NATURE AND RELATIVE TIMING OF BURIAL AND DEFORMATION OF SEDIMENTS AND METASEDIMENTS SOUTH OF THE INDOSINIAN SUTURE, RATCHABURI THAILAND: IMPLICATIONS FOR FRACTURED BASEMENT POTENTIAL

Ng How Sik*

Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand
*Corresponding author email: howsik93@gmail.com

Abstract

The relative abundances of the stable isotopes carbon-13 and oxygen-18 in a carbonate cement will change according to the fluid chemistry and temperature in the environment where it forms. Thus, a C-O isotope plot is used to indicate diagenesis history in a carbonate study. The same technique can be used with calcite veins to indicate the ambient environment during vein formation. Veins formed at different times in the subsurface experienced different fluids in the burial environments, thus will show different isotope signatures. Previous isotope studies in Thailand have grouped veins of different orientations under one category. This study classified veins according to their orientations in order to identify the relative timing of vein formation using the contrasting isotope signatures. Calcite veins samples are collected in two quarries in the Ratchaburi region of Thailand, and their respective orientations are measured, and timing relationships indicated by any crosscutting of veins are noted. Respective isotope values are then plotted in a C-O isotope plot and clustered according to vein orientation. Older veins tend to cluster together and are separate from younger vein clusters in the C-O isotope plot. The result is then checked with veins cross-cutting relationship to confirm the reliability of the interpretation. The relative timing of vein formation can be defined reliably with stable isotopes and so used to refine any structural analysis. The C-O isotope trend in Ratchaburi can be used as a comparison of relative temperature. When C-O outputs are compared to isotope results from other regions in Thailand, the result can be used to indirectly define relative positions in the Sibumasu and Indochina plates relative to the distance from the Indosinian suture belt. This isotope approach is also useful in studying diagenetic evolution n subsurface carbonates when only well cuttings are available. With a reliable burial curve to compare to, values from drill cuttings in Permian carbonates be used to estimate the age of the subsurface carbonate and infer a possibility of primary or secondary porosity.

Keywords: Carbonate, Isotope, Burial trend, Ratchaburi, Sibumasu

1. Introduction

Structural deformation creates fractures in rocks which are then filled with pore fluid, precipitating calcite veins. Fractures and calcite veins form parallel to the maximum resolved shear stress, $\sigma 1$. This is the common assumption in all kinematic analysis (Kaymakc, 2006). Different episodes of tectonic deformation have different maximum principal stresses, thus creating veins of different orientations. Under this assumption, this study tries to identify vein orientations belonging to the early Indosinian orogeny (Permo-Triasisic) and those of the more recent Paleogene event, respectively.

Increasingly negative $\delta^{18}O_{PDB}$ values of a calcite cement/vein is related to increasing temperature during burial deformation (Moore, 2001, Ahr, 2008, Warren et al., 2014). Progressive burial and deformation under higher temperatures leads to fractionation of oxygen isotopes in the pore fluid. Continuous fractionation of pore fluid causes it to have less $\delta^{18}O$. This is because $\delta^{18}O$ is left behind during each cycle of fractionation, thus more evolved and warmer fluid has more negative $\delta^{18}O_{PDB}$ value. More negative $\delta^{18}O_{PDB}$ values correspond to warmer pore fluid temperatures and indirectly tend to indicate deeper burial.

By combining vein orientations and $\delta^{18}O_{PDB}$ values, we can tell which orientations of veins formed under deeper burial and/or more intense deformation. These are the vein orientations tied to more negative $\delta^{18}O_{PDB}$ values.

The objectives of this study are: 1) To identify the relationships between vein orientation and relative temperature (indicated by $\delta^{18}O_{PDB}$ values). 2) To identify the vein orientations belonging to the early Indosinian orogeny and the more recent Paleogene event, respectively. 3) To compare and contrast the patterns of C-O isotope plots between Sibumasu and Indochina plates. 4) To better understand the influences of; type of deformations, intensity of deformation, and deformation history on the cluster patterns in C-O isotope plots.

2. Study area

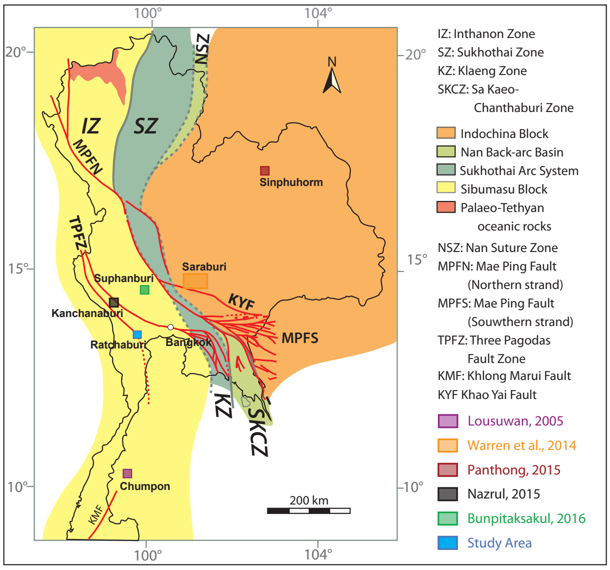

Figure 1. Location of study area and location of previous studies that are used.

Two major tectonic events affected Thailand; 1) Triassic - Early Jurassic Indosinian orogeny and, 2) Paleogene collision of Indian plate with Eurasia. Indosinian orogeny was the result of the merging of two continent blocks, carried by the Sibumasu and Indochina plates. During the Indosinian orogeny, the oceanic plate of Sibumasu was subducted under Indochina, continuing subduction eventually fused the Sukhothai island arc and Sibumasu with Indochina, forming Sukhothai Zone (figure 1). Sibumasu and Indochina are separated by Sukhothai suture zone (figure 1).

Starting from Early Eocene, the Indian plate begins to collide with Eurasia, ultimately creating the Himalayas. This collision also caused the formation of large-scale strike-slip faults across SE Asia (Tapponier et al., 1986). The result of this Paleogene event is the formation of Three Pagodas faults and Mae Ping faults (figure 1). The location of study area is within Three Pagodas Fault Zone (figure 1), near to the Sukhothai Arc suture zone. Figure 1 also shows location of previous studies that are used later in a comparison to refine our understanding of the isotope clusters as they relate to position on different tectonic plates and distance away from Sukhothai Arc suture zone.the isotope clusters as they relate to position on different tectonic plates and distance away from Sukhothai Arc suture zone.

3. Methodology

3.1 Isotope sampling

The purpose of isotope sampling is to capture a range of diagenetic events from early mesogenesis to late mesogenesis, including those of the Indosinian Orogeny and Paleogene Event. Vein orientations are measured and sampled. The textures sampled are matrix, vugs, veins, bed parallel slippage, bed parallel brecciated calcite and speleothem.

3.2 Cross-cutting relationship

The tested hypothesis is that earlier regional deformation (deformation caused by Indosinian orogeny) has a range of negative $\delta^{18}O_{PDB}$ values. Latest deformation (deformation caused by Paleogene event) can have more negative $\delta^{18}O_{PDB}$ in fault-focused vein positions. Regional Indosinian deformation has a range of values, in shallower burial the temperature of pore fluid is lower compared to deeper burial during intense orogenesis. From the cross-cutting relationship, we deduce that the oldest vein is NW, followed by NE, N-S, NNW, and youngest E-W.

By comparing the relative timing of veins with the isotope result, we can then test the hypothesis that veins formed earlier in shallower burial has lower pore fluid temperature (less negative $\delta^{18}O_{PDB}$).

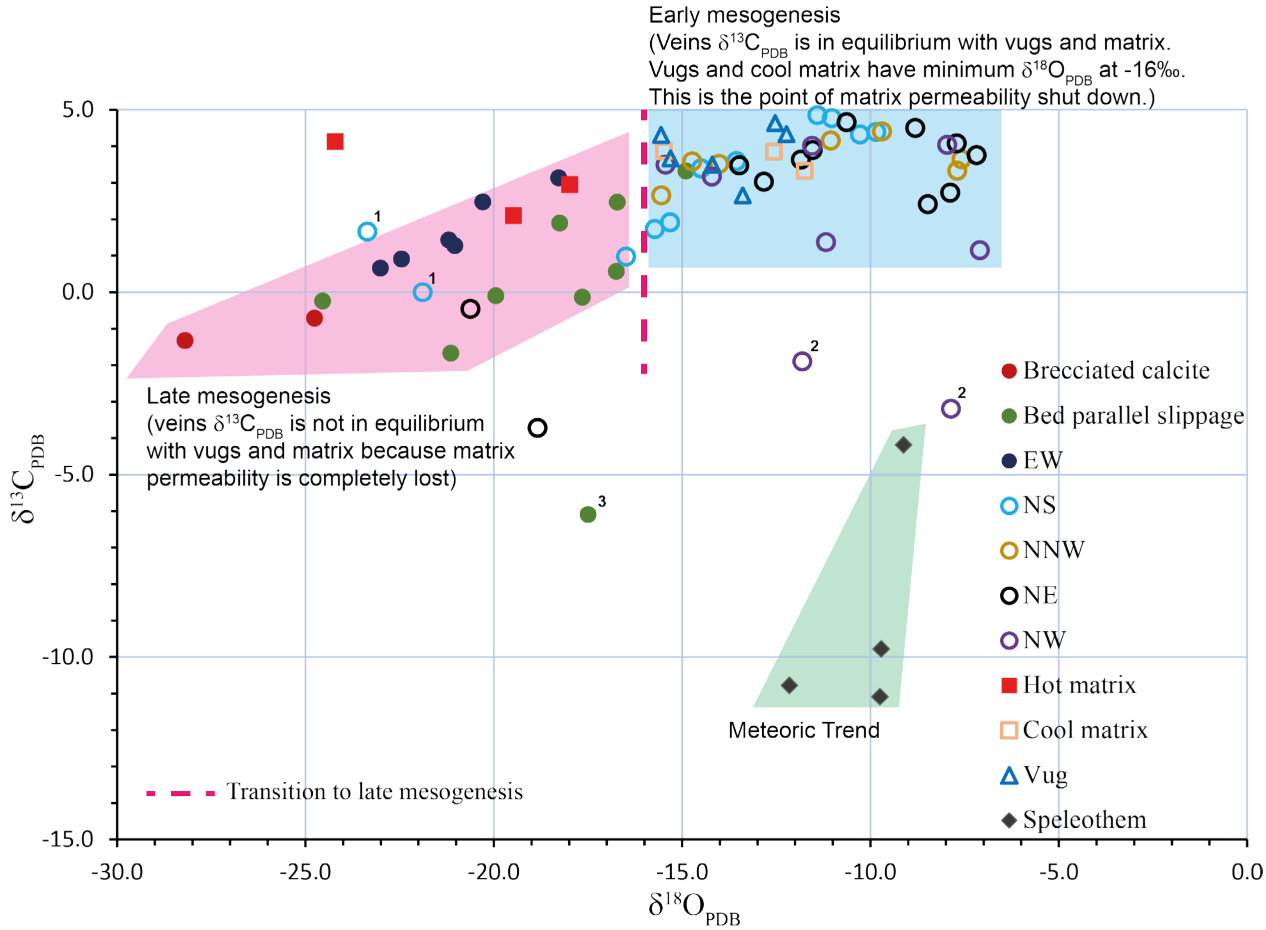

Figure 2. C-O isotope plot after reorganization. Labelled 1 are late N-S veins. Labelled 2 are samples affected by surface material. Labelled 3 is organically richer sample.

4. Discussion of isotope data

4.1 Isotope Signature of Vugs and Matrix

When carbonate is deposited, there will be porosity and permeability in vugs and matrix. Porosity and permeability allow fluid cross flow from matrix to vein and vein to matrix. This cross flow or fluid interaction between matrix and veins, allows $\delta^{13}C_{PDB}$ to be in equilibrium. When matrix, vugs and veins have similar $\delta^{13}C_{PDB,}$ this indicate that there was permeability that allowed the pore fluid to flow in between. Below -16‰ $\delta^{18}O_{PDB,}$ $\delta^{13}C_{PDB}$ shows increasingly negative trend (Figure 2). This means there was not sufficient permeability to allow cross flow between matrix and veins. The pore fluid that precipitated the hotter calcite veins likely had an increasingly catagenic influence tied to the heating of organic material. This catagenic influence is reflected by increasingly negative $\delta^{13}C_{PDB}$. Since the veins with values less than -16‰ $\delta^{18}C_{PDB}$ were not interacting with matrix, their $\delta^{18}C_{PDB}$ values are different. This also means that matrix lost its permeability in the presence of fluids precipitating calcites with values around -16‰ $\delta^{18}O_{PDB.}$ That is as deformation progressed until the pore fluid temperature corresponds to -16‰ $\delta_{18}O_{PDB,}$ rock matrix lost its permeability (permeability shutdown). As similar shutdown was documented in Warren et al., 2014.

4.2 Vein isotope and cross-cutting relationship

The hypothesis of this study is that older veins formed during Indosinian are cooler in pore fluid temperature and their $\delta^{18}O_{PDB}$ values will be less negative. This is because the burial of early-mid mesogenesis is shallower thus the temperature will be lower. The younger veins, formed during the Paleogene Event can be warmer

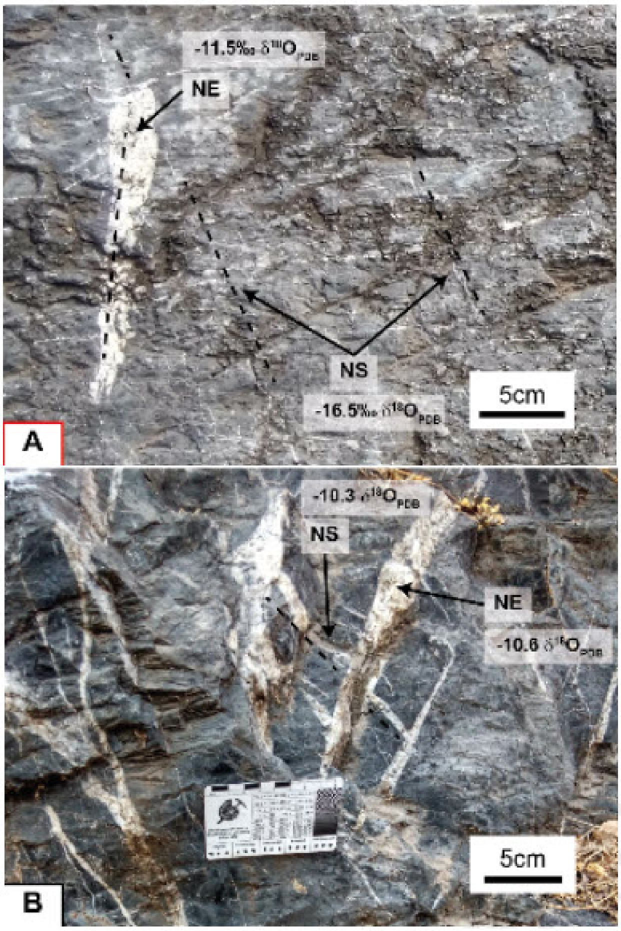

Figure 3 A) Younger NS vein cuts across NE vein B) Older NS vein cut by NE vein.

in their pore fluid temperatures, that is show more negative $\delta^{18}O_{PDB}$ values, especially in the vicinity of fault-focused hydrothermal fluid flows. This is because 1) burial of late mesogenesis is deeper and hotter in collision belts and 2) in transtensional fracture belts there are deep-seated faults that can focus the upward flow of hot fluids and so the temperatures in the vein calcites in or near the fault damage zones can be hotter than in adjacent rocks (Nazrul, 2015). Figure 2 shows that all E-W veins have $\delta^{18}O_{PDB}$ below -16‰, and the cross-cutting relationship indicate that it is the youngest set of veins. NW, NE, NNW and NS veins are plotted above -16‰ $\delta^{18}O_{PDB}$, and they are older than E-W in cross-cutting relationship. However, notice that NS and NE have a few samples plotted below -16‰ $\delta^{18}O_{PDB}$ although the majority of the samples plot above -16‰ $\delta^{18}O_{PDB}$. They plot far away from the majority of veins with the same trends and obviously create different clusters from samples above -16‰ $\delta^{18}O_{PDB}$. If these samples are continuous in a plot trend then we might say they are one cluster, but in this case, there is a big gap between two clusters, above and below -16‰ $\delta^{18}O_{PDB}$.

Figure 3 shows two cross-cutting relationship between NE and NS trending veins. In figure 3a, a thin NS vein cuts across a NE vein. The thin NS vein has a -16.5‰ $\delta^{18}O_{PDB}$ value, while NE vein has a -11.5‰ $\delta^{18}O_{PDB}$ value. The late warmer NS vein cut across older NE vein. However, in figure 3b, the thick NS vein is cut by a NE vein. Their $\delta^{18}O_{PDB}$ values are -10.3‰ for the NS vein and -10.6‰ for the NE vein. This example shows that in one case the NS vein cuts across the NE vein and in the other case the NE vein cuts across NS vein. Notice that when the younger NS vein cuts across the NE vein, the NS vein has a warmer isotope signature at -16.5‰ $\delta^{18}O_{PDB}$. When NE vein cut across the older NS vein, the NS vein has a cooler isotope signature of -10.3‰ $\delta^{18}O_{PDB}$. This is consistent with our hypothesis that younger vein has warmer isotope signature.

The reason that there are younger NS vein and older NS vein is that there are two episodes of opening of veins in NS direction; an earlier opening of NS veins when the fluid is cooler, and a later opening of NS vein trends when the pore fluid is warmer. When checked against the texture, the warmer NS vein samples are all consistently thin veins, while the cooler NS samples are thicker veins. This probably give us the explanation of two isotope clusters with the same vein orientation, that is two temperature-separate, and likely also time-separate, episodes of vein opening in same direction.

4.3 Evidence from thin section

Despite intense deformation in most of the outcrop, there is a corner outcrop with small patches of dolomitic clasts encased in calcite cement. The dolomitic clasts are fine grained with no porosity, and they are not cut by later veins. The calcite cement completely encases the dolomitic clasts showing the cement is later than the dolomitic clasts, which are derived from a tectonically-brecciated dolomite. The muddy fine-grained dolomite in the clasts seems to have lost permeability and porosity at some time soon after deposition. There is no evidence of ongoing dolomite recrystallisation and thin sections show there are no microveins or calcite cements within the dolomitic clasts. Their isotope signatures show that the dolomitic clasts retain a cooler $\delta^{18}O_{PDB}$ range of values from -2.9 to -4.9‰ (range extends over three samples). These dolomite clasts values are the coolest values in the study area database and are closer to a Permian seawater value. The cement enclosing clasts or "matrix" is actually a mixture of fine dolomitic grains and calcite spar cement. It has an intermediate $\delta^{18}O_{PDB}$ range of -9.5 to -11‰, while the late calcite spar cement has a warmer $\delta^{18}O_{PDB}$ range of -14.3 to -16.9‰. Once again this shows that a younger fluid has a warmer isotope signature.

4.4 Isotope samples with values below -16 $\delta^{18}O_{PDB}$

EW veins, bed-parallel slippage and bed-parallel brecciated calcite samples show values that are below -16‰ $\delta^{18}O^{PDB.}$ They show a significant increasingly negative trend in $\delta^{13}C_{PDB,}$ in contrast with the samples above -16‰ $\delta^{18}O_{PDB}$ value, which have a flat-lying trend in terms of $\delta^{13}C_{PDB.}$ They have a warmer pore fluid signature (more negative $\delta^{18}O_{PDB}$), and likely formed after the matrix permeability shutdown (indicated by the negative trend of $\delta^{13}C_{PDB}$). This indicates that the vein calcites formed in later mesogenesis, when the temperature was relatively high and the rock matrix had already lost its permeability. Thus we can say -16‰ $\delta^{18}O^{PDB}$ is the point where late-stage mesogenesis begins. It is also defined as the value where samples plotting to the left of this (more negative) must have experienced complete matrix permeability shutdown.

4.5 Veins and their corresponding tectonic events

Bed-parallel slippage and bed-parallel brecciated calcite were formed by strike slip movement between bedding surfaces. The bedding is NW-SE, consistent with the strike of Three Pagodas Faults. Since bed-parallel slippage and bed-parallel brecciated calcite samples relate to movement on the Three Pagodas Fault, and the samples show values and orientations that are relatively hot and recent, calcites in these samples are interpreted as forming during strike slip movement in a NW-SE direction, likely tied to movement of the nearby Three Pagodas Faults (Paleogene event; Figure 1).

EW and some NS and NE veins have values below -16‰ $\delta^{18}O_{PDB,}$ so they are relatively high temperature precipitates, but I am not sure whether they belong to the Paleogene event or the Indosinian orogeny. This requires regional stress field analysis, which is beyond the scope of the current project. Although this study cannot conclude the actual tectonic events responsible for respective vein sets, it helps better define the problem.

First, this study separates more recent EW vein from the others. Second, this study identifies two episodes of NS and NE veins, this is important in stress field analysis. Third, this study identifies older NW and NNW vein trends. Finally, bed parallel slippage and brecciated calcite are likely to be formed by Three Pagodas Fault (Paleogene event).

It is very important to note that the reliability of this study depends on the number of samples collected. For example, EW veins consistently plot below -16‰ $\delta^{18}O_{PDB,}$ but we cannot be absolutely sure that there is no older, cooler EW vein with $\delta^{18}O_{PDB}$ above -16‰. Maybe there are older EW veins but we did not encounter it in the current study area. Again, the conclusion made in this study is based on the results in an areally limited region. The more samples we collect, and the greater area we cover, the more reliable a plot of vein timing tied to vein orientation will become.

4.6 Summary of relationship between vein timing and relative temperature

The relative timing of carbonate-cemented veins can be reflected in a C-O isotope plot. During early mesogenesis, permeability is preserved, the older veins will have similar $\delta^{13}C_{PDB}$ with rock matrix and vugs, and less negative $\delta^{18}O_{PDB}$ (which is above -16‰ $\delta^{18}O_{PDB}$ in this study). During later mesogenesis, permeability is shutdown, the younger veins will have increasingly negative $\delta^{13}C_{PDB}$, and more negative $\delta^{18}O_{PDB}$ values (below -16‰ $\delta^{18}O_{PDB}$ in this study). A value of -16‰ $\delta^{18}O_{PDB}$ is regarded as the point of transition into later mesogenesis. In short, relative timing of veins formation can be reliably reflected in C-O isotope plot and we can also identify features of earlier and later mesogenesis from a C-O isotope plot.

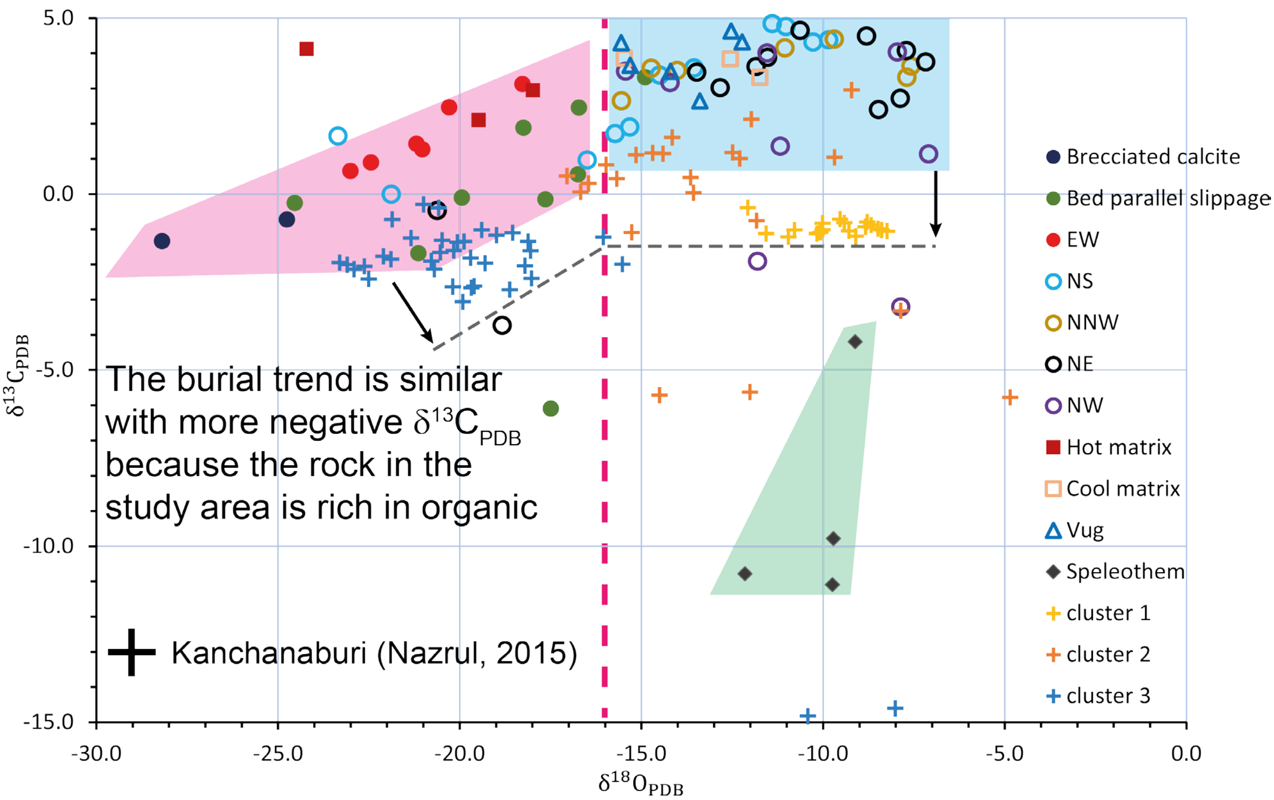

Figure 4. Comparison of Kanchanaburi with Ratchaburi isotope plot. Kanchanaburi (crosses in figure) has more organic content in the rock.

5.0 Comparison with other studies in Thailand

5.1 Is an isotope trend from Early Mesogenesis to Late Mesogenesis Real?

Figure 1 shows the location around Thailand of isotope studies with a vein-timing approach similar to this one. So, the result of this study is first compared to a study in Kanchanaburi (Nazrul, 2015). The study in Kanchanaburi and this study (Ratchaburi) are both located in Three Pagodas Fault Zone, Sibumasu. The only difference between the two studies is the rock type. Kanchanaburi centers on the Ordovician Manao Limestone while Ratchaburi focuses in the Permian Ratburi Limestone.

Figure 4 shows that Kanchanaburi has a parallel isotope burial trend with the Ratchaburi area. It also experienced the transition from earlier mesogenesis to later mesogenesis. Cluster 3 is made up of younger veins (NE-SW, ENE-WSW), while cluster 1 is made up of older veins (NW-SE, WNW-ESE). The result is consistent with this study where younger veins have higher relative temperature (more negative $\delta^{18}O_{PDB}$). The negative $\delta^{13}C_{PDB}$ trend also starts around -16‰ $\delta^{18}O_{PDB}$. Thus, the point of transition from earlier mesogenesis to later mesogenesis is around -16‰ $\delta^{18}O_{PDB}$, for both Kanchanaburi and Ratchaburi. Kanchanaburi has more negative $\delta^{13}C_{PDB}$ because of the higher organic content in Manao Limestone. The effect of more organic content in the Manao is similar in its effects to that in samples in the Ratchaburi area, where the more organic-rich vein had a more negative $\delta^{13}C_{PDB}$ value compared to the vein adjacent to it.

The isotope results of Kanchanaburi and Ratchaburi vein samples are is agreement, independent of the age of the limestone under study. The point of transition from early to late mesogenesis is similar at -16‰. This is because both areas are located in the Three Pagodas Fault Zone, Sibumasu, and both areas experienced a similar deformation history and intensity.

5.2 Factors Influencing Isotope Trend

Regionally, isotope burial trends will vary from location to location and relate to differences in geothermal gradient and vein timing. However, the fundamental concepts remain the same. Increasing relative temperature is indicated by increasing negative $\delta^{18}O_{PDB}$, increasing organic influence is indicated by increasing negative $\delta^{13}C_{PDB}$. From the comparison with other studies discussed next, the isotope trend is influenced by:

1. The type of deformation (subducted vs obducted)
2. The intensity of deformation (distance away from the suture zone)
3. The history of deformation (undergo uplifting vs without uplifting)

5.3 Influences of Type of Deformation (Sibumasu vs Indochina)

During the Indosinian orogeny, the Sibumasu plate was subducted beneath the Indochina plate (figure 1). Thus, Sibumasu and Indochina experienced different types of deformation. Sibumasu plate experienced more downward flexure and so was buried relatively deeper, while Indochina experienced folding and thrusting, but remained as the overlying plate. Figure 5 shows the isotope plot of Sibumasu (Kanchanaburi and Ratchaburi) and Indochina (Saraburi; Warren et al., 2014).

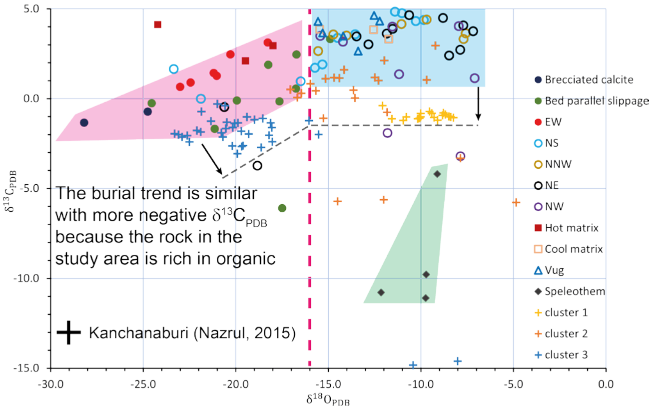

Figure 5. I. = Indochina, S. = Sibumasu. The point of transition from earlier to later mesogenesis of Sibumasu is indicated by a slightly more negative oxygen value than Indochina.

The burial trend and meteoric mixing trend are similar for both Indochina and Sibumasu. As $\delta^{18}O_{PDB}$ becomes increasingly negative, $\delta^{13}C_{PDB}$ also become negative. This is common to episodes of continuous ongoing burial or deformation. The meteoric mixing trend has more negative $\delta^{13}C_{PDB}$ because of organic influence from the surface, brought in to the precipitation site by bicarbonate carried by groundwater or meteoric water. $\delta^{18}O_{PDB}$ values in a surface-fed meteoric mixing trend are less negative because of lower fluid temperatures compared to the mesogenetic realm.

Based on the high temperature extent of their respective burial trends, it seems Indochina experienced less intense deformation and many some primary textures such as bioclasts are preserved, so giving a less negative $\delta^{18}O_{PDB}$ range. $\delta^{18}O_{PDB}$ at the beginning of burial trend is -1.9‰. The Sibumasu plate, on the southern side of the Indosinian suture was subducted and buried deeper and so experienced more intense deformation. Most of the limestones in the study area are recrystallized with many approaching metamorphic textures. Thus, little primary texture remains, although the least negative $\delta^{18}O_{PDB}$ value is -2.9‰ and preserved in a fine-grained (not coarsely recrystallized) dolomite clast.

The point of transition into later mesogenesis is similar for both Kanchanaburi and Ratchaburi. In contrast, the point of transition into later mesogenesis is less negative in Saraburi, at -13‰ $\delta^{18}O_{PDB}$ (Figure 5). This indicates that late mesogenesis in the Saraburi region occurred at relatively lower temperatures compared to Kanchanaburi and Ratchaburi. This is because Sibumasu was subducted and buried deeper, thus the later mesogenesis occurred at relatively higher temperature.

Notice that there is overlapping of late mesogenesis and early mesogenesis in the Indochina isotope plot (figure 5, dashed box). The reason for overlapping of late and early mesogenesis samples is that the veins are grouped as one category during sample collection and analysis. Vein orientations were not the main objective of study in Warren et al., 2014. All veins are classified as late mesogenetic regardless of orientations, thus earlier and later veins are grouped as a late mesogenesis texture. The veins isotopes in dotted box are probably early veins with cooler isotope signatures. This is the likely reason that they plot among earlier mesogenesis samples. The concept of early and late veins was discussed in a previous section. If this approach had been applied in the Warren et al. (2014) study, the separation and relative temperature field plots could have been less confused.

In summary, the isotope burial/deformation trend is consistent in both Sibumasu and Indochina with different $\delta^{18}O_{PDB}$ values at point of transition into late mesogenesis. The relative temperature of Sibumasu (subducted plate) during deformation is higher than Indochina (obducted plate)

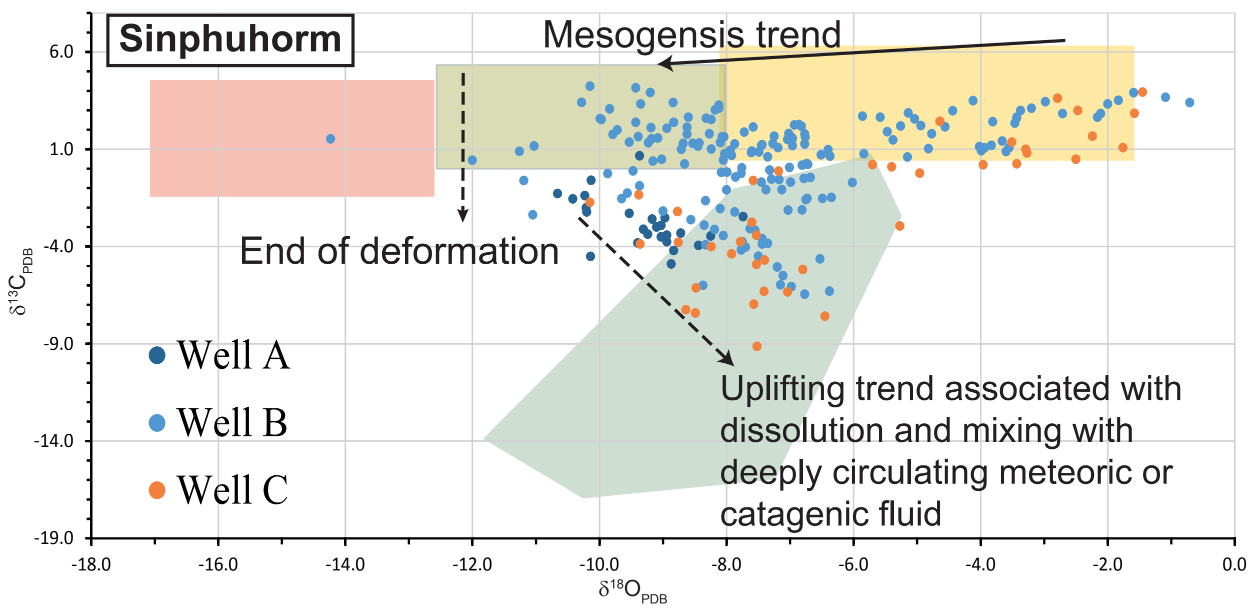

Figure 6. Isotope plot in Chumpon (Nang Nuan field) with Ratchaburi shading as reference. Deformation in Chumpon did not enter late mesogenesis (Lousuwan, 2005).

5.4 Influences of Deformation Intensity and Deformation Histories

After a comparison across two continental plates, we will now do a comparison from different locations within a continental plate. This is to see the effect of deformation intensity and deformation histories on the C-O isotope plot in locations nearer and farther from a sutured plate edge. Locations closer to the suture zone will experience a higher intensity of deformation, while locations further away from the suture zone will have lower intensity of deformation. In terms of longterm deformation histories, some locations in a plate can experienced later uplift, while others do not. These differences can be seen in the following comparisons.

5.4.1 Intensity of Deformation

Typically Indochina (obducted) plate has less negative $\delta^{18}O_{PDB}$ values, while Sibumasu (subducted) has more negative $\delta^{18}O_{PDB}$ values. In this section, the comparison is done with the same continental plate to isolate the influences of different type of deformation (obducted vs subducted).

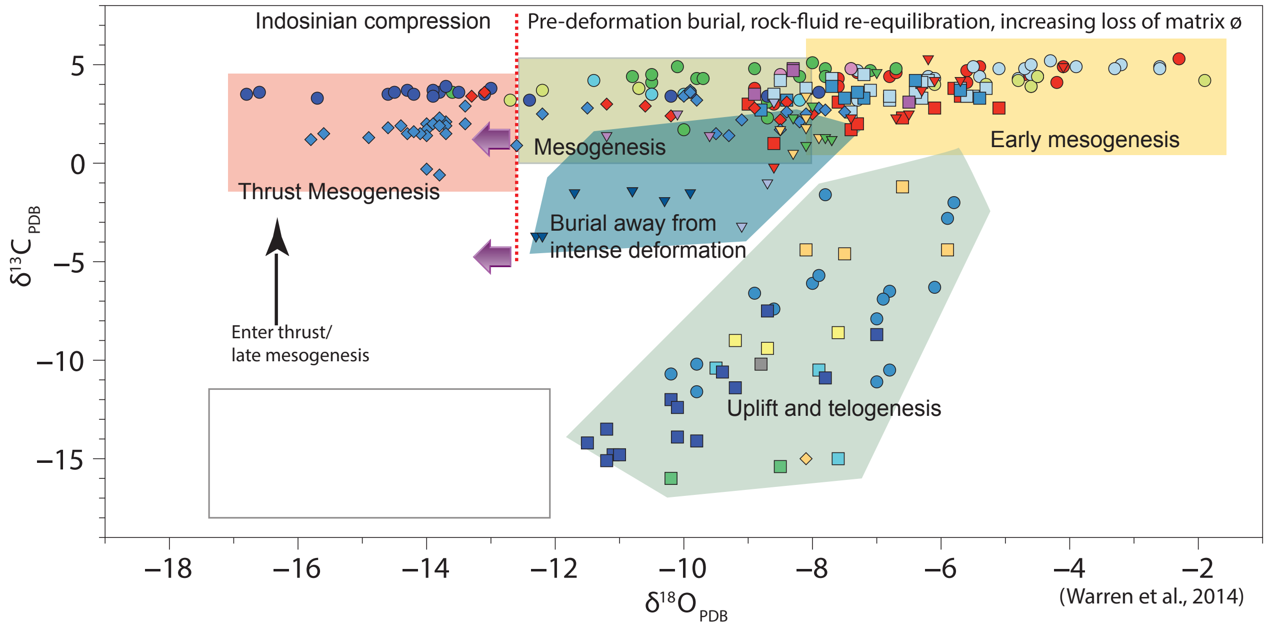

Figure 7. Isotope plot in Saraburi. Showing transition from early mesogenesis to thrust/late mesogenesis (Warren et al., 2014)

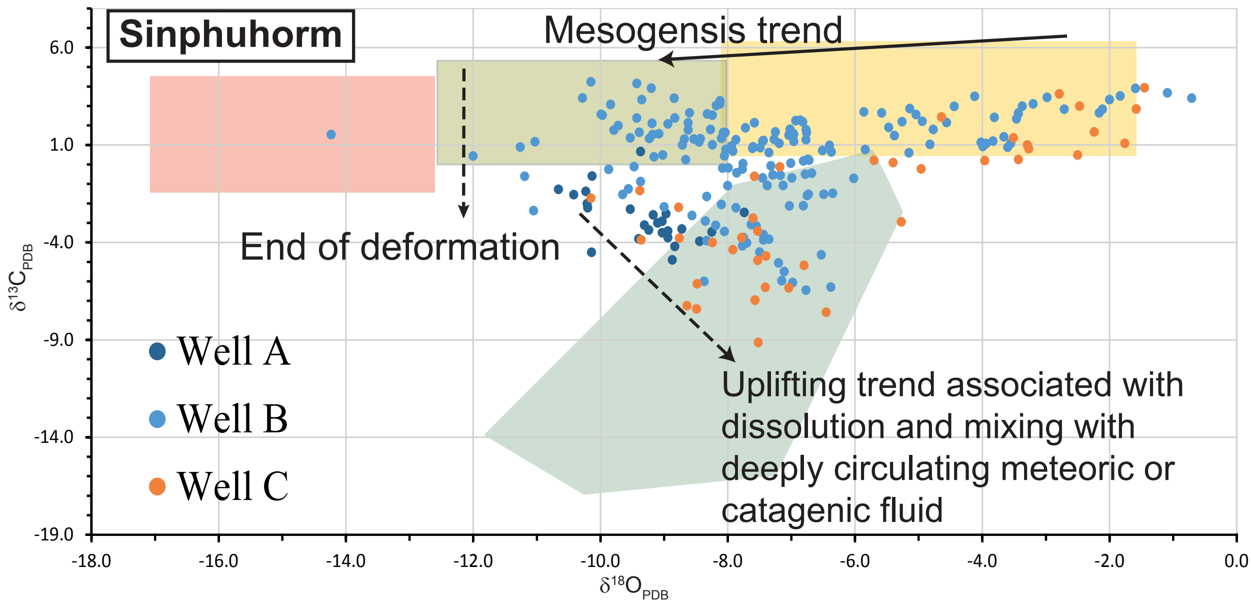

Figure 8. Isotope plot in Sinphuhorm field with Saraburi shading as references. Deformation in Sinphuhorm did not enter late mesogenesis. Shows an uplift trend in the deformation history (Panthong, 2015).

Figure 6 shows the isotope burial deformation trend in the Saraburi region (after Warren et al., 2014). The shadings represent stages of diagenesis in Saraburi, showing transition from early to late mesogenesis. The shadings from Saraburi isotope plotfields are overlain with the Sinphuhorm isotope plot to give a direct comparison. Figure 7 shows the cooler parts of the burial deformation trend exist in Sinphuhorm field. Sinphuhorm is located in northeastern of Saraburi, far away from the suture zone (figures 1 and 10). Unlike Saraburi, the burial deformation trend in Sinphuhorm does not extend into late/thrust mesogenesis (figure 7). This implication is proven by poroperm textures in the cores from Sinphuhorm which preserve vuggy porosity and detailed bioclast textures. This is because deformation less intense away from suture zone and so at Sinphuhorm the burial signature is preserved in the isotope plot without a strong structural overprint. Thus, carbonate in Sinphuhorm did not enter the realm of late/thrust mesogenesis. It did however experience later uplift that requilibrated some carbonate precipitates along a deep meteoric mixing trend (Panthong, 2015)

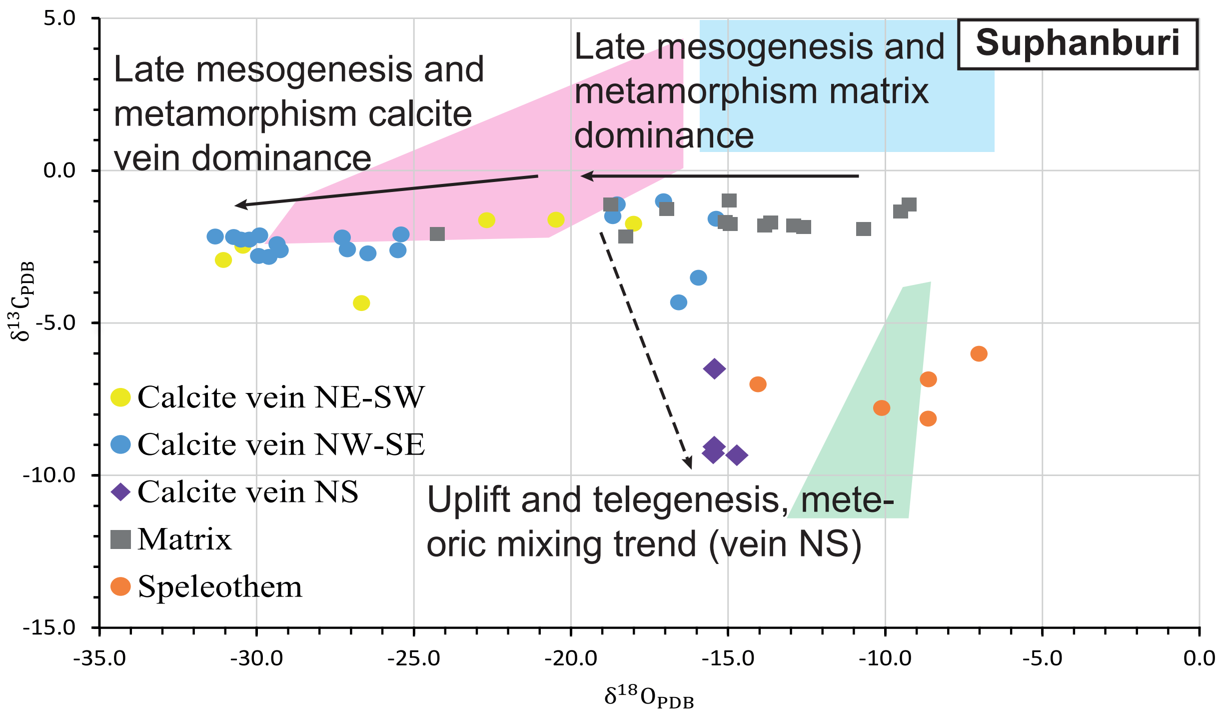

Figure 9. Isotope plot in Suphanburi with Ratchaburi shading as a common reference to this and Figure 9. Minimum $\delta^{18}O_{PDB}$ in Suphanburi is more negative than Ratchaburi. It shows an uplift trend in the deformation history not defined in the Ratchaburi plot (Bunpitaksakul, 2016) .

Isotope data from Suphanburi and Chumpon (Nang Nuan field) are now compared with the Ratchaburi plotfield. Shadings representing stages of diagenesis in Ratchaburi are used as a reference in comparisons between locations. Chumpon (figure 9) shows similar burial effect as Sinphuhorm. The burial deformation trend does not extend into late mesogenesis. Chumpon is located far to the south of Ratchaburi, and so is some distance away from the suture zone (figure 1). Thus, the deformation intensity is lower and isotope values from the Permian carbonate reservoir indicate it did not experience late mesogenesis (as at Sinphuhorm).

Suphanburi is nearer to the Indosinian suture zone compared to Ratchaburi (figures 1 and 10). The minimum $\delta^{18}O_{PDB}$ values of Suphanburi are more negative than Ratchaburi (figure 9). Suphanburi has a minimum $\delta^{18}O_{PDB}$ value at -31.3‰, while Ratchaburi has one sample at -28.2‰. Suphanburi has more samples with negative values beyond -28‰ $\delta^{18}O_{PDB}$. This can be attributed to more intense deformation, as it is closer to suture zone.

Sinphuhorm, Chumpon and Suphanburi all show the influence of distance to suture zone via their values in $\delta^{18}O_{PDB}$ in a C-O isotope plot. Distance away from the suture zone influences the intensity and style of diagenesis. For example, Sinphuhorm and Chumpon did not enter late mesogenetic realm (indicated by the lack of a more thermally evolved set of calcites).

Locations closer to suture zone experienced more intense deformation, and thus show the evolution of their \carbonate precipitates into more negative $\delta^{18}O_{PDB}$ (more thermally evolved) isotope signatures.

5.4.2 Histories of Deformation

Isotope analysis across all areas show some locations experienced uplift later in their deformation histories, while others did not. Sinphuhorm experienced uplift and thus in addition to a burial trend has another isotope cluster or trend indicative of uplift tied to a deep meteoric mixing trend (figure 7; Panthong, 2015). In contrast, Saraburi does not have this uplifting Saraburi does not have this uplifting and deep meteoric mixing trend.

An uplift and deep meteoric mixing trend has increasingly negative $\delta^{13}C_{PDB}$ values sloping back into cooler (less negative) oxygen values. This indicates the deeply circulating meteoric waters or groundwaters have dissolved Permian carbonate. The resultant bicarbonateions, now in solution, mix with fluids from the surface and so precipitate new calcite with values that plot along the meteoric mixing line. The descending fluid circulation also brings bicarbonate tied to organic content from the surface, when these fluids precipitate new younger calcites they will possess more negative carbon values, compared to the adjacent Permian carbonate matrix. That is, an uplift isotope trend has less negative $\delta^{18}O_{PDB}$ because the depth of burial is becoming shallower and the temperature of the circulating pore fluid is also becoming less.

Similarly, Suphanburi isotope values also show an uplift and deep meteoric mixing trend (figure 8; Bunpitaksakul, 2016). Ratchaburi and Kanchanaburi do not show this uplift trend, probably because they did not experience uplift fluids related to transpression, while in the Three Pagodas Fault Zone. It is important to note that uplift and dissolution by meteoric water entry are the processes that create porosity in these heavily deformed carbonates. Both Sinphuhorm and Suphanburi are producing fields, and they derived their porosity from these processes. Chumpon (Nang Nuan field) is also a producing field, but it derived its porosity from hydrothermal leaching (Heward et al., 2000). In that field calcite is not precipitated during hydrothermal leaching, but siliceous sinters are (Lousuwan, 2005). Thus, Chumpon does not show a deep meteoric uplift trend, unlike Sinphuhorm and Suphanburi. These examples show that different deformation histories can be reflected in C-O isotope plots, even when using cuttings not core samples.

Figure 10 is a schematic diagram showing the relative position of individual studies and their respective C-O isotope plots. The purpose is to demonstrate the influence of position on different plates and distance away from suture zone on a C-O isotope plot.

6.0 Economic implications

Permian and Ordovician carbonate in Thailand once entering the late mesogenetic realms has lost all primary porosity and permeability. Studies in Suphanburi and Sinphuhorm (Bunpitaksakul, 2016, Panthong, 2015) documented porosity creation by later uplift and dissolution. Studies in Chumpon (Nang Nuan Field, Lousuwan, 2005) document porosity creation by hydrothermal leaching. This study in Ratchaburi did not observed visible porosity in either outcrop and in thin section. The Permian Ratburi limestone in the Ratchaburi area is heavily deformed and recrystallized.

Heavily deformed carbonate needs later leaching or dissolution, in order regain economic levels of porosity and permeability. The deep meteoric mixing trend, coming from leaching and dissolution, is shown in figure 7 and 8. Secondary porosity coming from leaching and dissolution requires a different exploration and production concept compared to a carbonate platform depositional model. For example, the hydrothermal play concept in Chumpon (Lousuwan, 2005) predicts poroperm creation along fault zones. Thus the play concept is not related to a structural high but localized linear lows (Lousuwan, 2005).Similarly, poroperm derived from late stage uplift and dissolution require different exploration concept compared to a normal eogenetic to early

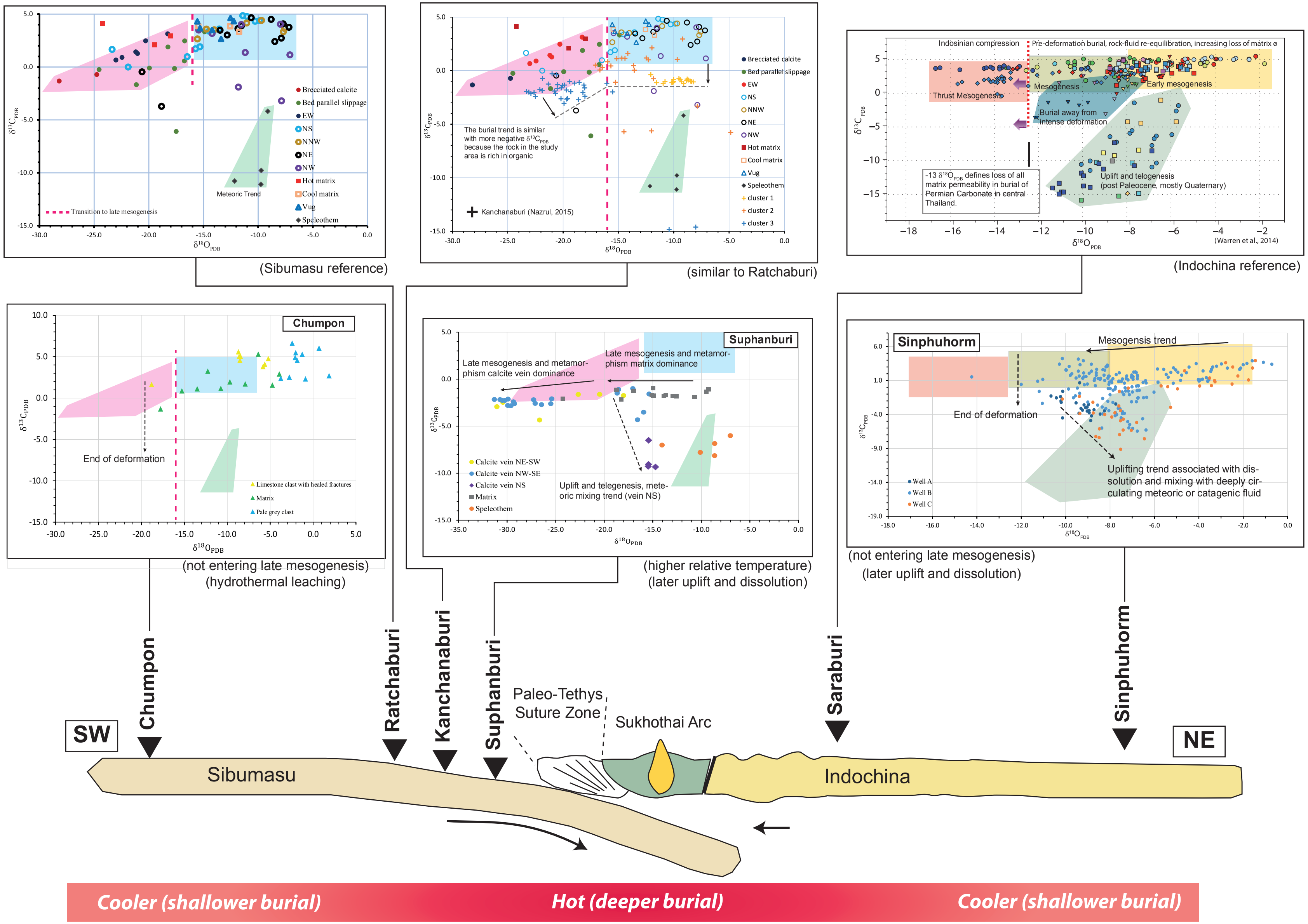

Figure 10. Schematic diagram showing the relative positions on tectonic plates of individual studies. The locations far away from suture zone (Sinphuhorm and Chumpon) did not enter late mesogenesis (less thermally evolved). Locations subducted (Ratchaburi, Kanchanaburi, Suphanburi) were buried deeper and thus have warmer isotope signatures compare to Saraburi.

mesogenetic dissolution reef model. Well logs (with appropriate corrections for porosity types) indicate a likely porosity value at a particular depth. But isotope analysis using well cuttings or core samples further refines our understanding of the mechanism of porosity creation and the likely distribution of the resulting porosity in three-dimensional subsurface space.

This study documented a typical burial deformation trend which can be used to reference burial style in Sibumasu plate. It can be used to compile comparisons that determine if the potential carbonate reservoir has entered late mesogenesis. This can be done using samples coming from either cuttings or core. If reservoirs experience late mesogenesis, then a meteoric mixing trend (uplift and dissolution/telogenesis) is what we are looking for, if we want to identify targets in a background of otherwise tight massively-cemented carbonate.

The isotope burial trend from this study also helps in estimating the age of carbonate in Sibumasu plate, especially in subsurface reservoirs. For example, in Chaikajornwat (2017), the C-O isotope plot from this study is used in a comparison to cuttings values and deduces that basement rock is probably Permian carbonate, instead of Tertiary carbonate reef in the offshore Pattani Basin. This is because isotope signature of the basement rock is more thermally evolved, and in that study shows a similar range of negative $\delta^{18}O_{PDB}$ to those measured in Ratchaburi. In contrast, Tertiary carbonate reefs, if present, would experience less deformation and show less negative (less evolved) $\delta^{18}O_{PDB}$ isotope signature (not the case in Chaikajornwat, 2017).

7.0 Conclusion

The findings of this study are summarized as below

1. Relative timing of different orientations of veins can be characterized by a C-O isotope plot. In Ratchaburi, the older veins are > -16‰ $\delta^{18}O_{PDB}$ while the younger veins are < -16‰ $\delta^{18}O_{PDB}$

2. In term of the vein's relative timing, first, this study separates youngest EW veins from the others. Second, there are two episodes of NS and NE vein formation. Third, I identified older NW and NNW veins. Finally, recent bed-parallel slippage and brecciated calcite are probably formed during movements and fluid flows in conduits created by movement of the Three Pagodas Fault (Paleogene event).

3. Documented the transition from into late mesogenesis in C-O isotope plot of calcite cements, which can be used for relative thermal comparisons with limestones in other parts of Sibumasu.

4. The point of transition into the late mesogenetic realm in Indochina (obducted plate) is -13‰ $\delta^{18}O_{PDB,}$ and Sibumasu (subducted plate) is -16‰ $\delta^{18}O_{PDB.}$ Sibumasu enters the late mesogenetic realm at a higher relative temperature.

5. Locations away from the suture zone experienced less intense deformation and so have plotfields that indicate lower relative temperature (less negative $\delta^{18}O_{PDB}$). Carbonates in these areas generally do not enter stages of elevated temperature burial, which is typically related to zones of higher temperatures tied to late mesogenesis.

6. Locations experiencing uplift and telogenetic dissolution will be reflected in a meteoric mixing trend in C-O isotope plot. This meteoric mixing trend is important to indicate secondary poroperm in carbonates that have experienced late-stage mesogenesis (Suphanburi, Sinphuhorm, Chumpon).

9.0 Acknowledgement

I would like to thank Professor Dr. John Warren, Professor Dr. Joseph Lambiase and Mr. Angus Ferguson for the guidance throughout the programme. I would also like to thank Chulalongkorn University for the scholarship to enrol in this programme.

10. References

Ahr, Wayne M., 2008, Geology of carbonate reservoirs: the identification, description and characterization of hydrocarbon reservoirs in carbonate rocks. John Wiley & Sons.

Bunpitaksakul, T., 2016, Poroperm controls in outcrop analogs for "Ordovician" fractured carbonate reservoirs in the Suphanburi basin, western Thailand.: MSc thesis, Chulalongkorn University, Bangkok.

Chaikajornwat, P., 2017, Depositional and diagenesis character of carbonate sediments atop a subsurface basement high offshore Thailand: A new exploration paradigm for the region?.: MSc thesis, Chulalongkorn University, Bangkok.

Kaymakci, N. (2006). Kinematic development and paleostress analysis of the Denizli Basin (Western Turkey): implications of spatial variation of relative paleostress magnitudes and orientations. Journal of Asian Earth Sciences, 27(2), 207-222.

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

Moore, C.H., 2001. Carbonate Reservoirs e Porosity Evolution and Diagenesis in a Sequence Stratigraphic Framework, vol. 55. Elsevier, p. 444.

Nazrul, M., 2015, Fluid evolution through different deformation stages: a carbonate outcrop-based study in the western highland of Thailand.: MSc thesis, Chulalongkorn University, Bangkok.

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.

Tapponnier, P., G. Peltzer, and R. Armijo, 1986, On the mechanics of the collision between India and Asia: Geological Society, London, Special Publications, 19, p. 113-157.

Warren, J., C. K. 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, 55, p. 100-121.