in an advanced analysis of drill cuttings selected from a number of wells in the area. An analysis of the stable $\delta^{13}C$ - $\delta^{18}O$ isotope signatures of the cuttings, tied to a detailed petrographic and XRD study of the same chips, shows that the "reef-like" feature is not a Tertiary-age carbonate buildup. Rather, the drill cuttings show the two distinct diagenetic types linked to; 1) a basement section or 2) an overlying section. The basement section, including the distinctive reef-like feature, is a complex lithology responding to variable hydrothermal diagenesis in heavily-cemented calcareous (calcite - ferroan dolomite) mosaic of Permian siliciclastics and dolomitic-limestones. The isotope signatures in the basement complex indicate a number of these basement lithologies experienced a similar burial diagenetic intensity (and thermal evolution) to onshore outcrops of Ratburi limestone. Moreover, the $\delta^{13}C$ - $\delta^{18}O$ isotope signature in the carbonate-cemented siliciclastics in overlying Lower Miocene section show two diagenetic responses: 1) siliciclastic cements produced in a shallow burial sulfate-reducing environment, 2) Carbonate lithoclasts retaining the burial signature of their Permian precursor. It seems conditions in the Pattani Basin never allowed marine reef formers to flourish. Isotope signatures in the basement indicate a potential for fracture and karst reservoir formation during the Oligocene syn-rift stage. Then there were places where the basement high was subaerially exposed and fault conduits could carry undersaturated meteoric waters into the carbonates, so generating zones of enhanced secondary porosity.

Keywords: stable $\delta^{13}C$ - $\delta^{18}O$ isotope, basement high, Pattani basin, the Gulf of Thailand

1. Introduction

Carbonate reservoirs in the South East Asia (SE Asia) are found in many countries and host numerous economic accumulations of hydrocarbons. These carbonate reservoirs can be classified by two endmembers; first is Paleozoic fractured limestone and second is the Tertiary carbonate buildups.

When focusing at the basement high structure in the central part Pattani basin, it was found the interesting features located below the main production intervals. These lower zones have a distinct wireline character and in seismic can show outlines similar to that of a carbonate build-up (Figure 1)Based on these new observations, this study will test the nature of these anomalous features and so can perhaps define a new hydrocarbon play type for the Gulf of Thailand.

Unfortunately, at the time the relevant wells were drilled, the hydrocarbon potential in this near-basement section was not recognized, so we lack core data and other helpful information that would be useful in better testing of a carbonate model. We also have to deal with vagueness and unresolved contrasts in current interpretations of depositional environment below the main production interval.Consequently, improved well cutting classification, XRD determinations, C-O isotope values, and reinterpretation of wireline log information are the keys to any improved understanding of the depositional and diagenetic environment in these deeper settings and in evaluating play type for the region.

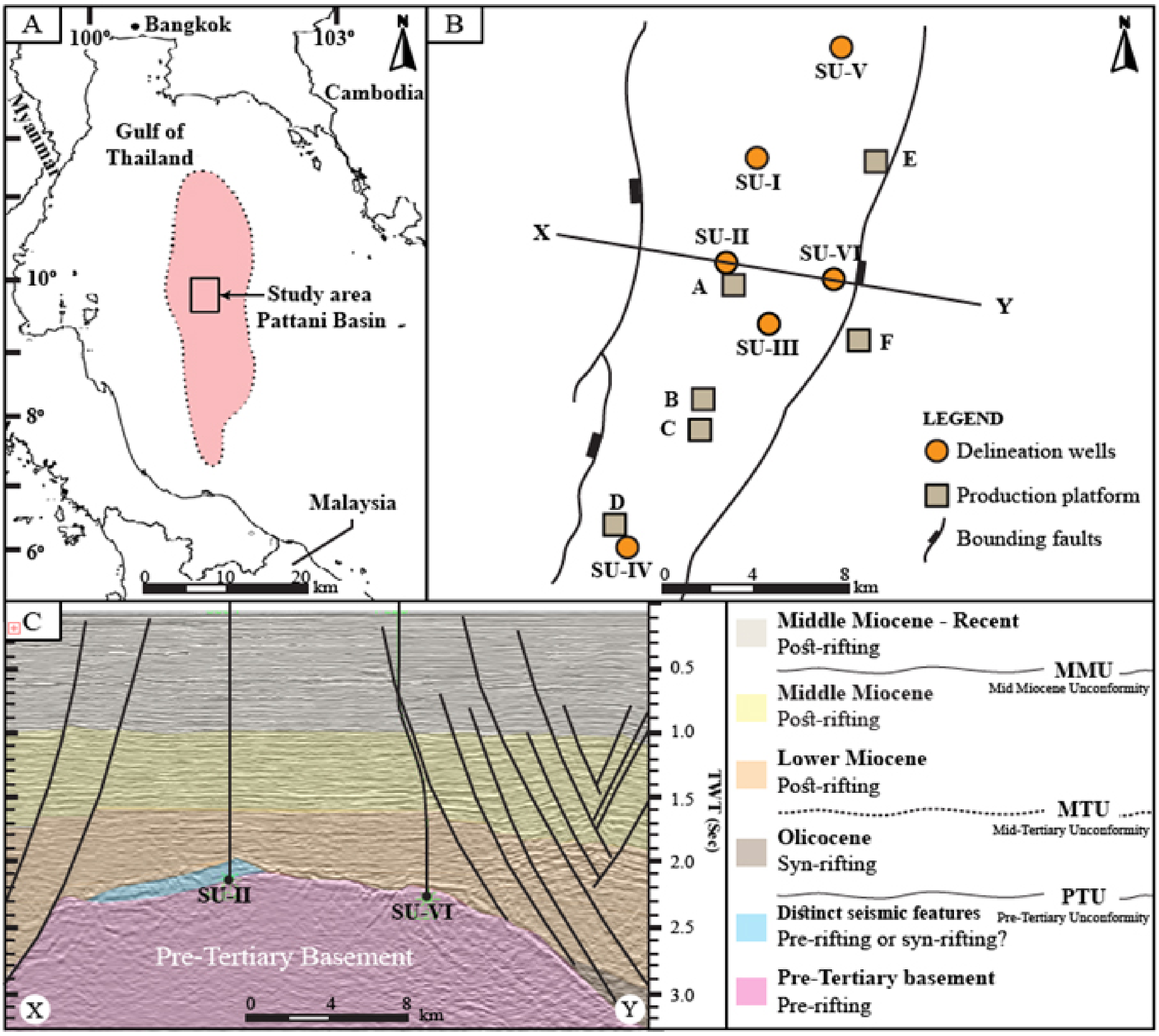

Figure 1: A) Basement high area, central part of the Pattani basin, Gulf of Thailand. B) Well location, bounding faults and horst structure. C) West-East cross-section of study area with stratigraphic overlay showing a reef-like build-up (in blue).

2.1 Lithological study via wireline logging

The wireline log data over the section of interest covers six delineation wells and seventy-six development wells. Wireline log data consists of triple combo logging, which will be used for depositional and diagenetic interpretation, along with the supplemental data (including a number of relevant seismic lines). Overall the study area is mostly siliciclastics deposited as a flat-bedded stratigraphy during the upper part of the Lower Miocene to Middle Miocene.

In a number of the studied wells the various wireline trends, crossplots and overlays suggest intervals with tight carbonate features composed of limestone and dolomite that are distinct from the more typical signatures in the overlying siliciclastic section. Wireline indicators of a carbonate section include; 1) the blocky shape of low gamma ray (25 - 47 API), 2) high resistivity (200 -2000 ohm.m), 3) high bulk density (2.7 - 3.0 g/cc), and 4) low neutron porosity (1 - 7 % neutron porosity)

These combinations are found near the bottom parts of wells SU-II, SU-IV, B-01, B-03 and A-07. Limestone-indicative features are displayed by a combination of low gamma ray and narrow positive crossover between the neutron and density logs, while the dolomite features are displayed in wider negative crossovers between neutron and density logs, as a result of the higher specific gravity of dolomite.

From log shapes, crossovers and cross-plot the zones with carbonate-dominant features are low to non-porous based on sonic and neutron porosity logs. These carbonate features are best developed in the middle and eastern side of the basement high, within a N-S trend in study area. Seismic and correlation panels illustrate these distinct carbonate features, comprising three different zones northern (SU-I, SU-II and A-09), central (B-01, B-02 and B-03) and southern (SU-IV and D-07).

For the overlying section in the upper part of Lower Miocene, previous studies of core prove it as a nonmarine deposit, fluvial - alluvial fan, associated with occasional marine transgressive influence and marginal marine – estuarine deposits (Champasa, 2015).

2.2. Petrographic study

The petrographic samples focused on carbonate features that were selected from six wells considered representative of the carbonate intervals, as defined by wireline logging data. The cutting sample intervals used in the study were collected at a standard 30 feet (9.14 meters) spacing, and prior to examination for this study were treated by the wash and dry method. All samples were classified under a binocular microscope, then thin-sections were prepared from cuttings and half-stained with Alizarin Red (ARS) and Potassium Ferricyanide (PF). This better identified the variety of carbonate minerals in the thin sections so giving a better

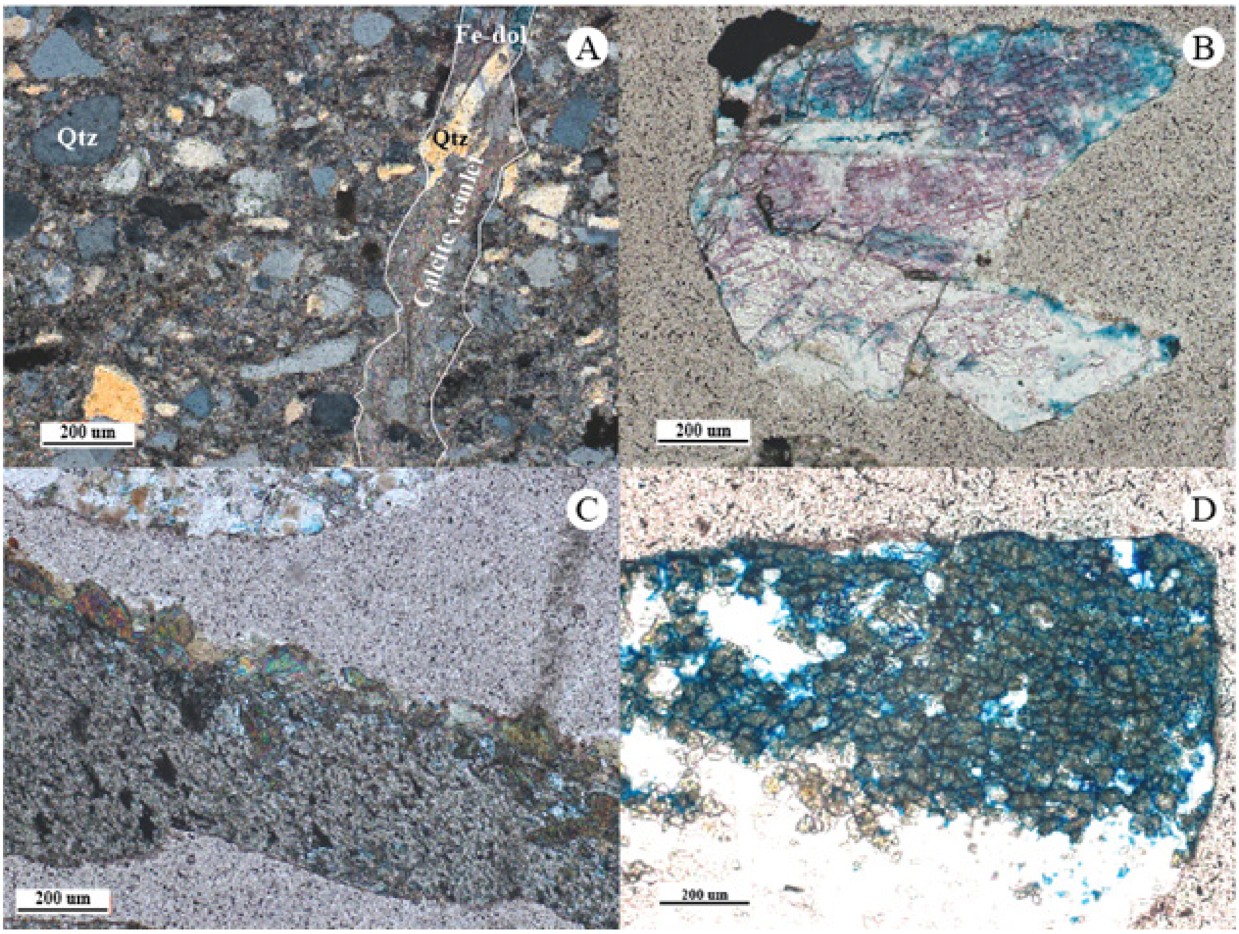

Figure 2 A) SU-II: CPL Calcareous sandstone with calcite veinlet developed along fracture. B) SU-II: PPL One single grain chip show evidence of calcite (pink) - ferroan dolomite (blue turquoise) spar with subeuhedral texture. C) SU-II: CPL Nonplanar - cement showing saddle ferroan-dolomite crystal growth on the calcareous mudstone surface indicate minimum burial temperature of 60-80°C. D) SU-IV: PPL: Planar crystal dolomite (Euhedral -subeuhedral) indicate growth temperature below 50°C

understanding of the relationships between diagenetic processes and stable C-O isotope values.

Thin sections from well SU-II, which has classic limestone features in its wireline character, is actually made of calcareous and dolomitic cement in a compacted quartzose sandstone overprinted by late stage saddle ferroan dolomite cements (Figure 2C). Saddle dolomites cements in the fractures in this siliciclastic lithology (sandstone - mudstone size) indicate the minimum burial temperature 60o - 80oC (Sibley and Gregg, 1987). Carbonate cements occur in intergranular positions between compacted quartz grain as well as being developed as vein or veinlet infilling in fractures (Figure 2A). The latter represent hotter fluid temperatures in later stages burial diagenesis and likely damaged any remaining reservoir quality. On the other hand, some of the southern wells (C-30, SU-IV) show evidence of lower temperatures in the form of mosaic carbonate textures, along with euhedral crystals of ferroan-dolomite (Figure 2D). This combination may indicate the final product of dissolution-surface dolomitization (Woody et al., 1996).

Not only were calcareous cements in sandstones seen in the cutting chips, sparry crystals of limestone or dolomitic-limestone (Fig 2B) were present, these may indicate the presence of carbonate nodule or carbonate vugs.

Unlike core, cutting samples are collected on the rig floor from circulating drill mud. This leads to high uncertainty in the exact depth interval, due to mixing with chip samples from above as the mud returns to the surface. Hence the difficulty is classifying the actual lithology and texture at a particular depth from cutting chips. Overall, at a broader scale, cutting chips do generally correspond to the wireline character and so it is possible to interpret a low porosity dolomitic-limestone and cemented compacted sandstone with calcite, dolomite and ferroan dolomite cements and fractures in the interval of anomalous wireline character in the vicinity of the basement unconformity.

In summary, based on the observed thin sections of cuttings, the lithology atop the basement high in central of Pattani Basin encompasses calcareous cemented sandstone and dolomitic-limestone, which vary in lithology and diagenetic intensity from area to area. There was no petrographic evidence of a Tertiary reef or carbonate build-up above the basement high.

2.3 Mineral analysis via XRD

The XRD samples are selected by drill chip picking in each interval to study whole-rock associated mineralogy in each interval. Chips were sorted then crushed into appropriate sample powders and then analyzed by the XRD. XRD results outline three general mineral groups, carbonate, siliciclastic and metamorphic rock

The carbonate group includes calcite, dolomite, ferroan dolomite and siderite. This mineral group is common as a trace or accessory mineral assemblage in the overlying siliciclastic section (Lower Miocene), but is dominant or co-dominant in the vicinity of the basement unconformity. Siderite, which is often an early diagenetic nodule cement in the early stage of diagenesis, only occurs in the section above the basement unconformity.

The siliciclastic group includes quartz, clay mineral mixtures (kaolinite, illite, montmorillonite) and/or muscovite. This mineral group dominates in almost all sections (both overlying & basement sections) and is dispersed across the whole study area.

The igneous group includes; quartz, potassium feldspar, plagioclase feldspar, amphibole, clinopyroxene, chlorite and/or muscovite. This mineral group (excluding quartz) is present only as trace or accessory minerals, except in some specific intervals in the lower parts of well SU-II

Based on XRD results, the study area is dominated by the siliciclastic mineral association. The carbonate mineral association occurs as cements in the section above the basement and some areas of basement. Carbonates are generally trace or accessory mineral in shallow section, these are the intervals with strong evidences of siliciclastics in the wireline logs. The basement section of well SU-II, which is quartz dominated and

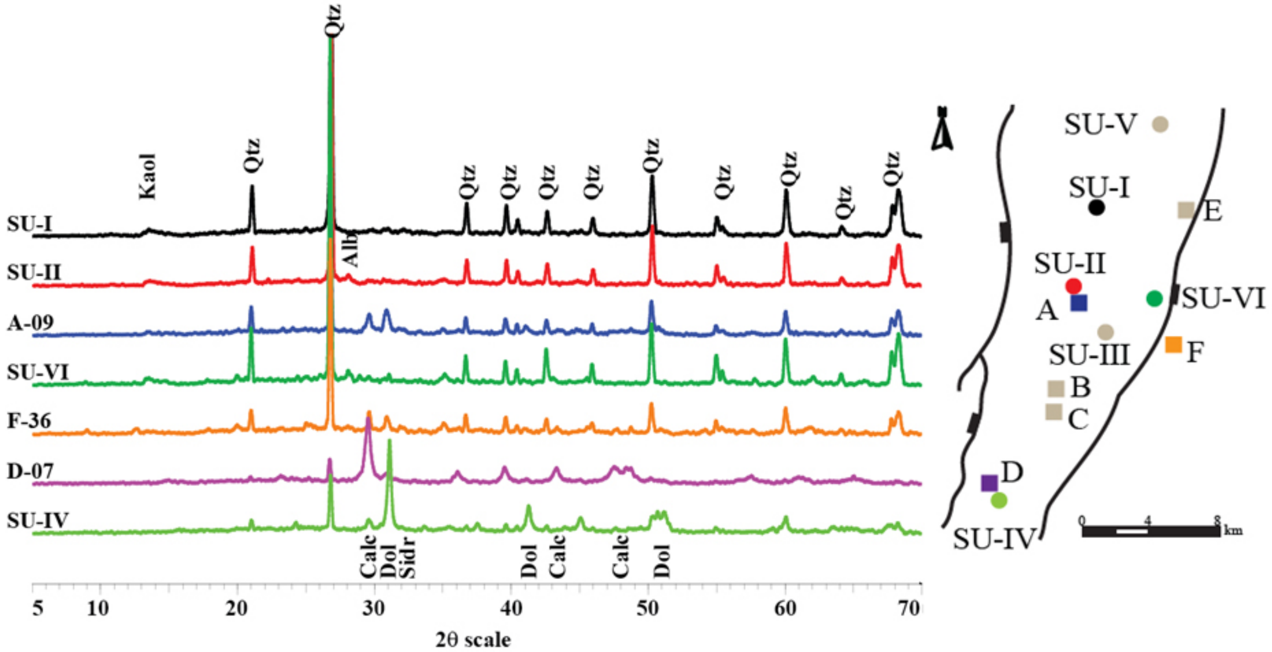

Figure 3 Relative minerals component XRD results from North to South wells [Kaol: Kaolinite, Qtz: Quartz, Alb: Albite, Calc: Calcite, Dol: Dolomite, Sidr: Siderite]

co-dominated with calcite - dolomite. This mineralogy supports the calcareous sandstone character of the chips seen in the petrographic study, yet the interval in wireline show as the overlay character (neutron density) of a pure limestone section in the wireline log.

On the other hand, the lowest part of well SU-II, which is interpreted as igneous or metamorphic rock in the XRD result and the mud logging report, shows distinctive reef-like seismic features (Figure 1C). Clearly, there is no Tertiary reef in this position. Basement lithologies in this area are structurally complex with a combination of dipping calcareous sandstones and a mosaic of igneous or metamorphic lithologies that vary in both depth and area.

Although, calcite and dolomite are now proved as an associated mineralogical grouping in the vicinity of the basement unconformity, the presence of this grouping generally indicates cements and is not indicative of a pure carbonate phase in most of the samples. But in wells SU-IV and D-07, it is the dominant mineral association and it corresponds the limestone or dolomite interval based on wireline log interpretation. Thus, it may represent the local presence of a near-pure carbonate basement lithology (Permian limestone or a marble). The conclusion must be that there are a variety of rock types ranging from carbonates to carbonate-cemented sandstones to metamorphics and igneous rocks in basement in the study area.

2.4 Stable C-O isotope (δ13CPDB - δ^{18}OPDB)

δ^{18}O and δ^{13}C isotopes were analyzed in terms of relative burial temperature and organic content, respectively. The carbonate samples were prepared from drilled cuttings from eleven wells. Based on color, texture, lithology and intensity of reaction with dilute HCl acid, the samples were classified into five groups; 1) Black dolomitic-limestone fragments (DLF), 2) Black streaky limestone (BSL), 3) Calcareous cemented siltstone (Calc ST), 4) Calcareous cemented shale and (Calc SH) 5) Crystalline calcite (CC)

Based on δ^{13}C - δ^{18}O isotope plotfields and trends, two separate diagenetic pathways are seen, which separate C-O values of the cuttings collected 1) in the overlying section and 2) basement section (Figure 4). The two trends are

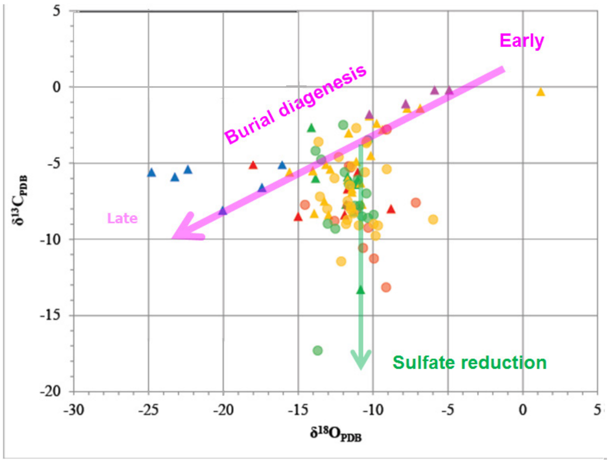

Figure 4 stable δ^{13}C and δ^{18}O isotope crossplot shows two different trends between samples from overlying section and the basement section. ○ : Overlying section, △ : Basement section, ■ :DLS, ■ :BSL, ■ :CC, ■ :Calc ST, ■ :Calc SH]

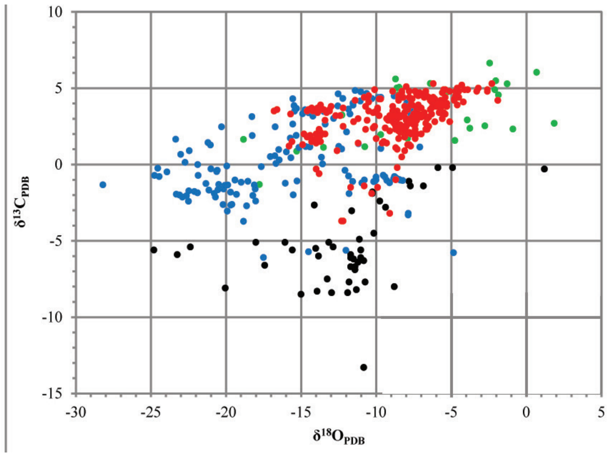

Figure 5 δ^{13}C and δ18O isotopes relationships among of the Central Pattani basin basement, black; Saraburi Permian limestone (Central of Thailand), red; Ratburi Permian limestone (Nang Nuan field), green; and Ratburi Permian limestone (Western of Thailand), blue.

now analyzed. The majority of the lithological textures in the basement section are BSL, Calc SH and CC; of which limestone (BSL), dolomitic limestone fragments (DLF) and calcite (CC) are likely to be found in a variety of carbonate lithologies, while the calcareous shale (Calc SH) are likely in shaly limestone or calcareous cements in siliciclastic lithologies. In contrast, cuttings samples from the overlying section are dominated by Calc ST, Calc SH and DLF, the first two of which are varieties of calcareous cements related to calcareous siliciclastics, while the dolomitic limestone (DLF) are related to eroded and reworked fragments (lithoclasts) from outcrops of the basement bedrock.

The basement section's δ^{13}C - δ^{18}O isotope trend is represented by increasingly negative value of δ^{18}O and δ^{13}C. The more negative δ^{18}O indicate higher temperature fluid precipitates from increasingly elevated temperatures of ongoing burial, while more negative δ^{13}C indicate a catagenetic or fresh water/meteoric influence (Warren, 2000). All these basement values plot far away from typical δ13C - δ18O values of Permian seawater (Veizer et al., 1999). This implies ongoing re-equilibration during burial Saraburi limestone (Figure 5), Indochina-block, onshore, central of Thailand (Warren et al., 2014). For a more regional comparison, Figure 5 also illustrates C-O values for Permian carbonate in Nang Nuan field, Ratburi limestone, Sibumasu block, offshore, Southern of Thailand (Lousuwan, 2005). Its burial trend parallels those established in the recent study of the Ratburi limestone (Figure 6), onshore, western of Thailand (Ng, 2017).

All these burial trends, including those from the basement samples of the present area are indicative of the high temperature burial association common to the sub-Tertiary basement across onshore and offshore Thailand. Elevated temperatures, postulated from dolomite textural evidence in basement cuttings (Woody et al., 1996) is supported by the isotope evidence. There is no evidence of a lower temperature trend that would be associated with burial of a Tertiary reef-like feature in the Pattani Basin.

Based on all observations, the basement section can interpreted as a hydrothermally-influenced burial diagenetic environment, with alteration taking place in a complex mix of lithologies made up of heavily-cemented calcareous sandstones (calcite and ferroan dolomite cements) and/or ferroan dolomitic-limestones (from petrographic study) which in a few specific areas is associated with igneous and metamorphic assemblages

The overlying section is represented by a

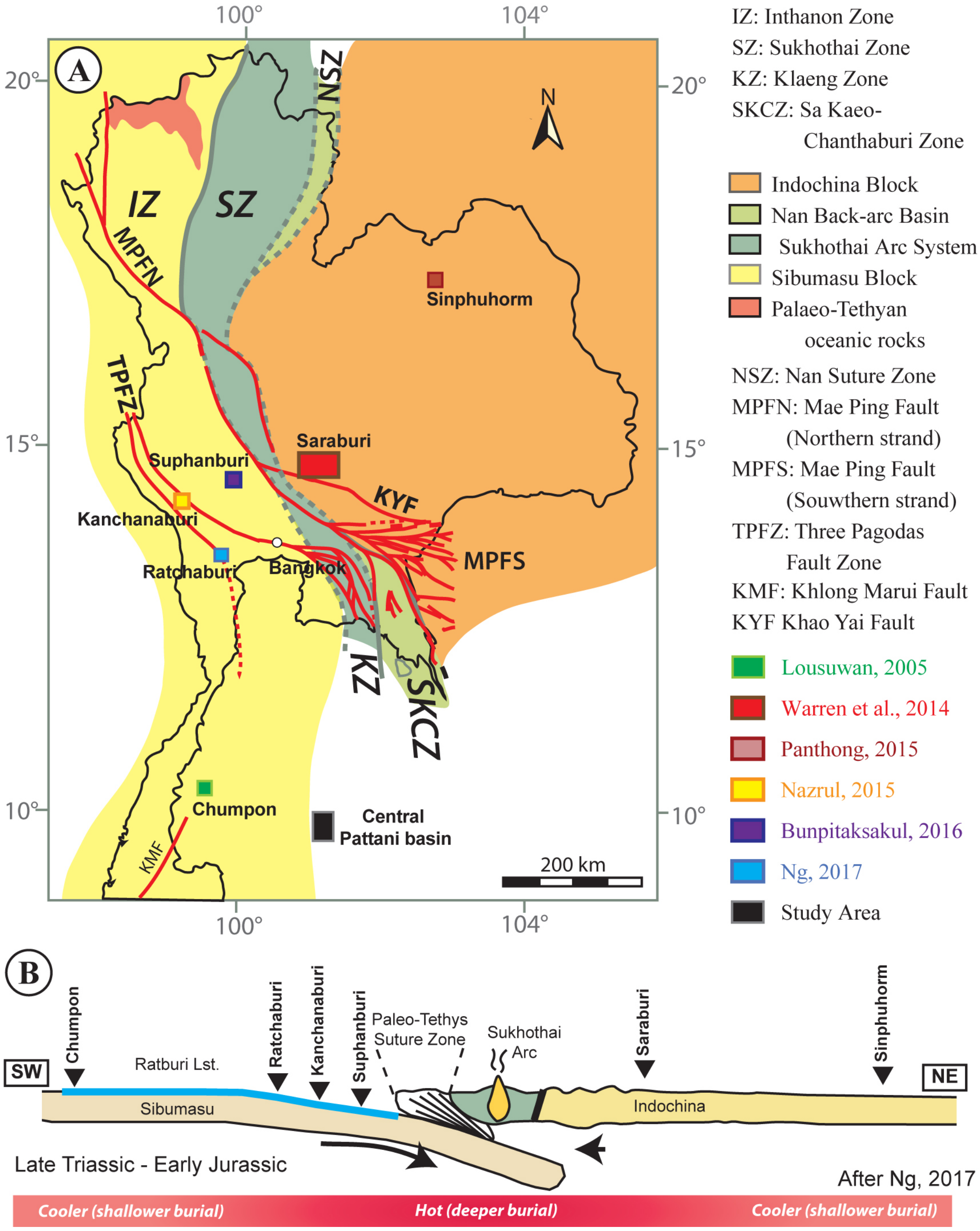

Figure 6 Tectonic setting of Thailand A) Tectono-sedimentary subdivisions of Thailand are made up of five main zones, which are: Sibumasu block, Inthanon zone, Sukhothai zone Nan back arc basin and Indochina block. (After Sone and Metcalfe, 2008; Ueno and Charoentitirat, 2011) B) Tectonic cross-section SW-NE; displayed relative intensity of burial diagenetic from $\delta^{13}C$ - $\delta^{18}O$ isotope study (After Ng, 2017)

relatively narrow range of $\delta^{18}O$ values (-6.0 to -14.5 %) and wider range of $\delta^{13}C$ (-2.5 to -17.3 %), together this displays in a C-O crossplot as a broad sub-vertical trend. Compared to the burial trend it is depleted in $\delta^{13}C$ values that are possibly indicative of related methane genesis from bacterial process, or a sulfate-reducing environment which can depleted $\delta^{13}C$ to values of -25% (Irwin et al., 1977). The latter interpretation is supported by occurrences of sulfurous coaly shale (Figure 7A) and defines anoxic conditions.

The $\delta^{13}C$ - $\delta^{18}O$ isotope crossplot in the overlying section overlaps the results of a previous core-based study of early diagenetic

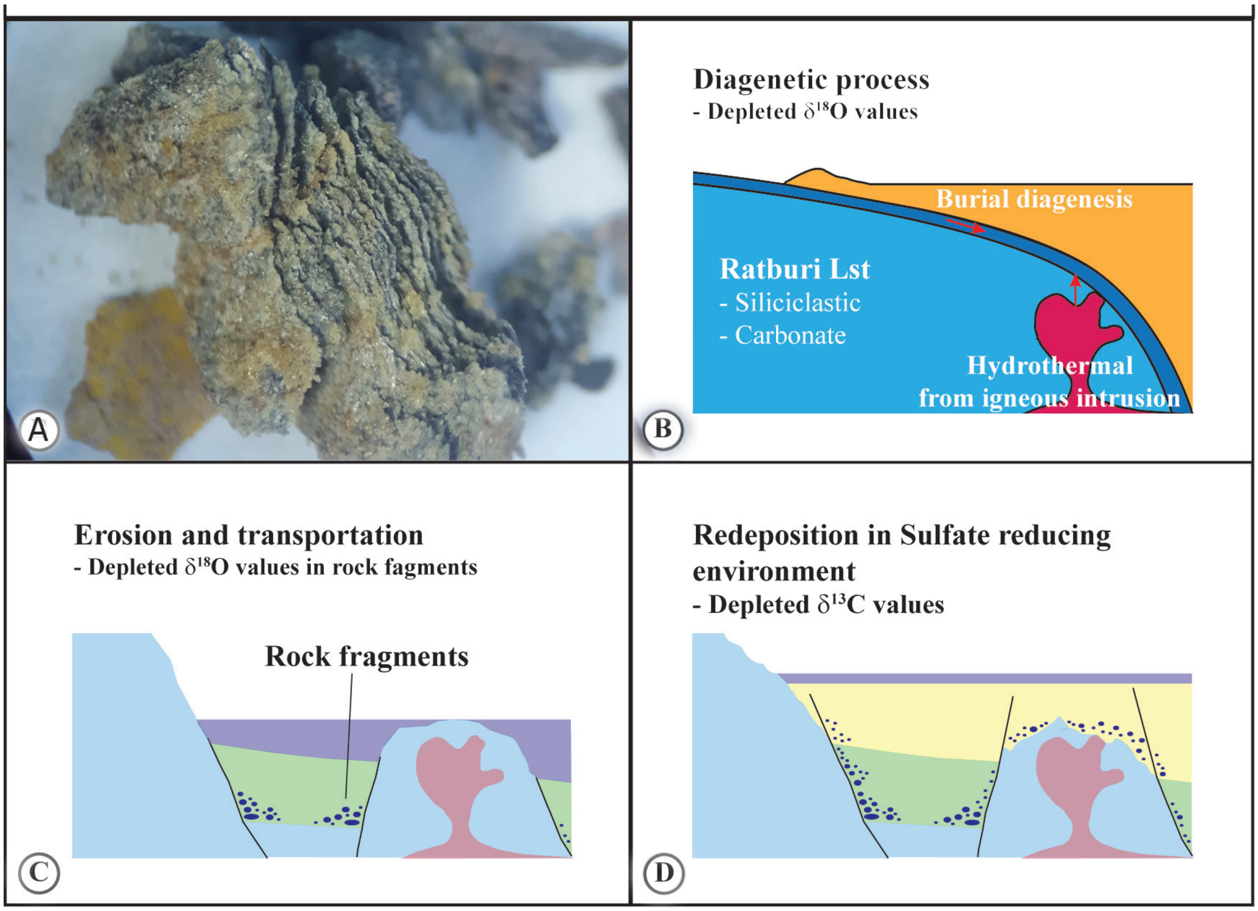

Figure 7 A) SU-II: Sulfurous coaly shale in cutting samples from $\delta^{13}C$ - $\delta^{18}O$ isotopes sampling interval. B-D) Hypothesized high temperature carbonate cements in fragments reworked from burial Permian limestone bedrock.

siderite and calcite nodules and cements in sands and clays of Lower Miocene section, in southern part of Pattani basin (Chokasut, 2005).

However, a separate set of carbonate samples coming from the overlying section plot in the burial trend plotfield, and there is some overlap between burial and sulfate reduction trends in the study area. Moreover, all of the isotope values in this present study showed more negative oxygen values than typical modern and Tertiary-age sulfate-reduction precipitates (Woo & Khim, 2006). These apparent isotope conflicts can be explained if the overlying setting interval contains cuttings from carbonate fragments (lithoclasts) reworked and eroded from bedrock outcrops that preserve burial diagenetic isotope signatures in the Permian detrital lithology.

Initially, the Permian bedrock complex was buried, or intruded by igneous material, and so preserved a high temperature signature. Then, the bedrock was exposed in the Tertiary drainage basin and eroded into rock fragments that were ultimately deposited in the basin. Even though it passed through a sulfate-reducing environment it retained its high temperature signature. So, the burial trend, as seen in a plot of some of the samples from the overlying section, is interpreted as coming from reworked carbonate rock fragments (lithoclasts) of Permian bedrock.

3. Conclusions

This present study shows that a proposed reef-like build-up in the Lower Miocene section is actually a variably eroded and weathered basement high. The basement is not pure carbonate high but a mosaic of heavily-cemented calcareous Permian sandstones and limestones/ dolomites, as well as igneous and metamorphic lithologies. So, this "reef" hypothesis is considered an example where a combination of the limits involved in wireline logging of low-porosity lithologies and 2-D seismic interpretation, can give a misleading interpretation.

It was not possible to test the validity of a “reef” hypothesis using either the seismic or the wireline method, as both are indirect or secondary approaches that are not based on actual rock property data. Only when the drill cuttings were sampled and studied beyond the initial level of description in the various well’s mud logs were the validity of the “reef” hypothesis tested and found to be wanting.

Results of the outcomes of the integration of wireline logs, petrographic study from cutting chips, mineral analysis by XRD, and $\delta^{13}C$ - $\delta^{18}O$ isotope data are summarized in Table 1

Conclusions based on this integration are:

1. Distinctive “reef-like” seismic features in the basement (SU-II) are actually an expression of the top eroded layers in the basement section, which is made up of a mosaic of heavily-cemented calcareous Permian sandstones and limestones/dolomites, as well as igneous and metamorphic lithologies

2. The evidences of a sulfate reduction environment and high siliciclastic sediment supply in Lower Miocene interval are not associated with a carbonate reef build. The Pattani is different from the other nearby Tertiary basins as in offshore Indonesia, Myanmar or Vietnam where reef structures do cap basement highs.

3. Stable $\delta^{13}C$ - $\delta^{18}O$ isotope analysis, using drill cuttings from a number of wells that intersect the basement, found two different diagenetic trends. One indicates a burial trend with temperatures in a mixture of Permian sediments that vary from south to north across the structure. The other indicates low temperature diagenetic nodule formation and carbonate cements in a matrix of fluvial and alluvial Tertiary-age siliciclastics. Offset of the two trends defines the position of the unconformity located between hydrothermally-altered calcareous sandstone in the Permian basement section and sulfate reduction cements of in siliciclastic making up the overlying section.

4. RECOMMENDATIONS

Base on the scope of this study, the following recommendations are made to improve the validity of future studies.

1. The use of stable $\delta^{13}C$ - $\delta^{18}O$ isotope analysis of drill chips are a cheap and reliable way to identify diagenetic history and some specific depositional environments. The same method has application in conventional core or side wall core made up of either carbonate-cemented sandstone, or pure carbonate.

2. Wireline log interpretations have limitations when used to separate lithology between a low-porosity heavily-cemented carbonate-rich siliciclastic and a typical limestone or dolomite. Separation requires the back-up of cuttings petrography under a microscope to verify the true lithologies.

3. Accuracy in cutting sample collection should be of concern as it is important when studying variations of $\delta^{13}C$ - $\delta^{18}O$ isotope values at a number of well depths and to better define the degree of possible mixing in a cuttings interval.

4. Consistency in cutting classification across wells is necessary, and so a sample of washed cuttings should be documented and photographed soon after collection

5. The stable $\delta^{13}C$ - $\delta^{18}O$ isotope samples should be submitted in sufficient quantity to control variations of $\delta^{13}C$ - $\delta^{18}O$ isotope versus depth, while sampling should also be done at an appropriate density across multiple wells to capture lateral variations.

6. In terms of geological exploration, a future study of the carbonate reservoir potential in the southern part of study area could be undertaken. It should be designed to give more detail about the timing and fluid migration in a region where it is likely the carbonate basement was exposed at surface during initial rifting through to the syn-rift stages. In such a setting meteoric water may have flowed along fault conduits and possibly generated telogenetic porosity.

Table 3 Summarized whole study and the final interpretation in each study sections.

Sections	Wireline logging	Petrography	Mineralogy	$\delta^{13}C_{PDB}$ - $\delta^{18}O_{PDB}$ isotope	Intepretations
Overlying section (Onlapping above the basement) *Lower Miocene*	**Siliciclastic** Sand - shale interval *Upper part of Lower Miocene* More shaling-upward sequences *Lower part of Lower Miocene* More sanding-upward sequences	-	**Siliciclastic minerals** Dominated: Quartz Associated: Clay minerals, Calcite, Dolomite, Siderite, Muscovite, etc.	**Reworked deposit of Permian rock fragmenets and recementation in sulfate reduction environment** High depleted $\delta^{18}O$ anomaly values in normal sulfate reduction environment trend (Irwin, 1977, Woo & Khim, 2006)	**Reworked carbonate cement in Flood plain / fan delta deposit** *Upper part of Lower Miocene: I-III* Fluvial system associated of marine influence from core study (Champasa, 2014), *Lower part of Lower Miocene: III-BM* More anoxic upward to IV marker
Basement section *Pre-Tertiary*	**Dolomitic/ Limestone** Blocky shape in GR Low porosity (NPHI-Sonic) High bulk density Calcite: ~2.7 g/cc Dolomite: ~2.9 g/cc	**Calcareous sandstone** Intense calcite & ferroan-dolomite cements in fracture pores Early - late stage diagenesis with indicative dolomite texture **Dolomitic-limestone** (Minor) No porosity or open fractures In-situ carbonate concretions	**Siliciclastic and Carbonate minerals** Dominated: Quartz Calcite / Dolomite Associated: Calcite, Dolomite, Ferroan-dolomite,	**Hydrothermal diagenetic** Depleted in $\delta^{13}C$ and $\delta^{18}O$ isotope values, with low catagenetic effects. Increasing burial temperature from South to North	**Permian: complexed lithology** - *Calcareous cement sandstone* - *Dolomitic limestone* Deep burial diagenesis trend of severe calcareous cement in sandstone and early - late bural diagenesis in dolomite texture (Warren, 2000). C-O isotopes show the same intensity of burial with Ratburi limesone (Ng, 2017)
	Igneous and/or Metamorphic rocks High radioactivity Low porosity (NPHI-Sonic)		**Igneous and Metamorphic minerals** Associated: Albite, Chlorite, Clinopyroxene, Amphibole		**Late Triassic - Early Jurassic granite** The plutonic was associated with the Ratchaburi limestone, which relate to Sibumasu subducted Sukothai arc event (Sone and Metcalfe, 2008),

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