Structural geology related with fracture development and fluid evolution at Khao Tham Phedan, Nakhon Sawan Province, Central Thailand

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Abstract

Owing to the complexity of structural geology and diagenetic history across Permian carbonates at western margin of Indochina block in Nakhon Sawan province, in the northern part of Central Thailand, there are still many poorly understood aspects. The overprint from several tectonic stages and multiphase fluid crossflows, means an integration of the study of structural evolution and characterisitc of isotopic signatures is required to better understanding the carbonate diagenetic and tectonic history across the region. The study area preserves two structural styles, less and more intensely deformed zone along with two main fracture orientations, NE-SW and NNE-SSW. Carbonates textures show the rocks responed to deformation by forming cross-cutting veins, reactivated fractures, fractures exposed to multiple phases of fluid flow, and an abundance of microfractures in matrix portions of the rocks.

Using stable carbon-oxygen isotope plots, the area's diagenetic history is categorized into two stages. Firstly, deformation with two main relative timings: earlier deformation and reactivated deformation. The early deformation indicates a fluid history active during mid-mesogenesis (using the fluid classification of Warren et al., 2014). Secondly, NW-SE fracture reactivation led calcite precipitation from hotter fluids in re-opened fractures during reactivated deformation stage in the late mesogenetic also seen in some samples collected from deformed intervals with calcitic bed-parallel slippage. Subsequently, a new set of opened fractures were established during uplift when meteoric water entry enhanced dissolution and calcite precipitation as fracture fills in NW-SE and WSW-ENE, slickenside coats and speleothems. Additionally, there was an organic matter influence on bicarbonate ions in burial water, which is captured by isotope signatures in samples plotting in the "transitional to more negative carbon isotope" field (indicating possible catagenic fluids). Regionally, oxygen isotope signatures in the study area indicate higher fluid temperatures when compared to other areas within Indochina block. An early mesogenetic characterisitc is absent when compared with isotopic signatures from same age carbonates in the Saraburi and Sin Phu Horm areas.

Keywords: Permian carbonate Thailand, Fracture development, Diagenetic history, Stable carbon-oxygen isotope.

1. Introduction

Saraburi Group, Permian carbonates are the focus of this study, they outcrop in Central and NE Thailand and are the main carbonate gas reservoirs in the northeast of the country. These carbonates reservoirs are characterized as possessing very limited remaining porosity, while fractures are also important to reservoir performance (Booth and Sattayarak, 2011). There are a number of detailed studies of structural geology and fluid flow evolution in fold and thrust belts in central Thailand, especially in Saraburi and Lopburi areas (e.g. Ampaiwan, 2011; Yingyuen, 2014 and Warren et al., 2014, Panthong, 2015). Their results have given an improved understanding of diagenesis, fracture development, and fluid migration. Some Permian carbonates in other areas of Thailand, such as in Nakhon Sawan Province, northern part of central Thailand are antithetical.

Permian carbonates diagenesis within the fold and thrust belt of Thailand, developed mostly during the Early Triassic-Early Jurassic Indosinian Orogeny (Sone and Metcalfe, 2008; Morley et al., 2013). Diagenetic history of Permian carbonates in Thailand was initially driven by burial on a rifted passive margin, followed by folding, thrusting, uplift and erosion during the Triassic. This was followed by additional burial under 2-3 km of clastic sediments during the Late Triassic-Cretaceous and subsequent exhumation during Paleogene due to transpression and Neogene-Quaternary regional uplift, which are the distal effects of the India-Australian collision (the Himalayan Orogeny) (Racey, 2009; Morley, 2012; Morley et al., 2013) (fig. 1).

The study area is an elongate exposure in a quarry located in Khao Tham Pedan, Phayuha Khiri District, Nakhon-Sawan Province, northern part of Central Thailand, some 200 km north of Bangkok city. These older rocks crop out only in scattered north-south trending monadnocks, and thus the stratigraphic relationships and structural development between outcrops are generally unclear. Depositionally, the outcrop exposures are interpreted as Permian carbonate platform successions (Dawson and Racey, 1993; Ueno and Chareontitirat, 2011) on the western margin of the Indochina Terrane (Sone and Metcalfe, 2008).

Overall, this study focuses on better defining the relationship of fluid evolution with structural deformation in a detailed field investigation, as well as collecting samples for stable isotope analysis and petrography and so better understand the stages of texture-based diagenetic evolution as it relates to fracture evolution. This study categorizes calcitic fractures and veins, based on structural style and orientation, in order to identify the relative timing of fluid flow and structural evolution. It uses contrasting isotope signatures to classify fracture trends in outcrop and the relative timing of fracture development.

2. Methodology

The study area is an inactive elongate limestone quarry with a 400 m-long curved exposure face ranging from a northwest to southeast orientation. The quarry face was photographed and sketched, and structural orientations recorded. Orientations of bedding planes, fault planes, calcite veins were measured, and joints were recorded as planes (strike/dip angle with right hand rule). Lineations of slickensides and cleavage intersections were documented (trend/plunge angle). Oriented hand specimens were collected for laboratory investigation of XRD, stable isotopes, and petrography. A total of 78 samples were taken, along with measurements of rock texture, diagenetic features, calcite-filled fractures with different orientation, and fossils. There are minor volcanic rocks in study area and these were also sampled for laboratory study. Samples were slabbed, photographed and made into thin sections and half-stained with Alizarin red S and potassium ferricyanide in order to identify common minerals and intracrystalline chemical variations.

To gain an understanding of fluid evolution associated with structural deformation, a total 124 samples were prepared for stable isotope analysis. These samples are tied to variations of textures such as cross-cutting relationship of calcite veins, different orientation of calcite vein, rock matrix, speleothems, fossils, calcite bed-parallel slippage, striations. Powder samples were collected using a dental drill from slabbed faces. Lastly, overall isotope results were integrated with detail field investigation and other laboratory analyses.

3. Results

Detail field investigation and laboratory analysis were integrated to build an improved understanding of structural and fluid evolution. The long quarry exposure is subdivided into six sections for detailed outcrop study.

3.1 Structural style and fracture orientation

Based on overall observations, there are two structural styles in this area: 1) less intense deformation with inclined and massive limestone beds related to thrusting (fault bend fold) and a thin layered volcanic sill in southern part of the quarry and 2) more intense deformation zone in the northern part of the quarry with folding and thrusting of bedded limestones interbedded with thin shale beds that are organic rich (fig. 2).

Typically, thrust faults are parallel with bedding planes in section 2 and 3 (fig. 3). Fault orientations are varied, trending from SE to SW, with dip directions from SW to NW. To the north of the study area, section 5, the fault inclination changes from sub-horizontal and parallel with beds in bottom to steeply inclined

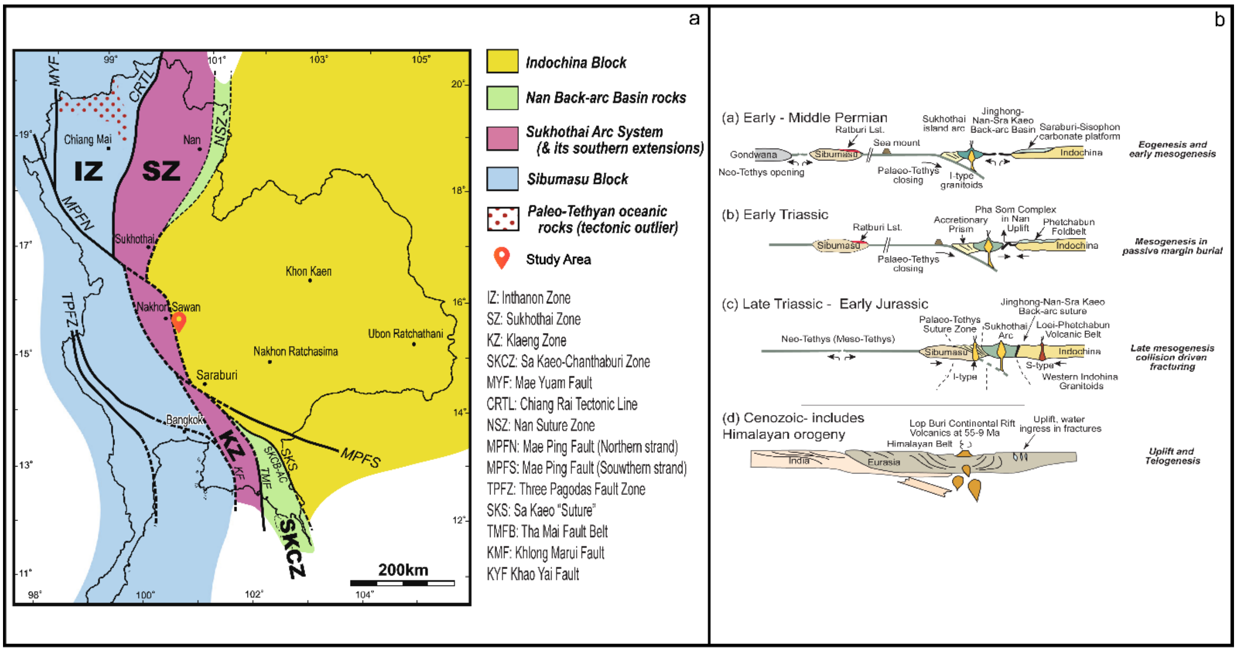

__Figure 1__ Tectonic setting of Thailand, a) Geotectonic subdivision of Thailand into five tectono-sedimentary zones, b) Tectonic evolution of Thailand from Late Paleozoic to Cenozoic drive carbonate rock diagenesis and fluid evolution (modified from Sone and Metcalfe, 2008; Ueno and Charoentitirat, 2011).

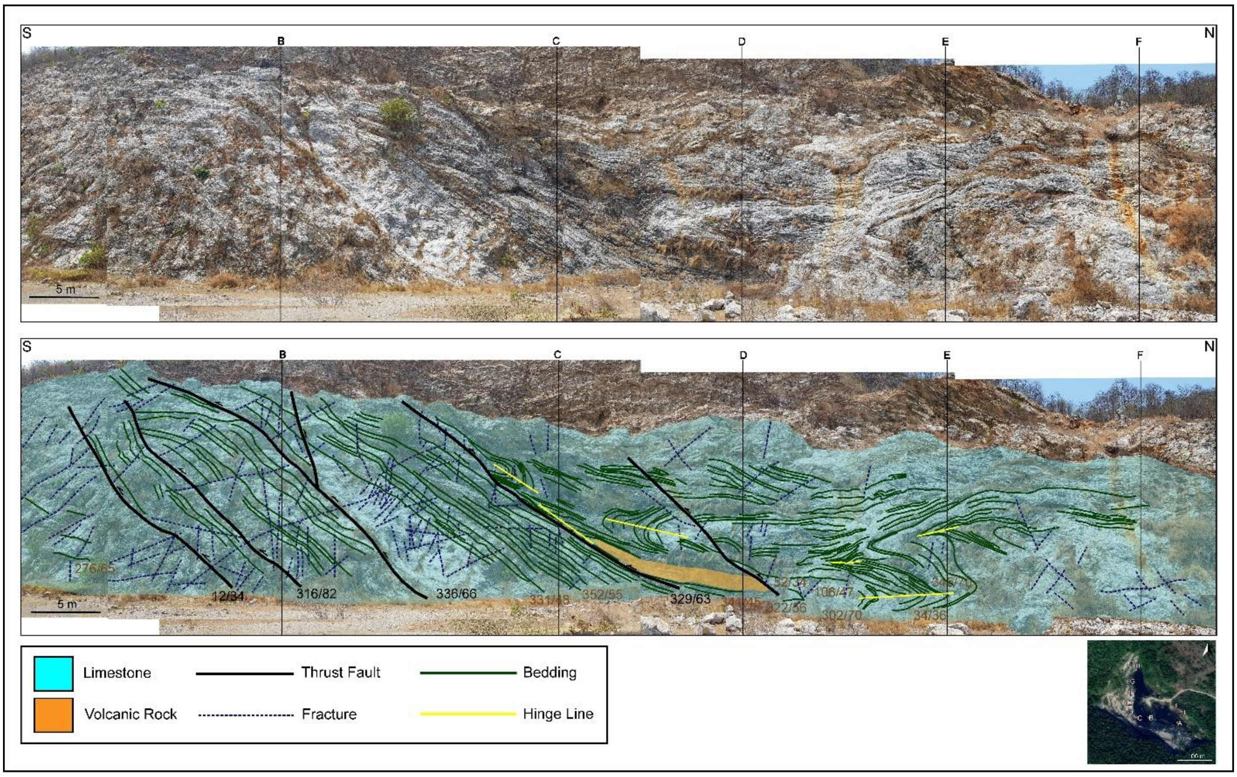

__Figure 2__ Mosaic photograph of the limestone quarry face with two structural styles: 1) less intense deformation made up of inclined limestone and thrusts and 2) more intense deformation zone associated with smaller-scale folding and thrusting.

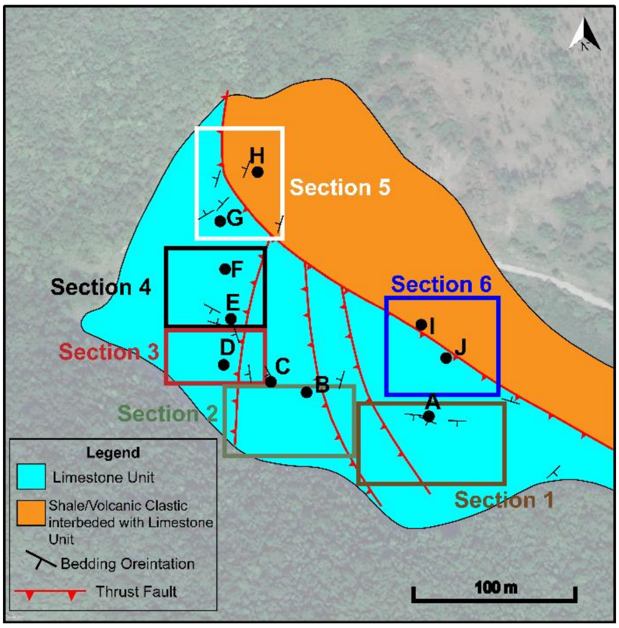

Figure 3 *Simplified geological map of the study area divided into two lithologic units.*

in the top of quarry face. Conversely, thrusts are imbricated from sections 1 to 3 and steeply inclined, with dips of 65^o to 85^o. In terms of the overall structural orientation, there is one main thrust fault with a NW-SE orientation in section 5, with its associated splay faults, which are clearly seen in section 2 and 3, the top view map illustrates the fault orientation. Some of calcitic bed- parallel slippage and breccias are formed along the thrust zone.

Fractures in study area are measured as orientations of calcite-filled fractures and joints. Several styles of calcite-filled fracture are present; cross cutting, calcite bed-parallel slippage, variations of veins at the fold hinge, and *en-echelon* tension gashes.

Overall fracture orientation in the area is made up of two main trends: NE-SW and NNE-SSW, with occasional WNW features. Each section in the quarry has a distinct set of fracture orientations. In section 1 and 3, there are two mains fracture trends, NNE and SSE, while fracture in section 2 are mainly oriented NE with variations from NE to SSE and WNW. In contrast, WNW-SSE and NE-SW fracture trends dominate in sections 4 and 5, corresponding to more intense folding in the northern part of quarry.

3.2 Petrography

Calcite-filled fractures show multiple responses to deformation, such as cross-cutting, reactivated vein sets, multiphase fluids, and an abundance of microfractures. Multiple phases of fluid can be found in both vein and matrix. Some samples show late-stage ferroan carbonate cement in the middle positions of calcite veins, in the same fractures (fig. 4a). Such reactivated calcite vein fabrics are especially associated with calcite-filled fractures with NW-SE trends in main thrust zone in northern part of quarry (fig. 4b). Reactivated veins can occur together with cross cutting veins (fig. 4c). Typically, most of rock samples exhibit cross cutting veins made up of two to four vein sets that represent many stages of structural deformation (fig. 4d).

3.3 Stable carbon-oxygen isotope signature

Overall, C-O isotope plots in the study area show more negative oxygen isotope values than many other previously studied areas. Oxygen values range from -10 to -24 ‰, and some plot points transition to more negative carbon isotope values, ranging from 2 to -2 ‰. As well, speleothem and slickenside fills reveal more negative carbon isotope values with some as low as -9 ‰.

The signatures of C-O isotope plots from the two deformation zones are separate. C-O isotope plot of samples were taken from less intense deformation zone (blue dots in isotope plot, fig. 5), show a cluster of oxygen isotope values between -10 and -15 ‰, with some plot points ranging up to -20 ‰. In the same samples there are only few points with low carbon isotope values. In contrast, samples from the more deformed zone show a wider distribution of C-O isotope plot points (red dots in isotope plot, fig. 5) and are divisible into three groups: clustered isotope values, more negative oxygen values (up to -24 ‰), and more negative carbon values (down to -9 ‰). This shows that the contrast in structural styles is paralleled in the isotope signatures.

Rock samples for isotope analysis were collected based on textures and orientation, which were categorized into 8 classes (fig. 6). According to structural analysis, fracture

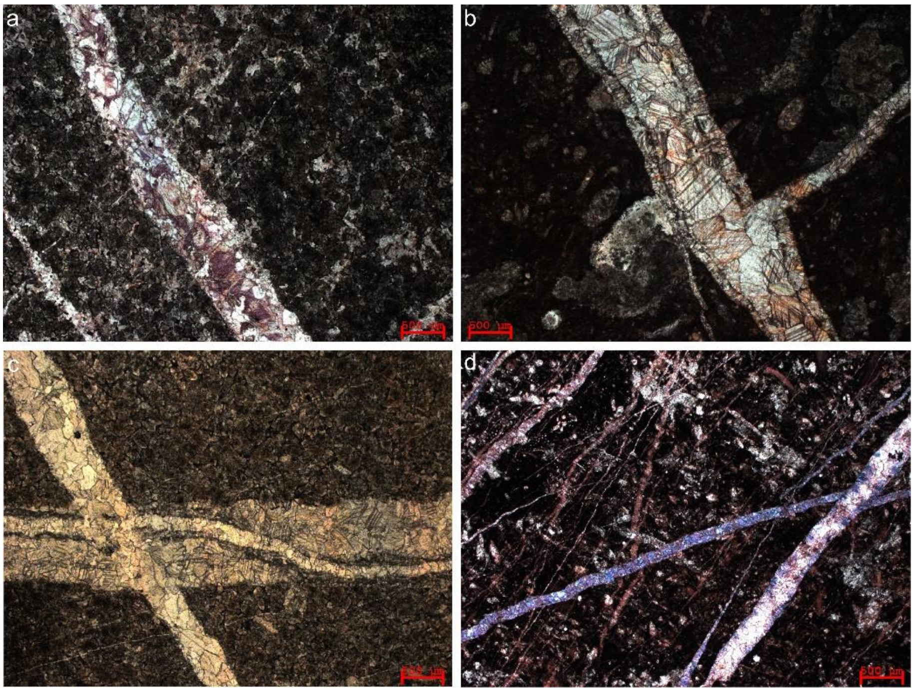

Figure 4 *Photomicrographs illustrating variations in limestone texture: a) multiple phases of cement and rock matrix, b) reactivated calcite vein, c) later smaller cross cutting calcite vein that also reactivated (re-entered) the earlier calcite vein, d) cross cutting veins with a number of microfractures in the matrix portion of the rock.*

orientation is divided into 4 trends as; 1) NNE-SSW, 2) WSW-ENE, 3) WNW-ESE and 4) NW-SE. Most of fractures were filled by calcite or another carbonate cement. Together with the calcite vein samples, matrix portions of the rock were also collected for isotope analysis with the assumption that the matrix likely preserved signatures indicative of the earlier burial trends of carbonates. Because of the highly deformed nature of some structures, calcitic bed-parallel slippage precipitated and filled space in between thin limestone beds deformed by thrusting and folding. Some samples were taken from striated surfaces with calcite coatings, a texture that is typically seen in section 5 and 6. For defining the rainfall-dominant end of a meteoric mixing trend, speleothems samples were collected and prepared for isotope analysis.

Samples of matrix in the study area show only more negative oxygen isotope, that almost all < -10 ‰. The lack of less negative oxygen value in matrix samples likely caused by pervasive matrix re-equilibration, indicated by the abundance of microfractures noted in several petrographic samples. The large cluster of isotope values are seen in figure 6 comes from calcite-filled fractures with NNE-SSW and WNW-ESE orientations, as well as from the rock matrix. NNE-SSW fractures are predominantly associated with *en-echelon* tension gashes and give oxygen isotope value in the range -11 to -12 ‰ (yellow shading).

Both NW-SE fractures and bed- parallel slippage samples showed more negative oxygen value, with sample location associated with

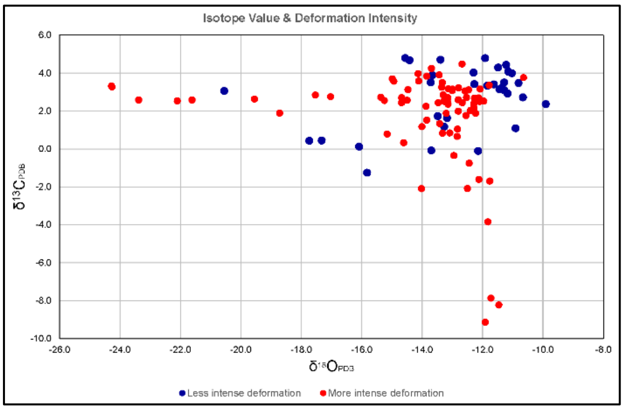

Figure 5 *Overall isotope plot related to the two structural styles in the study area, between less deformation zone (blue dot) in southern part of quarry (section 1-3) and a more intensely deformed zone (red dot) in the north of quarry (section 3-5).*

positions near the main thrusts and splay fault in the more intensely deformed zone (pink shading). Thin sections of the same samples show reactivated calcite veins and cross cutting relationships. The later hot fluid event is identified based on the presence of reactivation veins, which tend to be large sparry-calcite cement-filled fractures.

Carbon isotope value of some calcitic bed-parallel slippage and WSW-ENE small calcite filling fractures show separate clustered values tied to more negative carbon isotope, which decrease from +2 to 0 ‰. The samples have an organic-rich shale matrix which contributed to the decrease in carbon isotope values. It is noted that the low carbon isotope (0 to 1 ‰) and more negative oxygen isotope (-15 to -18 ‰) samples are also taken close to volcanic sill.

Generally, speleothem samples generate more negative carbon isotope with carbon values in the study area decreasing to -9 ‰. In addition, some slickenside-coating samples exhibit the same signature as the speleothems. Open fracture fills with NW-SE and WSW-ENE trends generated more negative carbon isotope values. Petrographic features in the same samples show evidence of multiphase fluid entry.

As shown, when isotope signatures are combined with rock textures and petrographic features, the C-O isotope plot field can be categorized as four clusters: 1) more negative oxygen isotope or hotter fluids, 2) clustered isotope value field, 3) transitional to more negative carbon isotope value field and 4) more negative carbon isotope field. NW-SE fractures and calcitic bed-parallel slippage show as two clustered plots: 1) hotter fluid and 2) transitional to more negative carbon isotope. Abundance of microfractures in the matrix is representative of several tectonic overprints and explains why all samples show oxygen isotope values that are < -10 ‰. While samples with more negative carbon isotope signatures relate to speleothems and calcite coats on slickenside (planes and lineation oriented in SSW and E) that were open to meteoric fluid entry.

4.Discussion

4.1 Isotope signature and diagenetic history

Based on the integration of rock texture and isotope values, there are two main relative timings that tie to earlier deformation episodes and reactivated deformation (fig. 6). Early deformation is a series of mid-mesogenetic events that encompasses the plot fields of

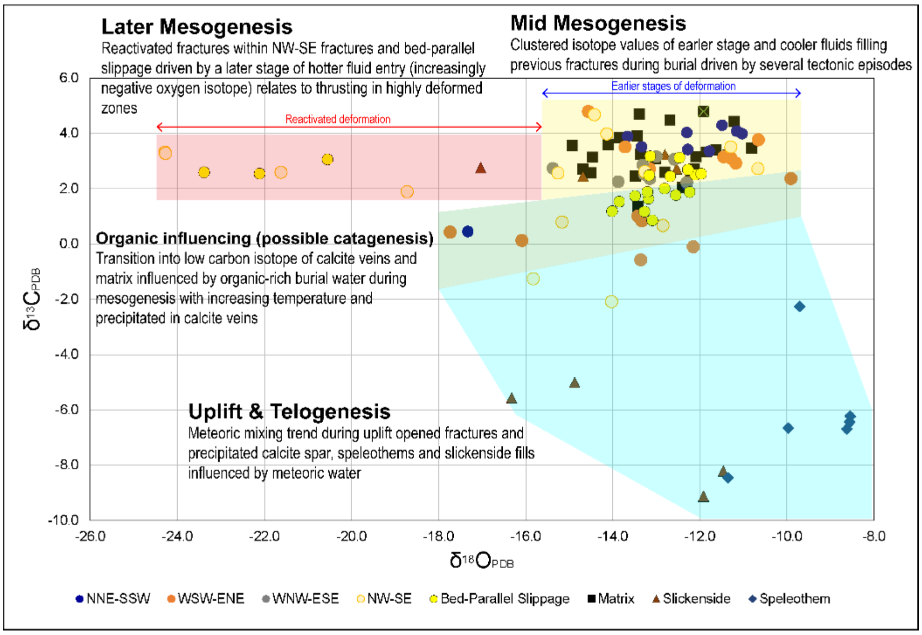

Figure 6 *Stable carbon-oxygen isotope plot after reorganization and categorization of texture associated with deformation style, can be divided into four zones as 1) Mid-Mesogenesis, 2) Later Mesogenesis, 3) Organic influenced (possible catagenic fluids) and 4) Uplift and telogenesis.*

clustered isotope value and transitional to more negative carbon isotope values (yellow and green shading in fig. 6). Structural reactivation is represented by fracture-focused entry into the later mesogenetic realm that created local migration pathways for hotter fluid precipitates, indicated by more negative oxygen isotope values (pink shading in fig. 6). Subsequent uplift driven entry into the telogenetic realm, allowed entry of meteoric water and during increasing exposure to surface fluids set up the isotopic mixing trend plot field (blue shading in fig. 6).

There is no presence of the signature of early burial (eogenesis to early mesogenesis of Warren et al., 2014) as the majority of oxygen isotope are lower than -10 ‰. Microfractures are abundant in the matrix and obvious in thin sections helping explain the more negative (warmer) values of all oxygen isotope values in the quarry. Clustered oxygen isotope values from -10 to -15 ‰ indicate mid-mesogenetic burial and the earlier stage of deformation with major fracture orientation in NNE-SSW and WNW-ESE directions. In addition, reactivated veins and samples with an abundance of microfractures plot with clustered isotope value field.

If bicarbonate from some form of organic matter is carried in burial waters, some isotope value of calcite will deviate from the clustered isotope value and transition into a more negative carbon isotope plot field. Precipitational timing is probably the same as the clustered isotope field of carbonates.

Calcites precipitated from hotter fluids are indicated by more negative oxygen values, and tie to later mesogenetic fluids. This group of hotter-fluid samples ties to zones of reactivated deformation. These calcite samples were taken in proximity to fold/thrust zones in the northern part of quarry.

The lower end of the meteoric mixing trend is mainly represented by speleothem samples. On the other hand, some of slickenside calcite coat samples also show more negative carbon values. Additionally, NW-SE and WSW-ENE opened fracture can show low carbon values that plot in the mixing trend, indicating some of these fractures were open during uplift.

4.2 Comparison with other areas

<u>Comparing with the Saraburi area</u>

C-O isotope plots from the Saraburi area show and evolving diagenetic history during both burial and uplift (Warren et al., 2014). Compared to isotope values in this study, there is no isotope signature to represent early mesogenesis (fig. 7). Overall oxygen isotope values are more negative than in the Saraburi area (< -8 ‰), largely because of the abundance of microfractures. The study area is located at the western margin of Indochina block, where it experiences high intensities of ongoing tectonic stress. Moreover, isotope plots from the study area are unable to define the burial trend seen at Saraburi as there is little preservation of transitional linear isotope fields. Clustered isotope values plot between the mid mesogenesis and thrust mesogenesis fields as defined in the Saraburi region. Furthermore, the transitional to more negative carbon isotope is clearly observed in the study area, but was not recognized in the Saraburi data.

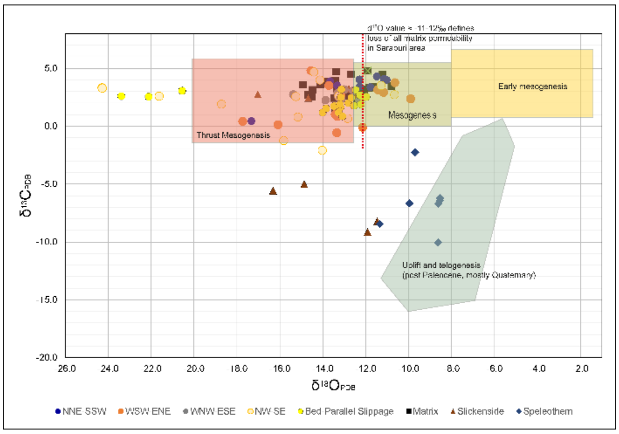

Figure 7 *C-O isotope plot comparison between study area (northern part of central Thailand and Saraburi area from Warren et al., 2014 (shown as shaded color polygons).*

<u>Comparison with other studies in Thailand</u>

C-O isotope signatures vary according to intensity of deformation and temperatures of associated fluids, which in turn depend on the position within a tectonic regime. C-O isotope plots in the Saraburi area (Warren et al., 2014) were initially chosen to represent Indochina isotope fields and compared to the Sibumasu area (Ng, 2017). However, when compared with

Saraburi area, the study area of Nakhon Sawan is located in a proximal position along the western margin of Indochina. Accordingly, the overall isotope value of this study shows more negative oxygen values than Saraburi (fig. 7, 8b) and no points are preserved that would represent early mesogenesis or early burial. Clearly, carbonates in Saraburi experienced less intense deformation and isotopic indications of some primary textures, such as bioclasts, are preserved, providing a less negative oxygen isotope range with the Saraburi burial trend beginning at -1.9 ‰ δ^{18}O. In contrast, the beginning of burial trend in this study is -9.9 ‰ δ^{18}O (fig 8c).

The Sibumasu continental block was subducted and buried deeper than the Indochina block and so experienced more intense deformation. Thus, primary texture is poorly preserved in such rocks. The point of transition into later mesogenesis is similar for both the Kanchanaburi and Ratburi areas, -16 to -17 ‰ δ^{18}O (fig 8a). This is similar to the Nakhon Sawan area. In contrast, the point of transition into later mesogenesis in the Saraburi area is around -13 ‰ δ^{18}O. Therefore, carbonates in Saraburi region experiences relatively cooler burial fluid temperatures compared to the other three area. Ng (2017) believed that Sibumasu was subducted and buried deeper, thus the later mesogenesis occurred at relatively higher temperatures. Likewise, the western margin of Indochina block, with its more intense deformation, as seen in the Nakhon Sawan area, has also experienced relatively higher fluid temperatures.

If we compare C-O isotope plots between Sin Phu Horm gas field and Saraburi area, it seems both areas are located in the Indochina terrane, but the gas field is distal from suture zone. Sin Phu Horm isotope signatures revealed two trends: 1) early burial deformation and 2) uplift with deep meteoric circulation (catagenesis) (fig. 8f). The isotopes values show that the reservoir carbonates did not experience later mesogenesis or thrust mesogenesis. Reservoir carbonates experienced later uplift that re-equilibrated some carbonate precipitates along a deep meteoric mixing trend (Panthong, 2015). Similarly, Chumphon (Nang Nuan field), the C-O isotope signatures shows similar burial trend as Sin Phu Horm (Lousuwan, 2005) (fig. 8d). Chumphon is located within Sibumasu block and away from the suture zone.

Conversely, the Suphanburi area is close to the suture zone (fig. 8e). C-O isotope plot fields show more negative oxygen values reaching to -31.3 ‰ (Bunpitaksakul, 2016). This attributed to more intense deformation, as it is closer to suture zone. However, there is still an uplift trend that created late stage meteoric-induced porosity.

The study of isotope signature in Nakhon Sawan area shows evidence of earlier and later deformation along the western margin of Indochina block. This result updates the regional picture of diagenetic history and extends the observations into to later mesogenesis when compared to the Saraburi area. Similarly, diagenetic history information at Suphanburi, which is located close to the eastern margin of Sibumasu terrane, also reveals hotter fluids, with temperatures that are even higher than in this study.

5. Conclusion

The study area is located in the northern part of central Thailand at the western margin of Indochina block and has experienced a high intensity of deformation. There are two structural styles exposed in the studied quarry face, 1) less intense deformation zone and 2) more intense deformation zone. There are two main fracture orientations in this area, NE-SW and NNE-SSW. Distinct rock texture and isotope signature show that Permian carbonate responded to this deformation by forming cross-cutting veins, reactivated fractures, fractures exposed to multiple phases of fluid flow and an abundance of microfractures in matrix portions of the rocks. Oriented observations of these features were combined with isotope data in order to categorize the diagenetic and structural history.

Based on the resulting stable carbon-oxygen isotope plot, NNE-SSW and WNW-ESE fracture trends retain evidence of single phase of fluid. In contrast, some fracture trends and fills

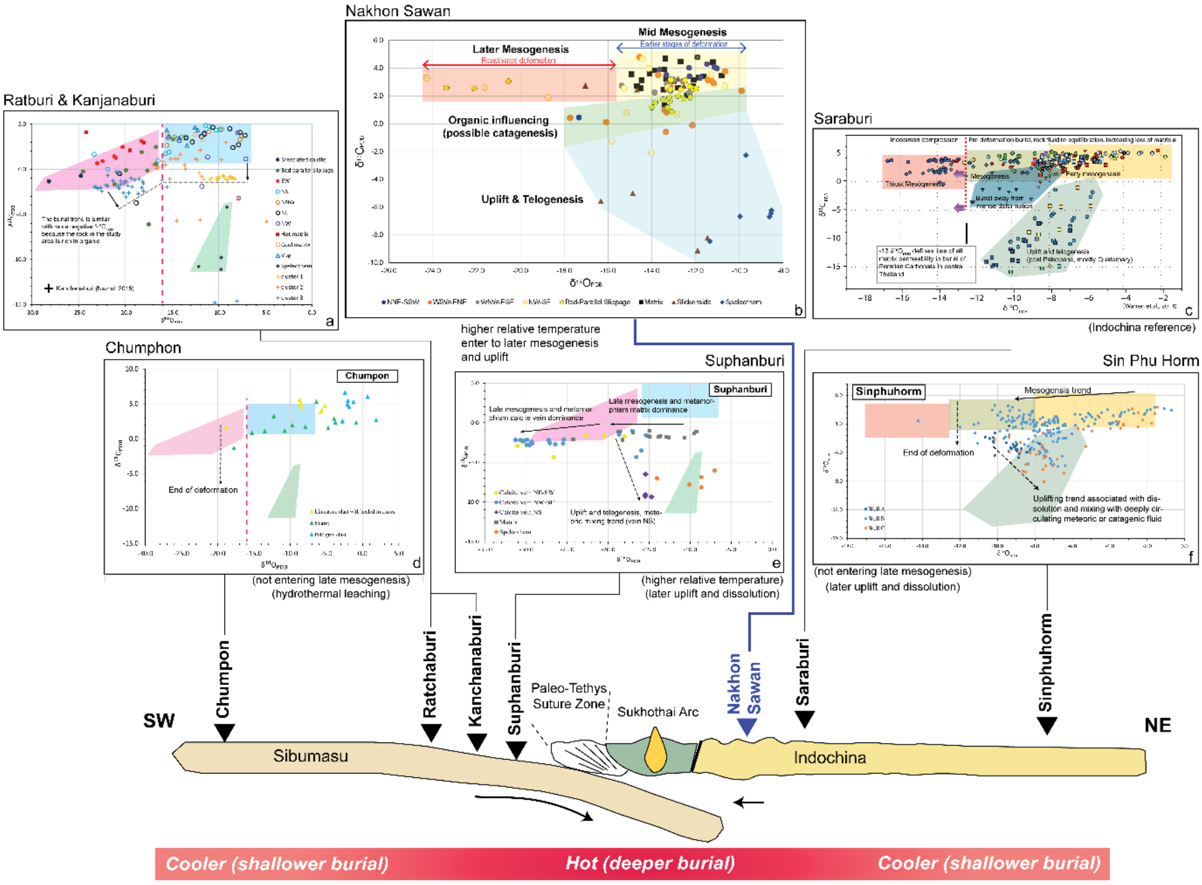

***Figure 8** Schematic diagram showing the relative positions on two tectonic blocks of the individual C-O isotope studies. Nakhon Sawan isotope plots are addded to this diagram showing more intense deformation with later mesogenesis and hotter fluids because the area is located proximal to western margin of Indochina block than the Sarburi region.*

preserve evidence of different stage of fluid evolution. For example, NW-SE fractures show textural and isotopic evidence of at least two stages of fluid evolution. Firstly, fractures were reactivated during later mesogenesis indicate by more negative oxygen isotope, a signature that is also seen in some samples collected from intervals of calcitic bed-parallel slippage. These reactivated regions occur within fold/thrust features in the high deformation zone in the northern part of the quarry. In addition, opened fractures with NW-SE and WSW-ENE trends were created during uplift allowing meteoric water to enter, dissolve and reprecipitate calcite as fracture fills. At the same time, the entry of meteoric water created porosity and permeability in uplifted carbonates.

Overall, oxygen isotope signatures in the study area indicate higher fluid temperature compared to other nearby areas, especially within Indochina block. That is isotopic evidence for early mesogenesis is absent when compared with same age carbonates in the Saraburi and Sin Phu Horm areas. The study area also experienced hotter mesogenetic fluids than either area.

Based on C-O isotope plot, the study area’s diagenetic history records two stages. Firstly, deformation with two main relative timings: earlier and reactivated deformations. The early deformation indicates a fluid history active during the mid-mesogenetic (as defined by Warren et al., 2014). Secondly, a later deformation event during late mesogenesis reactivated some fractures driving calcite precipitation from hotter fluids in re-opened fractures. Finally, a new set of opened fractures were created during uplift when meteoric water entry drove dissolution and calcite precipitation as fracture fills, slickenside coats and speleothems. Additionally, there was an organic matter influence on bicarbonate ions in some burial water which is capture by isotope signatures in samples plotting in the "transitional to more negative carbon isotope" field (indicating possible catagenic fluids).

7. Acknowledgements

I would like to express my deepest appreciation to all people involved in helping me to complete this research project. Firstly, I would like to thank PTT Exploration and Production Ltd. for the opportunity and a full scholarship to study in the M.Sc. Petroleum Geoscience Program at Chulalongkorn University. I honestly thank Prof. Dr. John Keith Warren for overall support and recommendations during my time working on this research project. As well as, I would also thank Prof. Dr. Christopher K. Morley giving me the opportunity to study in this area and his supervision in the field and giving of his broad knowledge of structural geology. Also, I must thank Asst. Prof. Dr. Thasinee Charoentitirat for her supervision and managing the budget that allowed the financial support for this study and giving me her ideas in terms of depositional setting.

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