Fracture Development in Phanok Khao Reservoirs from Outcrop Integrated with FMI, Korat Basin, North-East Thailand

Jakkree Kongchum*

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

Abstract

Production from fractured carbonate reservoirs in North-East Thailand has been ongoing in the Phu Horm field and focused in the "Pha Nok Kao Formation". There, the relative timing of fracture events, the relationship to fluid-cement histories, and ties to the Indosinian or Himalayan Orogenies are not well understood. Therefore, in an attempt to look more regionally at defining effects from both tectonic events, this study focused on three outcrops across North-East to Western Thailand, where previous mapping has shown structures related to both orogenic events are present. The selected areas are; Chum Phae quarry, Banphot Phisai quarry and U-Thong quarry. The most significant area is the Chum Phae quarry, which contains lithologies, structures and diagenetic features that can be directly related to the Pha Nok Kao reservoirs in Sinphuhorm field.

Fracture orientation analysis was integrated with petrographic study to better define relative timing and model the structural geometry with the integration of fracture development across the three areas. Stable isotope crossplots of carbon and oxygen (C-O), using orientation-aware isotope samples, defined variable fluid events, which can classify the diagenetic evolution in each fracture. The isotopic plotfields define 2 trends of reactivated fractures that experienced crossflows of deep mixing meteoric waters during later tectonic uplift. Moreover, North-East Thailand in the vicinity of Sinphuhorm field did not experience significant cross-flows of Indosinian deformation fluids, nor the Mesozoic hydrothermal fluids that have overprinted once-fractured metamorphic carbonates in Central and Western Thailand. The highest potential for open fracture trends is found in fractured carbonates preserving isotopic evidence of being subject to reactivation during the youngest tectonic event (Himalayan Orogeny).

Keywords: Fracture evolution, Diagenesis process, Uplift, Pha Nok Kao Formation.

1. Introduction

Historically, most reservoir targeting has focused on clastic plays with partially preserved primary porosity. Today, the volume in primary porosity reservoirs is insufficient to meet demand. Secondary porosity reservoirs, such as fractured-carbonates are an alternative when looking for new petroleum sources, but fractured reservoirs are one of the more challenging secondary porosity reservoirs to produce. Thailand has been exploring and producing from fractured reservoirs in a number of fields, such as Sinphuhorm and Nangnuan (Figure 1), but a better understanding how and when these reservoirs formed is needed for future success.

Understanding fracture development, combined with how diagenetic fluids can fill evolving fracture networks across a wide area in Thailand, has not been done any detail before. In order to help address this lack of knowledge, and better indicate if a particular fracture trend could be associated with a reservoir, I have classified fracture trends in outcrop and the relative timing of fracture development tied to evolving diagenetic processes that have controlled the fluid fills during "fracture evolution".

Hence, the objective of study is to gather outcrop data and integrate its interpretation with well log information from a producing field, and so gain a better understanding of fracture development and the diagenetic processes controlling quality of potential fracture reservoirs. In the subsurface, this study concentrates on the Pha Nok Khao Formation that represent the main reservoir rock in Sinphuhorm field.

2. Data Availability

A detailed field study and laboratory analysis of fracture samples collected from three

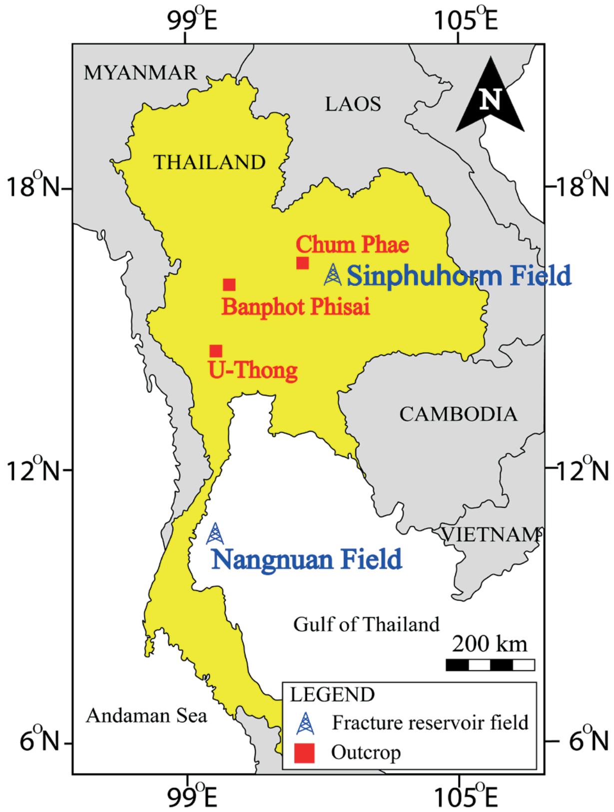

Figure 1. Outcrop study area and Field location of carbonate fracture reservoirs.

Data	Quantity
Outcrops	
1. Fracture orientation	421 fractures
2. Stable isotope analysis (calcite vein)	113 samples
3. Thin section	15 samples
4. XRD analysis	6 samples
Sinphuhorm field	
1. Image log (FMI)	1 well
2. Stable isotope analysis (cutting)	214 samples

Table 1. Summary of available data.

outcrops (Figure 1). There are show fractures in host rocks different rock age. To understand the surface linked to subsurface, I have integrated image log data and isotope data from wells in Sinphuhorm field with my interpretation of the samples from the Chum Phae quarry as both lie with the same Permian-age formation.

3. Methodology

The purpose of the field measurement of fracture orientation is to determine a number of fracture trends and then use the results to select the samples for further analysis (isotope, thin section and XRD). Each of the three inactive quarries were noted structures that preserve geological information and details were taken in terms of rock type, bedding, fracture orientation and fracture style (fissure, joint, shear fracture and stylolite based on Khattak, 2017).

All the fracture orientation and style are plotted on a stereonet, where results are displayed as either planes or poles. Groups of fractures are defined by making contours on stereonet and are generated either from pole or plane data. Each fracture group was converted to a strike direction and plotted as rose diagrams. At this point, the number of fracture trend can be counted. Consequently, vein samples of each fracture set were collected for stable isotope and thin section analysis.

Stable isotopic sampling focused on calcite-filled fractures (with different orientations) in order to better understand the fluid types that have circulated through the various fracture sets. Therefore, each stable isotope sample was drilled in each calcite vein, while noting the related vein orientation.

Powder samples were analyzed to determine their $\delta^{18}O_{PDB}/^{16}O_{PDB}$ and $\delta^{13}C_{PDB}/^{12}C_{PDB}$ values. The result for each sample consists of a value for the oxygen isotope and the carbon isotope. Carbon isotope that are increasingly negative depend largely on the source of CO_2 (bicarbonate) that supplies the calcite cement. Bicarbonate can be generated from soil weathering, biogenic activity, hydrocarbon maturation and fractionation. Temperatures increasing during burial give oxygen isotope value that are increasingly negative with rising temperature. This is related to ongoing rock-fluid driven burial re-equilibrium and fractionation in subsurface environment (Hoef, 2009).

Next, petrographic study defined the type of cement in a fracture, subject to the understanding of the host rock types and diagenetic processes. Furthermore, thin sections indicate crosscutting meso-scale and micro-scale fractures. Sections can be used to help indicate the order of fracture sequences in each trend a younger fracture will cut through older fractures (Singhal and Gupta, 2010).

X-ray powder diffraction (XRD) technique characterizes crystalline compounds based on the variation in diffraction pattern in the lattice structure of various materials. In this study, XRD is used to identify the mineral composition of samples with unknown minerals. The main sampling in focused on vein calcites because the result can be interpreted in terms of variations in the mineral displacement/fluid type that filled in fractures. In addition, the results from XRD help make the interpretation of petrography more accurate.

Finally, strike directions, so defined, are combined with relative timing and rock-fluid interactions of the vein filled fractures (from isotope and thin section) to better develop an understanding of fracture evolution across the three quarries.

4. Result

4.1 Chum Phae quarry

Chum Phae quarry is an abandoned quarry located in the western Kon Kaen province, North-East Thailand. The main exposed lithology is a massive wackestone (based on Dunham, 1962). It is medium to dark grey, with few fossils of bivalves, crinoids, and fusulinid grains and fragments. This limestone was likely deposited in a lagoonal environment (Geological Society of London, 2011-Geology of Thailand). Most of the bioclastic grains were transported from nearby sources beneath shallow lit waters. The index fusulinids] "*Schwagerinids sp.*" indicate a Permian age (Ueno and Charoentitirat, 2011).

Major geological structure exposed in the quarry is a strike slip fault that moves to the right (dextral). This fault has a NW-SE trend and a variety of related fractures is present. Most are filled with calcite, and there are some fractures that are open (confirmed by thin section). Based on numerous measurements, three fracture trends are seen (rose diagram - Figure 2b).

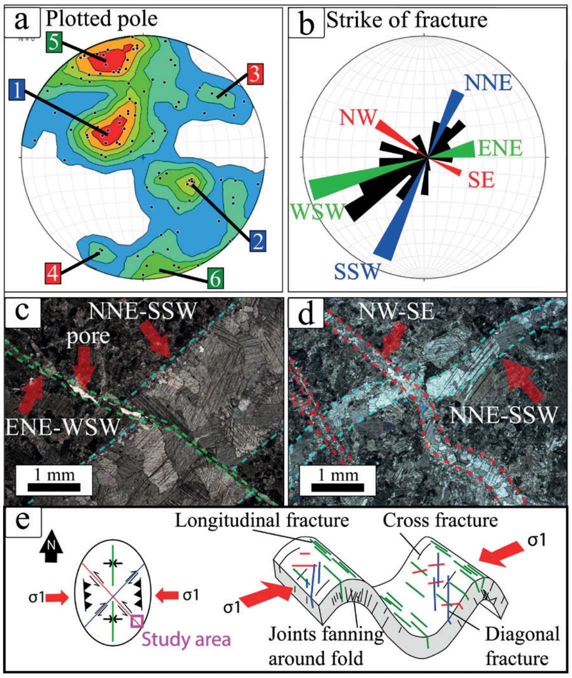

Figure 2. (a) All Chum Phae field data plotted on a streonet and divided into 6 groups. (b) Three fracture trends analyzed by using rose diagrams with a color-code to represent each trend. (c&d) Cross-cutting relationships show the NNE-SSW trend is developed before the ENE-WSW trend (c) and NW-SE trend formed (d). (e) Fracture patterns follow fold geometry.

- NNE-SSW → low angle and parallel to bedding.
- NW-SE → high dips of 70^{O} and parallel to the dextral strike-slip fault.
- ENE-WSW → high dips of 80^{O}.

This area was mainly influenced by the Indosinian orogeny. It has experienced compressional forces as three time-separate sub-events (Hahn, 1982). The NNE-SSW fracture trend tends to correspond to fold axial trends, as mapped by DMR, 1984 - Geological map of Changwat Phetchabun. Therefore, the paleo-stress for the NNE-SSW trend is parallel to the E-W maximum stress of the compressional regime present during the Indosinian event (Figure 2e). Moreover, this fracture trend is parallel to chert nodule layering that indicates bedding orientation. The trend can be considered as representing the slip plane of fold geometry.

The other two trends are interpreted as diagonal fractures, which follow the fold geometry but occurred later, based on cross-cutting fracture evidence (Figure 2c&2d). The extensional fracture with ENE-WSW and NW-SE trends cuts across the NNE-SSW trend. Therefore, the NNE-SSW fracture trend developed prior to ENE-WSW and NW-SE fracture trends. The NNE-SSW trend is associated with an earlier Indochinian event. Then, ENE-WSW and NW-SE fractures follow, but all may be re-activated during subsequent uplift, which is supported by stable isotope result.

The stable isotope cross plot can be divided into two main trends; 1) main compaction burial trend, 2) a cooling and uplift mixing trend that differs from the previous meteoric trend study in Warren et al., 2014 (Figure 3). This new trend of increasingly negative carbon isotope values is related to the provenance of bicarbonate in the calcite-precipitating pore waters. It suggests these calcites are derived from dissolution of the carbonate host rock as deeply circulating stagnant meteoric waters moving along open fractures that have been reactivated by depressurization during uplift. In addition, more negative oxygen isotope suggests fluid-cement temperature is similar to temperature burial waters by increasingly active meteoric phreatic waters.

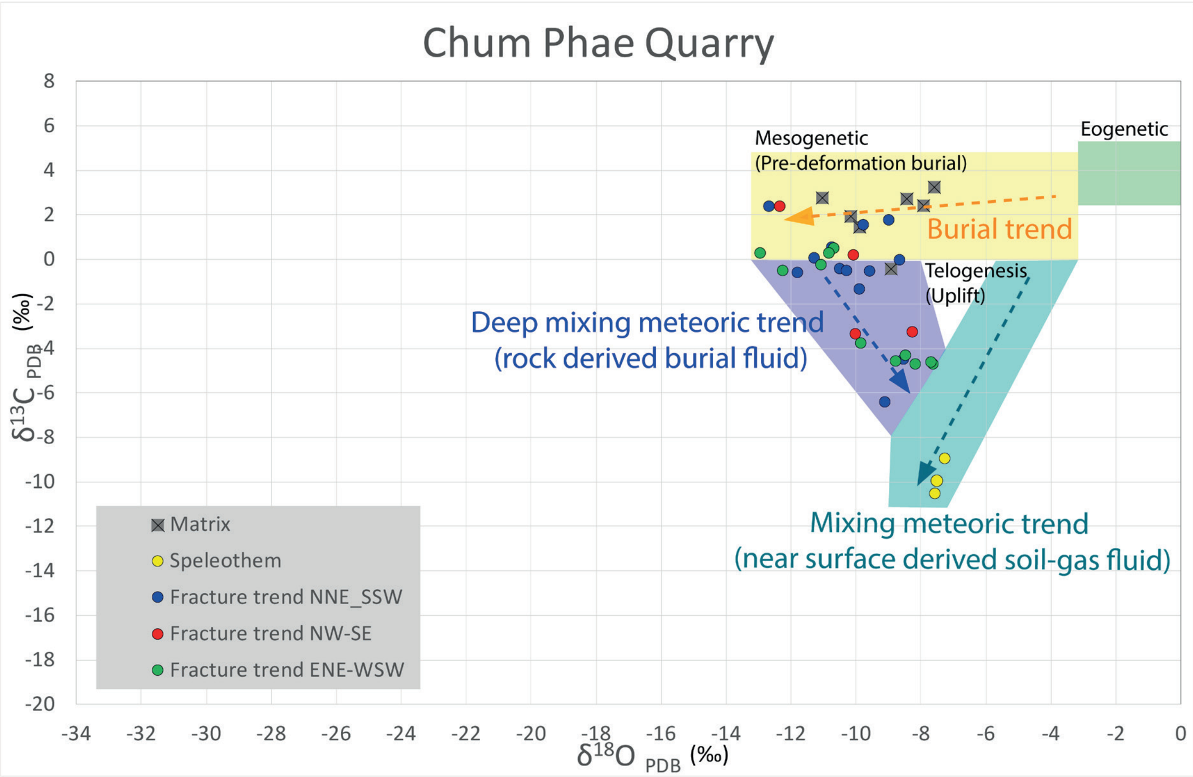

Figure 3. C-O isotope plot illustrating sample values from Chum Phae quarry. The data defines two main diagenetic trends, a mesogenetic burial trend and deep mixing meteoric trend.

Therefore, this uplift plotfield (shaded blue in Figure 3) is related to latest tectonic activity in the Khorat Plateau. This uplift was driven by the distal effects of the Himalayan orogeny, as documented in the Geology of Thailand - Geological Society of London, 2011. During uplift all the fractures were de-pressurized and increasingly exposed to crossflows of surface-derived telogenetic waters. This flow created and enhanced vuggy, cavern and solution channel porosity. In influence began deep where slow-flowing undersaturated meteoric waters began to enter along the opening fractures, dissolving the rock and then calcite precipitated from the same waters as their dissolved solute load reached calcite saturation. The isotope spread in this plot field shows calcite replacement occurred across all fractures but those of the younger ENE-WSW and NW-SE trends are more like to be open.

4.2 Banphot Phisai quarry

The second study area is an inactive quarry and located in the northern Nakon Sawan province, Central of Thailand. Tectonic activity in this area is from two events; Shan-Thai-Indochina suturing (Ueno and Charoentitirat, 2011) and the Himalayan orogeny (Morley and Charusiri, 2011). The host rock consists of a Devonian marble based on rock texture and the age dating was published in Geological Society of London, 2011-Geology of Thailand. Rock texture is finely-crystalline calcite and locally microcrystalline micrite. It is a metamorphic rock without discernible fossils so its original depositional setting is unknown. Bedding is hard to observe in this area due the rock being a massive marble. However, the lithostratigraphic contact between the marble and sa late can be assumed to represent regional bedding in the area and is oriented NW-SE with dips of 50^{O}.

Main structure in this area is an anticlinal fold complex. There are 3 main fracture trends developed in this area that are illustrated in a rose diagram (Figure 4b).

- NW-SE → moderate angle and parallel to bedding and fold axis.
- NNW-SSE →high dips of 80^{O} and parallel to youngest strike slip fault (Mae Ping fault).
- ENE-WSW → high dips of 80^{O}.

The NW-SE fracture trend was possibly formed by the Shan-Thai and Indo-China collision during the late Paleozoic to early Mesozoic as this trend conforms to the maximum stress that created the fold axes, which consistently aligns to the maximum stress direction of the two plate collision as defined by Ueno and Charoentitirat in 2011.

In addition, the more recent tectonics tied to strike slip faulting also has influenced this trend, which shows asnreactive stylolites related to younger tectonism and associated bending calcite cleavages that tie to aligned shear fractures (Figure 4c). Based on this evidence, a younger tectonic Himalayan orogeny may have been active in overprinting the original calcite veins formed earlier during the Shan-Thai-Indochina suturing.

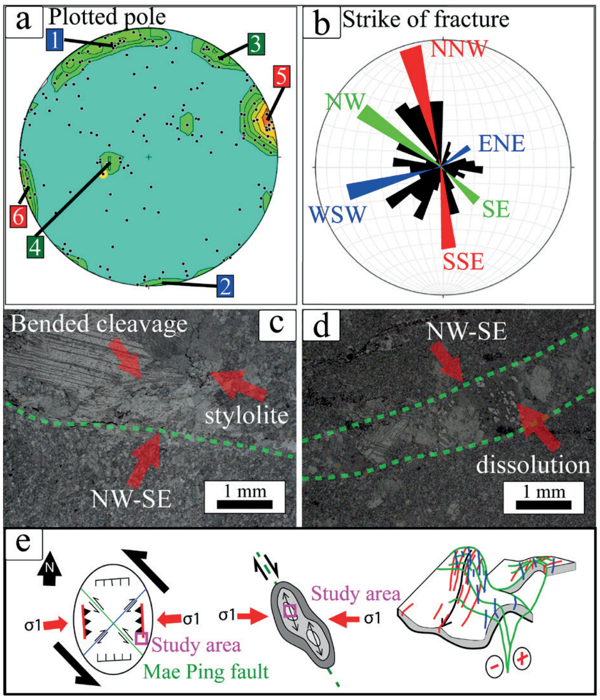

Figure 4. (a) All measured data plotted on a streonet and divided into 6 groups. (b) Three fracture trends analyzed by using rose diagrams which uses a color-code to represent each trend. (c) NW-SE forces created stylolite cutting thought the calcite vein of the NW-SE fracture trend. (d) NW-SE fractures show evidence of dissolution by meteoric water circulation during uplift. (e) Fracture patterns follow a left lateral strike-slip fault.

Furthermore, the maximum stress direction may not have changed too much but the structural style changes from compressional folding to left lateral strike-slip faulting (based on strain ellipsoid analysis in Figure 4e). The NNW-SSE trend also is younger when we compare it to the other two trends present, because this is only fracture trend which does not have associated dissolution or stylolitization. On the other hand, latest tectonic uplift has re-actived a varying proportion of the original calcite. Therefore, it is likely that the calcites NNW-SSE fracture trend were generated by the Himalayan orogeny, while some calcites in the NW-SE shear fracture and in ENE-WSW extension fracture trends formed during re-fracturing. This process of reactivation can create extensional fracture porosity and so classify it as good potential trend in terms of future reservoir quality.

The carbon and oxygen stable isotope shows most of the calcite veins are associated with variable exposure to deep mixing meteoric fluids (Figure 5). This resulted in more negative carbon isotope values, when compared to the late mesogenetic plot field of Warren et. al., 2014. The spread of values of carbon and oxygen isotope reflects an environment of more moderate fluid

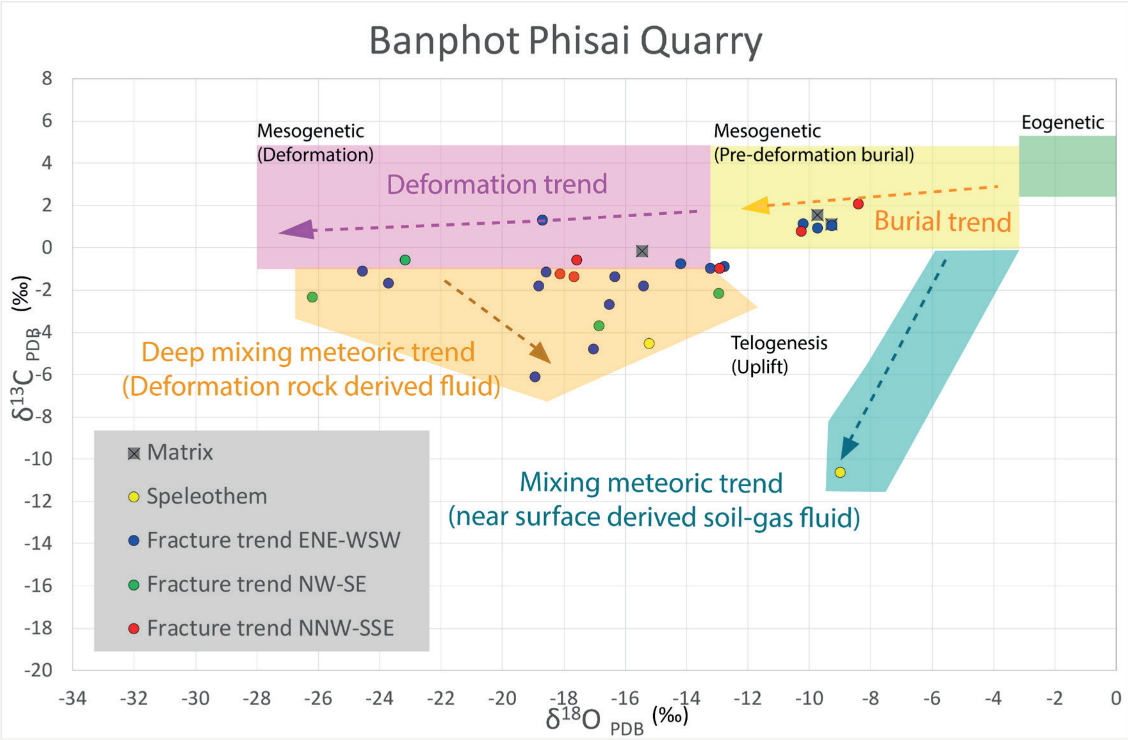

Figure 5. C-O isotope plot illustrating sample values from Banphot Phisai quarry. Most of data is influence by bicarbonate from a rock dominant source and perhaps the deep circulation of stagnant meteoric water as shown by the spread of the more negative carbon isotope values below the deformation zone values (plot field shading based in part on Warren et al., 2014).

temperatures and likely indicate a spread of bicarbonate values in the veins derived from deep dissolution input of rock-derived bicarbonate in the fluids that precipitated vein-fill calcites. The integration of fracture trend and isotope data shows NNW-SSE trend is more likely associated with deep mixing meteoric related uplift waters that excavated cement in the original fracture.

Moreover, NNW-SSE fracture trend is younger, parallel to the NNW-SSE strike-slip orientation and also is very steep, so likelier it was easier to expose this network to subaerial connections, allowing meteoric water to enter in the early stages of meteoric uplift. Hence, many caverns develop in this trend and it can be concluded that the deep-mixing meteoric-related uplift more influenced the younger fracture network that formed via the distal effects of the Himalayan orogeny.

4.3 U-Thong quarry

This exposure area is located in Suphanburi province, western Thailand, which is a part of highly deformed region overprinted by two major tectonic events, which are the same as in Banphot Phisai quarry, but this area is overprinted by a different strike-slip fault, namely the "Three Pagoda fault" (Morley and Charusiri, 2011). The outcrops were mapped as a highly foliated Ordovician marble called the "Thung Song formation" (Geological Society of London, 2011-Geology of Thailand). Lithology consists of thin layers of calcitic marble with different colors ranging between dark grey and light grey color to form a "banded" metamorphic texture. In addition, a light grey finely crystalline diorite sill is present in the area and believed to be of Mesozoic age (DMR, 1976 - Geological map of Changwat Suphanburi).

The main structure is a large normal fault with a wide fault core. This fault is oriented in a NE-SW direction with a high dip angle of 70O. This structure was probably generated by left-stepping left lateral strike slip faults as shown in Figure 6e). All fracture orientations are measured along the outcrop face. There are three fracture trends defined in the stereonet and rose diagrams (Figure 6a, b).

- N-S → low dips of 40^{O} and parallel to direction of Shan-Thai-Indochina suturing.

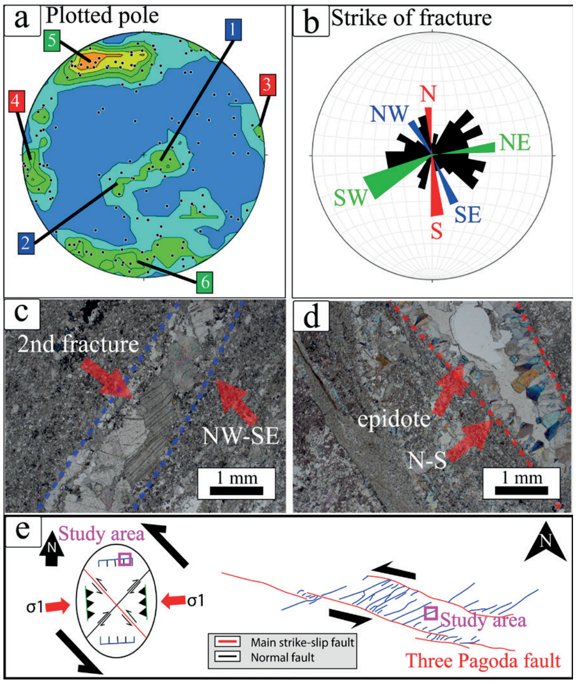

Figure 6. (a) All measured data plotted on a streonet and divid ed into 6 groups. (b) Three fracture trends analyzed by using rose diagrams which uses a color-code to represent each trend. (c) Supporting evidence of tectonic re-activation based on the 2nd period of fracture development following the original NW-SE trend. (d) Epidote minerals were deposited in N-S fracture trend. This mineral is typically a hydrothermal vein precipitate. (e) Fracture patterns follow the left lateral strike-slip faulting.

- NW-SE→ high dips of 80^{O} and parallel to the strike-slip fault (Three Pagoda fault).
- NE-SW → high dips of 80^{O} and parallel to the normal fault.

There are reactivated fractures within the same trend. From this evidence, there was more than one episode of tectonic overprint. The N-S and NW-SE fracture trends contains two minerals i.e. calcite and epidote veins, but the NE-SW fracture trend is seen only in calcite vein crystals present in the fault core. This suggests NE-SW fractures define the youngest fracture set

Based on the field evidence, the structural style can be separated into two groups; 1) compressional and 2) transtensional, related to 2 different tectonic events. In principle, collision must be related to compressional stress, while strike-slip faults & normal faults are related to transtensional stresses. So, the N-S fracture trend should be related Shan-Thai-Indochina suturing. The other two fracture trends correspond to activity in the Three Pagoda fault zone, generated by the Himalayan orogeny,, which is the same as indicated by the strain ellipsoids in Banphot Phisai quarry.

In this quarry, the stable isotope sample show one major trends of diagenesis based on Warren in 2014 and Bunpitaksakul in 2016 that is the "hotter fluid" trend (Figure 7). This trend is not observed in the previous two quarries. Accordingly, most of the samples show much more negative oxygen values. These calcite vein fills precipitated under the influence of hotter vein fluids. Epidote is seen in thin sections of the vein fill, along with co-precipitated calcite, suggesting the involvement of hydrothermal waters.

5. Implication for Subsurface

Understanding the trends of fractures in reservoirs in the subsurface is very difficult due to limitations of data especially in regions of tectonic complexity. Application of surface-integrated data models is valuable in gaining more knowledge as to fracture evolution in the reservoirs. This study now compares outcrop data in the Chum Phae quarry with Sinphuhorm well data as both structural data sets come from the same formation, and stable isotope results have been collated in both regions.

The FMI data from Sinphuhorm well focuses in the carbonate reservoir section. Four kinds of dip were interpreted, as shown in Figure 8a (based on Hess, 2006-FMI interpretation of Sinphuhorm field). According to Hess (2006), open fractures are related to karst, interpreted as developing in the phreatic zone, but with an unknown timing.

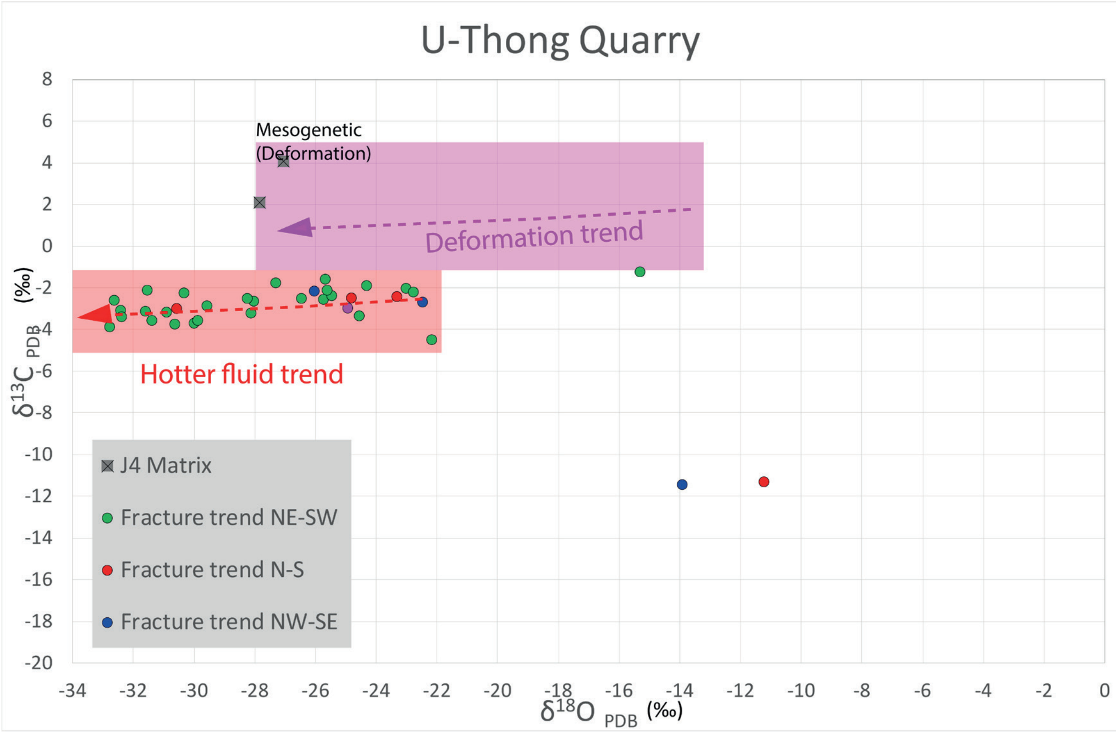

Figure 7. C-O isotope plot illustrating sample values from U-Thong quarry. The data define main diagenetic trend as the "hotter fluid" trend documented by Bunpitaksakul in 2016. It could be from hydrothermal fluids associated with intrusive igneous rocks that are found in this area.

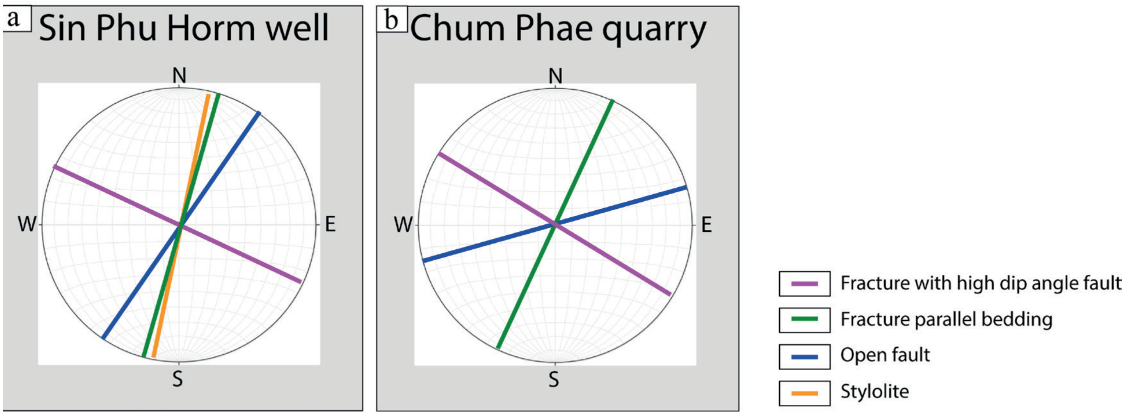

Figure 8. Comparison result of fracture trend and fault trend between Sin Phu Horm well in (a) and Chum Phae quarry in (b) showing the same trend.

The strike comparison result between outcrop data and Sinphuhorm well data indicates the similar trends for each fracture type (Figure 8a & 8b). It seems the same tectonic overprint influences both areas, with the same maximum E-W stress field imposed by a broad scale compressional regime. The open fractures are parallel to longitudinal fractures when modelled in fold geometry (Figure 2e).

The second comparison between the two areas uses plots of the carbon-oxygen isotope data (Figure 9). The results show the retention of eogenetic and early mesogenetic values in Sinphuhorm well in a plot field that is not present in any of the three quarries (shaded plot fields are based on Warren et al., 2014). The later pre-deformation fields overlap strongly between the Chum Phae and Sinphuhorm samples. This implies that the Sinphuhorm matrix in the reservoir rocks have experienced less diagenetic

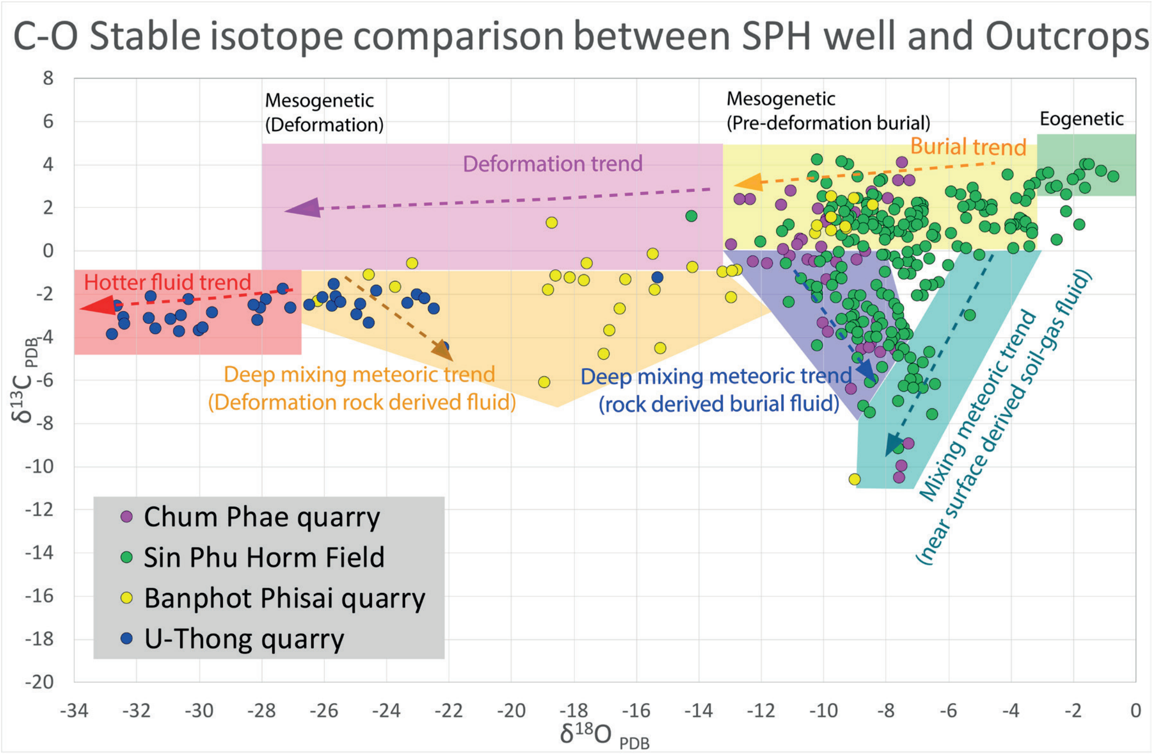

Figure 9. Comparison result of carbon-oxygen isotope between Sinphuhorm well and three studied outcrops. The North-East Thailand data indicates a deep meteoric water was involved calcite cement during the uplift that caused by Himalayan orogeny.

overprint by later mesogenetic waters compared to the quarry sequences.

Interestingly, post-burial, both the isotope spreads from the Sinphuhorm and Chum Phae quarry show a strong overlay in plot fields. This sloping "inverted J trend" indicates exposure to similar temperature burial waters (left-half of the yellow shaded field in Figure 9) and later, to a deep mixing meteoric environment during early telogenetic uplift (the dark blue region in Figure 9). Isotope spreads from both regions imply the bicarbonate supplying the precipitated calcites in the early telogenetic zone came from the dissolution of adjacent rock during early depressurization and uplift. Later as uplift continues and strata moved closer to the landsurface, the rocks entered the active phreatic realm where vugs, molds and caverns grew, and speleothem calcites precipitated. In this zone of more active crossflow, much of the bicarbonate caught in the various speleothem calcites came from fluids that had moved through the zone of soil gas and so picked up more negative carbon values.

6. Conclusion

Fracture orientation analysis integrated with petrographic study can better define relative timing and model the structural geometry and fracture development. Likewise, the integration of structural data with stable isotope crossplots of carbon and oxygen (C-O), using orientation-aware isotope samples, defines variable, but tectonically controlled, fluid-cement histories in each fracture orientation set.

Integration of results from outcrop and existing well data from Sinphuhorm field shows open fractures experienced crossflows of deep mixing meteoric waters related to later tectonic uplift (instigated by the distal effects of the Himalayan Orogeny). This process drove both calcite dissolution and precipitation, but dissolution was more critical in that open fracture remain as illustrated in Figure 10.

The North-East Thailand area did not experience significant cross-flows of Indosinian-deformation fluids, nor the Mesozoic hydrothermal fluids that have overprinted once-fractured metamorphic carbonates in Central and Western

Thailand (Figure 11). The highest potential for open fracture trends is found in fractured carbonates preserving isotopic evidence of being subject to the uplift influences of the youngest tectonic event (Himalayan Orogeny).

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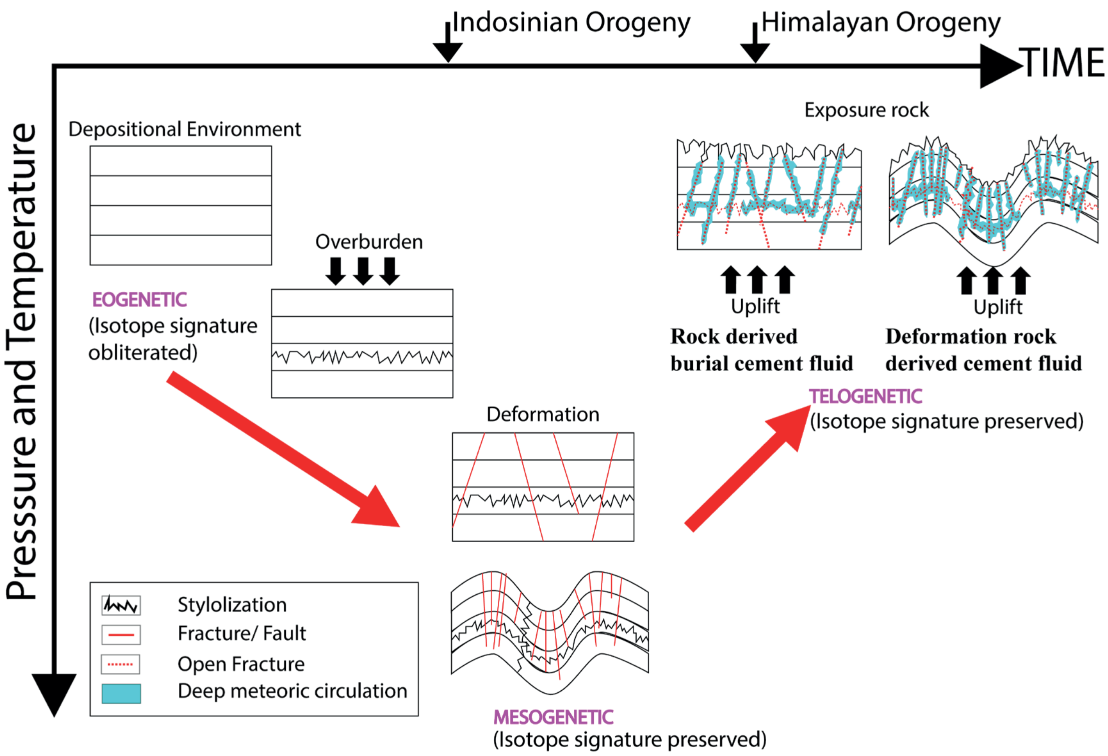

Figure 10. Diagram of Deep meteoric circulation fluid evolution related uplift documents a diagenetic trend not previously recognized in Thailand.

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