Structural and Diagenetics Contrasts Across a Duplex in Deformed Permian Carbonates in the Saraburi of Central Thailand

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Abstract

The studied region is part of a previously unrecognized duplex thrust complex. Detailed field and laboratory study of duplex exposures in Permian limestones across three quarries (Quarry1, 2 and 3), Saraburi Province, central Thailand show that the varying rock type response to the imposed compression are directly tied to mechanical strength contrasts across the main thrust. A highly tectonised portion of the geology veisible in all three quarries sits in and below the main duplex and is dominated by highly folded beds of deeper water cabonate sediments. Structurally above the tectonised zone of the main thrust is a sequence of less-deformed carbonate platform sediments. These structurally overlying platform sediments are actually younger in terms of stratigraphic age as is proven by the use of fusulinid index fossils. The package of deeper water carbonates that sits within and below the main thrust is Middle Permian, as identified by the presence of fresh fusulinid index fossils (Neochwagerina and Pseudodoliolina). The upper unit of mostly platform carbonates that lies structurally above the main thrust is older, these sedimnets have a Lower Permian age, as identified by the fusulinid index fossil; Chalaroschwagerina.

The deformation history evidenced by outcrop patterns in the study area documents previously-unrecognized interbedded deeper water volcanic-derived mudstones and crinoidal rudstones. These beds are present in all three areas as inclined beds with an approximately E-W strike direction and dips around 60-80 degrees, with bed orientations that are conformable across all the 3 quarries. The strain of structural deformation is at a maximum in Quarry 2, and lessens in Quarry 1 and Quarry 3, respectively. Detachment folds are present, with the main fold axes trending approximately E – W. Most fractures in the outcrops are calcite-filled and exhibit two dominant trends: 1) NE-SW and 2) NW-SW.

The structural evolution, as mapped in the field, is supported by stable isotope measurements (carbon and oxygen) of vein-filling calcites, which show a clear temperature and time-related separation along the same burial trend. Almost all of the samples from Quarry 1 that were taken from samples in its steeply dipping beds, plot at the upper end of the C-O crossplot-defined burial trend. Samples from quarry 2 and 3, with their much more complicated structuration (heavily deformed and calcite-veined) plot further along the burial trend in a zone related to somewhat hotter

fluids. As these fluids passed through the rock they drove both re-equilibration/recrystallization in permeable parts of the matrix and the precipitation from warmer fluids in structurally formed veins. Interestingly, samples from the upper part of quarry 1, that were collected in the deformed zone below the thrust, also plot in the same temperature field. Yellow-tinged calcite vein samples from Quarry 1 show a mixing trend related to the influence of meteoric waters.

The fractured Permian reservoirs of the Sin Phu Horm and Nam Phong gas fields in NE Thailand, to the north of the study area in the Khorat Plateau, have proven difficult to understand and predict in term of their reservoir properties. Therefore, the results of this outcrop study provide a potential analog for the currently producing fractured Permian Limestone reservoirs of this region.

Keywords: Carbonate, Permian, Dolomitization, Fractures

1. Introduction

Of fundamental importance to fractured reservoir development in Thailand and the SE Asian region is a knowledge of fault, fold and fracture geometries and their relationship to thrust – fold development but in Thailand there has only been limited exploration success in the folded and fractured Permian carbonates of the Khorat Plateau area. Malila et al., (2008) notes that "the fractured Permian reservoirs of the Sin Phu Horm and Nam Phong gas fields in NE Thailand have proven difficult to understand and predict". A quarried hillside of a Permian limestone located in Saraburi Province, central Thailand was selected for detailed study of structural development in the core zone of a thrust and fold belt in order to help better understand the structural history and fracture development of a Permian reservoir analog in Thailand.

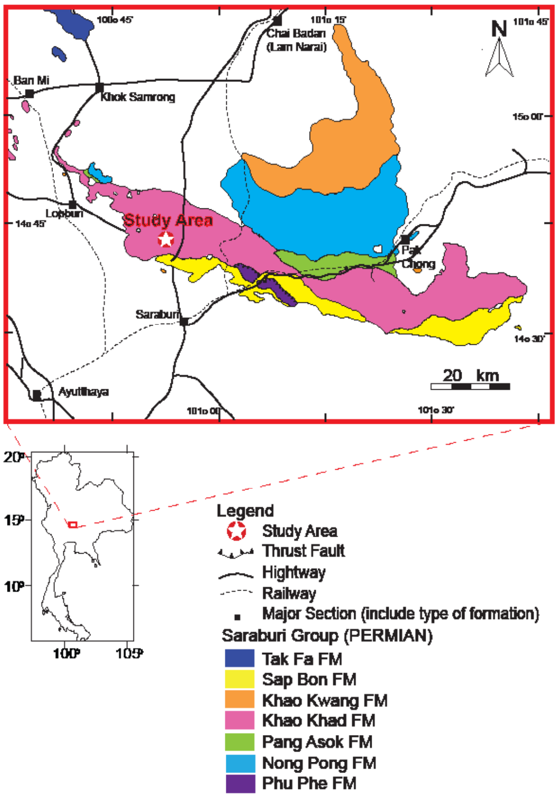


Figure 1: Geologic map of Saraburi Group (Permian) in Saraburi area, Thailand. Modified from Ueno and Charoentitirat (2011) to show study area location.

2. Methods

The study integrates fieldwork datasets, Laboratory - processed datasets and litera-ture studies. Fieldwork datasets consist of; Three quarried limestone hillsides that are the focus of this study, were mapped and geological information documented by taking photos, sketching structures,taking structural - related orientation mea-sure-ments. All measured field data, mostly fold and fracture geometries, were plotted in stereonets and Wintensor® was used for palaeostress analysis of fault kinematic data , and collecting samples at representative stations for laboratory analysis. For the laboratory studies 16 rock petrographic samples were made with stained offcuts, and 12 XRD samples run. Samples were sent to Pontifex Laboatories and Monash University laboratories in Australia. The thin sections and laboratory determinations were fully observed in Bangkok during June to July 2013. In addition 113 samples that were representative of all calcite vein directions, lithology end members were run to determine stable oxygen isotope ($\delta^{13}O$) and carbon ($\delta^{13}C$) values. The isotope samples were collected using a carbide-tipped dental technicians drill and analysed in the Isotope lab at Monash University in Australia. Samples were prepared and analysed using standard techniques, as described in Allegre (2008). Integration of the field and laboratory results are used to better define the relationship between fluid flow and structural evolution in the study area.

3. Results

1. Field Observations

Across the study areas of Quarry 1, 2 and 3 analysis is done at 3 scales of observation, as below;

1.) Macroscopic scale; in this scale observations are made as overviews of outcrop distributions and relationships to surrounding areas, and the field mapped relationships in and between the 3 quarries.
2.) Mesoscopic scale; in this scale observations are made on the detailed geology of the 3 quarries, such as lithology and textures, bedding orientations, fracture trends, stylolites, structural style and strain, etc.
3.) Microscopic scale; in this scale observations focus on details of rock textures using thin sections to study in variations in lithofacies character and diagenetic features. X-ray Diffraction (XRD) is to identify the overall mineralogy to rocks.

Macroscopic and Mesoscopic scale observations

The study areas are located in 3 inactive quarries (Quarry 1, 2 and 3) in Saraburi Province. The Figure 2 field map overlay shows the positions of the 3 studied quarries, that make up the northern and eastern sides of a single hill Permian limestone, that contains the mapped thrusts. Tables 1 and 2 summarize observations made at the macro and mesoscales

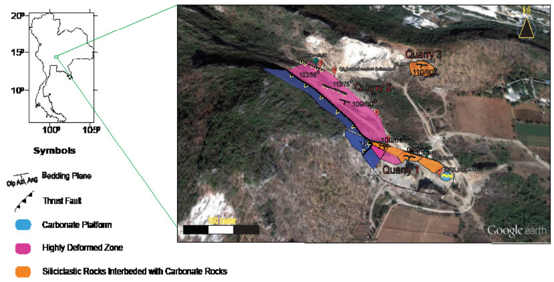


Figure 2: Structural map of the study area location (Quarry 1, 2 and 3) at Na Phralan, Chaloem Phrakiat District, Saraburi Province, central Thailand

2. Paleo-stress Analysis

The calculated stress tensor is characterized as S_1: 10/018, S_2 : 80/196, and S_3: 00/288. It defines a compressive

	Macroscopic scale		
	Quarry1	Quarry2	Quarry3
Overview	From Google Map and an overview of the outcrop you can see the thrust fault above the quarries that separate the area into a highly deformed layered zone and massive carbonate platform interval (Yingyuen, 2013)		
Size of outcrop (W x H)	50 m x 110 m	200 m x 160 m	40 m x 15 m
Structural Styles	Disharmonic asymmetric folds and detachment folds and inclined beds made up a interbedded crinoidal rudstone and siliciclastics (green and red beds of volcanic-derived mudstone.	- Disharmonic asymmetric folds, chevron folds, and duplex thrust in center of the quarry 2 - This quarry shows highly deformed structure and recrystallized calcite with inclined bedding orientation that are conformable all with quarry 1. - Sinistral strike-slip fault - Thrust fault and slickenside is seen inside the quarry 2 .	Inclined beds made up of interbedded carbonates and siliciclastics (green and red beds of volcanic-derived mudstones) that are conformable with quarry 1.
Strain	Medium (highly deformed beds and incline bedding).	High (highly deformed beds, duplex thrusts and sinistral strike-slip faults).	Low (inclined beds with sheared and deformed micro-textures).
Timing	Middle Permian limestone (indicated by Index Fossils: Neoschwagerina and Pseudodoliolina)		
Lithology & Texture	- Carbonate: crinoidal mudstone and breccia beds. - Clastic: volcanic-derived mudstone (Red and green colors from varying weathering; ferrous vs. ferric).	Crinoidal rudstone (Highly recrystallized).	-Carbonate: Crinoidal rudstone and conglomerate bed. -Clastic: volcanic-derived mudstone (Red and green colors from varying weathering; ferrous vs. ferric).
Bedding orientation	100 / 61° approximately E - W.	109 / 80° approximately E - W.	110 / 80° approximately E - W.
Fracture trend	2 major trends: NW - SE (highly deformed folded beds) and NE-SW (interbedded crinoidal rudstone and siliciclastics).	2 major trends: NW - SE (highly deformed folded beds) and E- W (in thrust zone).	2 major trends: ENE - WSW and NNW- SSE.

Table 1: Summary of observations at the macroscopic scale across the three quarries

Mesoscopic scale			
Structural type	Quarry1	Quarry2	Quarry3
σ_1	NNE-SSW	NNE-SSW	NNE-SSW
Fold Axes	ESE-WNW, plunge to the SSW.	Many directions.	-
Thrust Faults (Strike / dip)	n/a	- Duplex thrust : 113 / 75° - Thrust and sinistral : 103 / 56°	Riedel shear structures (R-R' of strike-slip tectonics).
Slicken Lines	n/a	Approximately E- W	-
Fracture Types	Calcite filled fractures.	Calcite filled fractures.	Calcite filled fractures.
Fracture Orientations	Fractures sub-perpendicular to bedding plane into 2 main directions. -NE-SW (inclined interbedded). -NNW-SSE (deformed folds zone).	Fracture orientations into 3 main directions. - NNE-SSW (before thrust zone and hanging wall). - E-W (parallel to bedding and thrust plane). - NW-SE (foot wall, highly deformed folds).	Fractures orientations into 2 main directions (conjugate fractures). - ENE-WSW (sub-parallel to bedding plane). - NNW-SSE (sub-perpendicular to bedding plane).
Bedding Planes (inclined beds)	100 / 61° approximately E - W	109 / 80° approximately E - W (The bedding orientations are conformable to quarry1).	110 / 80° approximately E - W (The bedding orientations are conformable to quarry1).
Bedding Planes (Deformed beds)	Various orientations with respect to folding shapes.	Various orientations with respect to folding shapes	-
Bedding thickness	Inclined bedding: variable 0.05 - 1 m, averaging 0.15 m. Deformed bed: 0.2 - 2 m, averaging 0.5 m.	Variable 0.15 - 5 m. averaging 0.5 m.	Variable 0.05 - 15 m. averaging 0.2 m.
Lithology and Texture	- Carbonate: Rudstone with crinoid and fusulinid grain-supported and breccia beds; mixing of crinoidal rudstone and red and green volcanic-derived mudstones. - Clastic: volcanic-derived mudstones both green and red beds show turbidity current indicated (Bouma sequence units b, c, d, and e) indicating of deep marine environment. The evidence includes parallel bedding, convolute beds, ripples and small-scale slumps.	Crinoidal rudstone with highly recrystallized calcites. The textures show very highly deformed zone from separate black and white minerals interlayer.	- Carbonate: Crinoidal rudstone and conglomerate bed with fusulinids, crinoids, and corals grains supported that variable clast sizes 0.1 - 10 cm. - Clastic: volcanic-derived mudstone in green beds show the parallel bedding, convolute beds, ripples of Bouma sequence indicate deeper marine environment.

Table 2: Summary of observations at the mesoscopic scale across the three quarries

thrust fault regime and is responding to NNE – SSW compression (typical in Indosinian).

3. Micro-scale observations

3.1 X-ray Diffraction (XRD)

Twelve samples were analyzed by X-ray diffraction to semi-quantitatively identify the overall mineralogies. The XRD results were matched to stained thin section observations, as described in the petrography section (Table 3).

3.2 Thin section study

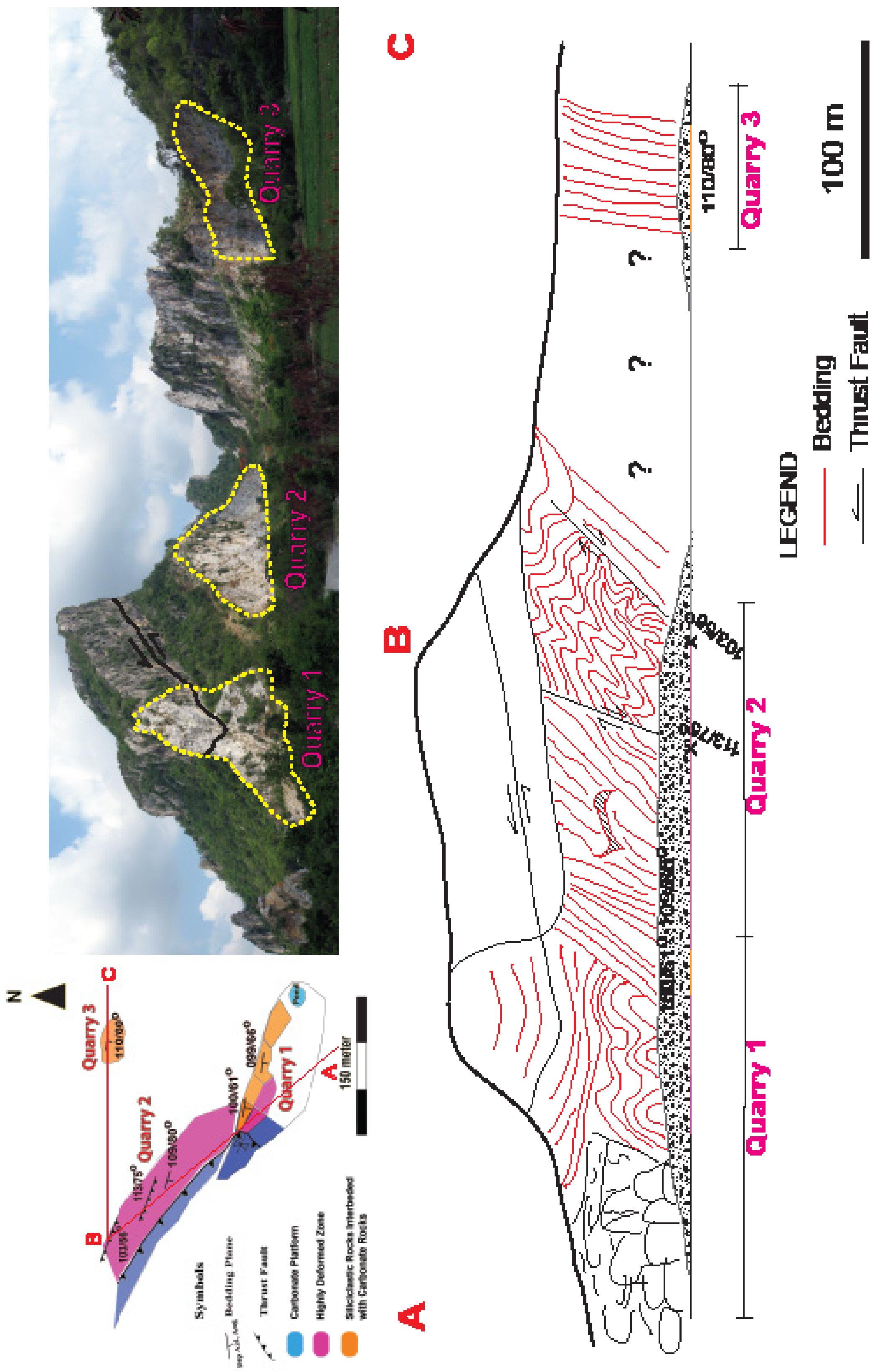
Sixteen samples were chosen for slabbing, with the more interesting portions of the slab faces chosen for thin sectioning and associated isotope work. Thin sections allow detailed study of lithofacies and diagenetic features. The summary of observations in each quarry at the microscopic scale from both of XRD and thin-section are in table 4.

4. Discussion

1. Age and Deposition Environment

From the integration across the three scales of observation in all 3 quarries it is clear that the main controlling feature is varying rock type response to the imposed compression relates to mechanical strength contrasts across the main thrust (Figure 4). The highly tectonised portion and below is dominated by highly folded beds of deeper water sediments. Above the tectonised zone it is overlain by less-deformed carbonate platform sediments (as studied by Yingyuen, 2013). The studied region is part of a previously unrecognized duplex thrust complex.

Strong evidence supporting this hypothesis is the difference in the age of rock units, whereby is the depositional ages of the units within and beneath the tectonised zone are younger that the structurally overlying platform carbonate units (in all 3 studied quarries). It is Middle Permian as identified the


Quarry 1
Quarry 2
Quarry 3
A
B
C
LEGEND
Bedding
Thrust Fault
100 m
Symbols
Bedding Plane
Thrust Fault
Carbonate Platform
Highly Deformed Zone
Siliciclastic Rocks Interbedded with Carbonate Rocks
150 meter
N

		Microscopic scale		
		Quarry1	Quarry2	Quarry3
XRD	Clastic	Red beds: Quartz and Albite. Green beds: Quartz, Calcite and Albite. Chert: Dominate Quartz and sub-dominate of Calcite.	-	In quarry3 have interbeds of red and green beds with carbonates.
	Carbonate	– Matrix in folds near late stage calcite vein (sub-parallel to bedding) : Quartz dominant and sub dominant with calcite. – Pink calcite veins in folds with sub- parallel to bedding (late stage): Calcite dominant and some traces of Dolomite.	Mineral in pink calcite vein in thrust zone: Calcite. Mineral in pink calcite vein in slickenside plane (thrust inside): Dominant calcite and some traces of quartz.	Mineral in conglomerate bed: Calcite.
	Accessory minerals	Red beds (clastic): Chlorite, Hematite and Muscovite. Green beds (clastic): Traces of muscovite and kaolinite. Pink calcite veins in folds (late stage): Traces of dolomite.	Some traces of quartz in slickenside planes in quarry2 (inside).	-

Table 3: Summary of the observations from XRD at microscopic scale in the three quarries

		Microscopic scale		
		Quarry1	Quarry2	Quarry3
Thin section	Lithofacies	– Textures of red and green beds: very fine grains of quartz (clay size) and some water-reworked volcanic-derived mudstones. – Grainstone in breccia with fusulinid grains as index fossils; named "Neoschwagerina" indicate Middle Permian age. – Grainstones in breccia with fusulinid grain as index fossils; named "Pseudodoliolina" indicate Middle Permian age.	Crinoidal grain-rudstone with wackestone matrix. The calcite crystals were coarsely recrystallised and deformed.	Crinoidal grain-rudstone with mudstone matrix (more ductile than Quarry1) show highly deformed and shear. See the fossil deformed shapes and laminate bands of white and black minerals.
	Diagenetic features	– In folded bed shows at least 3 stages of calcite veins; 1st calcite, 2nd Ferroancalcite and 3rd late stage calcite veins cutt-ing stage 1&2 and parallel to folded beds.	– Stylolites are often seen in the outcrop and thin sections and are related to highly deformed zones and thrusting. – Kink bands are seen in calcite crystals shows pressure solution modifies interlayer slip (planar foliated). – Calcite veins networks show many events and directions of calcite veining indicated very highly deformed zone (near thrust zone and folds). – Calcite veinsdisplacement by shear movement by thrust. – Fractures cut into crystal grains indicate highly deformed structures in this area.	– Quartz veins relate to late stage hydrothermal fluids; cut into crinoidal rudstone with mud- wacke stone matrix with grains having deformed shapes. – Fossil show deformed shapes indicating highly deformed structures and shear zones. – Drusy mosaic in a recrystallized calcite vein. – From outcrop and thin section can see R-R' of strike-slip tectonics.

Table 4: Summary of thin-section observations (microscopic scale) across the 3 quarries

presence of fresh fusulinid index fossils (Neochwagerina and Pseudodoliolina in figure 18) The upper units are older, they are Lower Permian as identified by the fusulinid index fossil; Chalaroschwagerina (Yingyuen, 2013).

2. Diagenetic History

The history of diagenesis and fluid processes are interpreted in this current report based on the combination of petrographic and isotope determinations tied, back to stuctural setting as defined by field maps. Standard carbon- oxygen crossplots outline a number of burial related trends. Figure 5 plots the isotope signatures from all three quarries and subdivides the plot fields in terms of the structural/geological complexity across the three quarries. Almost all of the samples from Quarry 1 that were taken from samples in its steeply dipping beds, plot at the upper end of the burial trend. This and other burial trends in the region are characterized by increasingly negative oxygen values, related to increasing burial temperatures in fluids precipitating $CaCO_3$ both in the matrix and in the calcite veins (Figure 6). Samples from quarry 2 and 3, with their much more complicated structuration (heavily deformed and calcite-veined) plot further along the burial trend in a zone related to somewhat hotter fluids. As these fluids passed through the rock they drove both re-equilibration/recrystallization in permeable parts of the matrix and the precipitation from warmer fluids in structurally formed veins.

3. Nature of the fluid flow in the thrust that carried the calcite cement into the fractures

Thrusting and folding zones are believed to play an important role in the control of fluid flow in the upper and middle crust. Hot solutions may be channelized along thrust fault through the generation of micro-cracks and fractures during deformation at high fluid pressures.(Badertscher et. al., 2002). The Permian limestone rocks in the study area have been highly de-

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	Diagenetic features	- In folded bed shows at least 3 stages of calcite veins; 1st calcite, 2nd Ferroancalcite and 3rd late stage calcite veins cutt-ing stage 1&2 and parallel to folded beds.	- Stylolites are often seen in the outcrop and thin sections and are related to highly deformed zones and thrusting. - Kink bands are seen in calcite crystals shows pressure solution modifies interlayer slip (planar foliated). - Calcite veins networks show many events and directions of calcite veining indicated very highly deformed zone (near thrust zone and folds). - Calcite veinsdisplacement by shear movement by thrust. - Fractures cut into crystal grains indicate highly deformed structures in this area.	- Quartz veins relate to late stage hydrothermal fluids; cut into crinoidal rudstone with mud- wacke stone matrix with grains having deformed shapes. - Fossil show deformed shapes indicating highly deformed structures and shear zones. - Drusy mosaic in a recrystallized calcite vein. - From outcrop and thin section can see R-R' of strike-slip tectonics.

Table 4: Summary of thin-section observations (microscopic scale) across the 3 quarries

Figure 4: The hypothesis of differing ages showing position of two areas with different age determinations as seen in a map showing duplex thrust position as the main control of the older rock (lower Permian), which is less deformed and a depositionally shallower carbonate platform but now lies on top the younger rock (middle Permian) which is highly deformed structure and deposited in a deeper marine environment.

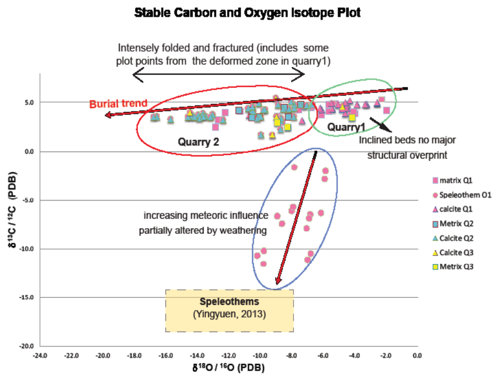

Figure 5: The isotope signatures from all three quarries, and subdivide into plot fields based on structural/geological complexity across the three quarries.

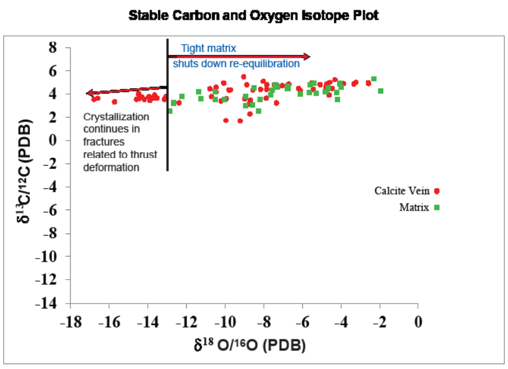

Figure 6: The isotope plot from samples in all three quarries in terms of matrix versus calcite cement in veins.

formed by a combination of thrusting and folding. Syn-kinematic fluid flow in the thrust and fold zone is evidenced macroscopically by the abundance of calcite shear veins within the outcrop of these Permian limestone. Calcite cements in the thrust faults and in the bedding planes were precipitated simultaneously with thrust movements due to shear opening. The vein-filling calcite crystals are variable in size from 200mm up to 3 mm, and on the fault planes show abundant mechanical twining planes, kink bands and drusy mosaic recrystallized calcite. All this evidence indicate simultaneous calcite growth tied to the thrusting.

4. Implications for fractures reservoir in NE Thailand

At the relatively small scale of the current study, it is clear that there is a high level of variation in structural complexity across the three quarries (variations at scales that are less than tens of meters). In all the outcrops the limestones are tight. Fractures, plus the effect of dolomitization and hydrothermal fluids in creating porosity, are thought to be key factors in developing storage and permeability within the producing subsurface limestone reservoirs. Observations and results from the rock and structural characterisation of the quarry and surrounding areas can be used as analogues to fractured reservoirs in NE Thailand.

5. Conclusions

This field study was conducted in a core area of thrusting and folding in a fractured Permian Limestone with the following conclusions that have direct implications for the interpretation of subsurface counterparts in Thailand and SE Asia.

1) The duplex thrust complex is the main control on the distribution of the older and less deformed shallower carbonate platform that lies structurally on top of the younger deeper water mixed carbonate siliciclastic succession which is more highly deformed structure. This underlines the importance of contrasts in mechanical strength as a significant control in fracture style and density.

2) The siliciclastics (green and red beds) are volcanic-derived mudstones, which are sandwiched into crinoidal rudstones. The texture of the siliciclastic rocks indicate turbidity flows as they preserve Bouma sequence units b, c, d, and e indicating a deeper marine environment. Features that typify channelised deposition dominated with unit "a"stacks were not seen.

3) The interbedded volcanic-derived mudstones and crinoidal rudstone typically outcrop as inclined beds with an approximately E-W strike and dip around 60-80 degrees, all show bedding orientations that are conformable across the 3 quarries.

4) Carbonate rocks in this area can be divided in to 2 groups; 1) Crinoidal rudstone interbedded with green and red beds. This association is typically in a less deformed zone than, 2) a highly tectonised zone dominated by recrystallized calcitic limestones, with highly deformed folds, sinistral strike-slip faults, and duplex thrust complexes. Association 2) is mainly seen in Quarry 2.

5) The trend of the major thrust fault is E113/75^{o} and is best seen in the walls of Quarry 2. The fault slip data indicates a compressive thrust fault regime with NNE – SSW compression, and the minor thrust fault, also located inside Quarry 2, trends E103/56^{o,} with sinistral strike-slip motion.

6) Two main, now calcite-filled, fracture sets in the quarry trend NE - SW and NW - SE, while the main fracture trend is E-W sub-parallel to the bedding orientation in the thrust plane. Sub-vertical open fractures and some open vugs are partially filled with calcite speleothem cements in the southern part of Quarry 1. These open fractured are the final phase of calcite cementation and formed during late karstification when faults and fractures were

exploited as fluid conduits by modern meteoric waters forming cements with characterisitic isotope plot fields.

7) Stable isotope studies of the various fossils, matrix cements and fracture fills, show that the Permian limestones in all three quarries underwent ongoing burial re-equilbration driven by ongoing crossflows of increasingly warmer mesogenetic fluids. This is indicted by increasingly negative oxygen isotope values in an C-O crossplot. The loss of matrix permeabilty shut down this equilibration signature as the limestones became tight. However, hotter calcite vein cements continued to form in fractures in the more intensely structured zones located adjacent to, or within, the thrust fault damage zones. Like the speleothem plot field, this set of increasingly warmer burial signatures has a distinct plot field. It can be used on cutting samples to help define structural evolution and the postions of unconformities in massively cemented limestones.

8) Burial and uplift-related changes in mechanisms of fold, fault and fracture formation and cementation, and changes in their associated fluids, are responsible for blocking old and creating new flow pathways during the rock's diagenetic and structural evolution. The quantification of these effects in the three studied quarries leads to a better understanding of the evolving poroperm regimes that typify the known fractured Permian Limestone reservoirs of Thailand. er circulation in the shallow subsurface.

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