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FLUID EVOLUTION THROUGH DIFFERENT DEFORMATION STAGES: A CARBONATE OUTCROP-BASED STUDY IN THE WESTERN HIGHLAND OF THAILAND

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Abstract

Veins offer the opportunity to study the burial and thermal evolution of rocks in complex geological settings. This study aims to determine the fluid evolution in Sibumasu block of Thailand in the context of structural deformation using a framework of texture-specific stable isotope sampling, controlled by field mapping and structural measurements. Structural measurements were taken and related rock samples were collected from two outcrops within the shear zone of the Three Pagoda Fault Zone (TPFZ). These meas-urements were then integrated via a combination of structural stereo plots, petrographic analyses and carbon-oxygen stable isotope determinations. Veins observed have wide-ranging orientations and show cross-cutting relationships. Vein orientations cluster into two groups: 1) sub-horizontal with NNW-SSE orienta-tions and 2) sub-vertical with ENE-WSW orientations. The cross-cutting relationships were validated by petrographic analysis. All veins are syntaxial and made up of different mineralogies (ferroan-calcite, calcite, dolomite and silica). Isotopes sampled from veins define three different data fields. These distinct isotope clusters relate to different vein orientations and ultimately are interpreted to be responses to different deformation events. Some of the isotopic signatures are consistent with established burial trend for the Indochina block of Thailand. Veins in clusters 1 and 2, are interpreted to have precipitated from fluids in a closed subsurface hydrological system where rock-fluid crossflows dominated. These earlier veins likely formed during deformation related to the Indosinian Orogeny. When all matrix porosity and permeability was obliterated in deep burial, fluid flow became confined to tectonic fractures. Veins in cluster 3 precipitated from hotter fluids in deep pressurised settings with no rock-fluid cross flow in the adjacent rock matrix. These fluids were probably derived from a deeper source. These cluster 3 veins have an isotope signature that may have formed in the early Palaeogene, concomitant with the Himalayan orogeny as India commenced docking with Asia. This created hot fluid crossflows in fracture sets created by transpressional deformation along the Three Pagodas fault.

Keywords: Stable isotope, structural evolution, Three Pagodas Fault

1. Introduction

Veins in outcrops present an opportunity to understand the geological history and subsurface palaeofluid systems. Most veins form by growth of minerals into voids created by fractures, hence veins are closely related to fracture mechanics and the timing of fluid crossflow. Understanding a fracture system, such as its orientation, timing and evolution is essential in exploring for and developing a fractured rock as a petroleum reservoir (e.g. Cuong and Warren, 2009) and in economically mining an ore deposit. More geologically realistic models can be built when relevant fractured outcrop analogues are available.

This project aims to investigate the structural and fluid evolution of veins in fractured carbonate outcrops in the Western Highland of Thailand

(Figure 1). Previously, a number of studies were conducted on the Indochina block, northeast of the suture in present-day Saraburi area (e.g. Warren et al. (2014)). The objective of this study are;

1) to establish an isotopic signature related to deformation on the Sibumasu block of Thailand, 2) to compare and contrast with the subsurface fluid evolution established for Indochina block and 3) to investigate the presence of Palaeocene fracture set based on field observation coupled with stable isotope trend and its implication to fractured basement analogue.

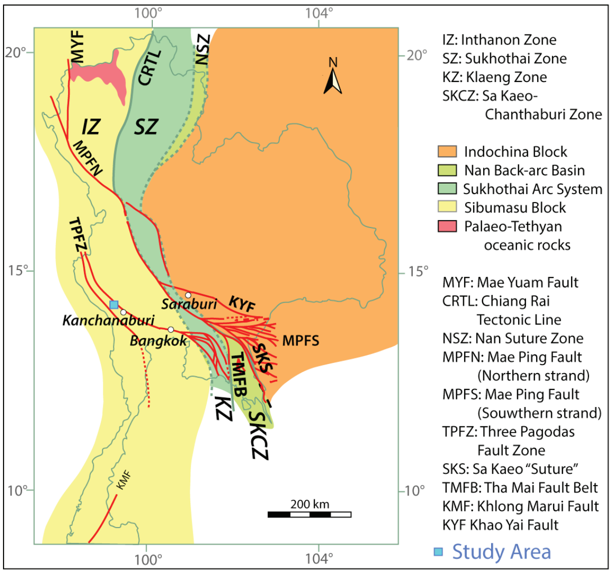

Figure 1. Geological map of present Thailand showing different tectono-sedimentary subdivisions. Study area is marked by a blue square.

2. Geological background

There are two main collisional periods that affected the geology of South-East Asia; the Indosinian Orogeny and a more recent Palaeocene collision associated with the docking of the Indian plate with the Eurasian block. The Indosinian orogeny in Triassic-early Jurassic assembled two major continental landmasses in Southeast Asia: the Indochina and the Sibumasu block. Evolution of the Indosinian Orogeny in Thailand involves Late Permian-early Triassic clo-sure of the Nan-Uttaradit-Sa Kaeo backarc basin, and collision of the Sukhothai Terrane with Indochina, followed by closure of the Palaeo-Tethys and collision of Sibumasu with combined Sukhothai-Indochina during the Late Triassic. The collision resulted in suture zones that run approximately North-South across Thailand, separating the Indochina block to the East and the Sibumasu block to the West (Figure 1).

The collision of India and Eurasia began in Early Eocene. Apart from the orogens such as the Himalayas that resulted from the collision, it also contributed to the evolution of large scale strike-slip faults across SE Asia (e.g. Tapponier et al., 1986). "Early escape" tectonic models proposed that as India hit Eurasia, the former acted as a narrow rigid body driving a lateral movement of the Eurasian continental blocks from the Himalayan collision zone (e.g. Molnar and Tapponier, 1975). This model requires a horizontal displacement of hundreds of kilometres along the strike-slip faults bounding the various blocks that extends far from the collision zone (Morley, 2002). Sundaland is bounded to the West by North-South striking Sagaing fault and to the East by the Northwest-Southeast striking Red River fault. Two large strike-slip faults trending approximately NW-SE, the Three Pagodas and Mae Ping Fault, cut across Sundaland and are both present in Thailand.

The field locations for this study are within the shear zone of the Three Pagodas Fault. Tapponnier et al. (1986) inferred that the main displacement on the Three Pagodas Fault was sinistral and, based on the offsets of Triassic granite belt in western Thailand, was on the order of hundred of kilometres. The left-lateral displacement of the fault is interpreted to have ceased around 33-30 Ma. Subsequently, the fault experienced right-lateral displacement, as manifested in three basins formed at releasing bends tied to this right-lateral displacement (Morley et al., 2011). These regional geological settings set up the framework for field observations and interpretations.

3. Field component

The studied outcrops are in the western highland of Thailand, Kanchanaburi Province. The outcrops are in an abandoned quarry

(14°23'45.41"N , 99° 8'32.61"E) and a road cut along Highway 3199 (14°14'0.97"N, 99°14'17.76"E).

The lithology at the quarry is composed of light to dark grey fine-grained grainstone. Grain components including fragmented bryozoans, crinoids, and algae were identified on thin sec-tion under the petrographic microscope. The outcrop at the roadcut is a light-grey, partly banded, mudstone. The white band minerals in the carbonate did not react when acid tested, and were later proven by XRD analysis to be siliceous. Calcispheres were observed in some samples in thin section. Along the road cut at 14°14'13"N 99°14'07"E, an indurated dark fine-grained rock was observed. It was weakly reactive to 10% hydrochloric acid, and XRD result later revealed that the dominant mineral constitu-ent is quartz, with trace of carbonate minerals. Speleothems related to the modern landscape were also observed at the roadcut outcrop and sampled for isotopic analysis.

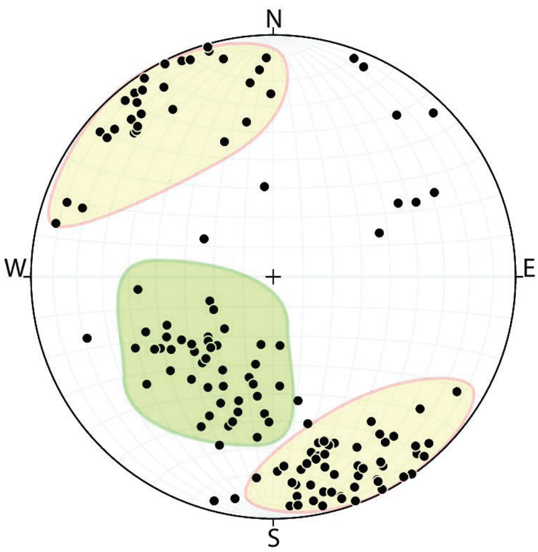

Figure 2. Orientations of the veins observed in field. Data is ploted as poles to planes.

The studied outcrops contain extensive arrays of veins which can be divided into two dominant trends: 1) sub-vertical, locally conjugated fractures, with an approximately northeast-southwest (NE-SW) orientation (Figure 2, yellow) and 2) sub-horizontal, trending approximately northwest-southeast (NW-SE) (Figure 2, green). Other veins have approximately east-west (E-W) and north-south (N-W) orientations. The order of the fractures formation is indicated by the observed cross-cutting relationship (Figure 3).

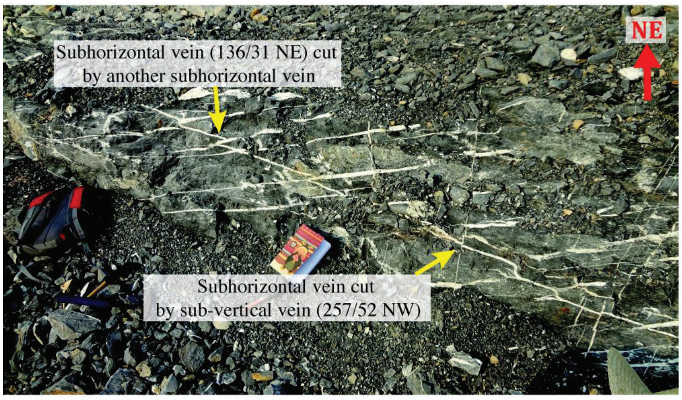

Figure 3. Cross-cutting relationship. Subhorizontal veins cut by younger vertical veins.

Calcite veins that lie along observed faults have slickensides that record the displacement direction of the faults. Veins along fault planes are thicker than along fractures. The observed faults tend to be oriented ENE-WSW and NW-SE, with slickensides pitching at low angles.

The bedding across the quarry outcrop dips uniformly north, at an average angle of 22 degrees. The road site area conveniently cuts through a set of clearly exposed beds, which dip in oppo-site directions on either side of the road: dip-ping East-Northeast and West-Southwest (ENE-WSW). The structure at the road site is interpreted as a tight antiform with a fold axis trending 04/153. At 14°14'13"N 99°14'07"E, a series of tightly-folded beds were observed with fold axis parallel to the interpreted fold axis at the road site. Veins at the fold hinge, probably associated with the folding event, were sampled for isotope study. Some parts of the vein fills were not reactive to acid, and are shown to be dominated by silica through XRD analysis. The maximum horizontal stress for the folding event is approximately in the East-West direction, and so is consistent with maximum horizontal stress being indicated by ENE-WSW trending veins, as was also observed at the roadcut outcrop. It is considered likely that these veins formed when the folding took place.

Boudinage structures and the associated veins were also observed at this location. At the core of the fold, boudins and the gaps are now filled with vein cements. The boudins are composed of carbonate (likely calcite), encapsulated in dark, brittle rock matrix that shows minimal reaction to acid (highly siliceous). The stretching that resulted in the formation of boudinage with associated veins infilling the gaps is likely to have formed simultaneously. The stretched layer of carbonate would have been more competent than the adjacent organic-rich, siliceous rock matrix. In parts of the outcrop where there is no variation in rock lithology, subtle pinch-and-swell structures were observed, with complex, randomly-oriented veins formed within the swell. Veins were not observed in layers that were not caught up in pinch-and-swell structures; instead a flowing texture was observed. The fact that the randomly-oriented veins are strictly constrained in the swell regions suggests this style of fracturing process was localised within the structure. The result of the isotopic sampling of these features are discussed later in this report.

Predating the formation of the boudinage, was the formation of linear features, as observed throughout the roadcut outcrop. The lineations are flat on bedding plane interfaces, and undulate across the swell structures. The exact timing of formation and folding related to the lineations is not clear, however the orientation of the lineations parallels the fold axis. The lineation is perhaps a stretching lineation, as its orientation is orthogonal to the maximum horizontal stress direction (approximately ENE-WSW) for the folding event.

4. Petrography

The minerals identified in the veins are: 1) calcite 2) dolomite 3) ferroan calcite and 4) silica.

The presence of multiple minerals in a single vein demonstrates that the fluid flow in the sub-surface from which the veins precipitated was polycyclic and likely occurred at different times in the burial history. Figure 4a is an example of a ferroan calcite (vein 1) cut orthogonally by a later calcite (vein 2). The same ferroan calcite vein is also crosscut by a later dolomite vein (Figure 4b). The three veins can be inferred to have formed at three different times and precipitated from three different phases of subsurface fluids. The order of the veins formation is firstly ferroan calcite vein, then dolomite and finally calcite veins. The formation of the ferroan calcite vein is likely to be at greater burial depths under a reducing environment, a condi-tion required for Fe ions to precipitate.

Open fractures provide spaces with high permeability, facilitating fluid flow, while fluid mixing, cooling or pressure changes lead to the precipitation of minerals in the veins. Permeability may not be completely destroyed, and allow further replacement or alteration. Figure 4b illustrates a dominantly dolomite vein (unstained) with patches of calcite (pink stained). Carbonate minerals have cleavages that may facilitate further flow advection. The cleavages of the dolomite have darker outlines, and the spreading of calcite into the dolomite crystals is closely related to the cleavage. Two phases of fluid flow could be inferred from this single vein: 1) Mg-rich carbonate fluid when the frac-ture was open and 2) carbonate fluid that seep through remnant permeability and along cleavage planes.

Siliceous veins are not very common at the quarry site. This could be due to a lack of siliceous content in the host rock. Siliceous minerals are seen to fill in voids between carbonate minerals and to fill new cracks within pre-existing veins.

Stylolites are present within the rocks and along vein edges from both the roadcut and quarry sites. In Figure 5, two sets of stylolite cut across each other at a high angle. The orientations of the two stylolites are different, indicating that they are not coeval and formed under maximum stresses from different orientations. The stylolites and the veins are likely to be closely related. Stylolite 1 postdates vein 1, and could be contemporaneous with vein 2. Both stylolites are aligned preferentially along the vein edges. It can be inferred that the vein-host rock interface became the zone for dissolution (as a result of pressure solution) and left insoluble residues along the former plane of contact between the vein and the host rock.

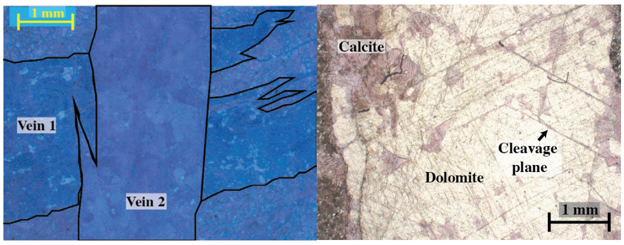

Figure 4. (a) Earlier ferroan vein cut by a later calcite vein. (b) Dolomite vein with clear cleavage planes. The pink-staine portion is calcite stained with Alizarin red-s.

5. Isotope

The isotope values in a carbon oxygen crossplot are covariant and the two outcrops plot at different levels in terms of $\delta^{13}C_{PDB}$ values (Figure 5). Samples from the quarry show more negative carbon values, compared to samples from the roadcut, which tend to have $\delta^{13}C_{PDB}$ values greater than 0%, with some exceptions.

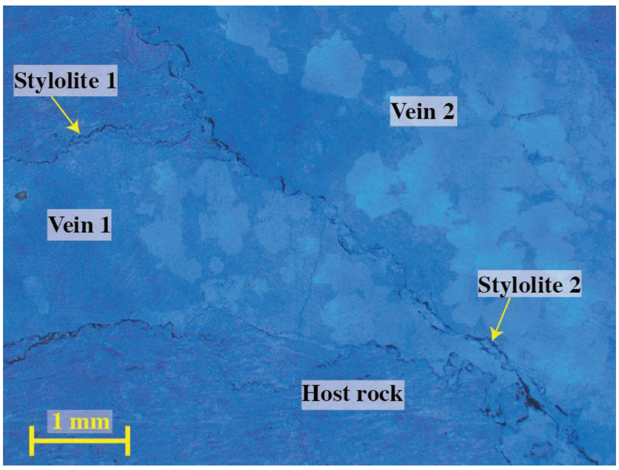

Figure 5. Two veins wit stylolite sutures that crosscut each other. The veins cut by the stylolites are calcite.

5.1 Host rock

Host rocks samples from quarry have $\delta^{18}O_{PDB}$ values ranging between -8 and -11%, and have $\delta^{13}C_{PDB}$ values in a narrower range between -0.5 and -1.5%. This may be explained by the less variation in the lithological composition, as observed in field and petrography analysis. In contrast, isotope data of host rock from the roadcut have wider range of carbon and oxygen isotope ($\delta^{18}O_{PDB}$: -5 to -19%, $\delta^{13}C_{PDB}$: 2 to -3.5%). This could be attributed to the greater variation in matrix composition, compared to the rock at the quarry. The host rocks from the roadcut generally have positive $\delta^{13}C_{PDB}$,
except three points with negative values (less than -2%). These samples with negative $\delta^{13}C_{PDB}$ values were drilled from host rocks that thin sections show contain elevated levels of organic matter. Thus negative carbon-isotope values in the roadcut calcites contain carbon likely contributed by the oxidation of organic matter. The samples with positive carbon-isotope values were collected from the cherty portion of the outcrop that thin sections show contains less or no organic matter. The four points that have $\delta^{18}O_{PDB}$ values <-14% indicate that the roadcut outcrop could have been buried deeper (warmer fluids at the time of calcite precipitation) than the quarry outcrop. Under thin section, these more oxygen-negative samples have a more recrystallised, almost marble, texture.

Speleothems were not abundant in either study area hence samples were limited. The $\delta^{13}C_{PDB}$ values from sampled speleothems range from -14 and -16%, suggesting negative carbon contributions from soil waters and other meteoric water percolating downwards during rock exhumation.

5.2 Vein systems

The samples collected from veins show a pronounced increasingly negative oxygen-isotope. The data points plot in three distinct clusters as follow (Figure 6):

1. Cluster 1 (blue shade): Veins samples with δ18OPDB values between -8% and

-12%, and $\delta^{13}C_{PDB}$ values between -1% to 3%)

2. Cluster 2 (green shade): Veins samples with $\delta^{18}O_{PDB}$ values between -8% and -13%, and $\delta^{13}C_{PDB}$ values between 0% and -2%)

3. Cluster 3 (red shade): Veins samples with $\delta^{18}O_{PDB}$ values between -18% and -24%, and $\delta^{13}C_{PDB}$ values between 0% and -3%).

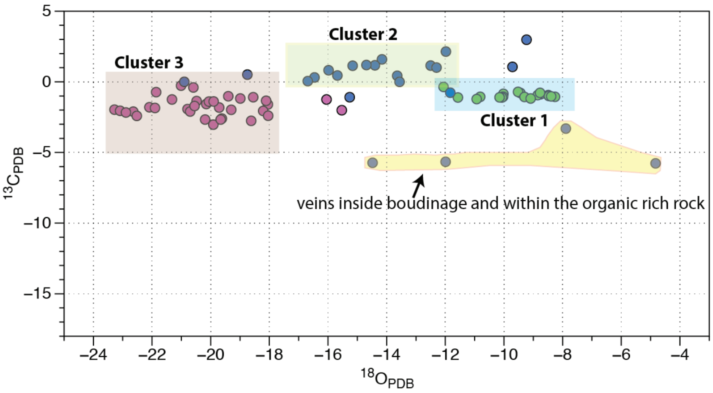

Figure 6. The carbon-oxygen crosplot of al veins.

Cluster 1 and cluster 2 have $\delta^{13}C_{PDB}$ and $\delta^{18}O_{PDB}$ values close to that of the host rocks in the roadcut and quarry, respectively. This sug-gests that there was a rock-vein crossflow, and the formation fluids were in isotopic equilibrium with local lithology at about the same temperature. This can indicate that the veins were formed by a simultaneous process of dissolution of the host rock and reprecipitation as veins in open fractures, generally referred as pressure solution (Dietrich et al, 1983). Pressure solution, manifested by stylolites, is not uncommon in the outcrop, and is observed and discussed in petrography section. This inference is supported by the observation that stylolites exist sub-perpendicular to veins. A stylolite plane forms perpendicular to the direction of maximum stress, while extension fractures form perpendicular to the minimum stress. These veins in the two clusters were likely formed in a closed system where there was an exchange between the rocks and fluids when matrix permeability was still present and simultaneous dissolution-redeposition process was ongoing.

The notion of a closed system is corroborated by the isotope points from boudinage-associated veins. The veins filling in the gaps between boudins, and solitary veins within the dark, organic rich rock surrounding the competent layers, have isotopic signatures close to the ad-jacent host rock. The fine-grained, organic rich lithology likely had minute permeability that would have hampered flow of external fluid. The veins are likely to precipitate from fluids locally derived, and in isotopic equilibrium with the local lithology.

Veins in cluster 3 have slightly negative values of $\delta^{13}C_{PDB}$ than the host rock at the quarry, and significantly more negative $\delta^{18}O_{PDB}$ values. The ^{13}C-depleted veins could have precipitated from low ^{13}C fluid generated by oxidation of reduced carbon during progressive heating. In the quarry outcrop, organic matter has been enriched at pressure solution seams (stylolites). The stylolites, as seen in thin section, occur at high angles to the veins, and any fracture crosscutting the stylolite would likely have access to CO_2 that was produced from the organic matter concentrated in the pressure seams. The low $\delta^{13}CCO_2$ was then mixed with fracture-filling fluids to precipitate calcite veins that have lower $\delta^{13}C_{PDB}$ relative to the host rock.

Another possible explanation is that the fluids forming the veins were allochthonous, transported from another site with slightly lower $\delta^{13}C_{PDB}$ values and considerably negative $\delta^{18}O_{PDB}$ values. In contrast to the veins in cluster 1 and 2 that were likely formed in closed system, the veins in cluster 3 could have formed in an open system, which allow externally sourced fluids to migrate in and mix. This inference is supported by the fact that many isotope points in cluster 3 were sampled from thick veins associated with fault planes. The fault may have introduced a significant perme-ability pathway that allowed fluid with anoma-lously low $\delta^{18}O_{PDB}$ to move in and mix. The veins would have precipitated out from the incoming fluids, and locked in the very low $\delta^{18}O_{PDB}$ values.

Significantly lower $\delta^{18}O_{PDB}$ values are not rec-orded in any host rock sample. The host rock might already have lost all porosity and permeability that would have allowed crossflow (fluid exchange) with the veins, and so equilibration was inhibited and did not register as more negative oxygen-isotope signatures in the rock matrix.

5.3 Isotopic variation in a vein

Samples across thick veins were drilled from vein edge to the centre to determine if there is a significant isotopic variation within a single vein. Only veins associated with fault plane that were thick enough to be sampled at least three or four times were suitable for this type of analysis.

In the veins along fault planes, the $\delta^{18}O_{PDB}$ values become less negative from the wall to the centre of the veins, with differences up to approximately 3.0%. The decreasingly negative $\delta^{18}O_{PDB}$ values from the wall to the centre of the veins suggest that there was either a decrease in fluid temperature over time within the span of the vein formation or a change in hydraulic influx of fluids with less negative $\delta^{18}O_{PDB}$. The samples from these veins are in cluster 3 and are interpreted to have precipitated out from fluid in an open system.

6. Discussion

6.1 Isotopic signatures in structural framework

From the wide-ranging orientations of the veins and the cross-cutting relationship observed in field and under thin section, it is likely that the strata preserve evidence of more than one deformation event, and this is consistent with the known regional structural framework. Cluster 1 and Cluster 2 from the quarry and roadcut respectively, are likely preserving evidence of a continuation of progressive burial, as can be extrapolated from comparison with the established isotope-based burial curve for the Indochina block (Figure 7) (Warren et al., 2014).

Veins associated with fractures from the roadcut consistently plot within Cluster 2. This suggests that the roadcut outcrop might only preserved evidence of a limited deformation event. This is consistent with the field and petrographic observation that show no cross-cutting between veins that would suggest otherwise. The folding and boudinage is likely to have formed prior to the deformation event, as the veins associated with the fold and boudinage have less negative $\delta^{18}O_{PDB}$ values, sug-gesting an earlier deformation at a shallower depth, under the same stress orientation.

The veins at the quarry show two clusters of isotope data; Cluster 1 and Cluster 3. There are likely two different fluid types corresponding to each individual cluster. This is consistent with the cross-cutting relationship between veins indicating at least two different deformation events taking place in the burial history of the rock.

The relationship between the veins and the isotope signatures can be inferred from samples combining thin sections and isotope data. The older vein that is cross-cut by the younger vein has an isotopic signature, plotting in Cluster 1, while the younger vein plots within cluster 3. The correlation between the relative timing of veins and the isotopic clustering collaborates in the structural orientations measured in the field. The poles of the veins (Figure 2) are grouped into two main clusters: 1) vertical to sub vertical veins trending approximately NE-SW and ENE-WSW and 2) sub-horizontal veins trending approximately WNW-ESE and NW-SE. From field observation (Figure 3), it is inter-preted that the more vertical veins are younger, cutting through the earlier, more horizontal veins. Samples collected from the horizontal to sub-horizontal veins have isotope points that make up cluster 1, while samples collected from the more vertical veins plot in cluster 3.

6.2 Burial curve: Indochina versus Sibumasu

The isotope results provide a new reconnaissance insight into the thermal and burial history of rocks on the Sibumasu block of Thailand. A complete burial history of the rock cannot be constructed because of the limited aerial extent of data, and so is beyond the coverage of this project. A stope-based burial history curve is established for Permian carbonate in Saraburi area, Central Thailand (Warren et al., 2014). The study documented isotope signatures of various calcite cements formed at different stages in the burial history. The evolution established in the area is as follow:

1. Regional pre-deformation isotopic signature in eogenesis realm that started off with value closest to original Permian seawater.
2. Progressive burial into early mesogenetic realms and subjected to Indosinian deformation. Matrix porosity was still preserved.
3. Continued burial into late mesogenesis and complete loss of matrix porosity. Calcite precipitation was restricted to structurally created fracture porosity in Indosinian deformation.
4. Uplift of the rock with influence of meteoric waters as a response to the Himalayan orogeny.

The new isotope data generally plot along the burial curve, but tend to have lower $\delta^{13}C_{PDB}$ values and significantly lower $\delta^{18}O_{PDB}$ (specifically in cluster 3)(Figure 7). The data points in cluster 1 and cluster 2 plot on the burial curve, along the trend that indicates an ongoing rock fluid equilibration in a condition with increasingly warmer fluid crossflows in host rock that had some degree of permeability. This shows that the burial curve established for Indochina block may be extrapolated to the Sibumasu block, on the other side of the Indosinian suture.

Cluster 1 overlaps data points that were sampled from spar cements in central portion of cavities and in veins. The fluids for the cementation and precipitation are interpreted to be introduced via open fractures when the matri was tight, or when the matrix had the last stage of matrix permeability. The interpretation is consistent with that of cluster 1.

Cluster 2 plot overlaps isotope points collected from the vicinity of thrust faults. Crossflow rock-fluid equilibration was interpreted to be occurring in Saraburi until $\delta^{18}O_{PDB}$ values reached approximately -13%, and all other calcite with values beyond that are exclusively from thrust-related calcite veins. The calcite is interpreted to precipitate after matrix permeability is somewhat destroyed, when hot fluid flow was confined to fracture porosity created by the Indosinian orogeny. While there is no thrust-related feature in the immediate vicinity of the roadcut, the high temperature-signature equivalent to thrust-related fluid on the Indochina block could be a function of deeper burial.

Isotope points for cluster 3 are exclusively from veins (both fractures and fault planes). The very low $\delta^{18}O_{PDB}$ between -18 and -24% are not seen in Central Thailand. The very negative $\delta^{18}O_{PDB}$ values indicate that the fluid was hotter. The age of the veins is not determined, however the veins are the youngest set observed in the field. Based on the burial curve (Figure 19), it could be inferred that the veins were likely formed in post-Indosinian fractures porosity.

6.3. Is there any evidence of a Palaeocene event?

The field area is located within the shear of the Three Pagoda Fault Zone (TPFZ) (Figure 1). This NW-SE striking fault most likely began in the early Palaeogene as a large sinistral shear zone in response to compressive stresses coming from the onset of collision between India and Asia (Himalayan event). The sinistral slip along the fault is interpreted to have ended around 33 Ma (early Oligocene) as determined from $^{40}Ar/^{39}Ar$ mica age dating (Lacassin et al., 1997). The sinistral sense of motion on the NW-SE oriented fault requires an approximately east-west maximum horizontal stress (in present day setting)(Morley et al., 2011).

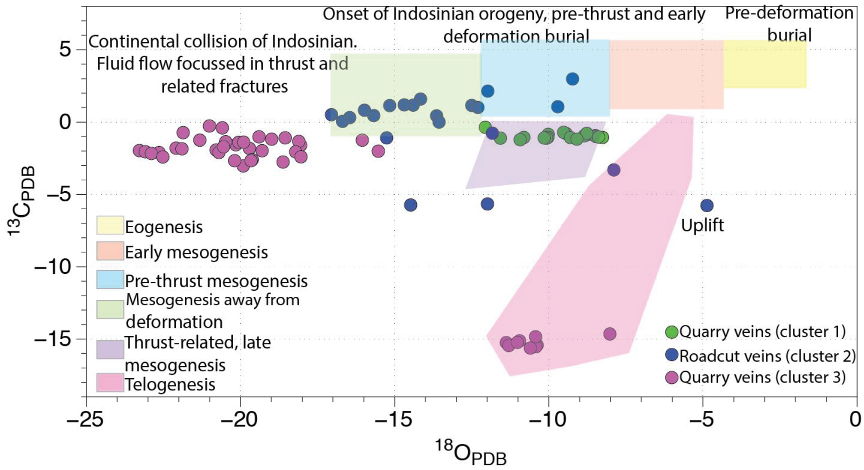

Figure 7. Imposition of the data in this study on the burial curve and diagenetic evolution established in Central Thailand (Indochina block).

The timing and geometry of the strike-slip fault is inferred as more characteristic of a transpressional orogenic belt than as a result of escape tectonics (Morley, 2007). Rhodes et al. (2005) also suggested that the left-lateral slip involved significant transpression, based on the intensity of northwest-trending tight folds and lack of any evidence for the formation of Paleogene basins.

The set of veins plotting in cluster 3 trend generally NE-SW and E-W, and the maximum horizontal stress was interpreted with the same orientation. With all the data available, it can be suggested that the younger veins observed in the field are a result of the transpersonal event that had driven the sinistral motion of the Three Pagodas Fault in pre-Oligocene time. The fluids that precipitated the veins could be basement-derived with higher temperatures, hence giving a very negative oxygen isotope in the resulting cements. Interestingly, in the vicinity of the field area is a slice of exposed Thabsila meta-morphic complex that was metamorphosed in the Eocene (Nantasin et al., 2012), showing there is evidence of a hot thermal regime nearby. The hot fluid in the study are could have been focused along open fractures that resulted from the transpressional deformation associated with the nearby metamorphism.

If the younger veins are associated with the strike-slip fault in the Palaeogene, the older veins are likely a result of the Indosinian orogeny. The prevailing trend of the Indosinian suture is envisioned as being North-South (e.g., Sone and Metcalfe, 2008), which leads to an inference that the maximum horizontal stresses during the closure of Paleothethys ocean was strongly East-West. Deviation from this general trend is also reported. For example, Morley et al. (2013) have argued that the Khao Khwang Fold and Thrust Belt on the Indochina block has an East-West orientation with a tectonic transport direction mainly towards the North. The older set of veins has a trend of approximately NW-SE and NNW-SSE. The inferred maximum horizontal stress is parallel to the trend of the veins, generally North-South. This does not fit the simplistic interpretation of a predominantly North-South suture model. This would require a maximum horizontal stress roughly in the East-West direction. The maximum stress direction in the study area is similar, but not necessarily related, to the direction reported in Morley et al. (2013).

6.4 Economic implications

Based on the comparison between the isotope data of this study and the trend from Warren et al. (2014), the burial curve established for Central Thailand could be extrapolated to the Western part of Thailand, across the Indosinian suture. The studied outcrops preserve no matrix porosity. Warren et al. (2014) also recommended that the primary and mesogenetic matrix porosity in Permian carbonates of central Thailand have very low preservation potential. Fracture porosities created during the Indosinian Orogeny are also now tightly cemented. The isotope data from the veins also plot along the burial trend. Likewise, the studied veins in this project also plot along the same burial trend, and extend the existing curve to a more negative oxygen-isotope range. Two groups of veins were interpreted in this study; associated with Indosinian Orogeny and a younger, possibly Pal-aeocene event. Later fracturing in rocks that have lost all the matrix permeability is important if a tightly cemented carbonate or a basement rock is to become a hydrocarbon reservoir. For example, Bach Ho field in Vietnam that is basement-fractured reservoir hosted in granodiorite, the fractures include pre-existing structures reopened during late Oligocene deformation and more recent syntectonic fractures (Cuong & Warren, 2009).

In another study by Panthong (2015) that utilised drill cuttings for isotopic study of a fractured gas field in Central Thailand, late stage secondary porosities were observed. Cuttings of calcite crystals from the high productivity well deviate from the burial trend. The points have more negative carbon-isotope values suggesting some contribution from meteoric water mixing. The calcite crystals are inferred to be from calcite veins in the subsurface, probably related to Palaeocene event. It is interpreted that the late stage porosities were derived from interaction of fluids along the fractures with the host rock, and attributed to the good overall porosity of the Permian carbonate reservoir. The younger set of fractures studied in this project shows no sign of late dissolution. This might be due to deep burial when the fractures were created, and were not reached by meteoric water.

While the fractures observed in this study have not been associated with any dissolution of the matrix for creating secondary porosity, the orientation of the fractures can be used as guide to model fluid migration pathways for an early Tertiary fractured basement/carbonate play. The different strikes of the different ages of fractures suggest a change in the fluid pathways and help to better constrain the fluid (that may include hydrocarbon) flow direction over a particular geological time intervals, such as the Tertiary of Thailand.

7. Conclusion

This outcrop-based study provides a reconnaissance insight on the burial history of carbonate rocks on the Sibumasu block, to the West of the Indosinian Suture. It establishes that the burial trend as defined by texture-aware isotope study of carbonates on the Indochina block can be extrapolated across the suture with no more than minor changes.

Field observations show that there are at least two sets of veins crosscutting each other in the study region. These crosscutting relationships are supported by petrographic observations. Of the three clusters of isotope data sampled from various vein sets, one set of veins clusters around very negative δ18OPDB values (below -20%), this data field was not seen in earlier studies. This set of veins is likely a result of hot fluids exchanges, driven by the transpressional deformation that displaced lithologies caught up in the Thee Pagodas Fault zone, in the early Palaeogene. The other two clusters in the C-O data fields are likely associated with the earlier Indosinian orogeny. The genesis of the veins does not fit with the pre-dominantly North-South Indosinian suture model, and suggests a more irregular suture with local variations in the active stress field.

Two fluid systems are proposed for the various veins and their C-O cluster fields. A closed fluid system was likely dominant when the host rock still retained some porosity and permeability in the earlier stages of the study area's burial history. This system is interpreted as controlling the formation of veins in clusters 1 and 2, both indicative of subsurface settings with a significant rock-fluid exchange patterns. Once matrix porosity and permeability was destroyed, the level of rock-fluid exchange became low or negligible. This was followed by fault-driven precipitates of vein calcite, derived from flows derived from deeper/hotter burial fluids.

A 'Palaeocene event' related to onset of the collision of India with Eurasia is often postulated to involve uplift that exposes the rock to deeply circulated meteoric water, mixing with signatures preserved in the resulting calcite veins. If the veins in cluster 3, which in the field show a fracture direction that parallels early Palaeogene strike-slip displacements, are features related to the same Palaeocene event, then isotope criteria indicate crossflow and exchange with hot fluids in this system that were derived from a deeper source, especially within the deformational shear zone that is the Three Pagodas Fault.

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9. References

Cuong, T. X., and J. K. Warren, 2009. Bach Ho Field, a fractured granitic basement reservoir, Cuu Long Basin, offshore SE Vietnam: A "buried-hill" play. Journal of Petroleum Geology, v. 32, p. 129-156.

Dietrich, D., J. A. McKenzie, and S. Honglin, 1983. Origin of calcite in syntectonic veins as determined from carbon- isotope ratios (Swizterland). Geology, v. 11, p. 547-551.

Lacassin, R., H. Maluski, P. H. Leloup, P. Tapponnier, C. Hinthong, K. Siribhakdi, S. Chuaviroj, and A. Charoenravat, 1997. Tertiary diachronic extrusion and deformation of western Indochina: structural and 40Ar/39Ar evidence from NW Thailand: Journal of Geophysical Research. Solid Earth (1978–2012), v. 102, p. 10013-10037.

Molnar, P., and P. Tapponnier, 1975. Cenozoic tectonics of Asia: effects of a continental collision. Science, v. 189, p. 419-426.

Morley, C. K., 2002. A tectonic model for the Tertiary evolution of strike – slip faults and rift basins in SE Asia. Tectonophysics, v. 347, p. 189-215.

Morley, C. K., 2007. Variations in Late Cenozoic–Recent strike-slip and oblique-extensional geometries, within Indochina: The influence of pre-existing fabrics. Journal of Structural Geology, v. 29, p. 36-58.

Morley, C. K., P. Ampaiwan, S. Thanudamrong, N. Kuenphan, and J. Warren, 2013. Development of the Khao Khwang Fold and Thrust Belt: Implications for the geodynamic setting of Thailand and Cambodia during the Indosinian Orogeny. Journal of Asian Earth Sciences, v. 62, p. 705-719.

Morley, C. K., P. Charusiri, and I. M. Watkinson, 2011. Structural geology of Thailand during the Cenozoic, in Michael F. Ridd, A. J. Barber, and M. J. Crow, eds., The Geology of Thailand, Geological Society of London, p. 273-334.

Nantasin, P., C. Hauzenberger, X. Liu, K. Krenn, Y. Dong, M. Thöni, and P. Wathanakul, 2012. Occurrence of the high grade Thabsila metamorphic com-plex within the low grade Three Pagodas shear zone, Kanchanaburi Province, western Thailand: Petrology and geochronology. Journal of Asian Earth Sciences, v. 60, p. 68–87.

Rhodes, B. P., P. Charusri, S. Kosuwan, and A. Lamjuan, 2005. Tertiary Evolution of the Three Pagodas Fault, Western Thailand, in Proceedings of the International Conference on Geology, Geotechnology and Mineral Resources of Indochina. Khon Kaen University, Khon Kaen: p. 498–505.

Sone, M., and I. Metcalfe, 2008. Parallel Tethyan sutures in mainland Southeast Asia: New insights for Palaeo-Tethys closure and implications for the Indosinian orogeny. Comptes Rendus Geoscience, v. 340, p. 166-179.

Tapponnier, P., G. Peltzer, and R. Armijo, 1986. On the mechanics of the collision between India and Asia: Geological Society London Special Publications, v. 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 tec-tonically driven fluid system. Marine and Petroleum Geology, v. 55, p. 100-121.