Bulletin of Earth Sciences of Thailand

Structural Analysis, Hydrothermal Brecciation & Diagenesis in a Permian Limestone Outcrop in the Krabi Province, Southern Thailand

Cheong Yow Lam

Petroleum Geoscience Program, Department of Geology, Faculty of Science,
Chulalongkorn University, Bangkok 10330, Thailand

*Corresponding author email: yowlam@gmail.com

Abstract

Some 8km WNW from the Krabi international airport is the studied quarry, which gives fresh exposures of heavily faulted Permian Ratburi limestone. Satellite image analysis of the surrounding area shows NW-SE, N-S and NE-SW as major lineament trends. These trends are in part related to movements of the Klong Marui Fault, which is a major regional periodically-reactivated strike-slip fault system. It cuts across this region of Thailand and defines much of dominant modern structural grain in the Thai Peninsula, including the study area. Field mapping in the quarry reveals strike-slip faulting, showing earlier E-W orientations evolving to NNE-SSW orientations. Also mapped are associated calcite-filled fracture trends made up of N-S, NW-SE, NE-SW and E-W that were expressed in planar, mesh and en-echelon fracture sets. The change in $\sigma 1$ from E-W to N-S is interpreted as a Paleogene response to the ongoing influence of the northward movement of Indian terrane and the Himalayan Orogeny. Regional magmatic activity in the late Cretaceous and Eocene triggered phreatic water heating, which were the precursor to hydrothermal circulations. Two episodes of non-radiogenic high temperature and high pressure hydrothermal fluids precipitated calcite with three styles of porosity-occluding cements (syntaxial, bladed and drusy) growing in and around the mapped faults and fractures, which also host many of the hydrothermal breccias exposed in the quarry. Despite pervasive calcite cementation related to the earlier fracture sets, two types of open porosity remain in the quarry in response to; 1) pressure release due to unroofing of the limestone, creating open joint sets and, 2) a weakly developed set of fracture porosities made by distal effects of Oligocene rifting creating open fractures tied to normal faults. Chumpon Basin lies to the east of the quarry and offshore of the peninsula, with the Klong Marui fault serving as the western boundary to the basin. The Nang Nuan Oilfield, in Chumpon Basin, is a hydrothermal karst play controlled by deep-rooted faults and fractures. The field and the prediction of high production zones suffer from poor understanding of the influence of faults and hydrothermal cements, which has lead to the current erratic production returns in the field. Hydrocarbons are produced from open fractures in the field, but same fractures have variably-cemented patchy porosity and it is likely that there is also a Tertiary-age subaerial exposure surface in the field situated at the top Permian and separating the underlying fractured Ratburi reservoir host from the overlying Tertiary seal. Other than the Tertiary cap, similar elements are found in studied outcrop, making it a good analogue for many aspects of the offshore Permian carbonate play.

Keywords: Permian Limestone, Ratburi, Fractured Carbonate, Hydrothermal Brecciation, Strike-slip Fault, Structural Geology.

1. Introduction

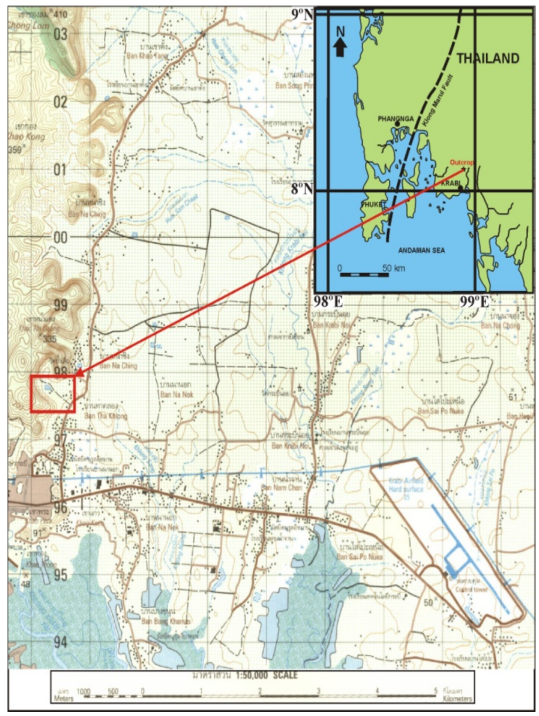
In Krabi area, the Permian limestones of the Ratburi Group are well exposed, with outcrop patterns that show the influence of the strike-slip Klong Marui fault. Lying along the right side of the peninsular in Gulf of Thailand is the Chumpon Basin, where the same fault is also the western boundary of the offshore Nang Nuan Oilfield.

Production data has shown that the driving mechanism of the petroleum system in Nang Nuan Oilfield is hydrothermal karst (Heward, 2000). Active hydrothermal flow that created the field is controlled by major deep-rooted faults and fracture systems. An improved understanding of the relationship between structure and fluid flow would be decisive in reviving the erratic production from Nang Nuan. Onshore, in the Krabi region, hydrothermal overprints in the Permian carbonates are prolific, as seen in numerous crosscutting calcite vein swarms. Given their similar geology and tectonic settings, these outcropping carbonates and vein swarms may record a fluid evolution that is relevant to the diagenetic and hydrothermal evolution of Nang Nuan. Therefore a quarry was chosen in Krabi to study the style and timing of faults and fractures in the Ratburi Limestone.

2. Methods

The outcrop is a heavily strike-slip faulted reservoir-scale quarry. The quarry (N 08º 07' 16.7" E 098º55' 12.8") is near Tiger Cave Temple, locally known as Wat Tham Suea (Figure 1). Three scales of observations were used to investigate the outcrop. Macro-scale observations with integration were done using satellite images and a literature search of the published papers relevant to the Krabi area. Meso-scale study of the outcrop was conducted during 21 days of field trips, while the micro-scale work involved analyzing the rock samples using XRD, thin section and stable isotope techniques.

Figure 1: Upper right insert map show the regional location, while the main topography map plots the quarry location as a red rectangle (Modified from Krabi Province Map by Royal Thai Survey Department, 2000)



3. Results

3.1 Satellite Image

From the macroscale observations, 3 main orientations of lineation were noted, these lineations are related to fracturing and faulting. The main trends are N-S, NE-SW, NW-SE. Five main tectonic events occurred in the Krabi region after the Permian carbonates were deposited; they are in order of youngest to oldest; onset of Himalayan

Event, Mid-Cretaceous uplift, Indosinian 3, 2 and 1. Some of these may have an overprint in the structural trends of the lineation seen in Figure 2.

3.2 Faults

There are only 2 types of faults developed in the quarry. Most, if not all are responses to strike slip faulting, with little normal faulting. Strike-slip faulting with minor extension drives tectonic movement in this area. 126 fault sites were measured and for each, the plunge, plunge direction, pitch, strike and dip of faults were measured.

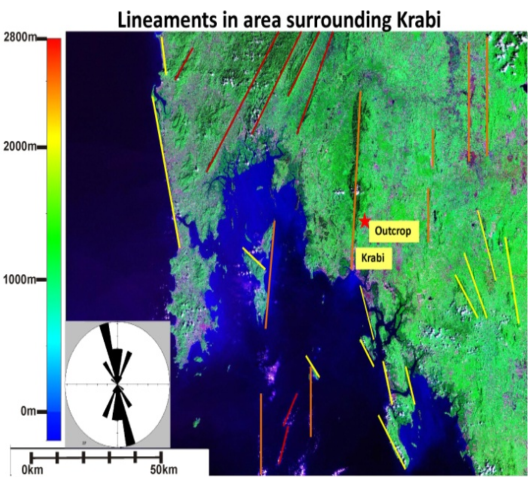


Figure 2: STRM and MrSid imagery of the Krabi region were overlain together and three main lineation trends were mapped

3.2.1 Strike-Slip Fault

Most plunge angle of strike-slip faults are low to moderate varying from 0 to 55 degrees. These ranges actually indicate that not all measured faults are pure strike-slips faults; many involve a component of dip-slip as well. The main strike orientations are NW-SE and E-W, most with steeply inclined dip planes of 85-90 degrees (Figure 3). All of the strike-slip fault planes were cemented with sparry calcite, forming grooves/calcite growths or slickenlines. There were no open fractures associated with this group of faults. The cross cutting relationship of the faults were documented and the age relation of the faults in respect to each other were compiled (Figure 4). Strontium analyses were not done because the high paleo-heat flows in the region would have compromised the values, therefore only the relative, not the exact ages of these faults is known. Most of the strike-slip faults are sinistral, with only minor dextral strike-slip. Varying volumes of brecciation is always found in the fault damage zones of these faults, indicating that most of the movements were brittle.

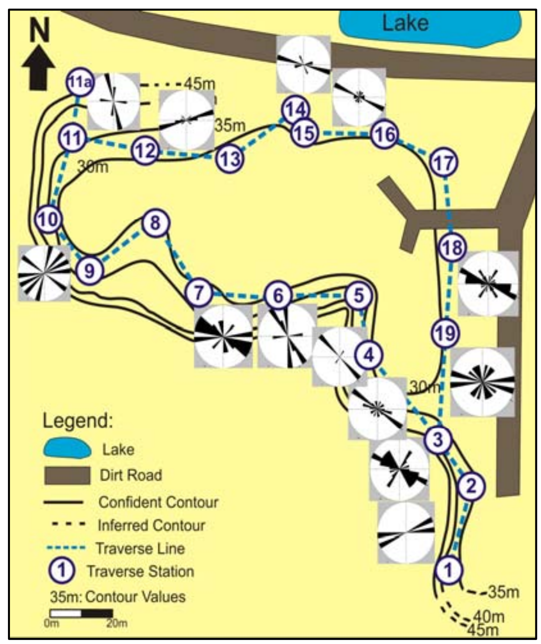


Figure 3: The stereographic plot of fault data for the whole outcrop. The main orientations are NW-SE and E-W.

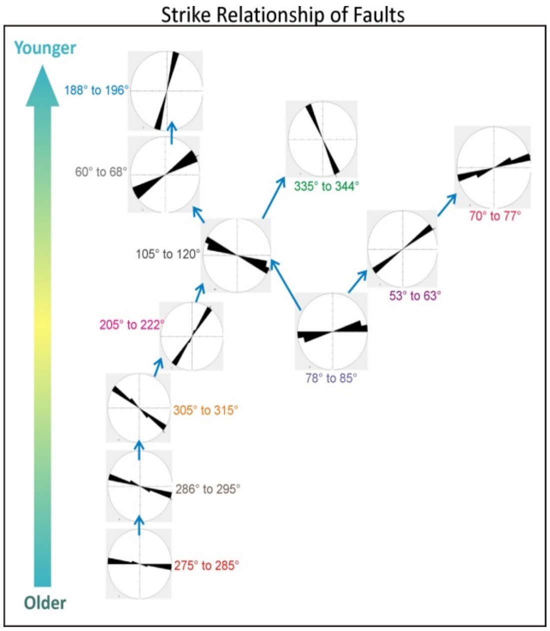


Figure 4: Cross cutting relationships between the faults seen in various parts of the quarry were fully integrated to produce a relative age relationship chart that show E-W is the older fault system, while the NNE-SSW is the younger of the faults seen.

3.2.1 Normal Fault

There are 2 normal faults that outcrop in the quarry and the fractures associated with both are open. One of the two faults is believed to be man-made due to the mechanical weight of lorries on the former dirt access road above the quarry outcrop, while the other is interpreted as a brittle response caused by pressure relief associated with the unroofing of the Permian Limestone in the area. Interestingly, the zone of weakness created by this regional unroofing is also the place where the most intense meteoric diagenesis has occurred. Dolomites were identified in the speleothem cements and fragment in the soil that infill former open solution joints and vugs along the fault plane. The unroofing faults are believed to be younger than Eocene, given the consensus that there was significant Eocene uplift in the nearby Surat Thani Province (Hansen & Wemmer, 2011).

3.3 Joints

Area in the quarry with most dense set of joints is sampled at Station 18, where planar joint sets developed in response to pressure release (Figure 5). The joints are open but localized in the Station 18 area. In other words, if we take the whole quarry to be a reservoir scale analog, then the joints in the vicinity of Station 18 have good fracture porosity but poor matrix permeability. The joints have uniform spacings, about 3-4cm apart, and were cut by “mechanical” micro-normal fault (anthropogenic-explosion indicators) at the Bench level.

3.4 Fractures

365 fracture measurements were made and plotted. For those faults where only 1D relationship could be observed, as in much of the quarry floor, they are classified as fractures. Nonetheless in areas where calcite cemented hydrothermal breccias were observed, fractures information was documented in great detail. These fractures are all closed due to the calcite cements that fill the former porosity. The diversity of fractures orientations indicates multi-stage intense deformation and cementation. The major fracture trends are E-W, NW-SE and N-S (Figure 6). Petrographic studies of the calcites that fill the fractures showed 2 styles (Figure 7): 1) Mesh fracturing, 2) Planar fracturing.

3.4.1 Mesh Fractures

Typically, they occur in non-homogenous rock ie: rocks that contain fossils or fragments. This is because rock such as wackestones, have internal shelly and other materials beside the fine matrix that have different mechanical strength. When shearing occurs, the internal material's varying rock strength necessitated stronger or weaker shear responses (depending of the filling material) in order to deform the rock.

3.4.2 Planar Fractures

They typically occur in a more homogenous rock, such as massive mudstone or highly recrystallized limestone. The mechanical strength of the rock is near constant across the unit.

4.0 Spectral GR

The recorded spectral gamma ray measurements are typical of most limestone facies, which tend to show low ranging API values. The hydrothermal calcite veining in the outcrop did not show any additional radioactivity compared to the adjacent limestone matrix. There is a general view in the local oil industry that, the colour of a limestone may be indicative of the

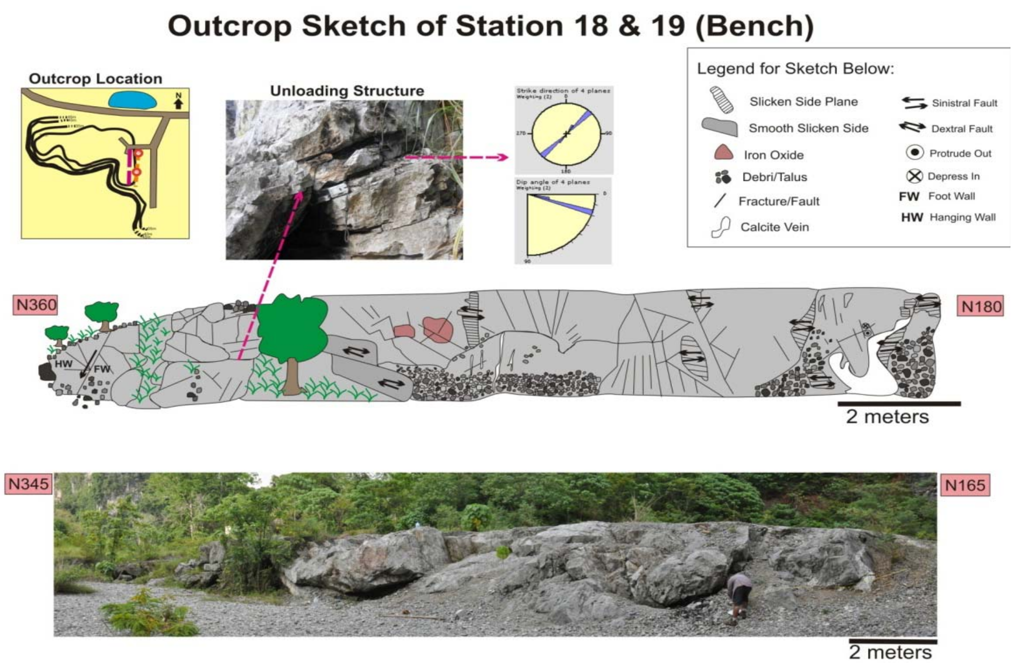


Figure 5: Unloading structures showing joints formed at the left side of the bench. Apart from that local effect, the strike-slip faults here are dominated by sinistral movement. Many calcite veins here striking NW-SE similar to the huge vein seen on the right side.

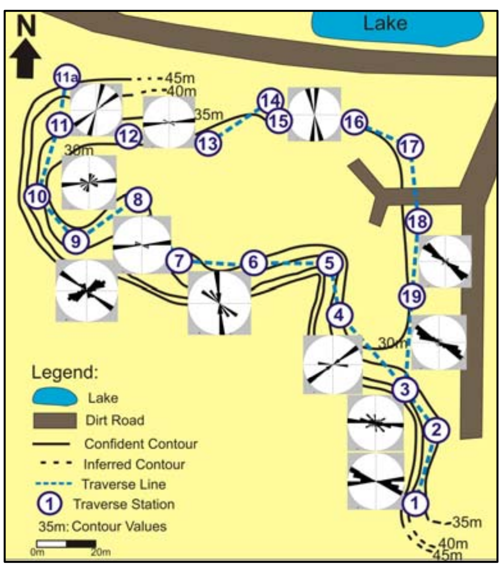
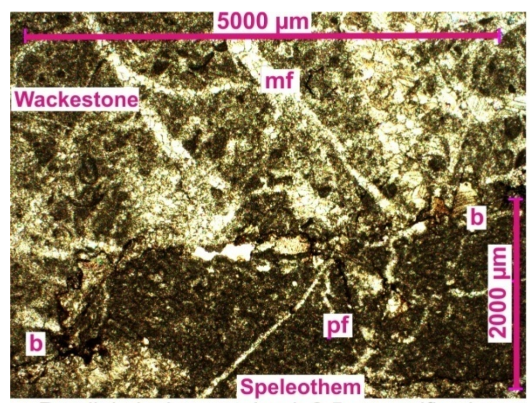


Figure 6: The stereographic plots of fractures orientations for the whole outcrop. Main orientations are N-S, NW-SE and E-W.



Parallel nicols, unstained, 2.5x magnification

Figure 7: 7m from Station 3; Comparison of mesh fracturing (upper part of photomicrograph) versus planar fracturing (lower part of photomicrograph) in strength contrast, b= stylolitised boundary.

organic content of the rock. There was no relationship observed in the quarry between limestone colour and radioactivity, all the matrix measurements were low even when the background colours changed from light grey to near black. The lack of gamma response was compounded by the fact that some of the limestones in the region have been overprinted/recrystallized by contact metamorphic fluids haloes driven by 2 episodes of magma emplacement (Charusiri, 1989; DMR, 1985 & 2008). The nearest granite intrusion is just 12km north of the outcrop location. There is a distinct possibility that recrystallization process has made the limestone even "radogenically cleaner".

The lowest value measured was 3.2 gAPI located on a NNE-SSW calcite filled slickenside plane, while the highest was 40.1 gAPI on the clayey micritic matrix of coarse calcite clast. Nonetheless, cross plot and histogram were plotted in order to study the distribution of GR in various stations in the quarry. The crossplot does not distinguish the various carbonate lithofacies, nor clearly breakout the more intensely veined zones; no particular trend can be observed. The only possible point to be taken away from the histogram plot is that the calcite veins tend to have slightly lower GR range than some of the host rocks. But, there is strong overlap between carbonates with a micritic matrix and those with intense calcite veining. It is doubtful if any gamma differentiation could be reliably applied to equivalent lithologies in the subsurface. Gamma analysis does show that hydrothermal fluids precipitating calcite veins were not particularly radioactive, even though we know there is Cretaceous granite mass only 12 km away. We can perhaps argue that a younger calcite cement event happened during the post Cretaceous magmatic heating episode, know to have occurred during the Eocene. Perhaps the heating and circulation of pore fluids associated with this younger event were indirect process responses to magmatic emplacement. Even if juvenile waters (which were likely to have been radiogenically enriched) were present in the surface, that seems to have never made it to the study area.

5.0 Diagenesis

The hydrothermal and burial activities in this area are associated with at least 2 phases of calcite veining. These calcites cemented the pore spaces and also effectively sealed most of the porosity and permeability in the outcrop. In terms of cementation, there are 3 styles observed which are namely; syntaxial, bladed and drusy calcite spar growths. (Figure 8)

5.1 Syntaxial calcite growth

Syntaxial growths are characterized by spar cementation occurring outside of a preexisting mineral in crystallographic continuity with the growth eventually covers and expanding outside the preexisting mineral of fragment. The youngest calcite spar is therefore at the edge while the older one is in the middle. Syntaxial overgrowths occur in crinoid fragments (stems and plates) and about small calcite clasts during burial cementation.

5.2 Bladed calcite growth

Bladed calcite growths are rare in the studied thin sections. They have an elongate crystal appearance with broad or pyramid-like terminations. Crystals are asymmetric. They are typically seen as a part of the calcite growth fill in formerly open fractures.

5.3 Drusy calcite growth

Drusy cementation is relatively common seen under petrography. They are characterized by increasing crystal size away from the sides toward the centre of the pores. These cementation are typically formed in the meteoric phreatic zone and also known as equant sparite or drusy mosiac (Adams et al., 1984). This phase of cementation is usually associated with shallow burial however drusy cementation can be observed in hydrothermal veining. Clear median planes of calcite growth can be seen at times.

5.4 Sericite Alteration

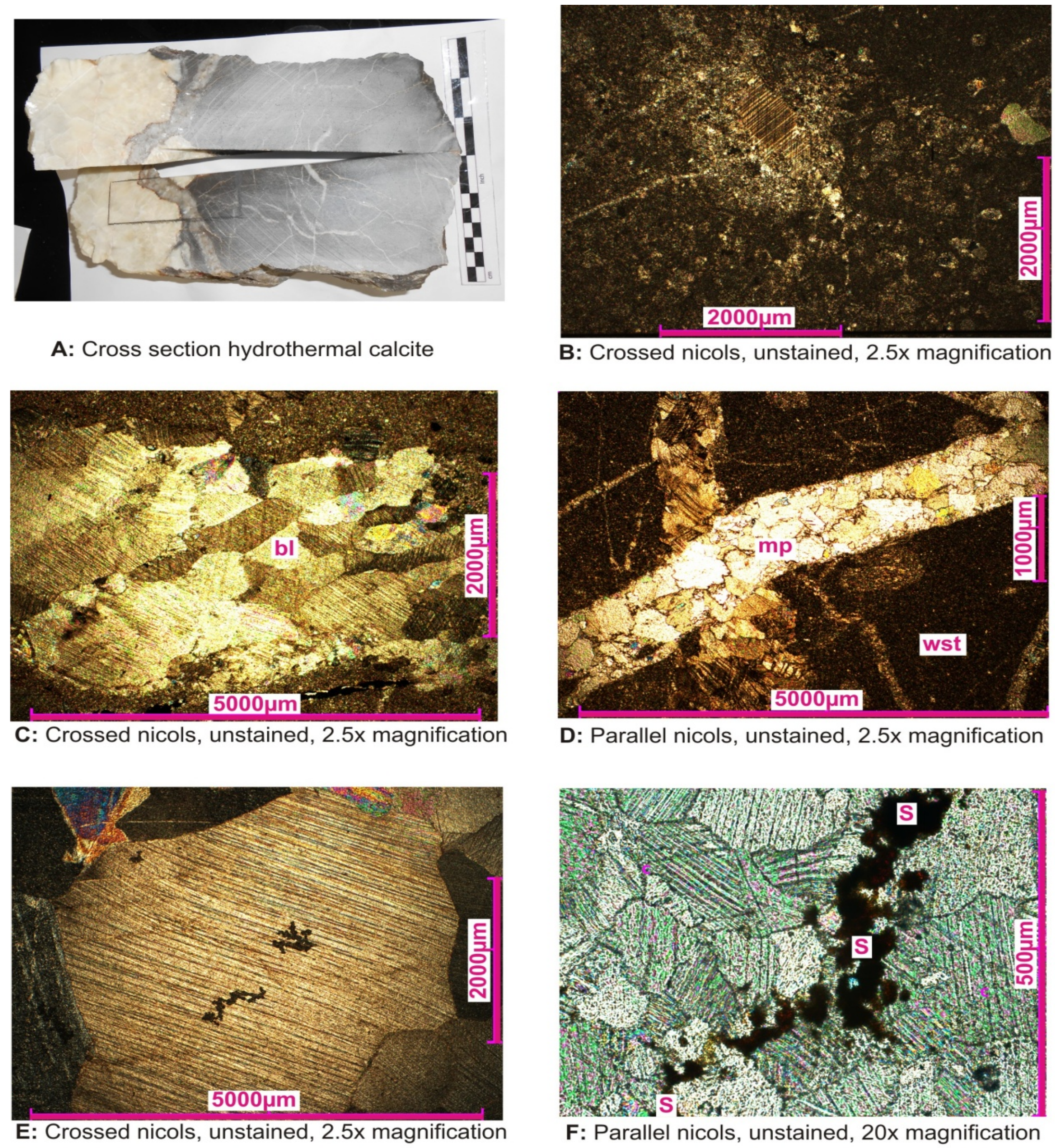
Occurrence of sericite in the calcite is not due to carelessness in sampling of weathered rocks. Sericites found in the thin section are interpreted as alteration products associated with hydrothermal veining. The hydrothermal fluid transformed the preexisting clays and broke them down into much simpler micas. It is similar to the clay breakdown that occurs in weathering process but is a more accelerated process. The contacts between 2 phases of calcite veining are characterized by sericite speckles. This is not a surface weathering related phenomena as the sericite is enclosed in unaltered calcite vein spar.

6. Discussions

6.1 Chronology of Events

Collision and subduction of Sibumasu terrane with Indochina during late Permian to early Triassic is also known as the Indosinian 1 event. Observed E-W faults and fractures in the quarry have orientations consistent with it. Early Triassic burial of the quarry limestones also drove the observed stylolization and silification. Most stylolites seen in the quarry are parallel or subparallel with the bedding therefore could be related to overburden stress that was possibly due to depositional of the Trang Group during the Mesozoic. Regionally there are Indosinian 2 unconformities that happen therefore erosion occurs in within the Trang Group. The first dextral ductile phase of the Klong Marui deformation and Western magmatism happen during the West Burma and Sibumasu collision in the Late Cretaceous (Kanjanapayont, 2009). The first major brecciation event is believed to have happen during this time.

This is evidenced by the breccias lineation which trends E-W. The fact that dominant E-W orientation was reported by Kanjanapayont (2002) in the Trang



A: Cross section hydrothermal calcite

B: Crossed nicols, unstained, 2.5x magnification

C: Crossed nicols, unstained, 2.5x magnification

D: Parallel nicols, unstained, 2.5x magnification

E: Crossed nicols, unstained, 2.5x magnification

F: Parallel nicols, unstained, 20x magnification

Figure 8. **A**: 12m from Station 3; Rock specimen of hydrothermal calcite showing at least 2 phases of cementation. **B**: 8m from Station 3; Microphotograph of syntaxial cementation of a calcite clast. **C:** 12m from Station 3; Microphotograph of bladed(bl) calcite cementation. **D**: Station 2; Microphotograph of drusy calcite cementation with clear median plane (mp) in a fractured wackestone(wst). **E**: 17m from Station 11; Microphotograph of sericite formed inside a calcite. **F**: 12m from Station 3; Microphotograph of sericite(S) that forms the 2 phase boundary of hydrothermal calcite.

Group which is Mesozoic age in the Krabi syncline meant that E-W deformation also happen post deposition of the last Trang Member which age Cretaceous therefore the best explanation would be the late Cretaceous collision that caused the Trang Group folding and brecciation of the Permian Ratburi. The Cretaceous event are believed to be responsible for most of the E-W fracture orientation besides Indosinian 1 because Krabi's closer proximity with West Burma rather than the face of Sibumasu and Indochina collision. The first hydrothermal activity was believed to have happen around the same time. The Cretaceous tectonic event produced uplift, fracturing and pressure solution calcite veining.

Magmatic activity heated up phreatic water indirectly as supported by non-radioactive calcite veining and also no exotic mineralization seen. Hydrothermal fluid percolation encouraged calcite precipitation in the empty voids that was created earlier on during the collision. This is also evidenced by the micro calcite veins seen inside the black cherts that are dominantly E-W orientated.

Kanjanapayont (2009) was the only one who studied Klong Marui faulting exclusively, apart from Watkinson et al (2008) who studied both Ranong and Klong Marui faulting therefore structural analysis were better cross compared with Kanjanapayont's Phd work because outcrop is located closer to the Klong Marui Fault while the Ranong Fault is too far up north. Although he reported the second dextral deformation of Klong Marui Fault which is more dominant, in the outcrop author could not differentiate whether the dextral faulting were from the first or the second deformation given that no cross cutting relationship were observed. Furthermore Argon dating was not done to separate the two. What was not seen by Kanajanpayont in his field observation stage at the core of Klong Marui was the third movement of brittle sinistral strike slip fault, however was seen as the dominant trend of faulting in the Krabi outcrop. The change of dextral to sinistal movement was caused by the Indian terrane collision during the Eocene to Oligocene. The second uplift happened during middle Eocene and produced N-S dominant faults and fractures. Magmatism during Eocene created the second hydrothermal activity that enables calcite precipitation of pressure solutions. The second phase calcite veinings were seen in outcrop and also rock samples collected. This hydrothermal activity were believed to be less intense than the first one given that nearest Cretaceous granite is 12 km from the outcrop compared nearest Eocene granite is 60km away. Radioactivity in the calcite veins were again low indicating hydrothermal heating were indirect. The open fractures that were created during the uplift were filled up by hydrothermal veining. The fluid temperature was 170° to 200° degrees based on calcite deformation and twining with high pressure enough to support some meter sized clasts breccia. The only way it could happen was the outcrop was buried deep underground during some time ago before being uplifted. Continuation of Himalaya Orogeny changes shortening from initial E-W to N-S in a clockwise direction (Kanjanapayont, 2009). The plunge of numerous strike-slip fault measurements from the Krabi outcrop showed that there was an element of dip-slip in the faulting mechanism, rather than pure strike-slip. This fits with the extension event that has been observed regionally and is represented by normal faulting in outcrop. The E-W extension would have been a result of general N-S directed maximum horizontal stress (Kanjanapayont, 2009).

6.2 Regional Significance

The question arises, based on the trend and features seen, as to whether they could be regional. This is economically important because the outcrop is a reservoir scale possible analogue to the subsurface and so can be compared vis-à-vis to the Permian carbonate reservoirs in onshore and offshore Thailand. Dissecting the factors that influence porosity in the outcrop, and comparing them with other data regionally, could help to understand poroperm behaviour in these Permian carbonates. The 2 most crucial porosity-influencing factors in the outcrop are namely; 1) fault controlled hydrothermal veining and 2) late stage faulting/fracturing. Dolomization did not play an important role in porosity evolution in this outcrop.

6.3 Fault Controlled Hydrothermal Veining

The two episodes of hydrothermal activities have effectively sealed the porosity and permeability of the carbonates here due to precipitation of calcite-rich water that percolated through the fault system in both the deep subsurface (mesogenesis) and later in the shallow subsurface (telogenesis). Fortunately, not all hydrothermal activity is porosity destructive, active hydrothermal activity in Nang Nuan Oilfield is the driving mechanism that produces hydrocarbon-hosting late stage porosity (Heward, 2000; Lousowan, 2005). What is important, as demonstrated in the outcrop, is that fracture and fault orientations/ intersections control the fluid flow that drives the hydrothermal veining. Therefore fractures analysis and characterization are needed to understand likely downhole fluid flows. The Klong Marui Fault is the West boundary of the Chumpon Basin; therefore the influence of strike-slip movements is perhaps stronger and clearer in the Nang Nuan oilfield. The fault orientation chart displayed as Figure 4 can be used to compare with faults and fractures in Nang Nuan. Argon dating should be used to date the faults in a more precise manner, as the currently constructed chart was based solely on cross-cutting relationship of the faults. In the case of the fractured basement granites of the Bach Ho Oilfield in Vietnam (Cuong and Warren, 2010), most of the current fluid flow is contributed by a single dominant direction related to a extensional Neogene fracture set, similar pressure modeling tied to a fracture orientation history in Nang Nuan could proved useful in determining the dominant flow orientation.

6.4 Later Stage Faulting/Fracturing

The later E-W rifting event was probably the reason why the quarry outcrop has only a few open fractures related to this normal faulting. The limiting factor for fracture development in the quarry tied to this event was that the intensity of rifting was not as strong in this part of upper southern Thailand compared to the intensity on the basin margin that is defined by the Nang Nuan oilfield. Nonetheless, if a Permian Ratburi carbonate was fractured, and fractures were partially filled with porous terra-rossa sediment, as seen in the solution fractures and caves of the outcrop, we would have active meteoric leaching focused in the fault plane. If this were buried below an organic-rich Tertiary lacustrine shale seal, it could evolve into a "buried hill" play with interconnected permeable antithetic fault conduits that contributed to the directional permeability. For that to happen we need burial, and a source of sediment to partially fill fractures, to have occurred after the Eocene uplift. This is likely the only hope for reservoir potential in any inactive calcite-cemented hydrothermal Ratburi system. This scenario can be compared to Nang Nuan Oilfield, which is, even today, an active hydrothermal karst system with open to partially-open fracture conduits.

7 Conclusions

The studied outcrop is a useful reservoir-scale analogue for a fractured Permian Limestone system in the subsurface. Therefore the observations and results can be compared with the nearby producing fractured Ratburi Carbonate reservoir, namely Nang Nuan. Based on my work, I conclude;

1) Strike-slip faulting dominated the structural style and the change from dextral to sinistral, coupled with a later normal component, matches with the trend of faulting kinematics documented in Klong Marui fault. Most of the structural components seen in the outcrop are equivalent to those associated with what is known regionally as the third phase brittle sinistral movement.
2) The ongoing structural evolution of rocks in the quarry area did not help in the creation of porosity and permeability, as former Indosinian fractures were pervasively cemented by at least 2 phases of hydrothermal activity. There are 3 styles of calcite cement that occlude the former Ratburi depositional and diagenetic porosity; syntaxial, bladed and drusy.
3) The floating calcite-surrounded clasts (up to a meter across) seen in some of the hydrothermal breccias in the quarry imply hydro-fracturing by hot fluids was capable of breaking up and altering the adjacent Ratburi matrix. Similar hydro-fracturing conditions are inferred by Heward (2000) in the hydrothermal karst model he proposed for Nang Nuan.
4) Calcite mineral deformations are not related solely to stress or strain. They are also related to the cross flow of hot hydrothermal waters, with temperature of 170° to 200° degrees Celsius, driving calcite precipitation.
5) The only visible porosity in the quarry outcrop was in pressure release joints and later stage faults, which were then partially filled with sediments that include speleothems and speleothem fragments.
6) Paleodiagenetic processes in the mesogenetic realm did not create nor retain porosity, instead modern day (telogenetic) karstification do.

8. Acknowledgements

The author would like to thank Mubadala Petroleum for sponsoring his studies in the Petroleum Geosciences programme. He is also grateful to have learned from Prof. John Warren during the thesis tutelage.

9. References

Adams, A., MacKenzie, W., & Guilford, C. 1984. Atlas of sedimentary rocks under the microscope. Longman Scientific & Technical, 106pp.

Antonellini, M.A., Aydin, A. 1994. Effects of faulting on fluid flow in porous sand stones: petrophysical properties. American Association of Petroleum Geologists Bulletin, 78, p.355–377.

Charusiri, P. 1989. Lithophile metallogenetic epochs of Thailand: A geological and geo-chronological investigation. PhD thesis, Queen's University, Kingston, Canada, 819pp.

Cuong, T.,X., & Warren, J., K. 2009. Bach Ho Field, a fractured granitic basement reservoir, Cuu Long Basin, Offshore SE Vietnam: A “Buried Hill” Play. Journal of Petroleum Geology, 32, 129-156.

Department of Mineral Resources(DMR). (1985). *Geological Map of Thailand, Scale 1:250,000*. Geological Survey Division, DMR, Bangkok.

Department of Mineral Resources(DMR). (2008). *Geological Map of Thailand, Scale 1:250,000*. Geological Survey Division, DMR, Bangkok.

Hansen, B., & Wemmer, K. 2011. Age and evolution of the basement rocks in Thailand. In M.F. Ridd, A.J. Barber, & M. J. Crow (Eds.), The Geology of Thailand. The Geological Society of London, p. 19-32.

Heward, A., Chuenbunchom, S., Makel, G., Marsland, D. & Spring, L. 2000. Nang Nuan oilfield, B6/27, Gulf of Thailand: karst reservoirs of meteoric or deep burial origin?, Geological Society of London Special Publication, 6, p.15-27.

Kanjanapayont, P. 2002. Geological structural model illustrated by the Mesozoic stratigraphic units in the upper southern Thailand, with special reference to Changwat Krabi and Surat Thani. Master Thesis, Chulalongkorn University, 103pp.

Kanjanapayont, P. 2009. Structural analysis and geochronology of the Klong Marui fault, southern Thailand. PhD Thesis, Vienna University, Austria, 137pp.

Kanjanapayont, P., Grasemann, B., Edwards, M., Fritz, H. 2012. Quantitative kinematic analysis within the Klong Marui shear zone, southern Thailand. Journal of Structural Geology, 35, p.17-27.

Lousuwan, K. 2005. Hydrothermal karst in the Nang Nuan oilfield, Gulf of Thailand. Master Thesis, University of Brunei Darussalam, 84pp.

Morley, A., & Racey, A. 2011. Tertiary Stratigraphy. In M.F. Ridd, A.J. Barber, & M. J. Crow (Eds.), The Geology of Thailand. The Geological Society of London, p.223-271.

Royal Thai Survey Dept. 2000. Geological Map of Thailand, Scale 1:50,000. Geological Survey Division, DMR, Bangkok.

Watkinson, I., Elders, C. & Hall, R. 2008. The kinematic history of the Klong Marui and Ranong Faults, southern Thailand, Journal of Structural Geology, 30, p.1554-1571.