Bulletin of Earth Sciences of Thailand

Diagenetic Evolution and Isotopic Characteristics of a Clast Breccia Reservoir in Nang Nuan Field, Chumphon Basin, Gulf of Thailand

Soraya Tongsuk*

Petroleum Geoscience Program, Department of Geology, Faculty of Science,
Chulalongkorn University, Bangkok 10330, Thailand
soraya519t@gmail.com

Abstract

Hydrothermal karst in the Pre-Tertiary Ratburi limestone plays a significant role in the formation of reservoir in the Nang Nuan oil field, offshore Thailand. Hydrothermal karstification is considered the most likely mechanism to explain reservoir geology in the Nang Nuan field, (Heward et al., 2000). However, the exact controls on the reservoir properties and the style of hydrothermal alteration or diagenetic evolution are still uncertain.

This research focuses on subsurface data from Nang Nuan wells and generates a carbon-oxygen isotope set of plotfields to identify the effects of ongoing diagenesis in fracture fills and the breccia matrix. Distinctive features of the breccias are documented and defined using rock textures and then integrated with thin section microscopy, stable isotope signatures and XRD determinations. Drilled cores and cuttings from 4 wells are selected for isotopic analysis and classified by lithology into 6 groups to differentiate diagenetic events in the Nang Nuan field.

Isotopic characteristics of diagenetic features in Nang Nuan field show two main trends: one follows a regional burial trend for the Ratburi limestone, similar to the burial trend seen in reservoir carbonates in Sinphuhom field in NE Thailand; the other trend implies a separate mixing trend. There are mixing trends in both Nang Nuan and Sinphuhom fields defined by significant decreases in$\delta^{13}C_{PDB}$ values that relate to deeply-circulating telogenetic fluids. But the $\delta^{18}O_{PDB}$ value range is different in Nang Nuan as it shows a vertical trend tied to increasing negative carbon values, with a limited and hotter temperature range in its oxygen values compared to Sinphuhom. Sinphuhom reservoir carbonates show a downward sloping trend tied to decreasing negative oxygen values that are related to exposure to ongoing shallower and cooler fluid crossflows that in turn tie to uplift and increasingly shallow meteoric waters. The difference in mixing trend between the two fields implies Nang Nuan experienced a shorter deeper (warmer) fluid event that would have allowed further porosity loss after the porosity-enhancing hydrothermal event. The differences in telogenetic fluid styles mean that Nang Nuan field will perhaps show lower proportions of connected permeability needed to allow lateral crossflows of reservoir fluids between matrix and veins, compared to Sinphuhom field.

Keywords: Nang Nuan, Diagenesis, Hydrothermal, Karstification, Clast Breccia, Telogenetic fluid

1. Introduction

Based on more than 50 years of onshore and offshore exploration testing Phanerozoic carbonate targets, karstified Permian Ratburi Limestone is considered the only viable carbonate reservoir objective within the Pre-Tertiary of Thailand. Typically, reservoir porosity and permeability in Nang Nuan field are enhanced by a combination of karstification, fracturing and leaching. Karstification appears to be largely of deep-burial origin, as indicated by the geometry of the karst, with substantial pore volumes, which are difficult to account for without temperature and flow anomalies that are also consistent with active geothermal circulation (Heward et al., 2000).

In terms of reservoir quality in Permian carbonates in Thailand, tectonic hydrothermal breccias often have a role in the reservoir, tied to evolving fluid origins and burial history. Burial-related diagenesis either can positively or negatively affect the reservoir quality (Katz, 2006). Importantly, uplift and meteoric dissolution, with deeply-circulating waters, are processes creating porosity in these heavily deformed carbonates. Sinphuhorm is a producing field that likely derived its porosity from these processes, and it extracts its hydrocarbons solely from a Permian carbonate reservoir. Nang Nuan field is also a producing field with a Permian carbonate reservoir, but it also has Tertiary siliciclastics in the reservoir zone, and likely derived its enhanced porosity from hydrothermal leaching (Heward et al., 2000).

This research focuses on refining the diagenetic history and fluid evolution of Nang Nuan, by better characterizing the reservoir properties, which are not yet fully understood. It uses subsurface data from Nang Nuan wells and generates a new set of carbon-oxygen isotope plotfields tied to textures in core and cuttings. The main aim is to identify the effects of ongoing diagenesis on the fracture cements, the breccias and the matrix. Relative abundances of the stable isotopes carbon-13 and oxygen-18 in a carbonate cement change according to fluid chemistry and temperature in the environment where it forms. Thus, a C-O isotope plot is useful indication of diagenetic evolution in subsurface carbonates, especially when cuttings, not core, must be used.

2. Geological Background

The Nang Nuan Field is situated in the northern part of the Chumphon Basin, western Gulf of Thailand. This elongate N-S rift basin measures 50 km by 110 km, covers an area of 5500 km^2 (C&C Reservoirs, 2019). Its half-graben geometry and the sedimentary section expands towards the Khlong Marui bounding fault along the western and northwestern margins of the basin (Figure 1) (Lawwongngam and Philip, 1993; Piggot and Sattayarak, 1993; Morley and Racey, 2011). Nang Nuan Field is located on a basement horst-block located on the gently-dipping eastern flank of the basin.

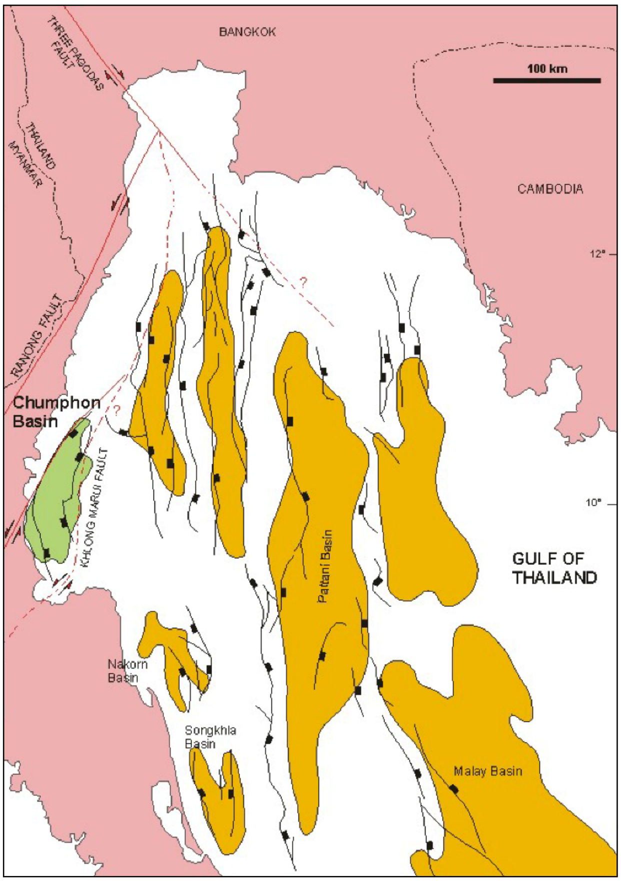


Figure 1 Basins & structural elements of the Gulf of Thailand (modified after Intawong, 2006).

The pre-Tertiary pre-rift rocks of the Chumphon Basin comprise Middle Permian karstified Ratburi carbonates, overlain unconformably by Mesozoic clastics (which are locally absent at Nang Nuan) (Figure 2) (DMF, 2007). Permian carbonates form the principal hydrocarbon reservoir in the basin and were deposited on an extensive warm-water shallow marine platform that occupied a large part of western and Peninsular Thailand (Baird and Bosence, 1993). Across Peninsular Thailand and the Chumphon Basin, the Ratburi carbonates are 200-300 m thick and in outcrop usually form karst towers, which are 100s of meters high and usually elongate in the prevailing fault direction. The carbonates are separated from overlying Mesozoic clastics by a regional unconformity formed in response to the Late Permian to Early Triassic Indosinian Orogeny (Indosinian I event).This orogeny, associated with collision of the amalgamated Sibumasu and Sukhothai terranes with the

Indochina Block, caused regional uplift and erosion across Thailand (Ridd et al., 2011). Subaerial exposure and meteoric diagenesis associated with this orogeny was originally considered to be the primary cause of karstification of the Ratburi carbonates in the Chumphon Basin, the principal reservoir at the Nang Nuan Field. However, later studies indicated that hydrothermal alteration via hot fluids is also a viable mechanism of karstification at the field (Heward et al., 2000).

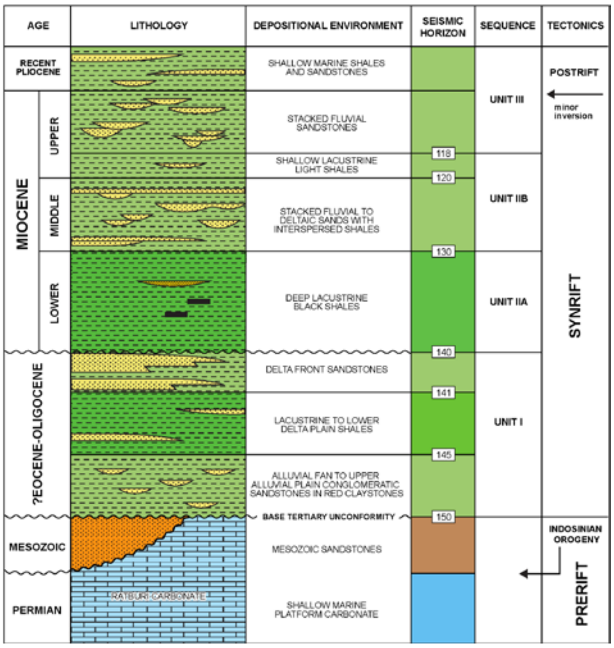
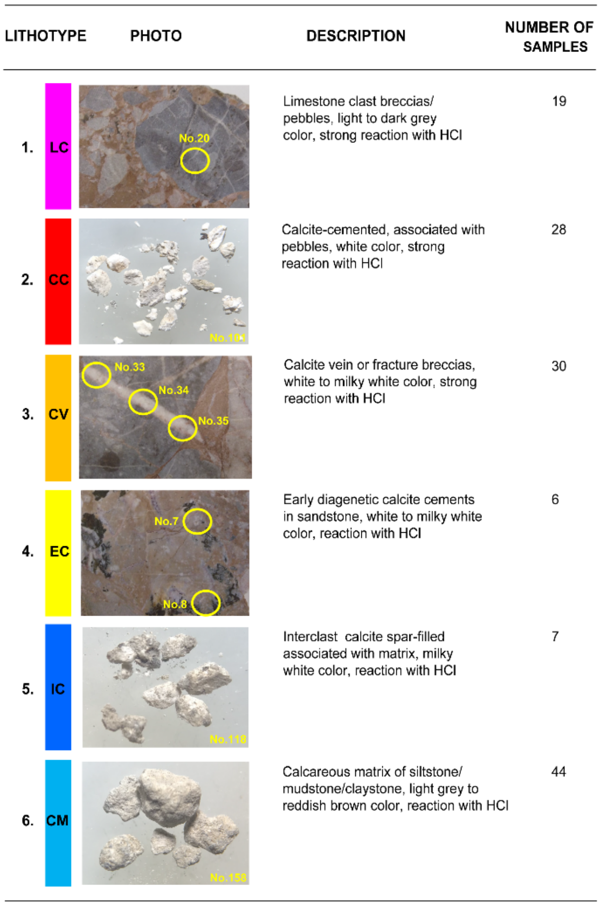


Figure 2 Stratigraphy, depositional environments and main sequences in the Chumphon Basin, Gulf of Thailand (modified from DMF, 2007; Morley and Racey, 2011). The reservoirs in Nang Nuan field comprise Eocene to Lower Oligocene conglomerates (Unit I) and Middle Permian Ratburi carbonates.

3. Data Available and Methodology

This research focuses on subsurface data from Nang Nuan wells, which were provided by PTTEP. Supplied data includes washed and dried cutting samples and conventional cores for petrography, XRD and isotope sampling. Conventional cores sampled from the clast breccia reservoirs for petrography, XRD and stable isotope analysis (carbon-oxygen isotope covariance) in order to better quantify the diagenetic evolution of the sediment. Furthermore, cuttings from 4 wells also selected covering karstified intervals.

A total of 134 isotopic samples were collected across the reservoir section from three wells. These samples were classified into 6 lithotypes based on color, texture, mineral composition, intensity of HCl reaction and C-O stable isotope results (Figure 3). Six groups of lithology/texture were identified; 1) Limestone clast breccias/pebbles (LC), light to dark grey color, strong reaction with HCl; 2) Calcite-cemented associated with pebbles (CC), white color, strong reaction with HCl; 3) Calcite vein or fracture breccias (CV), white to milky-white color, strong reaction with HCl; 4) Early diagenetic calcite cemented in sandstone (pedogenic?) (EC), white to milky white color, reaction with HCl; 5) Interclast calcite spar-filled associate with matrix (IC), milky white color, reaction with HCl; 6) Calcareous matrix of siltstone/mudstone/claystone (CM), light grey to reddish brown color, reaction with HCl.



LITHOTYPE	PHOTO	DESCRIPTION	NUMBER OF SAMPLES
1. LC		Limestone clast breccias/ pebbles, light to dark grey color, strong reaction with HCl	19
2. CC		Calcite-cemented, associated with pebbles, white color, strong reaction with HCl	28
3. CV		Calcite vein or fracture breccias, white to milky white color, strong reaction with HCl	30
4. EC		Early diagenetic calcite cements in sandstone, white to milky white color, reaction with HCl	6
5. IC		Interclast calcite spar-filled associated with matrix, milky white color, reaction with HCl	7
6. CM		Calcareous matrix of siltstone/ mudstone/claystone, light grey to reddish brown color, reaction with HCl	44

Figure 3 Six lithotypes representing the different kinds of rock texture.

4. Thin Section and Rock Property

Ten thin sections were prepared from cores in well 2, covering the karstified Permian Ratburi Limestone interval, to better determine the relationship between rock diagenesis and stable isotope values. The cored intervals are mainly composed of reddish brown, hematitic calcite-cemented conglomerate with limestone, dolostone and sandstone pebbles, and common pedogenic features (Clews, 2010). Examples of microscale thin section textures, with notation that relates to subsequent isotope plots are shown in Figures 4-6.

The conglomerate is dominantly lower to upper pebble grade, with common cobble horizons and minor very poorly sorted granule to pebbly, graded beds. Many siltstone and sandstone pebbles, particularly in the upper part of the interval are internally replaced by pyrite as shown in TS#1 suggesting micro-reducing conditions within the pebbles at shallow burial. Some pebbles have been split by clastic-filled fissures along inherited fracture planes, as shown in TS#7. The lower part of calcite-cemented conglomerate also shows occasional calcite-cemented fractures that pass from pebbles into matrix, as shown in TS#10. These fractures do not propagate far into the matrix and are locally stylolitised. They may be associated with minor late compactional collapse. Photomicrographs of pale to dark grey limestone clasts, which are comprised of dolomitic limestone, bioclastic grainstone, oolitic limestone, represent rock types in the Permian Ratburi Limestone, are shown in Figure 4.

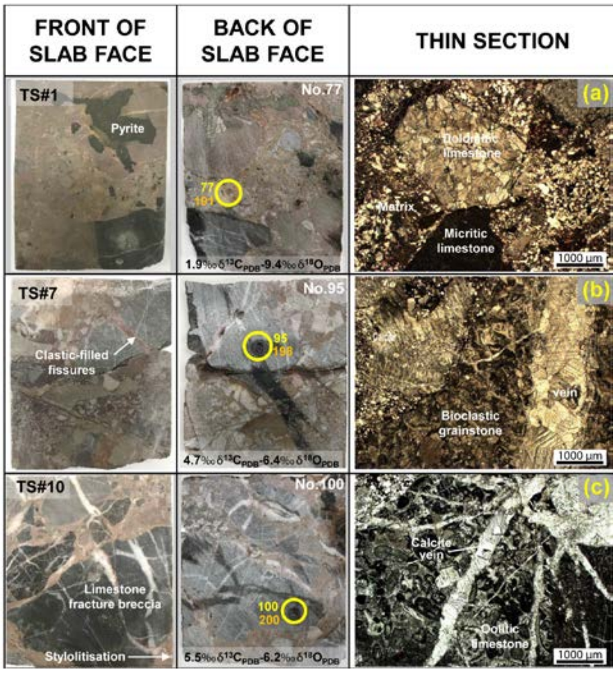


Figure 4 Photomicrographs of pale to dark grey limestone clasts, representing the Permian Ratburi Limestone (a) dolomitic limestone contact with micritic limestone, (b) bioclastic grainstone, (c) oolitic limestone with crosscutting calcite veinlet

The calcite-cemented breccia fractures, with limestone clasts, are obvious in TS#2 and TS#10, which sample a poorly sorted, grain-supported conglomerate, mainly composed of subangular to rounded fragments of fine to coarsely crystalline dolostone, with lesser siltstone and mudstone clasts. Dolostone pebbles are mainly anhedral and polymodal with zero inherited porosity, a few dolostone fragments are mosaic breccias. Intergranular areas are partly filled with very fine sandstone matrix and coarsely crystalline calcite cement as shown in TS#6. A phase of brecciation is interpreted to postdate the earlier calcite cementation and is evident in irregular late calcite-cemented fractures transecting pebbles and the earlier calcite cements. Photomicrographs of white calcite-cements inside limestone pebbles, and calcite veining associated with limestone clasts, are shown in Figure 5.

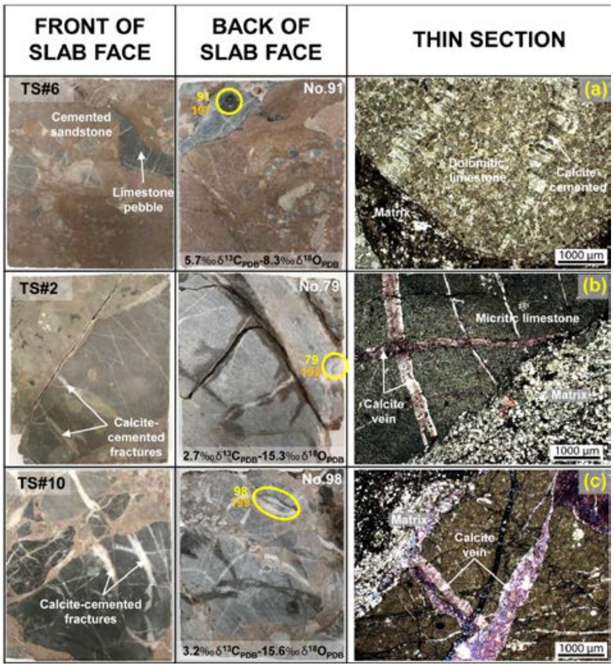


Figure 5 Photomicrographs of white calcite-cemented and calcite vein associated with limestone clasts, representing mid Mesogenesis stage along the burial trend (a) calcite crystal cement inside dolomitic limestone clast (b,c) calcite vein cuts across micritic limestone clast

Calcite-cemented conglomerate beds are made up of relatively coarse conglomerate interbedded with finer conglomerate, as shown in TS#4. Occasional clay drapes indicate temporary ponding and suspension deposition as shown in TS#3. Pedogenic disturbance is locally present, and evident in irregular fissures filled with argillaceous material and pebbly hematitic detritus. Stylolitisation predates calcite cementation and may have been the source for the later calcite cement, as shown in TS#5. These features may be partly formed by root structures later oxidised and infilled as root casts, or cemented as rhizoconcretions. Photomicrographs of interclast calcite spar-fills, associated with matrix, are shown in Figure 6.

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

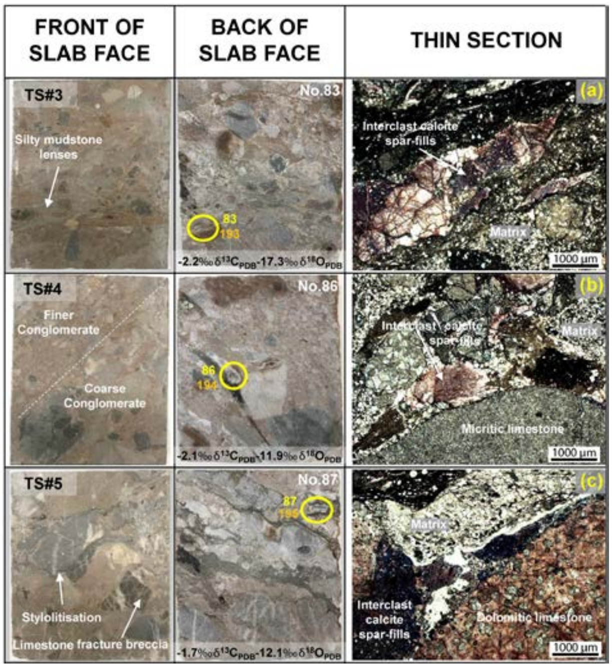


Figure 6 10 Photomicrographs interclast calcite spar-filled associate with matrix representing deeply meteoric circulation, corresponding to negative oxygen values in the C-O stable isotope plot (a) calcite spar-fill parallel to the bedding, (b,c) calcite spar-fill between limestone clasts and matrix

5. Stable Isotope Analysis

When subsurface C-O plots are tied back to rock types seen in cores and cuttings, there are four obvious covariant trends (Figure 7), which correspond to the designated descriptions in Figures 4 – 6.

The first trend, early diagenetic calcite cement in sandstone (pedogenic source?) (EC), represent an early mesogenesis stage (shaded yellow in Figure 7). It occupies the region at the earilest point of the burial trend (orange circle in Figure 7) and has 2‰ to -5‰ $\delta^{18}O_{PDB}$ values, along with +2‰ to +4‰ $\delta^{13}C_{PDB}$ values. This interval indicates contamination caused by very shallow burial depth (eogenesis?). Sediments undergo only very slight compaction and grain rearrangement during early diagenesis.

The second trend, limestone clast breccias/pebbles (LC), calcite-cements associated with pebbles (CC) and calcite vein or fracture breccias (CV), represents mid to late mesogenesis stage and overlaps the burial trend in isotope signatures now well-defined for

Permian carbonates across Central Thailand (Warren et al., 2014). It has a maximum value of -8‰ $\delta^{18}O_{PDB}$ and sits at the earliest point of mid mesogenesis (shaded green in Figure 7). A value of -16‰ $\delta^{18}O_{PDB}$ defines the transition into late mesogenesis (shaded orange in Figure 7) and corresponds to maximum relative temperatures at the cooler end of the burial trend, which perhaps ties to the entry of hydrothermal fluid.

The third trend, encompassing most of the cuttings samples and includes calcareous matrix of siltstone/mudstone/claystone (CM) in Tertiary siliciclastics. The vertical pull-down of carbon isotope values from the burial trend into a mixing trend (shaded blue in Figure 7) implies a diagenetic episode that relates to hot, deeply-circulating telogenetic fluids during Tertiary-age uplift. Most negative carbon isotope values range from 0 to -12‰$\delta^{13}C_{PDB}$ and some make up an abnormally negative cluster; -16‰ to -22‰ $\delta^{13}C_{PDB}$ (light blue dotted circle).

This cluster relates to possible mixing with fluids influenced by thermogenic methane, CO_2 or sulphate reduction fluids precipitating carbon in concretionary carbonate materials or cement patches.

Diagenetic conditions under which these carbonates originated tend be site specific and dependent on a range of local environmental controls (Nelson, 1996). The more typical negative oxygen values define a plot field (blue rectangle) across a relatively narrow but moderately warm temperature range (-9‰ to -15‰ $\delta^{18}O_{PDB}$). The field is considered to be indicative of a pulse of deep meteoric circulation or hydrothermal alteration, perhaps tied to the tectonic processes that drove Tertiary uplift. This will be discussed further when these results are compared with isotopes values from the Sinphuhom field, published in the Apsorn study (2015).

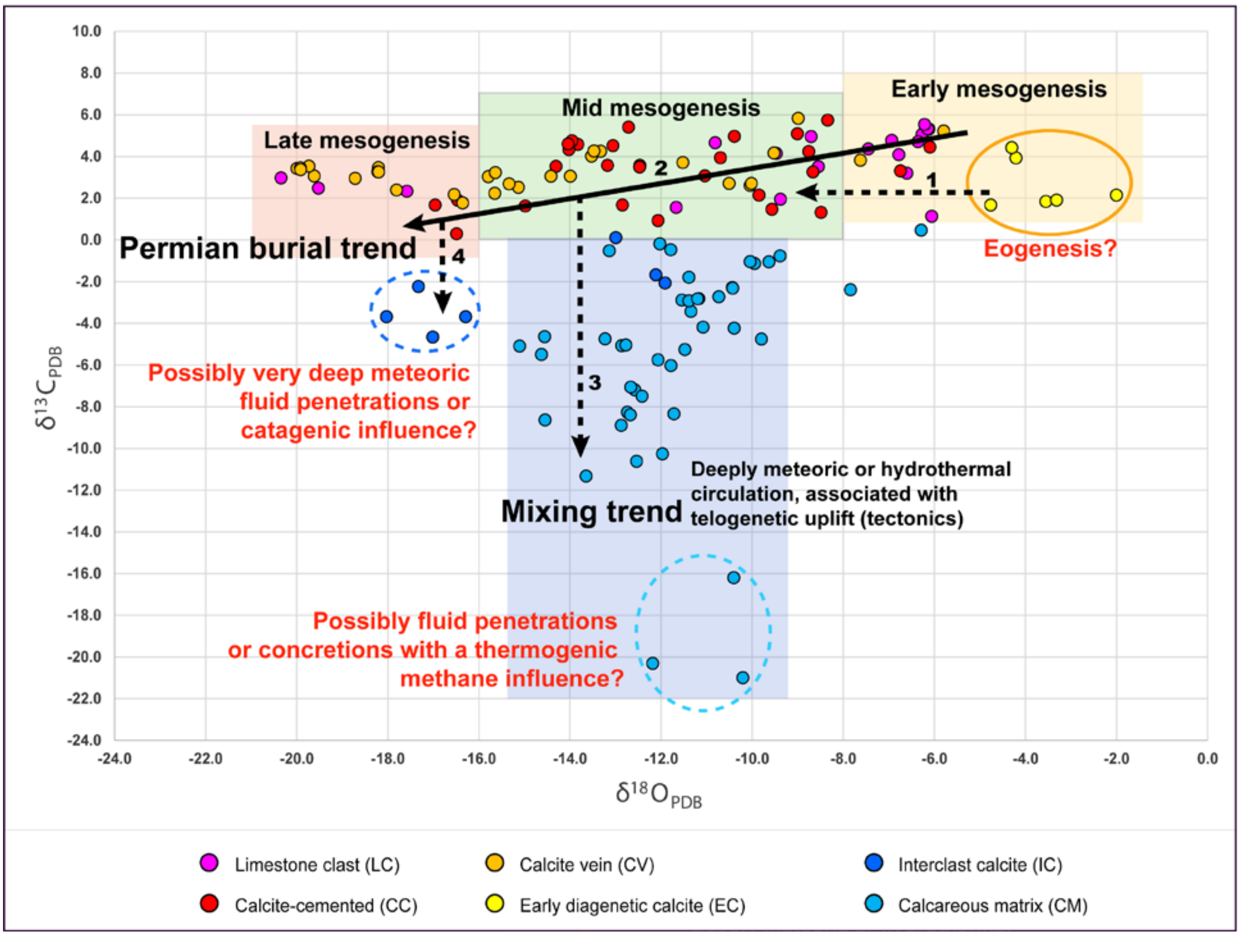


Figure 7 Carbon-Oxygen stable isotope cross plot and defines four main trends related to diagenetic stages.

The fourth trend, made up of few samples of interclast calcite spar-fill, associated with matrix (IC), defines a small cluster of isotope values (dark blue dot circle in Figure 7). This cluster has carbon values around -2‰ to -5‰ $\delta^{13}C_{PDB}$, along with significantly increased oxygen values ranging from -16‰ to -18‰ $\delta^{18}O_{PDB}$ compared to the main mixing trend. It indicates calcites precipitated at some time after the later mesogenetic stage and perhaps ties to the entry of organic-entraining (catagenic) fluids or hydrocarbons. This signature was not recognised in the work of Apsorn (2015).

Trend 1 forms during the early mesogenetic stage, when permeability is well preserved. Trend 2 of Nang Nuan field parallels the burial trend in isotope signatures that is now well defined for Permian carbonates of central Thailand (Warren et al., 2014). These two trends can be combined as a regional shallow burial trend, which implies a porosity and permeability decrease in the later stages of mesogenesis.

Trend 3 and 4 are new plotfields that were not present, or at least not recognized in an earlier study of Nang Nuan field by Lousuwan (2005), and are defined as mixing trend lines. These trends define the current reservoir potential and are related to later diagenetic episodes. Trend 3 is more related to deep meteoric circulation and hydrothermal alteration, while Trend 4 is possibly related to a catagenic influence.

7. How Are Subsurface Isotope Results Different Between Nang Nuan and Sinphuhom Fields?

It is important to note that uplift and dissolution by meteoric water entry are the processes that create porosity in these heavily deformed carbonates. Sinphuhorm is a producing field that likely derived its porosity from these processes, and it extracts its hydrocarbons solely from a Permian carbonate reservoir (Apsorn, 2015). Nang Nuan field is also a producing field with a Permian carbonate reservoir, but it also has Tertiary siliciclastics in the reservoir zone and likely derived its enhanced porosity from hydrothermal leaching (Heward et al., 2000).

Isotopic characteristics in Nang Nuan field show two main trend lines: one follows the regional shallow burial trend of Ratburi limestone, similar to Sinphuhom field in terms of the slope. But Sinphuhom seems to have overall lower carbon isotope values than Nang Nuan, implying more organic matter input into the isotope signature in the Sinphuhom rocks. The other trend implies a fluid with an oxygen and carbon grouping that is different from the burial trend fluids noted as the dominant mixing trend at Sinphuhom. Nang Nuan seem to give a hotter isotope signature for both trends, compared to Sinphuhom. This is especially obvious in the dominant mixing trend and indicates secondary poroperm developed in carbonates that experienced late-stage mesogenesis.

Mixing trends in both fields are characterised by a significant decrease in carbon isotope values that relate either to telogenetic uplift or deep thermal mixing fluids. But the range of oxygen isotope values in the mixing trends are different; Nang Nuan shows a vertical trend, tied to increasing negative carbon values with a limited and hotter temperature range compared to Sinphuhom. Sinphuhom shows a downward sloping trend tied to decreasing negative oxygen values, related to ongoing shallower and cooler fluid crossflows tied to uplift (as shown in Figure 8).

Increasingly negative oxygen values of a calcite cement/vein relate to increasing temperature during burial deformation (Moore, 2001, Ahr, 2008, Warren et al., 2014). Progressive burial and deformation under higher temperatures lead to fractionation of oxygen isotopes in the pore fluid. Continuous fractionation of warmer pore fluids causes it to have less ^{18}O. This is because ^{18}O is left behind during each cycle of fractionation, thus the precipitates from more evolved and warmer fluid has a more negative $\delta^{18}O_{PDB}$ value. Increasingly negative carbon values tied to warmer temperature (indicated in more negative oxygen values) implies that pore fluids precipitated in the hotter calcite veins likely had

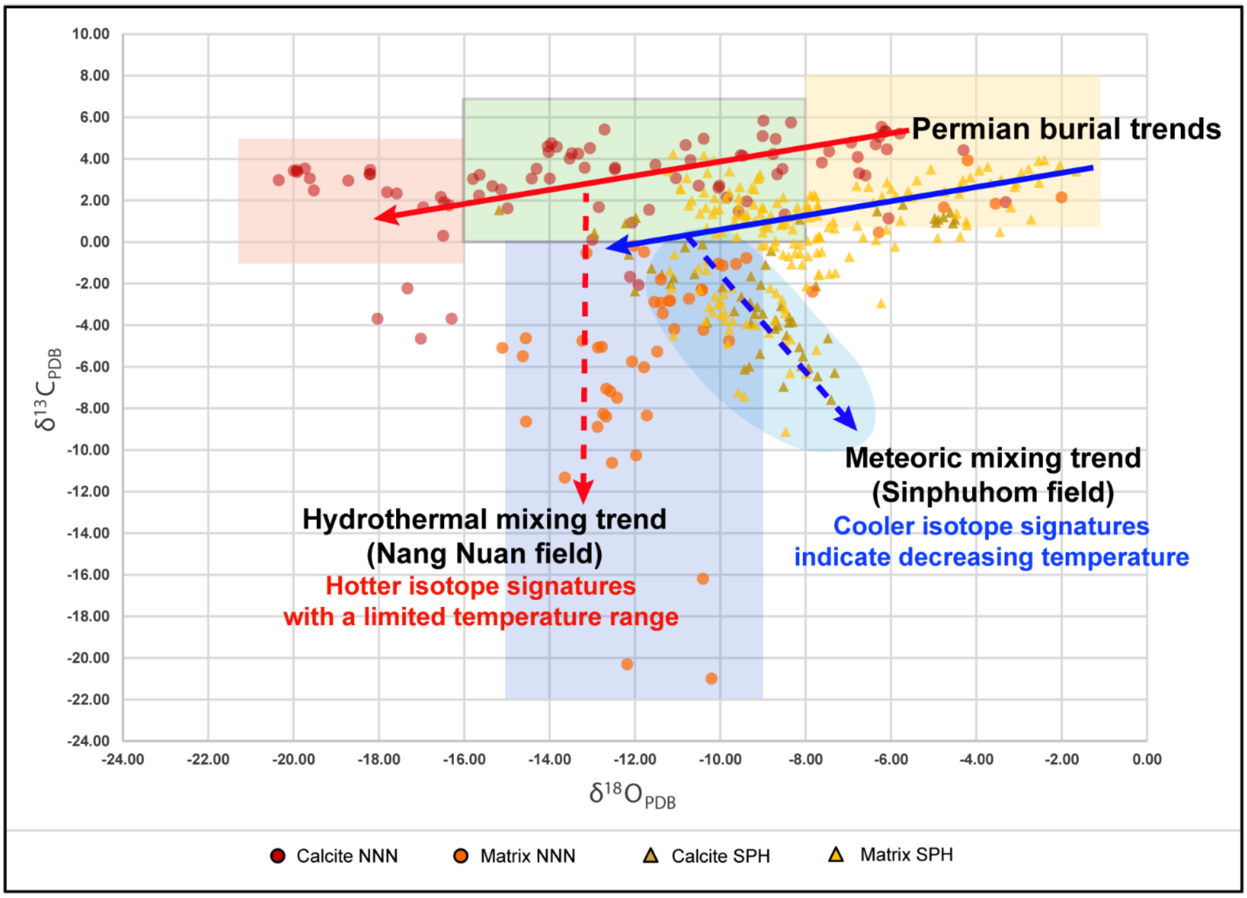


Figure 8 Carbon-Oxygen stable isotope cross plot comparison between Nang Nuan and Sinphuhom field.

experienced an increasingly catagenic influence, tied to the heating of organic material or to the crossflows of hydrocarbons. Later stage isotope signatures with a vertical trend, rather than the negative slope of uplift/telogenesis in Sinphuhom, means that Nang Nuan field will perhaps show lower proportions of sufficient permeability needed to allow crossflows between matrix and veins than in Sinphuhom field. That is, ongoing uplift, as indicated in the later stage mixing trend of the Sinphuhom isotope trend, implies a process whereby levels of porosity increase in parallel with fluid cooling tied to ongoing uplift. The limited oxygen range in the Nang Nuan mixing trend implies a shorter deeper fluid event, with a propensity in this subsurface setting of porosity loss after the porosity-enhancing event.

8. Implications

When carbonate is deposited, there will be porosity and permeability in vugs and matrix. In burial, porosity and permeability allow fluid crossflows from matrix to vein and vein to matrix, and is defined as ongoing rock-fluid interaction. This cross-flow or fluid interaction between matrix and veins, allows $\delta^{13}C_{PDB}$ to be in equilibrium with the evolving burial fluid chemistry. When matrix, vugs and veins have similar $\delta^{13}C_{PDB}$ values, this indicates that there was matrix permeability allowing pore fluid to flow and interact with the mineral phase (How, 2017 and this study). The mixing trend indicates a diagenetic process related to telogenetic uplift in an evolving set of Paleogene fluid events, in which secondary porosity development can be interrelated, and where pre-existing tectonic fractures can act as conduits for deeply circulating meteoric waters or hydrothermal fluids.

Secondary porosity produced by fluid circulation includes dissolution via meteoric waters in weathering zones, and deeper-seated alteration and leaching produced by hydrothermal circulation (Cuong and Warren, 2009). But based on the isotopic character in the study area, there is no evidence that surface-driven meteoric alteration was responsible for generation of secondary porosity in Nang Nuan field. In many areas of SE Asia, hydrothermal alteration plays an important role and tends to degrade effective porosity (Wilson et al., 2007), in a similar fashion to Bach Ho field of Vietnam. Porosity in the supergiant Bach Ho field is tied mainly to zones of brittle fracturing in a hydrothermally altered and fractured granodiorite, and its effective porosity is mostly associated with late Oligocene thrusting and subsequent gravity-driven extension (Cuong and Warren, 2009). In contrast, Nang Nuan porosity is largely tied to zones of thick limestone clast breccia sections, which can be identified by mapping thickening in the low relief areas atop the Ratburi in regions, with a localized structural control (Lousuwan, 2005).

In terms of concepts in this type of play, exploration should include the notion of testing low relief areas where thick breccia facies are likely atop areas that have been intersected by active extensional faults. The fault, fracture and thickened top seal association is required for this alteration system to be effective (Lousuwan, 2005; Davies and Smith, 2006). Such hydrothermally-enhanced fault-focused carbonate reservoirs tend to be laterally restricted and with most of the effective porosity residing in fractured and leached intervals (as shown in Figure 9). Moreover, targeting in breccia thicks tied to faulted zones, will require narrow well spacing or structurally-targeted directional drilling in order to maximize penetration in a potential reservoir zone situated in or close to a fault/damage zone.

Texture-aware isotope studies, as completed in this thesis, can evaluate how likely is porosity and permeability in a regionally distributed exploration plan, and can be based only on a sampling of existing well cuttings. The results give stronger evidence as to processes involved in porosity retention, or creation, in an evolving diagenetic history and quantifies, before the drilling of the next well, how much does burial diagenesis impact on potential reservoir quality.

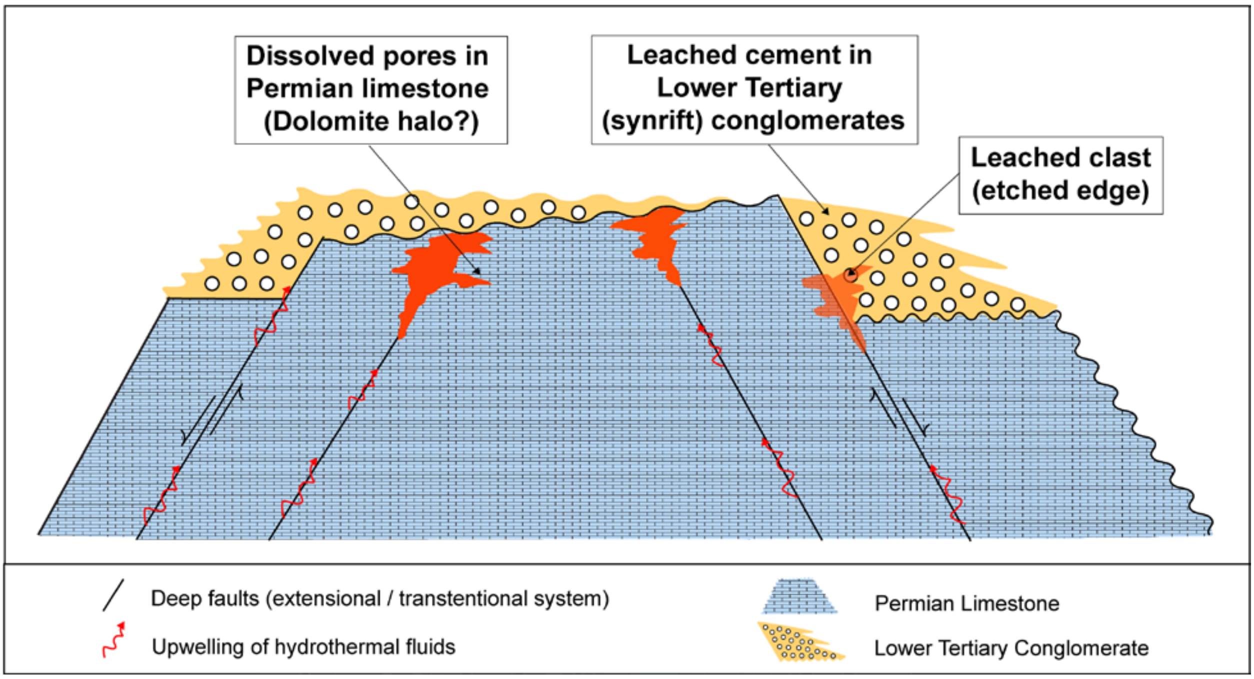


Figure 9 Hydrothermal overprint on uplifting basement block (bathyphreatic karst)

9. Acknowledgement

I would like to express my gratitude to all those who gave me the possibility to complete this research project. First of all, I am very grateful to PTT Exploration and Production Ltd. for a scholarship to complete this petroleum geoscience M.Sc. program. I sincerely thank Professor Dr. John Warren and Associate Professor Dr.Thasinee Charoentitirat for their oversight, recommendations and support during this research project.

10. References

Baird, A., and Bosence, D., 1993, The sedimentological and diagenetic evolution of the Ratburi Limestone, Peninsular Thailand: Journal of Southeast Asian Earth Sciences, v. 8, nos. 1-4, p. 173-180.

Clews, P., 2010, PTTEP Internal Core Description and Sedimentology of Nang Nuan Field.: PTTEP internal report, p.9-18.

Cuong, T. X., and Warren, J. K., 2009, Bach Ho Field, A Fractured Granitic Basement Reservoir, Cuu Long Basin, Offshore SE Vietnam: A “Buried-Hill” Play: Journal of Petroleum Geology, Vol. 32(2), p.129-156.

C&C Reservoirs, 2019, Nang Nuan field, Ratburi Carbonates and Lower Tertiary Conglomerates Reservoirs, Chumphon Basin, Thailand, p.15-27

Davies, G. R., and L. B. Smith, 2006, Structurally controlled hydrothermal dolomite reservoir facies: An overview: Bulletin American Association Petroleum Geologists, v. 90, p. 1641-1690.

DMF, 2007, Thailand petroleum province: Department of Mineral Fuels, http://www.dmf.go.th/bid20/petro_province.html, 10 p. (last accessed June, 21 2018).

Heward, A.P., Chuenbunchom, S., Makel, G., Marshland, D. and Spring, L., 2000, Nang Nuan oil field, B6/27, Gulf of Thailand: karst reservoirs of meteoric or deep-burial origin?, Petroleum Geoscience, Vol.6, p.15-27

How, N., 2017, Facies Nature and Relative Timing of Burial and Deformation of Sediments and Metasediments South of the Indosinian Suture, Ratchaburi Thailand: Implications for Fractured Basement Potential.: MSc thesis, Chulalongkorn University, Bangkok.

Katz, D.A., et al, 2006, Tectonic Hydrothermal Brecciation associated with calcite precipitation and permeability destruction in Mississippian carbonate reservoir, Montana and Wyoming: The American Association of Petroleum Geologists, v.90, No. 11, p. 1803 – 1841.

Lawwongngam, K., and Philip, R.P., 1993, Preliminary investigation of oil and source rock organic geochemistry from selected Tertiary basins of Thailand: Journal of Southeast Asian Earth Sciences, v. 8, nos. 1-4, p. 433-448.

Lousuwan, K., 2005, Hydrothermal karst in the Nang Nuan oil field, Gulf of Thailand.: MSc thesis, University Brunei Darussalam, Brunei.

Morley, C.K., and Racey, A., 2011, Tertiary stratigraphy, in Ridd, M.F., Barber, A.J., and Crow, M.J., eds., The Geology of Thailand: The Geological Society, London, p. 223-372.

Nelson, C. S., 1996, Stable oxygen and carbon isotope compositional fields for skeletal and diagenetic components in New Zealand Cenozoic nontropical carbonate sediments and limestones: a synthesis and review.: New Zealand Journal of Geology and Geophysics, 1996, Vol. 39, p. 93-107.

Panthong, A., 2015, Facies distribution and diagenetic evolution of a carbonate reservoir in Pha Nok Khao Formation, Sinphuhorm field, Thailand.: MSc thesis, Chulalongkorn University, Bangkok.

Piggot, J.D., and Sattayarak, N., 1993, Aspects of sedimentary basin evolution assessed through tectonic subsidence analysis. Example: northern Gulf of Thailand:

Journal of Southeast Asian Earth Sciences, v. 8, nos. 1-4, p. 407-420.

Racey, A., 2011, Petroleum geology, in Ridd, M.F., Barber, A.J., and Crow, M.J., eds., The Geology of Thailand: The Geological Society, London, p. 351-392.

Ridd, M.F., Barber, A.J., and Crow, M.J., 2011, Introduction to the geology of Thailand, in Ridd, M.F., Barber, A.J., and Crow, M.J., eds., The geology of Thailand: Geological Society of London, p. 1-17.

Warren, J. K., C. Morley, T. Charoentitirat, I. Cartwright, P. Ampaiwan, P. Khositchaisri, M. Mirzaloo, and J. Yingyuen, 2014, Structural and fluid evolution of Saraburi Group sedimentary carbonates, central Thailand: A tectonically driven fluid system: Marine and Petroleum Geology, v. 55, p. 100-121.

Wilson, M. E. J., M. J. Evans, N. H. Oxtoby, D. S. Nas, T. Donnelly, and M. Thirlwall, 2007, Reservoir quality, textural evolution, and origin of fault-associated dolomites: Bulletin American Association Petroleum Geologists, v. 91, p. 1247-1272.