Fracture Analogue Modeling and Fluid Evolution, Central Thailand: A Tectonically Driven Fluid System

Thananate Meerat*

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

Abstract

The ultimate aim of this study is to develop better relevant local diagenetic analogs for the fluid and structural evolution system that created the economic porosity in producing carbonate reservoirs in the subsurface of northeast and southern Thailand. This is done using field observations tied to detailed petrographic and stable isotope determinations focused on exposures in a quarry in Nakhon Sawan Province, central Thailand. There outcrop studies show the folds and thrusts in the Permian limestone underwent complex deformation related to the Indosinian Orogeny (Late Permian to Early Triassic) and that some fractures within this structural grain were reactivated during Cenozoic time. The deformation history evolved mainly under the influence of (approximately) NNE – SSW directed compression. The largest thrust faults in the study area trend SE-NW, and dip 30° – 40°. Fault bend fold and duplex structures are also present. Two types of fractures are present: parallel to sub-parallel of bedding and inclined or sub-vertical of bedding. Fracture sets can be grouped into two main categories: a) Bedding-parallel fractures with WNW– ESE trend, and b) inclined or sub-vertical fractures with bedding showing a NNE– SSW trend. These fractures progressively developed during folding and thrusting in the core zone of the deformation. The high-angle fractures in the fault zone are truncated by a late stage sub-horizontal pressure solution cleav-age, which probably developed during loading by a now eroded higher thrust sheet. Stable oxygen and carbon isotope signatures in calcite veins indicate that they are related to and evolv-ing tectonic history. Group I defines a C-O plot field that indicates lower burial temperatures, it is considered to reflect a cooler, likely earlier, part of the mesogenetic burial trend. Group I is especially apparent in the matrix across the quarry and is also associated with the development of widespread early fractures and stylolites. Group II is interpreted as a late burial stage calcites precipitated in what was a hotter and perhaps deeper sub-surface environment. Group III is an intermediate set of C-O values possibly derived during mixing of deeply circulating meteoric fluids in the early stages of telogenetic uplift. The bicarbonate in the pore fluids precipitat-ing Group III calcites is strongly influenced by dissolution of rock material in a deep stagnant phreatic zone. Recent speleothem samples give slightly variable oxygen numbers in an uplift trend with consistently more negative carbon values than Group III, and so defines the isotope cluster that is Group IV. Group IV samples come from zones of carbonate soil in karst, speleothems and slickensides calcites. The Group IV plot field de-fines a mixing trend where the CO2 and consequent bicarbonate in the precipitated calcites are strongly fluid influenced during fluid-rock interactions in the zones of active phreatic and vadose circulation. Much of its negative carbon signature indicates precipitation from rainwaters that have moved through zones of soil gas, that is, flow in the upper meteoric carapace to the uplifted sediments. Uplift and exposure, facilitating this me-teoric signature, is ultimately a response to the Himalayan event, which began in the Eocene. The meteoric mix-ing trend is defined by the combination of Group III and IV plot fields an is an example of the subsurface com-bination of infiltrated rainwaters with deeper fluids that have dissolved uplifted Permian carbonates entering the telogenetic zone. The fractured Permian reservoirs of the Phu Horm gas fields in Thailand, to the north of the study area in the Khorat Plateau, have proven challenging to understand and predict in term of their reservoir properties. Therefore, the results of this outcrop study are directly applicable to the fractured carbonate reservoirs of this region and elsewhere in worldwide.

Keywords: Permian limestone, fractured carbonate reservoirs, complex deformation, isotope stable, fault-bend fold, detachment fold, calcite veins

1. Introduction

There is therefore a need to investigate the geology of Permian carbonate in Thailand and to understand why successful economic production comes from this un-usual reservoir. The study area is located in Takhli, Nakhon-Sawan Province, Central Thailand. Outcrop exposure are Permian carbonate platform successions (Sone and Metcalfe, 2008; Ueno and Chareontitirat, 2011) (figure 1A). The significance of this outcrop outcrop is inactive quarry and there are many calcite filled fracture. That can be used for stable isotope analysis. Previously, number of studies were con-ducted on the Indochina Block, northeast of the su-ture in the present day Saraburi area (Ampaiwan, 2011; Yingyuen, 2014 and Warren et al., 2014).

Objectives of the research are to determine the frac-ture style and fluid evolution related to tectonic de-formation of the Permian carbonate in Thailand, es-pecially and use the result as an analogue for compar-ison with subsurface carbonate reservoir. The ap-proach is to integrate then interpret data collected from the outcrop down to microscopic scale. This will improve predict orientation and subsurface position-ing of hydrocarbon flow path and accumulation. It can be understand the current and future development in buried-hill karstified carbonate reservoir in Thailand.

2. Regional geological setting

The study area has undergone a complex geological history, first the Sibumasu Block separated from Gondwana during the Early Permain. Conse-quently, eastward subduction of the Paleotethys be-neath the Indochina Block commenced and the Su-khothai Volcanic Arc, and the opening of Nan Back-arc Basin occurred. During this time, the Permian car-bonate platform of Saraburi group developed along the western margin of Indochina Block. The study area are part of the Permian carbonate platform, which was accumulating sediment at this time. From the Late Permian to Middle Triassic, compression of the Nan Back-arc Basin drove uplifting, thrusting and deformation of this carbonate platform (Indosinian Orogeny) (Sone and Metcalfe, 2008; Morley et al., 2013). The termination of the back-arc spreading cen-ter created the Nan Suture Zone. Sukhothai Volcanic Arc subsequently merged with the Indochina Block and in Middle Triassic became a western part of the of the Indochina margin. The Paleotethyan Ocean continued to subjected beneath the Sukhothai Block terrane in an eastward direction. This led to formation of an accretionary prism. From Late Triassic to Early Jurassic, the collision between the Sibumasu Block and a com-bined with Sukhothai Arc and Indochina Block ended the Paleotethyan Ocean and the Paleotethys suture is represented by the Inthanon Zone (Sone and Metcalfe, 2008; Ueno and Chareontitirat, 2011; Mor-ley et al., 2013).

The Permian sedimentary rocks lying along the mar-gins and the interior of the I ndochina Block in rift basins were extensively fold, thrusted, uplifted and eroded during the Early Triassic (Booth and Sattayarak, 2011; Morley et al., 2013). They were subsequently covered by sediments during the Late Triassic (the extensional phase of the Kuchinarai Group, followed by the post rift stage of the Lower Nam Phong Formation; Booth and Sattayarak, 2011) Following a depositional hiatus, the Upper Nam Phong Formation was deposited in the Late Jurassic and is separated by an unconformity from the overly-ing Later Jurassic to Early Createaceous Khorat Group (Booth and Sattayarak, 2011).

A new subduction of the Mesotethyan ocean beneath Sibumasu Block took place from late Jurassic to early Cretaceous. This Caused I-type plutonic intrusions in western Thailand. Recently, from Eocene to Neogene, the Indian and Eurasian plate collided, driving exten-sional dextral strike slip movement in Thailand, Fur-thermore, regional uplift and inversion of the Khorat plateau, northeastern Thailand was driven by this enormous Tertiary-age collision. This recent major tectonic event caused the uplift and exposure of Per-mian carbonate platform in the study area and al-lowed intensive karstification to occur (figure 1B).

3. Methodology

The study focused on quarry exposures of Permian Limestone in the Takhli, Nakhon Sawan Province, central Thailand. The study area is to ex-tends 40 meters from North to South, that it was se-lected for detailed field work. The geological infor-mation that was collected at each sampling site in-cludes; lithology, bedding, fracture and fault orienta-tion, bed thickness, various diagenetic feature visible at the outcrop scale as stylolite and calcite-filled hydrothermal vug presence. Additional focus was given to fracture orientation and igneous dike present.

Samples were then selected for stable isotope measurement, thin section analysis, and XRD deter-minations. Finally at the results of the laboratory study were integrated with field observation to up-grade our understanding of diagenetic history, porosity evolution and structural evolution in karstified carbonates.

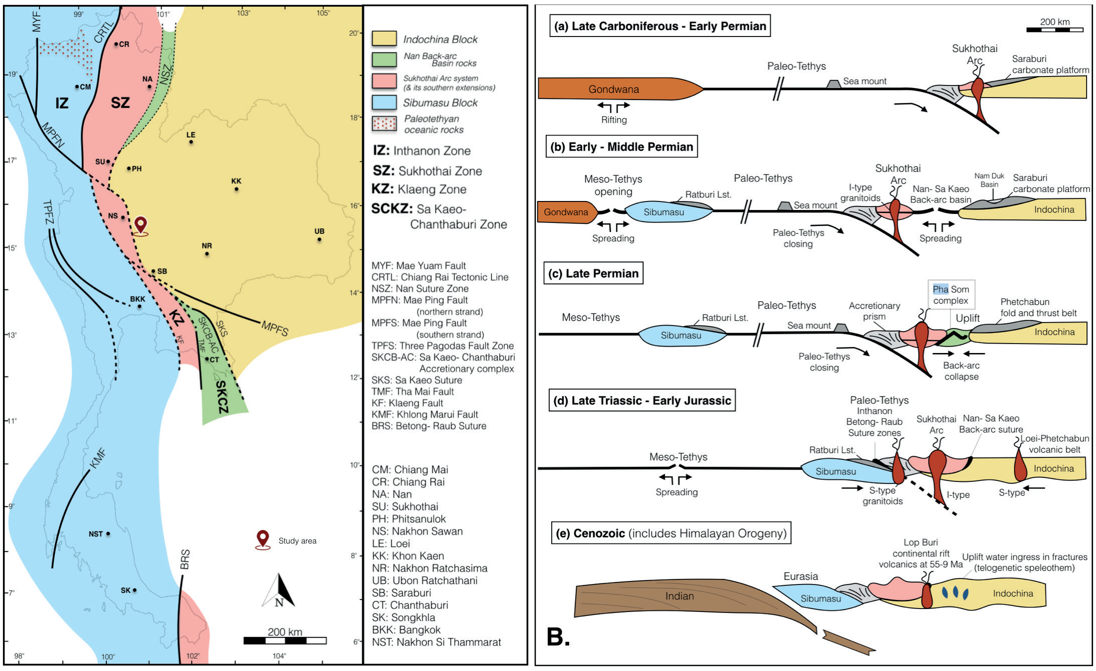

Figure 1: Tectonic setting of Thailand A) Tectono-sedimentary subdivisions of Thailand. B) Tectonic evolu-tion of Late Paleozoic to Cenozoic (Modified from Sone and Metcalfe, 2008; Ueno and Chareontitirat, 2011).

4. Results

4.1 Field Investigation

The studied area is inactive slab quarry lo-cated on Amphoe Takhli, Nakhon Sawan province. It beds showing S30E strike and approximately 30o SW dip direction. This quarry is part of Tak Fa Formation in the Saraburi Group. Stylolitized inclined bedding is the major factor controlling the karst formation ex-posed in the quarry (table 1).

Lithology: The texture of rock is character-ized by light to dark grey limestone with corals, cri-noids, smaller foraminifera and gastropods. Car-bonate textures, bound and mechanical, were identi-fied using Embry and Klovan's (1972) classification as wackestone to packstone indicating dominantly lower energy mechanical textures in carbonate plat-form environment.

Thrust fault: The thrust is marked by strong deformation zone including fault smear zone in shale and calcite vein parallel to the thrust. A thrust fault oriented sub-parallel tobedding with S45E/30^{o} SW direction intersects the quarry wall and creates a permeability contrast that influences cavern devel-opment and calcite veins. Close to the thrust, there is a higher intensity conjugate fractures compared to areas further from the thrust zone (figure 2).

Sylolite: The direction of stylolite was measured in quarry, nearly NW-SE trend with an average S60E strike (inclined to bedding) and NW-SE can trends can be found across the region but this is most intense in proximity of thrust faults.

Flexural slip: Duplex structure show evidence for flexural slip between bed contacts. Flexural slip is particularly well developed within fine-grained lime-stone beds composed of mudstone and fine grained, thinly bedding units.

Karst feature and soil filled: Most soil filled vugs and caverns are laterally elongate parallel to bedding, nearer to the land surface. They tend to be more aligned fracture and fault in the deeper part away from the land surface.

Table 1: Summary of macro scale (whole outcrop scale) and meso scale (local outcrop scale) of karst for-mation in study area.

ROCK APPERANCES		
Macro scale	Main control on karst development	Inclined bedding and fracture sets
Meso scale	Lithology	Thick to very thick-bedded limestone; mosaic facies of wackestone-packstone and mudstone
	Bedding	Mostly inclined beds, trending S30E/30° SW
	Stylolite	Inclined to bedding but not necessarily to thrust fault
	Fracture	Two main trends of conjugate fractures is a response to main thrust fault, creates duplex structure
	Karst feature	Terra rossa and soil pisolites
	Thrusting	Trend S45E/30° SW, Fracture intensity increases in vicinity of thrust
	Igneous rock	Andesitic dyke acts as permeability barrier during karstification
	Strike slip fault	Left lateral (sinistral) sense of motion, dip angle is 30° SW

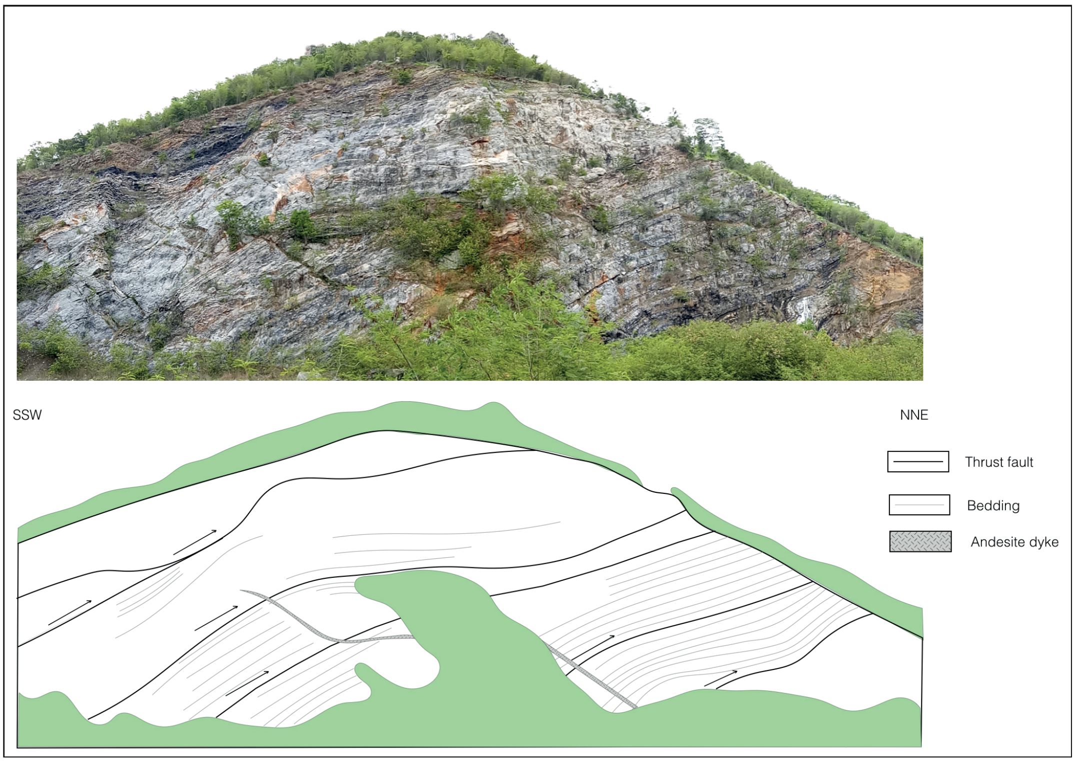

Figure 2: Mosaic pictures of studied outcrop in quarry clearly illustrating various features of karsitified lime-stone on slabbed surface, in the middle section of quarry.

Igneous rock: Igneous intrusions appears greenish grey on fresh surface and fine grained intrusive igne-ous rock with andesitic composition. Major minerals are plagioclase feldspar (albite), smectite and quartz. Most of the andesite dyke in the quarry trend ap-proxmately SW-NE and dips are around 30o implying that their em-placement may postdate much of the structural de-formation seen in the Permian limestone (figure 2).

Fracture: Fractures can be grouped into two main categories. The first rotated group is composed of bedding parallel to sub- parallel fractures, with con-sistent trends (related to deformation stresses) that are longitudinal, transverse and diagonal fractures, while the second group is non-orthogonal to bedding and shows dis-crete and varied dip angles, with no consistent trend (related to second deformation stresses).

There are two main fracture trends developed in quar-ry, which WNW-ESE (bedding parallel fracture) trends and NNE-SSW (bedding inclined fracture). Average strike of the former fracture set is 295° and 120° in WNW and ESE trends, respectively, with dip angles ranging from 35° to 60°. The late fracture trend (NNE-SSW) has N30E strike and dip angles ranging from 20° to 40°. A variety of fractures was observed in this area and were consistently filled with calcite.

Based on field investigations the orienta-tion of frac-ture are related to where they occur in the local zones of thrusting and folding and ulti-mately are a response to the regional compressive stress trend. Bedding par-allel fracture formed prior during early stage of stage folding and thrusting .During intense deformation, isotropic fractures trend to develop progressively until late stage of deformation, which was the same time of pervasive flexure slip in the limestone (figure 3A & 3B).

4.2 Fracture Analysis

Fracture intensity: Fracture density measures the number of fractures per thickness of bed. On the re-sult consider only the thickness of a bed within the same deformation zone; as is seen near the thrust fault of duplex structure, the relationship between bed thickness and fracture density shows the thinner bed have higher fracture intensities than thicker beds. The density of both parallel and perpendicular frac-ture sets varied for the outcrop in the study area, with the parallel fractures exhibiting greater variability. This variation was attribute preliminary to the struc-tural position, so the control position on the fracture density.

Paleo-stress analysis: The attitude of slickenlines, recognized by fault surfaces and mineral steps (chat-ter mark) was used to determine the orientation of slip and the sense of relative motion along fault plane. There are used to calculate that the three pa-rameters of paleostress tensors ($\sigma1$ $\sigma2$ and $\sigma3$). Its de-fine a compressive thrust fault regime and responding to NNE-SSW compression. The result shows $\sigma1$ and $\sigma2$ are generally sub-horizontal and $\sigma3$ is sub-vertical in stress tensors, which typical of a major thrust fault system.

4.3 Petrographic Study

Lithofacies: Referred to Embry and Klovan's (1972) carbonate classification, the carbonate rocks at study area can be classified to 2 texture;

1) Grain-support fabric, indicated by absence of mud, close packing of grains, and abundance of carbonate cement in interparticle pores. Most particles are ag-gregate grains, followed by some micritized bioclasts. There are made up skeletal of foraminifera (0.2-0.5 mm), crinoid (0.1-0.2 mm), algae (0.2-0.8 mm), gas-tropod (0.5-1 mm)and brachiopod grain (0.2-1 mm) (figure 4E).

2) Mud-support fabric indicated by grains, The mud-stone (containing less than 10% grains measured as grain-bulk percent) to wackestone (mud-supported carbonate rocks containing more than 10% grains. High variations in abundance and type of grains call for a breakdown of this category into informal sub-categories). The usual interpretation of mudstones is that they represent deposition of fine-grained sediment under low energy conditions allowing carbonate mud to settle in calm and quiet waters.

Cement morphology and patterns: Both inter and in-tra granular calcite cements show prismatic spar tex-tures overgrowth radial marine cement passing to dressy mosaic of equant carbonate spar growing as a centripetal void cement. Cementation has filled all the original void spaces in all samples; these rocks had little or no porosity and permeability prior to up-lift. Cementation and pressuring has created sutured contacts of the carbonate cement crystals and can be seen in intersects of thick lines in the twinning plane. The later stages of cementation probably occurred during deeper burial.

Stylolites and fractures: In quarry, WNW-ESE (bed-ding parallel) fractures were developed before the occurrence of stylolite and they were filled by calcite before this generation of stylolites formed. However, many fractures developed after stylolite forming be-cause on ongoing tectonism in this area. Thus in out-crop, we can define some fractures that cut trough stylolite as well as fracture sets related to styloliza-tion. Conjugate fracture set with WNW-ESE and NNE-SSW trends were formed under compres-sion stress near active thrust zones. They show a conse-quence of fracture development whereby NNE-SSW trends cut trough earlier WNW-ESE trends. In frac-ture fracture fills and across some stylolites, there are sim-ilar centripetal calcite cements. Such cements showed multiple phases of calcite generation and growth into voids. Thick line twinning and suturing of crystal grain contacts are also seen. Once again burial realm of the mesogenetic can be conclude based on these textures (figure 4A, 4B, 4C &4D).

Figure 3: Detailed of field documentation in quarry. A) Dominantly WNW-ESE (parallel sub-parallel bed-ding) fracture trends. B) Vein offset due to flexural bedding slip. C) Photograph show the andesite dyke crossed cut though limestone bedding and fault. D) Slickenline and mineral steps on a fault plane. E) Photo-graphs of study area show the andesite dyke(SW-NE) direction dip to northwest. F) Photographs of study area show the thrust fault (SE-NW) direction dip to southwest.

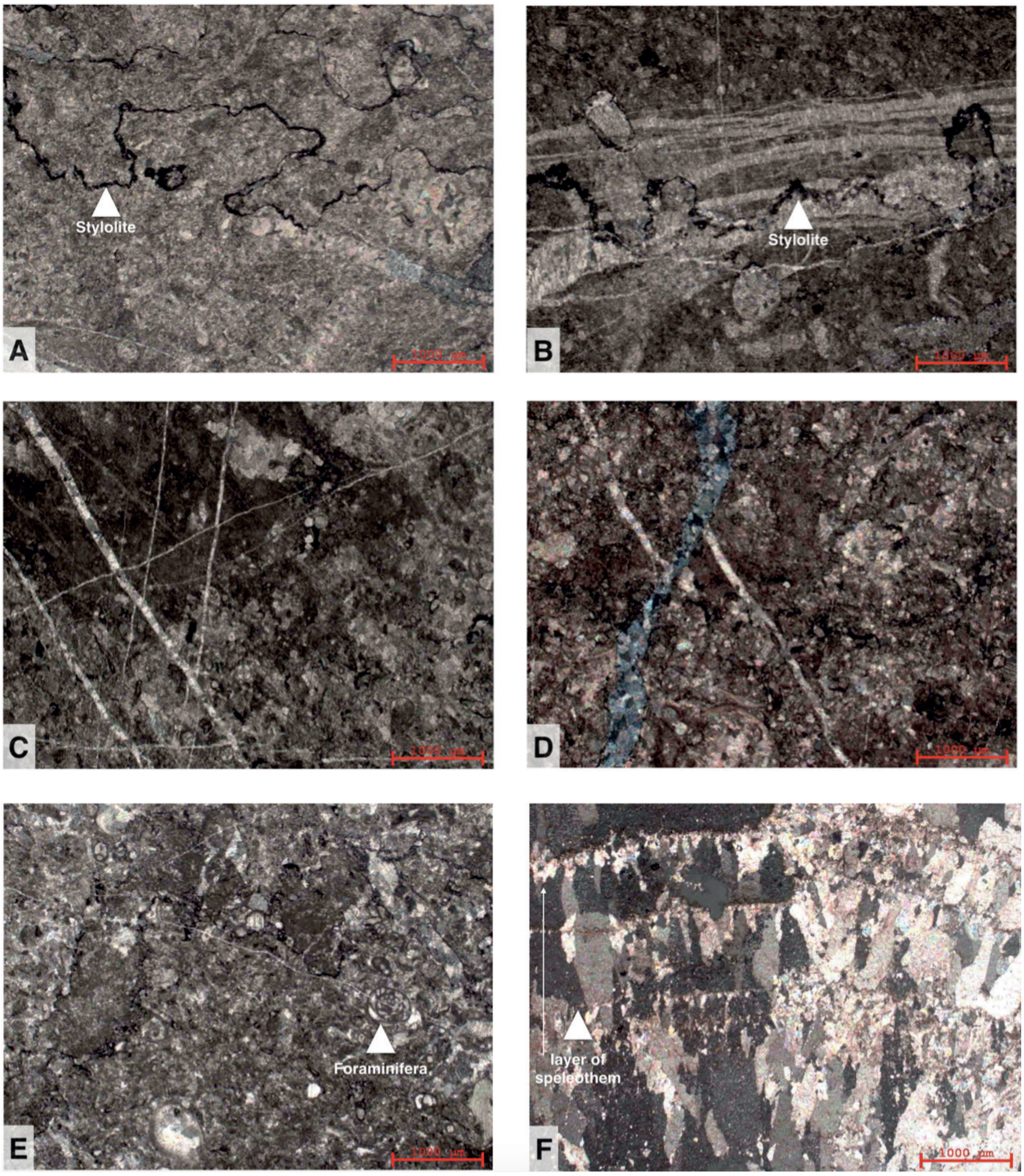

Figure 4: Detailed of petrographic study (2.5X magnification). A) Anastomosing sutured seams (microstylo-lite set) in lime mudstone, along pressure-solution surfaces and calcite, representing styloreactate (material that has crystallized at stylolite interfaces. B) Fracture (WNW-ESE) parallel irregular anastomosing stylolite seams. C) Microfracture sets, smaller foraminifera wackestone, crossed by calcite-filled. D) Wackestone, crossed by crosscutting calcite veins and show the displacement of movement. E) Encrusting foraminifera and very small microfossils, usually also assigned to foraminifera, are common constituents of Late Paleozoic shelf carbonates. F) Laminated internal sediment composed of calcite (show layer of speleothem).

4.4 X-Ray Diffraction (XRD)

X-ray diffraction(XRD) is an analytical tech-nique to identify mineral composition of the rock. In a quarries two samples were analyzed and the sum-mary table of mineral composition. One samples was taken from the intermediate andesitic volcanic rock. They are dominantly composed of albite, chlorite is subdominant and formed via alteration of mafic min-erals. Calcite, quartz and silicate clay minerals are also components of the andesite (figure 3C). The an-other sample was taken sample fault gouge. Calcite is dominant mineral composition, chlorite and quartz are accessory mineral.

4.5. Stable Isotope Analysis

The calcite crystals present in calcite veins, the limestone matrix and recent speleothem deposits were sampled (dental drill) for stable oxygen and carbon isotope compositions ($\delta^{18}O$ and $\delta^{13}C$) as pre-cipitated various stages of burial in the diagenetic and deformation history. Stable oxygen isotope composi-tion ($\delta^{18}O$) in a buried carbonate relies mainly on the isotope composition, temperature and salinity of the host fluid, while the stable carbon isotope composi-tion ($\delta^{13}C$) reflects the source of CO_2 ultimately pre-cipitated as a calcite cement (Nelson and Smith, 1996).

Cross-plots of $\delta^{18}O/^{16}O$ versus $\delta^{13}C/^{12}C$ for car-bonates can assist in identification of the depositional setting or in better defining the diagenetic evolution history in the study area. To be reliable, stable iso-tope interpretation in a carbonate must be related to the paragenetic set of textures observed in thin sec-tion. Two trends stand out. One is the burial trend which matches the isotope burial trends as define by previous studies of Saraburi Limestone; Ampaiwan (2011), Yingyuen (2013) and Warren et al. (2014). The other trend is a mixing trend tied to calcite pre-cipitated in recent speleothems.

Trends in the quarry are divisible into two trends namely; 1) Burial trend, which is interpreted as ce-ments and re-equilibrated matrix that preserve the signatures of somewhat cooler (shallower, possible earlier) stages of burial and next is interpreted as mostly derived from vein cements and preserves the isotope signatures of hotter (deeper, possibly later) stage of burial. and 2) Mixing trend, which is interpreted as speleothem that pre-serve signature of mixing meteoric water, response to nearby subaerial exposure (figure 5).

That is, samples in Group I were collected from of a combination of matrix and vein calcite. This group defines a C-O plot field that indicates lower burial temperatures, with less negative oxygen value, com-pared to group II, The thermally driven evolution of both matrix and vein calcite in group I implies that for those samples there was sufficient rock permeability to reset both the calcite cement and the constituents in the matrix. It is considered to be an colder likely earlier part of the earlier burial trend when there was pervasive and unfocused re-equilibration via matrix permeability rock fluid interaction. Clearly some vein calcite in fractures were formed in this earlier burial phase. This earlier burial trend is especially obvious in quarry and was associated with development of fractures and stylolites. This is a field well into the mesogenetic realm and ceased with complete cemen-tation of grain and matrix, shutting in down when re-fraction oxygen values around -10% to -11% PDB.

Group II is interpreted as a late burial stage with con-sistency higher negative oxygen isotope values that can more negative than can more negative to highest around -20% PDB. Sample that plot in group II are composed mostly of calcite vein. This calcite was precipitated in what was a hotter and perhaps deeper subsurface environment.

Group III is intermediate set of C-O values and indi-cated by pink shading was possibly derived via mix-ing of fluids from compacting deeper water sediments with those locally present in the platform pore waters, perhaps when thrusting had begun.

Recent speleothem samples give slightly variable and members of mixing trend. Group IV is zone of car-bonate soil, speleothem and slickenside, That is plot group can be recognized mostly using variation in carbon values. Group IV plot field contains elevate more negative carbon isotope value than other zone. This difference corresponds to proportion of carbon in pore water derived meteoric waters in the soil ma-trix speleothem and versus precipitative waters with chemistries in part by the dissolution of Permian clast versus bioclast and fracture. Hence Group IV plot filed define a mixing trend is the influence of meteor-ic waters superimposed on uplifted sediments. Uplift and exposure, facilitating this meteoric signature, is ultimately a response to the Himalayan event, which began in the Eocene (Morley et al., 2013). The mete-oric mixing trend is an example of the subsurface combination of infiltrated rainwaters with fluids that have dissolved from shallow uplifted Permian car-bonates that have entered the telogenetic zone (War-ren et al., 2014).

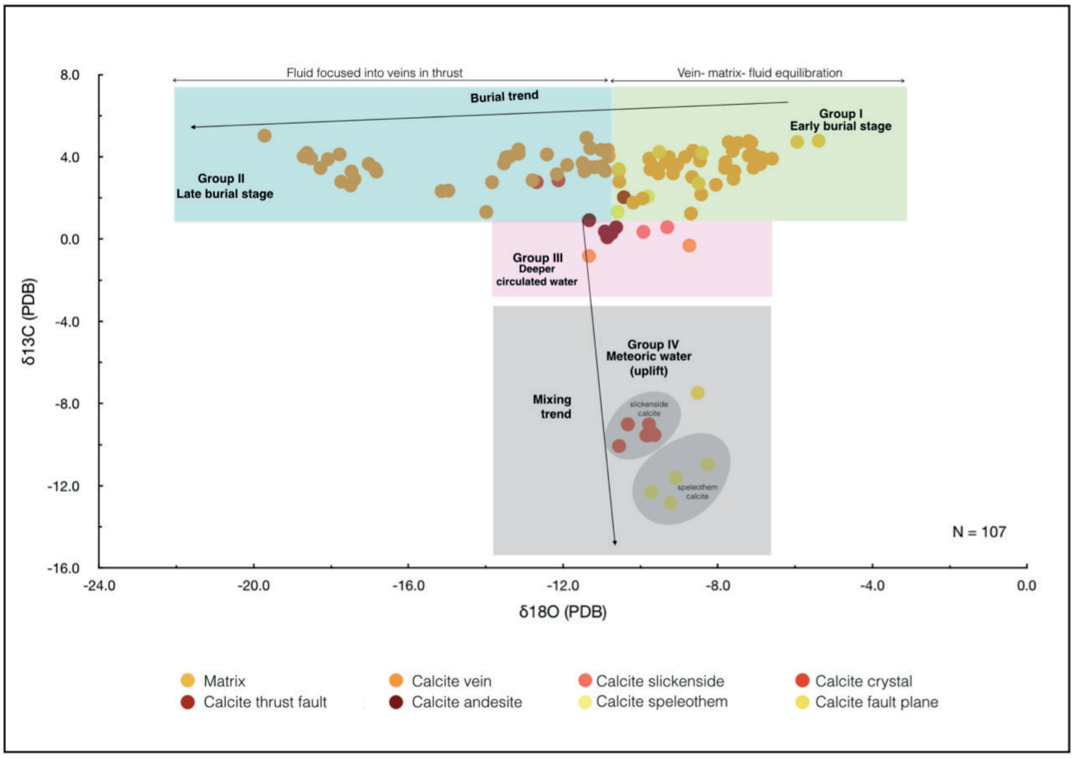

Figure 5: Cross-plot of $\delta^{18}O/^{16}O$ versus $\delta^{13}C/^{12}C$ in the study area.

5. Interpretations

5.1 Paleoenvironment and Diagenetic history

The depositional environments of carbon-ate rocks in the research areas can be interpreted from the results of petrographic and paleontology analyses. Lithofacies are dominantly gray-fossil-iferous pack-stone and mudstone to wackestone with smaller foraminiferas, corals, crinoids and gastropods shells indicating the sheltered shallow or lagoon environ-ment (figure 6).

The studied carbonate sediment were deposited and cemented in shallow marine sea water and moved into the burial environment. These is little textural or isotopic evidence of pervasive meteoric alteration during the transi-tion from deposition to burial. There is evidence of eogenetic marine cements. Through time, this drove a decrease in effective matrix porosity. Later recrystallization and local dissolution of calcite driven by hydrothermal fluid crossflows. This created selective isolated porosity along some fracture. This is probably because that time strata of quarry were adjacent to have been highly deformed by a combination of thrusting and folding, an intense fracture network developed.

The increasingly negative trend of oxygen and carbon isotopic signatures in calcite veins of Group II suggest that the calcite precipitated in these veins had been significantly influenced by the thrust, which was focusing and transporting a hot fluid from a deeper hotter location into the host rock. Calcite cements in the thrust faults and in the bedding planes were precipi-tated simul-taneously with thrust movements due to shear opening. All this evidence indicate simultaneous calcite grwoth tied to the thrusting and confirms and confirms that the associated temperatures in the Group II calcites came from the fault-focused escape of hotter deeper fluids.

Subsequently, the distal effects if the Himalayan Orogeny uplifted the studied carbon-ates as a subaerially fed karstified systems became active. This telogenic stage created vuggy and cavern porosity in quarry driven by meteoric water crossflows. Dissolution of the limestone allowed ongoing water entry, joining up along the expanding fractures and joints that enhanced the porosity. Terra rossa soils from the surface into some of the vugs. This allow accommodate space for carbonate soil to fill to earlier vuggy and so reduce permeability.

5.2 Structural and Tectonic evolution

The deformation history evidenced (figure 7) by outcrop patterns in the study area evolved largely under the influence of (approximately) NNE – SSW directed compression. This stress regime explains the investigated fault, fold and fracture geometries, and is consistent with other observations in the field includ-ing calcite veining and stylolization. In the thrusting and folding zones in quarry, there are two successive types of calcite veins, oriented perpendicular and parallel to the bed-ding and consistent with the regional compressional stress regime. Fracturing and filling of fractures by vein calcite occurred in multilayers, under relatively high temperature conditions (as indicated by the iso-tope values). Furthermore, isotopic and geometric relation-ships indicate that the fibrous calcite forming slickensides was derived either as a product of deep pressure solution or from the cross flow of hydro-thermal fluids.

Igneous rocks in the present study area consist entire-ly of dark-green to greenish-gray hypabyssal rocks forming minor intrusions, such as dikes. Geochemical results reveal that the rocks are of basaltic-andesitic to andesitic composition. The $^{40}Ar/^{39}Ar$ dating (Cha-rusiri et al. 1999) for hypabyssal dikes in the central Thailand indicates the age is Jurassic, probably indi-cating the younger phase of more widely exposed Permo-Triassic plutonics and volcanics. Petrographic investigation of the hypabyssal rocks reveals that the rocks consist mainly of relatively large-sized alkali feldspar, amphibole and a groundmass of plagioclase prism and quartz. Lath-shaped groundmass plagio-clases exhibit a well-defined trachytic texture, possi-bly suggesting that the rocks formed at a shallow depth.

After the Mesozoic era, the last orogenic episode took place, that is, the 45–50Ma Himalayan Orogeny (In-dia–Eurasia collision). The significant deformation associated with the development of the tensional tectonic regime resulted in the strike slip fault (sinistral) in the study area and possibly relates to group III isotopic signature.

The specific mechanisms of structural development involved in the formation of fracture and fault sys-tems in the carbonate outcrops that make up quarry summarized as a conceptual model. Deformation started as the Permian carbon-ate platform underwent WNW – ESE compressive stress, creating bed-orthogonal pressure solution stylolites and created open fractures (paral-lel with bedding). The next structures to from are in-clined or sub vertical fractures and a little sub paral-lel fractures, orientated with respect to folding shape and made up of two fracture sets. Ongoing tectonic stress continuously contributed to the deformation pattern in the area and was responsible for the in-creasing intensity of movements in the fold and thrust belt, including starting to form discrete, isotopic frac-ture in core zone of the thrusting. Increasing defor-mation and strong compressive forces facilitated fault offset and created an increased number of discrete and isotopic fractures. Moreover, the increased over-burden mass created by the overthrust sheet, in-creased the burial depth driving the formation of bed-parallel stylolites and deformation or attending of the grain structures in the rock matrix and imbricate thrust faults create duplex. The orientation and shear-ing sense for these structures changes with local compressive stress of the fold structure, resulting from layer-parallel faults or flexural slippage.

After that, the study area possibly under-went additional strong compressive force that further fractured the rock. This may explain the higher set of temperatures in Group II calcites compared to Group I sampes and the higher temperature samples that seem to dominated in both the matrix and the veins in the immediate vicinity of the thrust core. For example, sample which was collected from the core area of thrusting, shows a recrystalized matrix singnature that is indicative of a higher temperature than some of the calcite veins further for the thrust core.

For example, sample which was collected from the core area of thrusting, shows a recrystallized matrix signature that is indicative of a higher temperature than some of the calcite veins further for the thrust core. With Tertiary uplift, another set of late stage telogenetic fractures opened up, allowing the penetration of meteoric waters and precipitation of speleothems in modern (latest Cenozoic) near surface conditions.

5.3. Hydrocarbon potential

Diagenetic history is related to burial over-printed by uplift related effect to recent meteoric karstification. Summarize the diagenetic history in quarry and integrates evidence from the macro to mi-croscale in order to define what drives porosity modi-fication. If we use the studied intervals as a process analog for understanding possible "buried hill" trap quality in deeply buried limestone hosts, like the Permian limestones of Thailand, we can see that all vugs and caves were responses to diagenetically cre-ated permeability contrasts, which formed long after deposition. Carvenous porosity interfaces in quarry tends to be control by fractures set. These fracture enhance the permeability onece it was activated or reactivated and connected by trends that select a combination of bedding and fracture. Furthermore, vertical caverns in study area created by gravitational infiltration and these can join up the other fracture trends. However, terra rossa and widespread speleothemcements have reduced the permeability when they are located close to and unconformity surface.

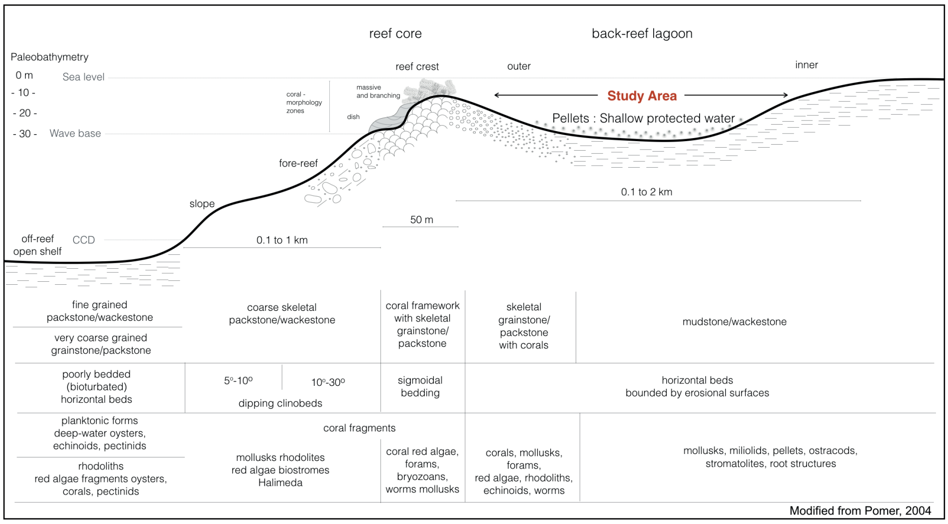

Figure 6: Model of Depositional environment of the study area. (Modified from Pomer, 2004)

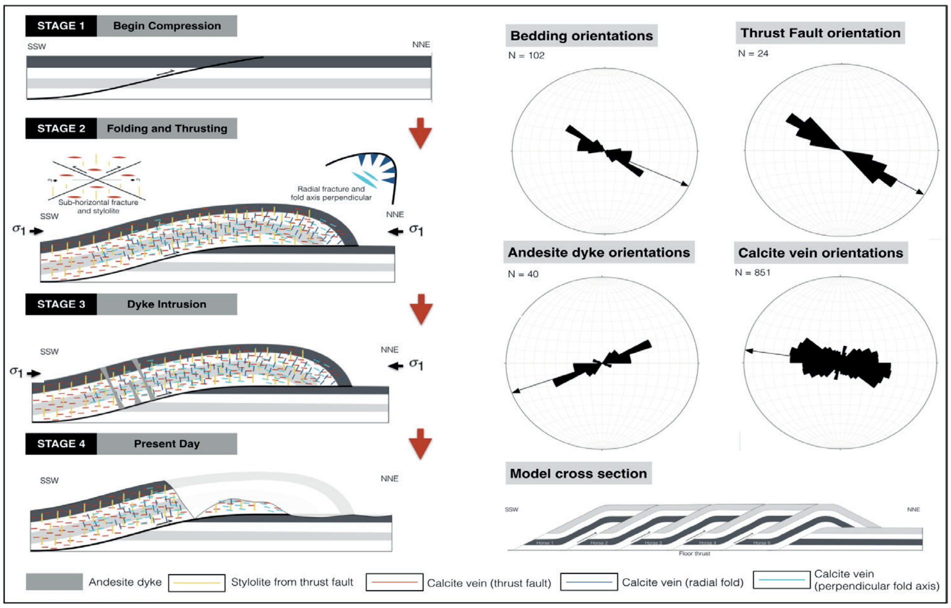

Figure 7: Conceptual model and rose diagram explaining the sequential development of structural elements in the study area.

6. Implications

6.1 Isotopic signatures vs previous study of central, Thailand

An isotope based on burial history curve is estab-lished for Permian carbonate in Saraburi area, central Thailand (Warren et al., 2014). The study document isotope signatures of various calcite cements formed at different stage in the burial history. The evolution established in the area is as follow:

1) Regional de-formation pre-deformations isotopic signature in eo-genesis realm that started off with value closest to original Permian seawater.

2) Progressive burial into early mesogenesis realms and subjected to Indosinian deformation. Matrix porosity was still preserved.

3) Continued burial into late mesogenesis and loss of matrix porosity. Calcite precipitation was re-stricted to structurally created fractured porosity in Indosinian deformation. 4) Uplift of the rock with influence of meteoric waters as a response to the Himalayan Orogeny, The data point on the burial curve along trends that indicates an ongoing rock flu-id equilibration in a condition with increasingly warmer fluid crossflows in host rock that had some degree of permeability. It seem that the rock fluid exchange that is occurring once matrix permeability is similar reflects central Thailand. Interestingly, an oxygen isotope value of -12%PDB was chosen by Warren et al. (2014) as defining the point in the fluid exchange temperature burial curve that defines the end of rock matrix fluid exchange in Thailand (more negative oxygen indicates warmer fluids). Values more negative than -12%PDB in Permian carbonate outcrops central Thailand come only from calcite veins created by Indosinian thrust faults. Using a val-ue of -12%PDB to interpret the thermal history of the study area (figure 8A). The speleothem in this study area plots along uplift curve established for the Indo-china block. This probably because the similar chem-istry of meteoric water percolating down when the rock was exhumed.

6.2 Isotopic signatures vs previous study of Phu Horm field, Thailand

Phu Horm field, Thailand study by Panthong, 2015, Drill cutting can be use to identify digenetically related fluid evolution. The calcite cutting are retain signature related to burial stage (warmer tempera-ture), and another set tied to calcite veins indicating cooling temperature and uplift stage. The C-O isotope signature curve of calcite fluid is defined by a slight increase in oxygen isot isotope value and decrease in carbon isotope value likely related to cooling and uplifted tied to later pos-sibly Paleocene event. It is interpreted that similar result in 2 trends (figure 8B); burial trend and mixing trend. But values on the negative side of -12%PDB oxygen isotope on the same covariant C-O trend indi-cate calcite veins in likely thrust fault damage zones. If so then the Phu Horm field show typical Indochina burial trends implying that rocks the vicinity of these wells did not experience focused high temperature fluid crossflows related to thrust damage zones. The oxygen decrease may indicate cooling, while increas-ingly negative carbon values imply either a catatonic carbon or an increasing mixed meteoric source for the carbon, So that trends is related to deep meteoric cir-culation event.

6.3. Implication to petroleum exploration and de-velopment of a carbonate play in Thailand

In general, Permian limestone resevoirs be-neath the Khorat Group such as Phu Horm gas fields are one of the main targets in the NE Thailand. Possi-ble hydrocarbon traces are seen with the calcite veins, as observed in thin sections shows deformed calcite crystals indicating shear has occurred with the veins and allowing the hydrocarbons to impregnate zones between the rock matrix and the vein. There may be possible mechanisms driving the filling se-quence of calcite cement and possible hydrocarbons. The first possibility is that the veins periodically re-opened (hydrofractured) and so allowed hydrocar-bons and hot fluids to migrate along the vein, which was subsequently deformed by further shear. Alterna-tively, the vein may have been reactivated during shear and so allowed hydrocarbons and hot fluid to infill along the vein at the same time as shearing oc-curred. Hydrocarbons may have migrated through the connected network of veins and fractures to concen-trate in areas of sheared fractures and so moved fur-ther into the localized areas that had increased con-nectivity. These structural elements were then path-ways for fluid flow within potential reservoir rocks.

The process of fracture and fault formation obviously created pathways for fluid migration and so the results of this outcrop study are most definitely applicable to the subsurface. The conceptual model shows the evolution of a connected pathway for fluid flow in the core zone of thrusting and folding. The folding-related fractures must have resulted in the formation of a zone made up a connected network of veins and fractures. Further shearing would have broadened the damage zone via the continued genera-tion of an expanding connected network of fractures and so provides ongoing pathways for hy-drocarbon migration.

The developed Phu Horm (figure 9A) and Nang Nuan gas fields (figure 9B) are related to hydrothermal al-teration and resulting from karsti-fication and enhanc-ing reservoir quality within different tectonic settings, both create a burial hill structure. Timing of karst formation in uplifted outcrops with post-uplift meteoric crossflows enhancing porosity by meteoric water crossflow. Meteoric effects must have occurred in both Nang Nuan and Phu Horm gas fields.Production in both is from zone immediately below an unconformity.

In Phu Horm the Unconformity separate Permian limestone from overlying Jurassic-Triassic fluvial sediments. In Nang Nuan it separates Tertiary age pluvials from the Permian carbonates. Clearly, both unconformities must have been subaerial features at some stage in the basin history and so there must have been a stage of meteoric flushing. Thus, the identification of karst zone in outcrops help to define the nature of the karstified reservoir in Phu Horn and Nang Nuan field.

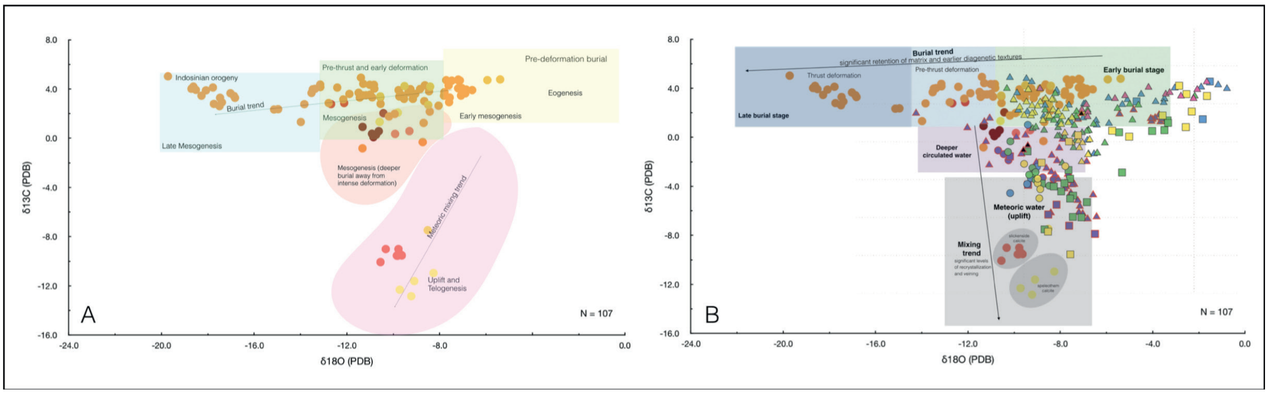

Figure 8: A) Cross-plots of $\delta^{18}O/^{16}O$ versus $\delta^{13}C/^{12}C$ superimposition of data in study area on estab-lished trend now indicated by shaded polygons only from Warren et al. (2014), B) Cross-plots of $\delta^{18}O/^{16}O$ versus $\delta^{13}C/^{12}C$ of Phu Horm, Thailand (Panthong, 2015), combined with the isotope signature of study area.

7. Conclusions

1. The trend of major thrust fault 120° /40° SW, shown the duplex series of thrust fault.

2. The two main fracture sets in the quarry are; E-W sub-horizontal and N-S sub-vertical calcite filled fractures.

3. Fluids within the fractured network participated calcite that filled fractures and in the earlier stages of burial evolution, when the matrix was still permeable, also formed re-equilibrated calcite cements in the matrix (both reduce effective porosity). There are 4 calcite group based on isotope result; Group I calcites after complete cementation of the matrix, Group II calcites formed during thrusting and folding and Group III and IV calcites precipitated by meteoric water.

4. Isotope study defines a burial trend and mixing trend. The burial trend show increasingly negative oxygen isotope values.This is followed by hotter (more negative) ongoing vein fracture fill, stylolite and fluid alteration overprints and

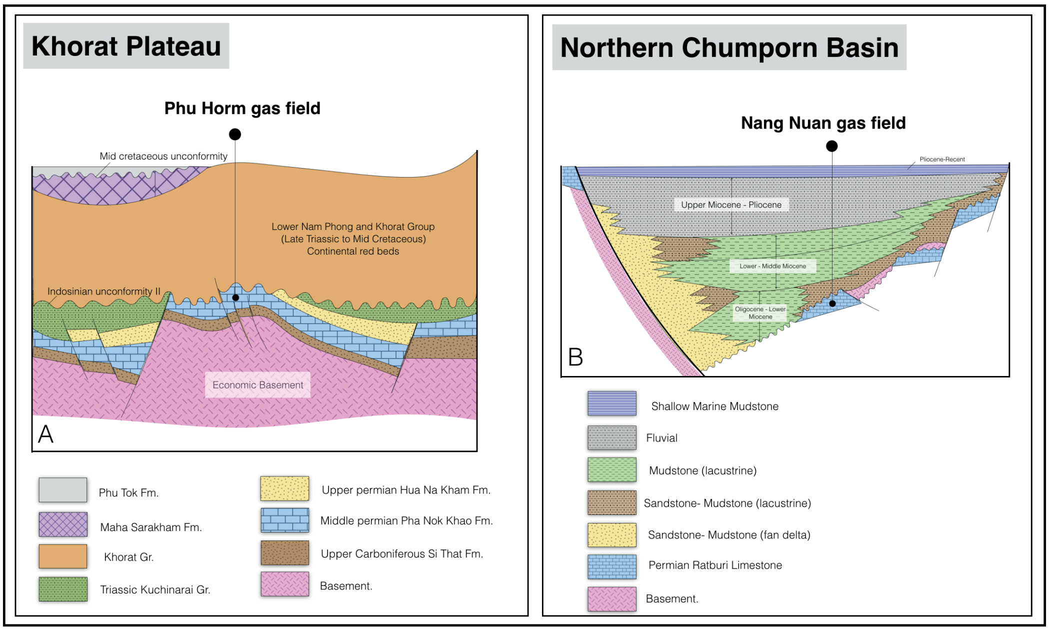

Figure 9: Cartoon schematic of Permian carbonate reservoir in Thailand. A) Thrust complex developed struc-ture in Phu Horm field. B) Nang Nuan field that developed in Horst block from extensional stress (Modified from Racey A., 2011)

indicat-ed by more negative oxygen isotope value. The mix-ing trend shows a board range of negative carbon iso-tope values that become less negative in karstified. This indicates mixing of purely meteoric waters with water influences by dissolution that define in the spe-leothem.

5. There are two main stages in the diagenetic history of the studied carbonates related to karstified devel-opment; 1) episode influenced by burial in the eoge-netic to mesogenetic and 2) meteoric dissolution epi-sodes in the telogenic realm in response to nearby subaerial exposure. Based on regional consideration the E-W sub-horizontal and N-S sub-vertical calcite filled frac-tures formed during Indosinian I (Early Triassic).

6. Buried hill reservoirs in Thailand fields (Phu Horm) are karstified carbonate rocks, which have been hydrothermally leached to create vuggy and cavernous porosity perhaps under deep burial condi-tion, but the nature of their geological column with fluvial sediment atop the uncon-formity shows they must also have experienced an episode of meteoric diagenesis, Furthermore, good permeability in reser-voir is associated with fracture distribution near faults. Karstification under the unconformity surface due to sub-aerial exposure improve reservoir quality when it connected the fractures.

8. Recommendations

According to results of isotope studies of the studied outcrops, separate subsurface burial trends and meteoric karstified were established. This may be an isotope tool that can be applied to cutting collect-ed across likely karst zone intersection in the subsur-face (in order to separate system created by by burial versus meteoric processes).

9. Acknowledgements

I want to thank Chevron Thailand Exploration and Production, Ltd. for full scholarship to pursue this M.Sc. course. I deeply thank Prof. John Keith Warren for their supervision, suggestions, recommendations and valuable ideas during this research project and throughtout the course. I am very grateful to Prof. Christopher K. Morley and Prof. Punya Charusiri for their availability, support, and their valuable teaching and fresh ideas. I have furthermore to thank Dr. Thasinee Charoentitirat for providing guidance and suggestions.

Especially, I would like to give my special thanks to Mr. Patiparn Pojanart, Mr. Nartmongkol

Songserm for all of their help during field work in Nakhon Sawan Province and always stay with me in a good time and a bad time. I would also like to extend my appreciation to my undergraduate students from the Department of Geology, Rungrot Suntornpakdee, Sri-amra Meepring, Dan Pinchaleaw, Anupong Veerapan, Thapanapong Liewkasemsant, Pawat Wat-tanachaleekul, Supavit Khamdech, Waris Nuamnim, Nutniti Suteerapongpan and Thanawat Prasertsiri for their supporting me in my research work.

10. References

Ampaiwan, P., 2011. Structural Development of Thrusts, Folds and Fractures in Quarry Expo-sures of Permian Limestones, Saraburi Province, Cen-tral Thailand: Implications for Fractured Re-ser-voir Development in NE Thailand. Chula-longkorn University, Bangkok, p. 44 (M.Sc thesis).

Booth, J., and N. Sattayarak, 2011, Subsurface Car bonierous - Cretaceous Geology of NE Thai-and. In: Ridd, M.F., Barber, A.J. & Crown, M.J.(eds), The Geology of Thailand, The Geolog-ical Society of London, p.185-222.

Charusiri P., Clark A. H., Farrar E. & Archibald D. 1999. Note on the 40Ar/39Ar dating results of the volcanic rocks of central Thailand. Journal of Asian Earth Sciences.

Embry, A.F., Klovan, J.E. (1972): A late Devonian reef tract on northeastern Banks Island. N.W.T. – Bull.Canadian Petrol. Geol., 19, 730-781

Morley, C.K., Ampaiwan, P., Thanudamrong, S., Kuenphan, N., Warren, J., 2013. Development of the Khwang Fold and Thrust Belt: implications for the geodynamic setting of Thailand and Cambodia during the Indosinian Oroge-ny. J. Asian Earth Sci. 62, 705-719.

Nelson, C. S., and A. M. Smith, 1996, Stable oxygen and carbon isotope compositional fields for skeletal and diagenetic components in New Zealand Cenozoic nontropical car-bonate sediments and limestones: a synthesis and review: New Zea-land Journal of Ge-ology and Geophysics, v. 39, p. 93-107.

Panthong, A., 2015, Facies distribution and diagenetic evolution of carbonate reservoir in Pha Nok Khao Formation, Sinphuhorm field, Thailand.Chulalongkorn University, Bangkok, p. 39 (M.Sc thesis).

Pomer, L., Gili, Bradano, M. and Westphal, H. (2004) Environmental factors influencing skeletal grain sediment associations: A critical review of Miocene examples from the Western Mediterranean. Sedimentology. 51, 627-651.

Racey, A., 2011. Petroleum geology. In: Ridd, M.F., Barber,A.J. Crow, M.J. (eds.), The Geology of Thailand, The Geological Society of London, pp. 351–392.

Sone, M., and I. Metcalfe, 2008, Parallel Tethyan su-tures in mainland Southeast Asia: New insights for Palaeo Tethys closure and implications for the Indosinian Orogeny: ScienceDirect, p. 166-179.

Ueno, K., Charoentitirat, T., 2011. Carboniferous and Permian. In: Ridd, M.F., Barber, A.J., Crow, M.J. (Eds.), The Geology of Thai-land. Geological Society, London, pp. 71-136.

Warren, J., and others., 2014. Structural and fluid evolu-tion of Saraburi Group sedimentary car-bonates,central Thailand: A tectonically driven fluid system. Marine and Petrole-um Geology, pp. 100-121.

Yingyuen, J., 2014. Diagenetic Evolution of “Buried-Hill” Carbonate Reservoir Analogs in Outcrop Permian Carbonates, Saraburi Province, Thailand. Chulalongkorn University, Bang-kok (M.Sc thesis).