FACIES DISTRIBUTION AND DIAGENETIC EVOLUTION OF A CARBONATE RESERVOIR IN PHA NOK KHAO FORMATION, SINPHUHORM, THAILAND

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Abstract

Structure likely controls the reservoir quality in the Sinphuhorm field, NE Thailand as is indicated by rapid lateral changes in reservoir quality between closely spaced exploration and delineation wells in this field. Fluids that entered the subsurface system are associated with different stages of deposition and diagenesis. Variations in oxygen isotope values are indicators of the fluid temperatures in different events. A field study in Permian carbonates in quarries in Central Thailand has documented the isotope signature of various fluid events that can be used as a template to classify the diagenetic evolution of these carbonates (Warren. et. al, 2011).

This research focuses on subsurface data from well cuttings in PhuHorm field and generates a carbon-oxygen isotope set of plotfields that are integrated with petrophysical data, core analyses and related information. Drill cuttings from 3 wells are selected for isotopic analysis and classified by lithology into 6 groups to differentiate diagenetic events in each of the wells. The isotopic results in a $\delta O^{18}P_{DB}$ and δC^{13}_{PDB} crossplot define 2 trends of diagenetic significance in Pha Nok Khao Formation. The main compaction burial trend in the study area is consistent with the typical Indochina burial trend, showing samples from this trend are not related to high temperature fluid crossflows that indicate veins in thrust-fault damage zones. Trend 2 was not recognized in the outcrop studied by Warren et al. (2014). It is defined by a slight increase in oxygen isotope value and decrease in carbon isotope value likely related to cooling and uplift tied to a later possibly Paleocene event. It is recommended that a core-based study is undertaken on existing core in Phu Horm field to test the isotope work on cuttings and to prove that trend 2 is related to a deep meteoric circulation event.

Keywords: Fluid evolution; Cutting; Uplift; Permian carbonate

1. INTRODUCTION

In Thailand, faults, the history of fractures, possible weathering at the Indosinian unconformity, and hydrothermal alteration in the Permian Saraburi Limestone can perhaps be related to the same structurally focused conceptual framework of diagenetic evolution. The Sinphuhorm field was originally discovered in 1983. An important factor in creating fractures and hence understanding reservoir reservoir quality is understanding the timing of diagenetic fluids related to the faulting and fracturing. Are the reservoir creating fractures related to Indosinian-age faults, or are the fractures later, possibly moving along Indosinian structures that were reactivated during Himalayan inversion (Paleocene).

The Pha Nok Khao Formation is the host formation in the Sinphuhorm field. It is a unit with a high initial carbonate mud content, while the later dolomitic overprints in the same formation generally have higher porosities than the precursor or host limestone. This leads to the question of what was the fluid evolution in the fault-related and fracture-related in the Sinphuhorm field? This is a question that can possibly be answered by a texture specific stable isotope study of cuttings in reservoir carbonates. Similar texture diagenetic studies have been done on nearby outcrops and resulted in the establishment of an isotope-defined set of burial and meteoric trends (Warren et al., 2014).

A carbon-oxygen isotopic study has not been done before in any oilfield in Thailand, so the overall focus of this study is to define the nature of the reservoir matrix and if there characteristic isotope signatures of late stage minerals that impact the fluid history of the Sinphuhorm reservoir, and possibly influenced reservoir quality.

The objectives of this research are to better understand the distribution of reservoir facies, reservoir porosity and diagenetic evolution, through the integration of carbon-oxygen stable isotope analyses, with information from petrographic analysis, wireline data and cuttings.

2. Locations

Sinphuhorm field is located in the western part of the Khorat Plateau Basin, between Kon Kaen and Udon Thani province, NE Thailand. This field is included EU1 and E5N concession block (Figure 1). It produces gas from the Permian carbonate reservoir in Pha Nok Khao Formation, Saraburi Group. There are three wells were using in this study as shown in Figure 1.

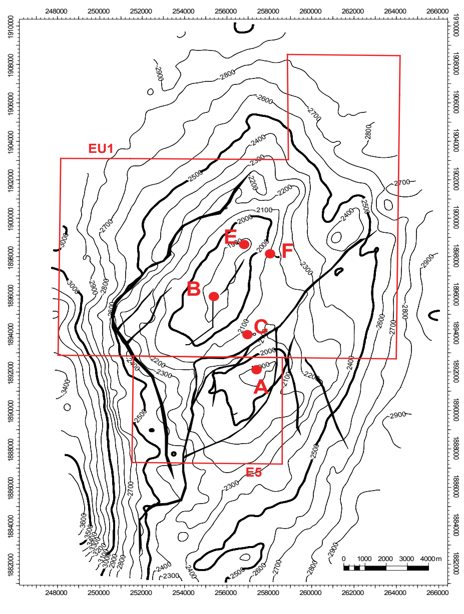

Figure 1 Sinphuhorm location map

3. Geological setting

The study area sits in the old Indochina landmass, where the oldest Carboniferous rock, is Ban Sa Ngao Formation. Deposition began in the late Devonian to earliest Carboniferous with abundant of radiolarian and ocean-floor basalts suggesting a relatively deep-water setting (Ueno and Charoentitirat, 2011). These sediments are in part strongly folded and faulted and are succeeded by siliciclastic strata with Middle Mississippian limestone lenses. The tectonic and sedimentary histories in this time interval are still not clearly understood in the Indochina block. The oceanic setting clearly turned into a shallow-water carbonate shelf setting during Middle Mississippian.

The main gas reservoir in Sinphuhorm field is the Permian carbonate of the Pha Nok Khao Formation, which in the study area was deposited as isolated platforms on horst blocks. It was eroded in places and at different times by the Indosinian unconformities and then buried by Mesozoic strata. The Phu Horm carbonate developed on a narrow north-south trending horst block and is tightly confined (Figure 1). The uppermost Mesozoic beds contain evaporites of the Maha Sarakham Formation, in turn overlain by the Phu Thok Formation sandstones. Siliciclastic rocks are dominant in the Carboniferous while carbonates dominate the Permian of Thailand (Figure 2).

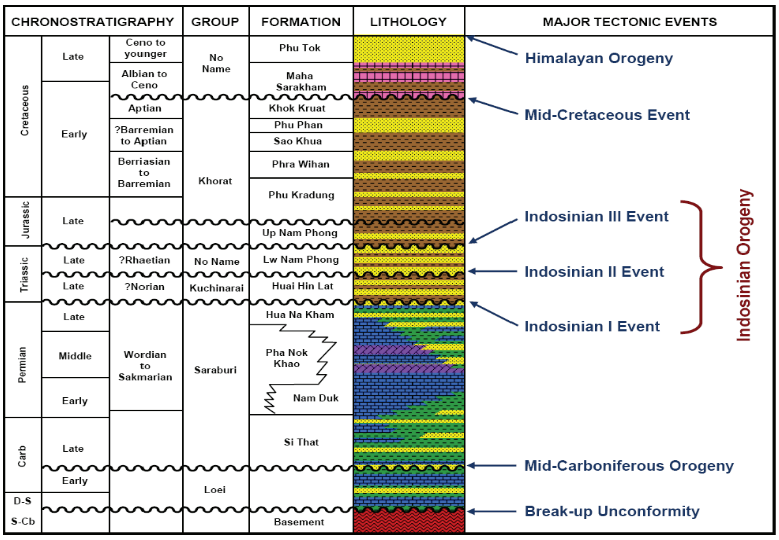

Figure 2 Tectono-stratigraphic column of the NE Thailand (Booth and Sattayarak, 2011).

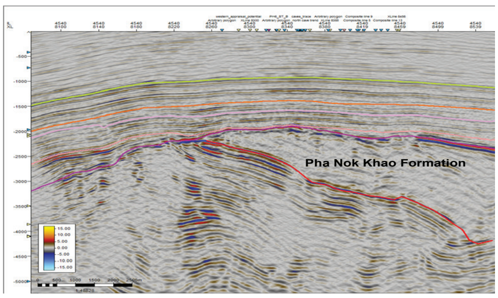

Figure 3 Seismic cross section in NW-SE direction across study area

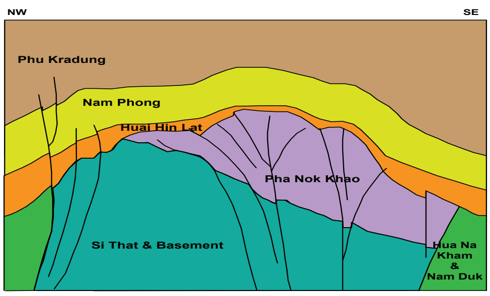

Figure 4 Schematic cross section in NW-SE direction interpreted as positive flower structure

The reservoir section in Sinphuhorm is tilted as a result of uplift during the Indosinian Orogeny. After the latest Permian the Indochina Block was caught up in a plate edge collision event that severely folded and faulted the sediments in Early-Middle Triassic time. These events created a significant set of unconformities (I-III) that define the Indosinian collision (Figure 2). Siliciclastic dominated sedimentation was ongoing in the remainder of the Mesozoic and evolved into a series of fault defined basins in the early Tertiary.

Triassic Indosinian and early Tertiary compressional events created several large-scale structural elements, including positive inversion features, often basement-involved, along with detached thrust faults and associated compressional folding (Booth and Sattayarak, 2011). During the Triassic – Early Jurassic Indosinian Orogeny, regional-scale fold and thrust belts developed, followed by a Paleocene strike-slip system, related to the Himalayan Orogeny, which ultimately drove the uplift of NE Thailand. These broad plate-edge tectonic events drove various sets of subsurface fluid crossflows that are recorded in the diagenetic evolution of the various calcite cements in matrix, fractures, and fault fills. The events have distinct isotopic-temporal signatures, which are 1) burial on a rifted Permian passive margin, 2) folding, thrusting in the Indosinian, and 3) Tertiary uplift and erosion (Warren et. al, 2014).

4. Methodology

The marker Top PNK (as used by PTTEP) was identified and correlated by using log characteristics from wells and this pick then guided cutting sample selection. Cutting samples were collected over reservoir interval in the Pha Nok Khao formation in all three wells. These washed and dried cutting samples were then subjected to XRD, petrographic and isotope analysis.

Six thin sections were made from two wells by the handpicking of more than one rock chip with the same texture in each reservoir interval. That is, thin sections were made of several rock chips with the same texture in a single-depth cuttings sample bag. Sections were stained with a combination of Alizarin and potassium ferri-cyanide in order to differentiate calcite from dolomite and to define any iron-rich carbonate phases (Scholle, 2003). Photomicrographs were taken showing the various fabrics, diagenetic histories and pore system evolution in the Phu Horm reservoir and so allowing comparison of microscale-textures with the relevant isotopic values.

The isotopic samples across the reservoir section were collected from three wells with a total of 237 samples (Figure 5). Six groups of cuttings lithology/texture were identified; 1) white calcite, rhombohedral shape, reacts vigorously with HCl; 2) massive dolomite, dark colored, lesser HCl reaction; 3) white, cloudy limestone, soft, reacts vigorously with HCl; 4) massive limestone with light to medium brown, reacts with acid; 5) crystalline limestone (reacts) associated with quartz (nonreactive) crystalline, medium to dark grey; 6) calcite crystalline clear/transparent, reacts vigourously with acid, probably developed in vugs (open space) in as a later stage mineral precipitate.

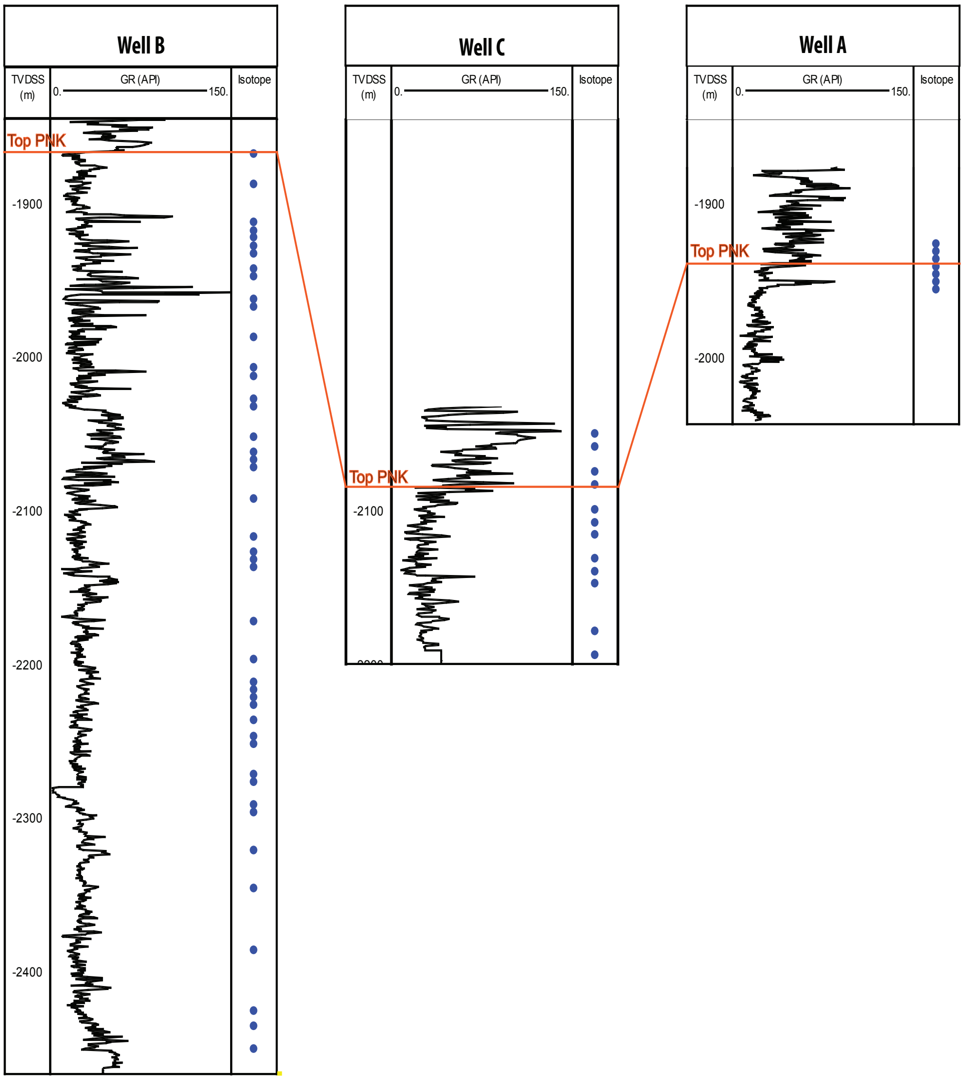

Figure 5 Well correlation of Well A, Well B and Well C, showing selected intervals of cutting samples used for isotope analysis along the reservoir interval.

5. Petrographic study

Six thin sections were prepared from cutting samples from two wells covering the reservoir interval in Pha Nok Khao Formation to better determine the relationship between rock diagenesis and stable isotope values. Two thin sections from well A, cover only in the upper part of reservoir section due to the limitation of cutting collection. Almost all of the cuttings in this well are too small for thin section preparation. Four thin sections were made from well B, where several chips were selected in the same interval to better understand lithology that were observed under binocular microscope.

The observation on thin sections from well A is less of bioclast preserved in this well. Almost of them associated with microstructures that cut through the rock and pore-reduced by calcite and dolomite precipitation in fractures (Figure 6). It is different from the well B petrographic observation. Four thin sections from well B dominant of limestone with grain supported are classified as packstone.

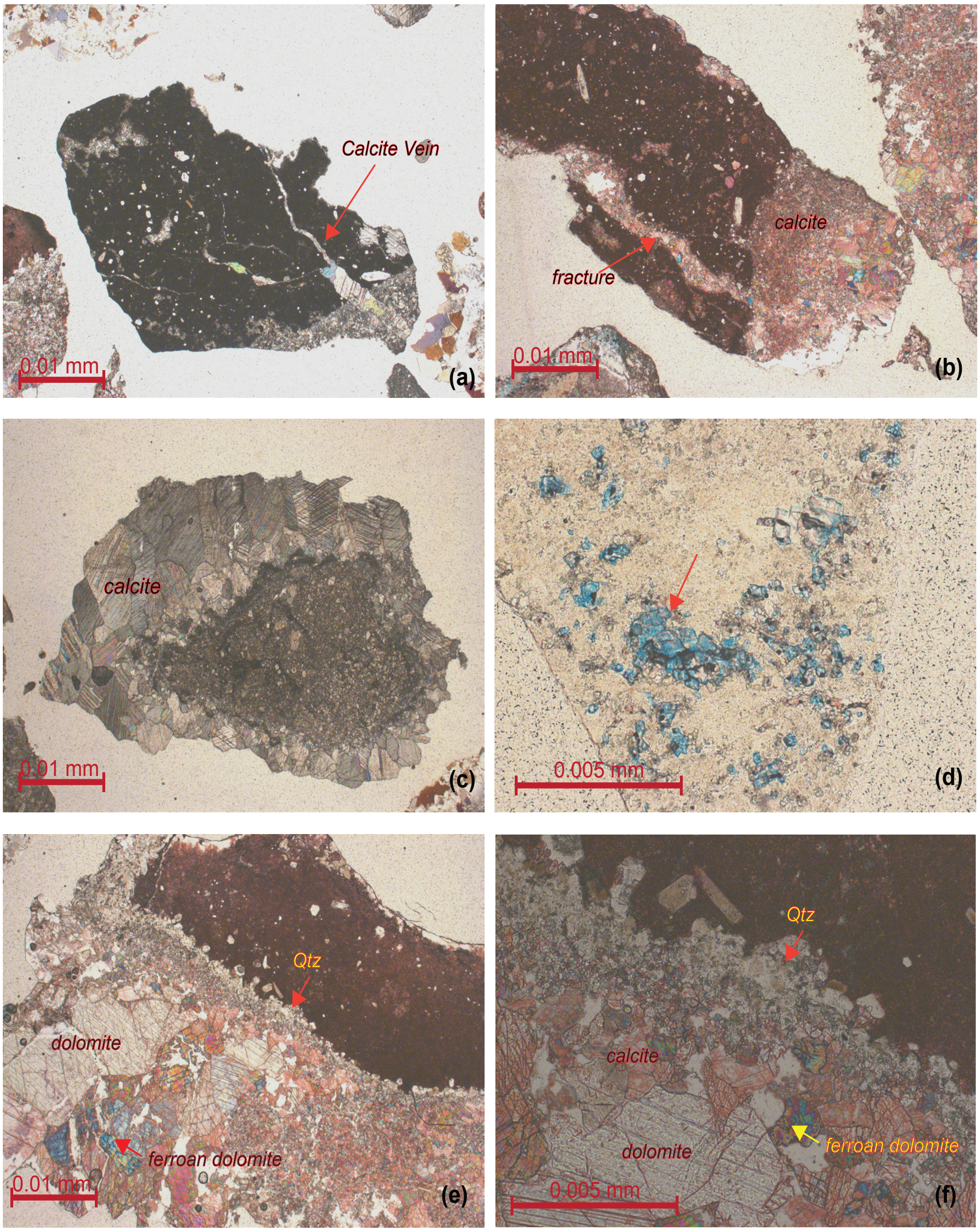

Figure 6 Photomicrographs cuttings chips from well A with 2.5 magnification (a-e) showing: a) Microfracture in a muddy limestone filled with recrystallized calcite and dolomite. b) Stained chip showing sharp boundary between muddy limestone and recrystallized calcite/dolomite c) Chip probably broken out from part of a calcite vein. d) Porosity in the blue color showing zones of a leached mineral, possibly pyrite. e-f) Quartz pore lining on a muddy limestone substrate, passing into a calcite then dolomite set of pore fills. Some of the calcite and the dolomite is ferroan and there is evidence of recrystallisation

There are abundant bioclasts that filled-up moldic porosity with calcite cementation. Late-stage porosities were created from microfractures cut through the rock, filled-up with calcite, dolomite and ferroan carbonate (Figure 7).

There are a variety and stages of calcite cements, veins and replacements

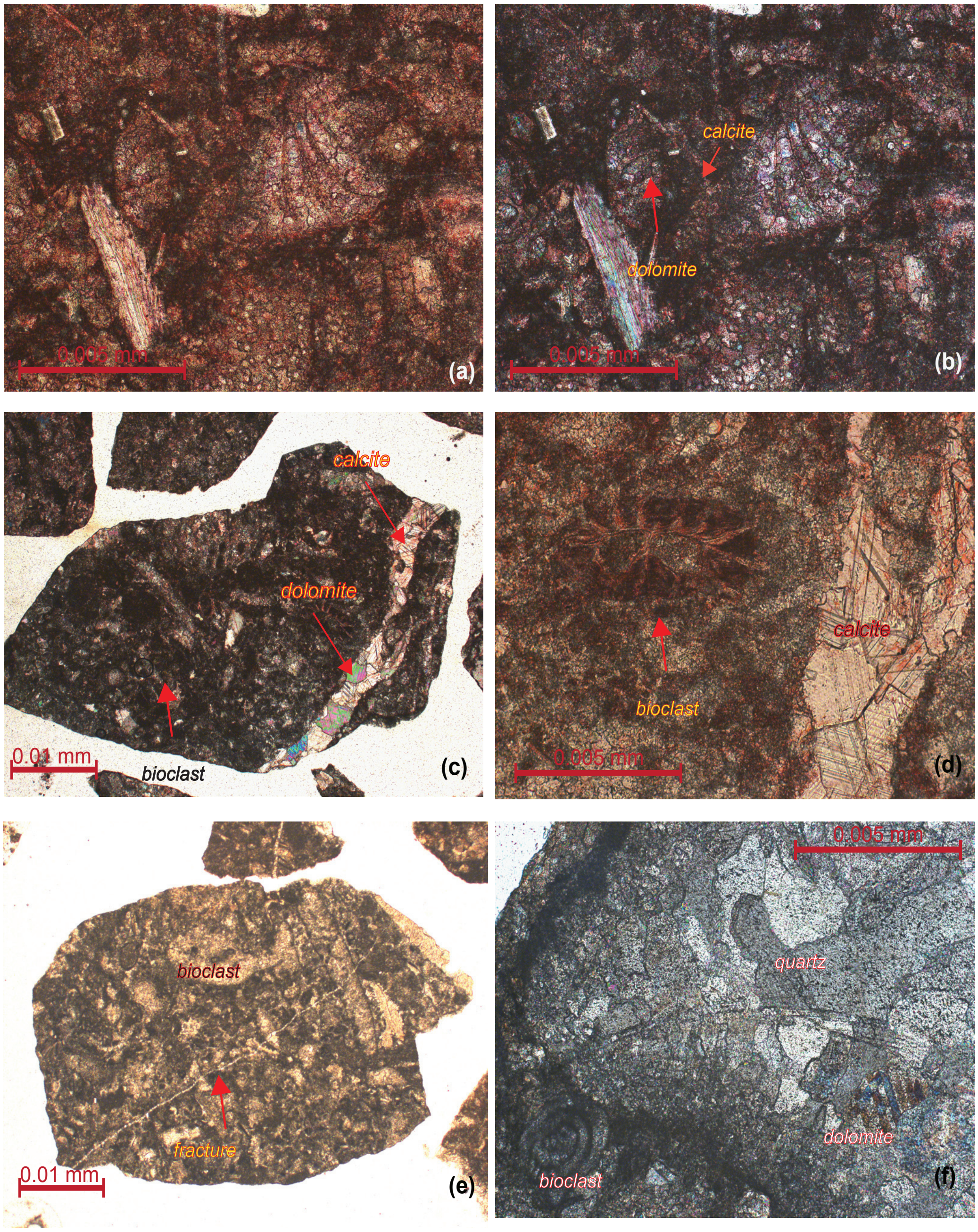

Figure 7 Photomicrograph from well B under plain polarized light in a) Cross polarized light in b) showing the recrystallized dolomite and how it pervasively reduced porosity. c) Grainstone was cut through by microfracture and filled with blocky recrystallized calcite and dolomite spar. d) Same sample as in previous photo and focusing on the pink colored interval with some local zones of ferroan carbonate replacement. e) Primary porosity in bioclast grainstone is filled with calcite and dolomite f) Intra-bioclast and vug porosity were blocked by a combination of quartz, calcite and ferroan dolomite.

(some ferroan) seen in the thin sections (Figure 7a-c). In some samples, quartz cements developed as an early silicification stage and lined what were once interconnected pores in the reservoir (Figure 6e-f). These pores were subsequently blocked by ongoing calcite and dolomite cementation and replacement, so that today there is very little poroperm remaining in the matrix. The diagenetic controls of the reservoir quality are silicification, dissolution, cementation, fracturing and late-stage cementation. The ferroan calcite and ferroan dolomite are associated with what appears to be a late-stage fracturing and occur as subsequent fracture filling cements (Figure 6f).

Because of how cuttings samples are collected at a shale shaker and have risen at varying rates in a rising column of drill mud, the thin sections made from cuttings (rock chips) are always a mixed sample of a variety of lithologies. So, unlike core, they are not clear identifiers of the depositional and diagenetic environment at a particular level in a well. However, they do sample a general set of depositional and diagenetic textures across a zone. In the collected thin sections there are chips composed of grainstones with abundant of bioclasts, including molluscs and some foraminifera. Overall the reservoir matrix samples indicate that the original depositional setting was shallow-open-marine. However, these bioclasts and the original interparticle porosity is now filled and replaced by various combinations of pervasive calcite and dolomite spar cements that have degraded matrix reservoir quality.

In general, the petrographic study shows that the reservoir matrix in Sinphuhorm has very low levels of porosity due to pervasive cementation with calcite, dolomite, ferroan calcite and ferroan dolomite.

6. Discussion

Trend 1 in the isotope plots of Sinphuhorm, as illustrated in Figure 8 and 9 overlaps the burial trend in isotope signatures now well defined for Permian carbonates of central Thailand (Warren, 2014). The fact that limestone and dolomite samples in the well B and well C wells fit this curve is not unexpected, as it is now known that the same burial trend exists in carbonate outcrops on both the Indochina and Sibumasu blocks and which now lie on either side of the Indosinian suture (Liaw, M.N., 2015). Interestingly, none of the oxygen values in limestone or dolomites samples from all three wells are more negative than -12‰. An oxygen isotope value of -12‰ was chosen by Warren et al. (2014) as defining the point in the fluid-exchange temperature burial curve that defines the end of rock matrix fluid exchange in Thailand (more negative oxygen indicates warmer fluids). Values more negative than -12‰ in the Permian carbonate outcrops across central Thailand come only from calcite veins created by Indosinian thrust faults. Using a value of -12% to interpret the thermal history of the three wells supports another notion put forward by Warren et al. (2014) that a covariant C-O trend on the positive side of this oxygen isotope value defines the typical burial trend across the Indochina block. Values on the negative side of -12% on the same covariant oxygen-carbon trend indicate calcite veins in likely thrust fault damage zones. If so, then well A and well C show typical Indochina burial trends implying that rocks in the vicinity of these wells did not experience focused high temperature fluid cross-flows related to thrust-fault damage zones. In contrast, the vein calcites in well B with values more negative than -12‰ have seen fluids that may be thrust associated. However the oxygen

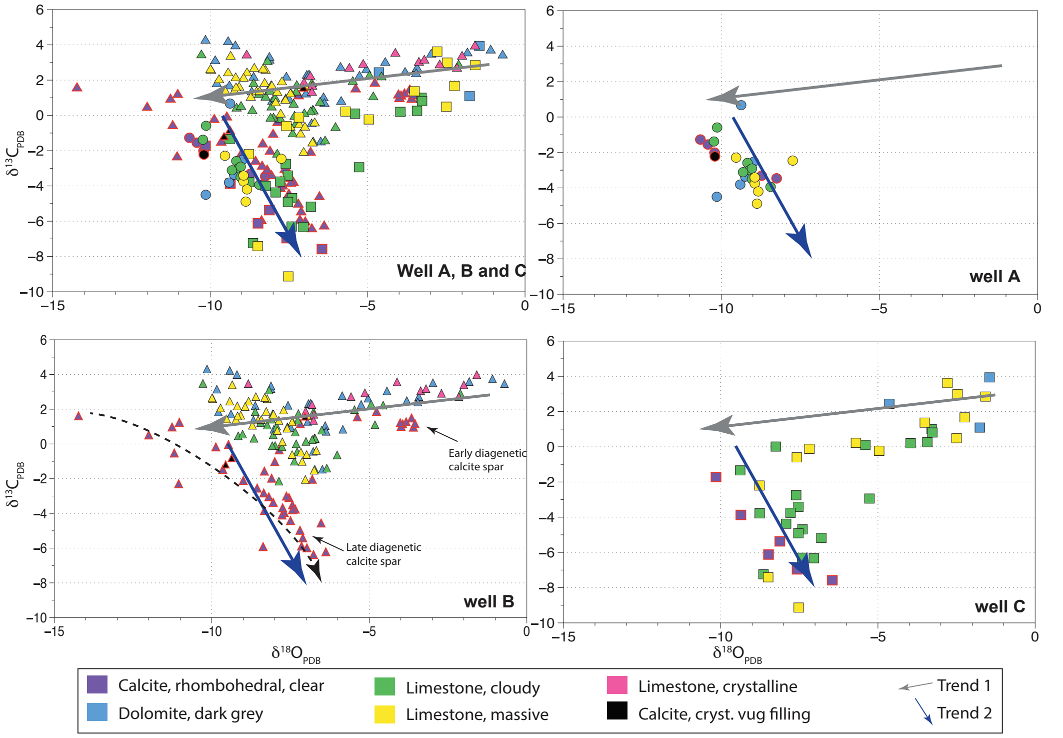

Figure 8 Carbon-Oxygen isotope crossplot of 3 wells showing two main trends in the isotopic signature, a burial trend and a late-stage diagenetic calcite spar trend perhaps indicative of cooling and uplift.

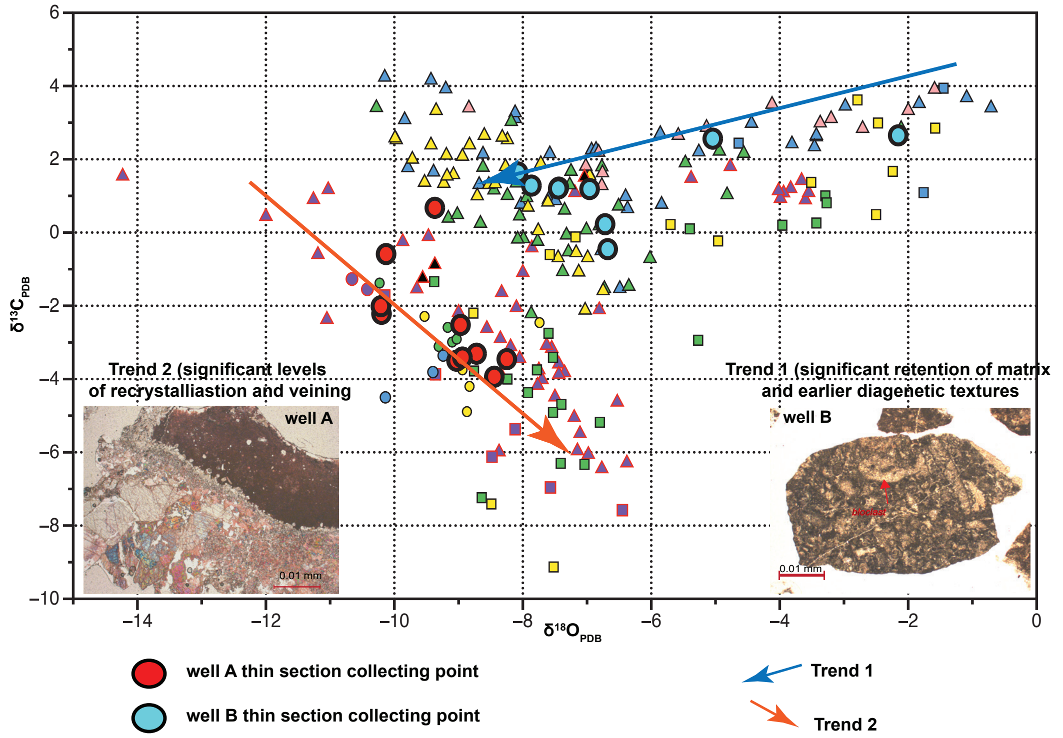

Figure 9 Isotope signatuures in 2 trends are distict as different stage of diagenesis. Trend 1 is associated with pack/grainstone textures which is represent burial. Trend 2 is associated with recrystallised calcite, best seen in well A, and possibly indicates cooling and uplift.

isotope values indicate temperature in a subsurface rock fluid interaction, not thrusting.

There is another cluster of calcite values seen in well B centered around $\delta^{18}O \approx -5‰$ and $\delta^{13}C \approx +1‰$ (Figure 8). This shows the limitations of using cuttings with isotope as this cluster probably indicates a stage of radiaxial calcite fill that is observed in a number of isotope burial curves across central Thailand (see Warren et al., 2014). That is not all clear calcite in the cuttings of the three wells has the same origin or fluid source.

The other covariant trend seen in all three studied wells is trend 2. This trend is seen in all three wells and is most obvious in the majority of the clear calcites in well B. The same trend is seen all samples (calcite, dolomite and limestones) of well A and well C. Interestingly in Well A, remnants of trend 1 (the regional burial trend is not present). This implies that the diagenetic episode that defines trend 2 was so pervasive in that well that it overprinted all precursor rock and matrix values, likely via a process of pervasive recrystallisation (possibly fault associated). Trend 2 is a new plotfield that is not present, or at least not recognizable in the outcrops studied by Warren et al. (2014) to define their burial trend and their meteoric mixing trend lines. Trend 2 lies outside both these already plotfields (burial and meteoric mixing). So the question is, what could this Trend 2 plotfield relate to? That it is a distinct covariant trend, not seen before in isotope studies of Permian carbonates of Thailand is undeniable.

Trend 2 is defined by two factors; 1) a slightly decreasing set of negative oxygen values and, 2) an increasingly negative set of carbon isotope values. One possible explanation is that it is related to the diagenetic event that created the fracture system that in turn created the post-Permian porosity and permeability storing hydrocarbons in Phu Horm. The oxygen decrease may indicate cooling, while the increasingly negative carbon values imply either a catagenic or an increasing mixed meteoric source for the carbon, in crossflowing waters interacting with both Permian matrix and spar. The working hypothesis that needs to be tested by further isotope work, hopefully on core from one of the producing Permian fracture/karst fields, is that Trend 2 is related to a deep meteoric circulation event . If so it may be tied to renewed fracturing driven by the regional Paleocene event. In other words it is a diagenetic cement response to fluid circulation in newly formed or reactivated fractures, driven by the collision of India with Eurasia.

7. Conclusions

Drill cutting can be use to identify diagenetically-related fluid evolution, base on the carbon-oxygen isotope signature in Permian carbonate, Thailand. The calcite cutting are retain signatures related to burial stage (warmer temperature), and another set in trend 2 tied to calcite veins indicating cooling temperature and uplift stage.

The carbon-oxygen isotopic signature curve of calcite fluid in Pha Nok Khao Formation have not been seen before in Permian carbonate hosts in Thailand. It is defined by a slight increase in oxygen isotope value and decrease in carbon isotope value likely related to cooling and uplift tied to a later possibly Paleocene event. It is recommended that a core-based study is undertaken on existing core in Phu Horm field to test the isotope work on cuttings and to prove that trend 2 is related to a deep meteoric circulation event.

The fluid's signature of this trend can be observed in relative timimg, not be absolute timing of generation (Indosinian or Paleogene event).

8. Acknowledgements

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9. References

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