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Dolomitization related to fracture porosity evolution: a case study of carbonate outcrops in Nam Maholan Formation

Doungdech Kananusak*

Petroleum Geoscience Program, Department of Geology, Faculty of Science,
Chulalongkorn University, Bangkok 10330, Thailand
*Corresponding author e-mail: doungdech@hotmail.com

Abstract

Dolomitization and fracturing are key mechanisms of porosity and permeability enchantment in the Permian carbonates in northeastern Thailand, constituting the main reservoir for gas fields in onshore Thailand. Many dolomitization studies have been carried out, using subsurface data to understand the reservoir development and dolomite formations. However, there are few outcrop studies concerning the process of dolomitization, which is an aspect of structural relationships. This research investigated the occurrence of dolomitization and its porosity evolution in the Nam Maholan carbonate outcrops. The structural geometry, fracture development and distribution of lithofacies were studied using data from field investigation. Porosity evolution was obtained and interpreted from petrological observation as well as integration with the literature reviews and geochemical analyses. The lithofacies are subdivided into three units consisting of a limestone unit, a partially dolomitized limestone unit and a crystalline dolomite unit. The dolomitized limestone has the highest estimation in terms of visible porosity. Based on a syncline structure lining in a NW-SE direction, the crystalline dolomite facies only occur in the hinge area. This dolomite unit is not formed in the limbs of the syncline, since the limb areas have fewer conduits (fractures and faults), compared to the hinge zone. There are two major sets of fracture orientations: 1) the NE-SW and N-S trends related to Indosinian events; 2) the ENE-WSW and NW-SE directions associated with Himalayan orogeny. In areas proximal to the hinge zone of the syncline, the non-planar saddle dolomite is dominant, while the texture is predominantly unimodal planar-e to planar-s in distal areas far away from the hinge zone. Reservoir quality is reliant on the vuggy, moldic, intercrystalline, fracture porosities. The effective porosity and vuggy cavern porosity could be enhanced by tectonic influence during Himalayan orogeny.

Keywords: Dolomite, Dolomitization, Permian carbonates NE Thailand, Nam Maholan Formation

1. Introduction

Dolomite reservoirs developed along faults and fractures, exemplified by the Permian carbonate platforms in Northeastern (NE) Thailand. Dolomites play an important reservoir among the Permian carbonates, which are the primary targets for petroleum exploration in the region (Booth and Sattayarak, 2011). These reservoirs were proven as productive reservoirs Nam Phong and Sin Phu Horm gas fields. The Permian carbonates generally show low porosity and permeability since core porosity in the limestones was between 1% to 4% and their permeabilities in the cores were low at 1-2 mD (Racey, 2011). However, the reservoir properties were improved by only where porosity and permeability have been enhanced by later dolomitization, fracturing and hydrothermal leaching, which can lead to porosities of up to 15% and locally core fracture permeabilities can reach ~2,000 mD (Racey, 2011; Warren et al., 2014).

1.1 Study area and geological background

The study area is located in the northern part of NE Thailand between Loei Province and and Nong Bua Lam Phu Province (Fig. 1).

Geotectonically, there are two major continental blocks are recognized in Thailand: Sibumasu in the west and Indochina in the east and this the study lies on the western margin of the Indochina block of NE Thailand. The carbonate outcrops in the area are recognized as the Nam Maholan Formation of the Loei Group.

Stratigraphically, these carbonate outcrops are equivalent to Pha Nok Khao Formation. The ormation is predominantly composed of pure grey limestone with local dolomitization. Depositional environment is a wide carbonate platform with shallow-marine conditions (Ueno and Charoentitirat, 2011).

This study is outcrop- and laboratory-based studies aimed to investigate characteristics of dolomite, understand origins and to quantify the variability in reservoir quality. The main aims are to investigate dolomitization impacts in Nam Maholan limestone porosity.

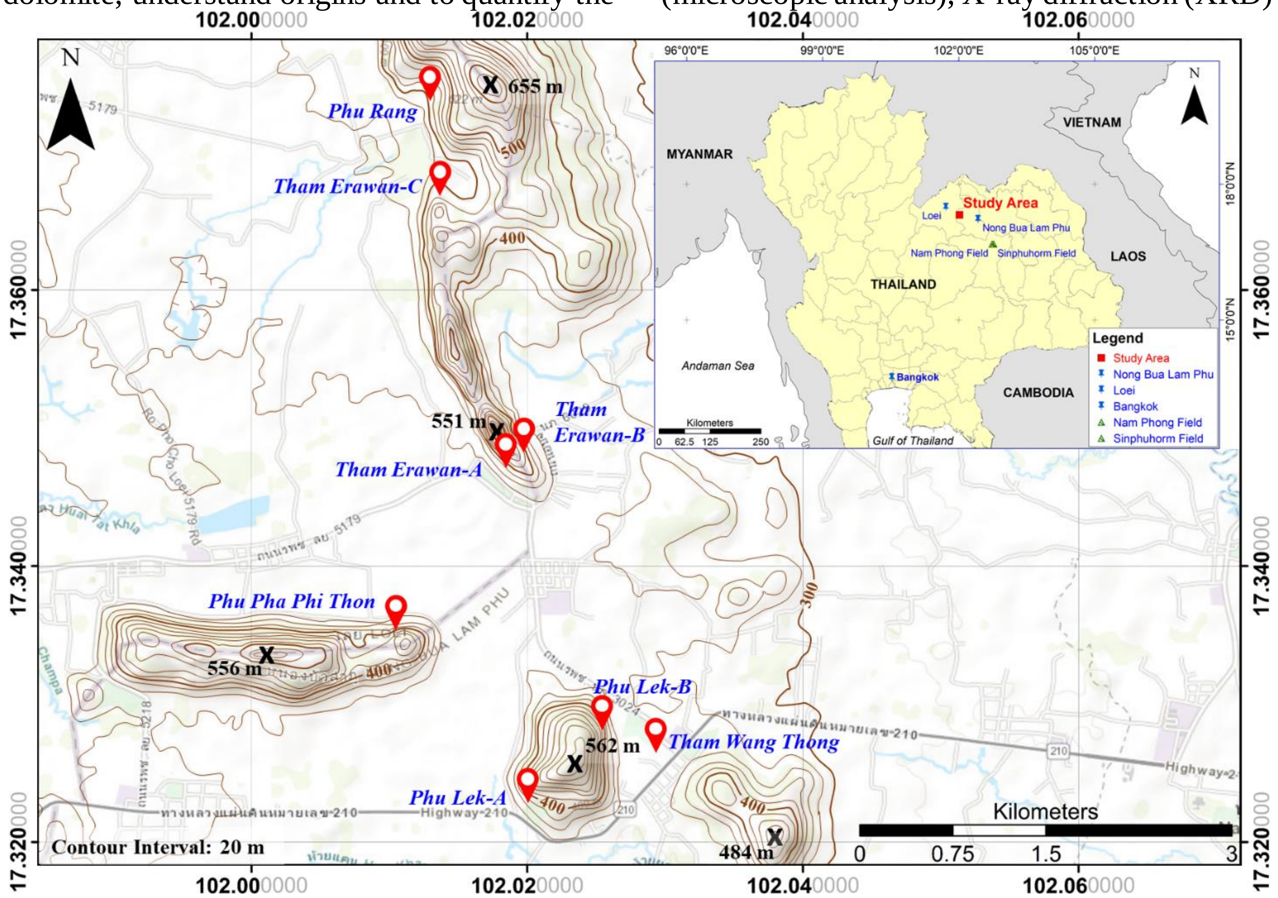

Figure 1. Location maps of the study area.

1.2 Methodology

This research integrates fieldwork datasets, laboratory-processed datasets and literature studies. The methodology is divided into two parts, which include field study and laboratory analyses.

Fieldwork programme was carried out in two steps: (1) the reconnaissance field investigation, which was done with rock geometry measurement for the whole area; (2) detailed outcrop investigation, comprising a traversing section and seven detailed outcrop stations, including the representative rock samples. Datasets of the fieldwork consist of the traversing section, rock samples, structural data measurements and field photographs.

Main laboratory techniques were used in the laboratory, comprising petrographic study (microscopic analysis), X-ray diffraction (XRD) and X-ray Fluorescence (XRF) determinations. The integration of results from these techniques can be used to understand interrelationships between diagenetic and fracture evolution.

2. Results

2.1 Lithofacies

Lithofacies are subdivided into three units consisting of a limestone unit, a partially dolomitized limestone unit and a crystalline dolomite unit. The map of lithofacies distribution is illustrated in Figure 2.

Limestone unit. The unit is distributed to the southern ward of the Phu Lek Mountain. The unit displays thin- to thick-bedded, medium to dark grey and black limestone. The northern part of the unit changes laterally to medium to dark grey beds of partially dolomitized limestone, in which the unit boundary is gradational. Lithologically, wackestone and packstone are types of limestone. Observed allochems are mainly made of skeletal fragments, which

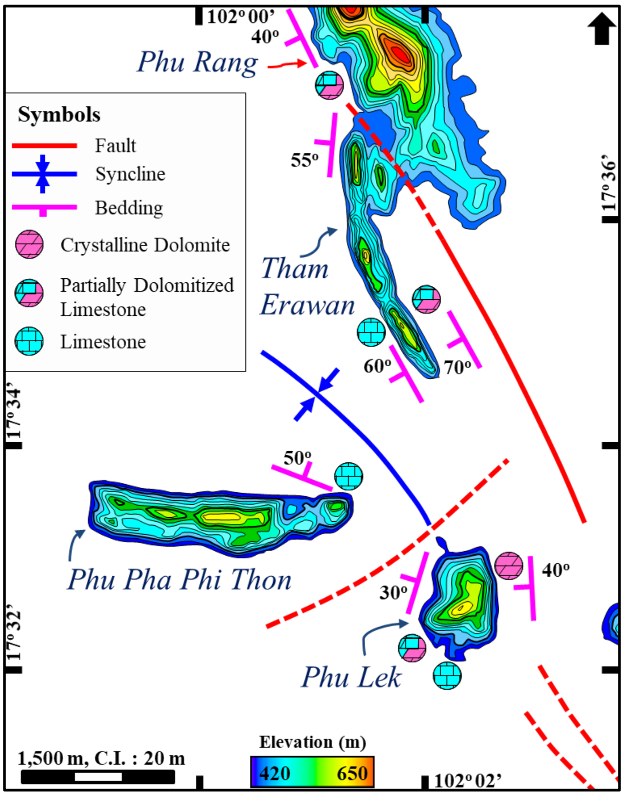

Figure 2. The maps of the Nam Maholan Formation in the entire study area with the subdivision of three lithofacies units.

foraminifers are abundant fossils. The lower part is characterised by black nodular and thin-bedded chert intercalation. Traces of bitumen in small vugs and along fractures can be observed.

Partially dolomitized limestone unit. This This limestone is partially dolomitized and mostly micritic. The lithologies consist predominantly of wackestone and occasionally packstone. In the upper part of the unit, the texture appears as vuggy and relict granular. There are many secondary pores, presumed to be related to the partial dissolution of relict dolomitized grains. Fossils of foraminifers (mainly fusulines) are abundant throughout the unit, while fossils of corals can be found near to the base of the Phu Lek Mountain. The unit is between the limestone unit in the south and the crystalline dolomite unit in the north, and these boundaries are gradational contact.

Crystalline dolomite unit. The unit is in the uppermost part of the Phu Lek Mountain. The unit is adjacent to the partially dolomitized limestone unit in the southern part. It occurs as gradational facies change. This 134 m apparently thick unit is characterised by light to medium grey, light brownish grey, fine-to-coarse grained crystalline dolomite. The relict granular texture generally occurs throughout the unit, whereas the sugary texture is found near to the top of the Phu Lek Mountain. Fossils are scarce, but fusulinid fossils can be found in the lower part of the unit. In some areas, silicified patches are apparent.

2.2 Field investigation

The stereographic plots and rose diagrams of beds and fractures are plotted and illustrated in Figure 3 They are indicated that there is a syncline lining in a NW-SE direction, where the Phu Rang, Tham Erawan and Phu Pha Phi Thon Mountains are the limbs of the syncline and the Phu Lek-A and Tham Wang Thong mountains are the hinge areas (Fig. 2). The bedding orientations offer evidence since their dipping directions are proven to be the syncline structure. For the fracture data, there are four directions: (1) NE-SW; (2) N-S; (3) ENE-WSW; and (4) NW-SE. Apparently, there are two major directions for these fractures, which are NE-SW and ENE-WSW. Furthermore, a detailed outcrop investigation was conducted in order to support the interpretation and better understand the structural styles in the study area. Seven stations were selected for this detailed outcrop study. There are five stations from the Phu Lek areas and one station each from the Tham Erawan and Phu Pha Phi Thon areas.

The first outcrop-station A (Fig. 4a) (Latitude: 17° 32' 27" N., Longitude: 102° 02' 05" E.) is located in Phu Lek-A area. The outcrop is some 20 m long consisting of dark grey limestone and dolomite. There is a fault, oriented in N-S with moderate dips of 65° (Fig. 4b). A brecciated zone (Figs. 4c and d) can be observed along the outcrop. It might not be a result of fault sliding, but it is probably formed as rock collapses. In the Phu Lek-A area, bedding planes are consistently oriented in a N-

S direction. Fractures and calcite veins show three main directions of NE-SW, NNW-SSE and NW-SE. The outcrops in Phu Lek Main A yield few fossils, discerned at the hand-specimen scale. However, a fossil of corals can be observed from this station (Fig. 4e).

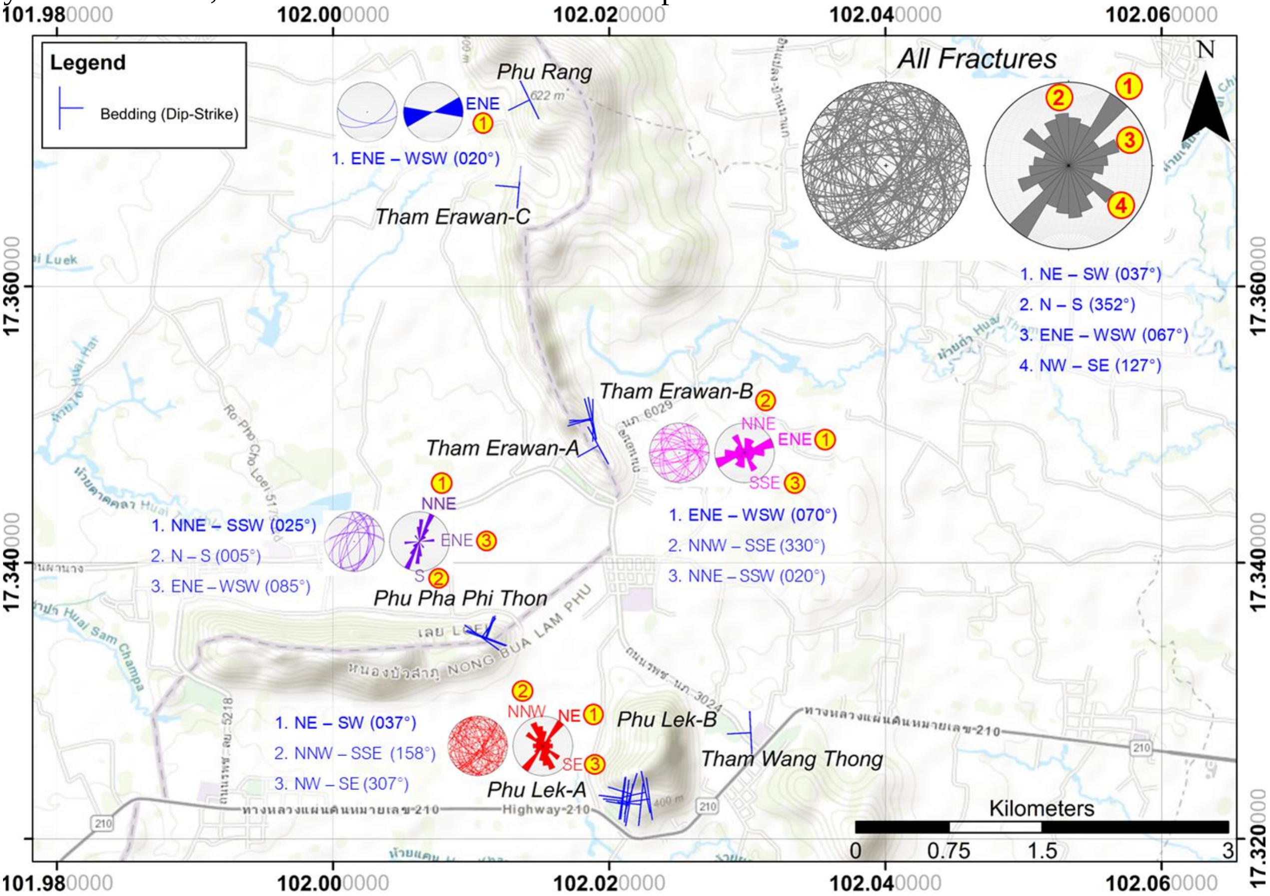

Figure 3. Location map of the study area with stereographic projections and rose diagrams for all bedding and fracture orientations.

The second outcrop-station B is mountain-cliff outcrop composed of dark grey limestone and dolomite layers. The outcrop is located in the Phu Lek-A area with coordinates of 17° 32' 30" N. latitude and 102° 02' 05" E. longitude. There are many fractures, calcite veins and vugs. The fracture styles in this outcrop area, in which most fractures are opened. There is a fault, located in the middle of the outcrop, and oriented in N-S with moderate dips of 55°.

The third outcrop-station C (Latitude: 17° 32' 30" N., Longitude: 102° 02' 00" E.) is located in Phu Lek-A area. The outcrop is about 25 m thick and 30 m long and the main exposed lithologies are dark grey limestone and dolomite beds. The middle of the outcrop is cut by a main fracture and the beds show a dipping direction toward this fracture. In this area, there are many calcite veins and opened fractures. The bedding plane is measured on the orientation and has the dipping in a westward direction.

The fourth outcrop-station D (Fig. 5a) (Latitude: 17° 32' 33" N., Longitude: 102° 02' 18" E.) is located in Phu Lek-A area. The outcrop is made up of about 8 m thick interval of dipping strata composed of dark grey limestone and dolomite layers with individual bed thickness ranging from 10-40 cm. The caves can be randomly found across the beds (Figs. 5b and e). Elephant-skin type weathering and vugs are common along the surfaces of the outcrop (Figs. 5c and d). This Elephant-skin texture allows generally simple recognition of the dolomitized layers in the outcrop.

The fifth outcrop-station E (Latitude: 17° 35' 02" N., Longitude: 102° 01' 83" E.) is located in the Tham Erawan-B area. This outcrop is roughly 3 km to the north of the Phu

Lek area and situated in the western side of the Tham Erawan cave. The cave is resulted from the pervasive dissolution process along the bedding plane of limestone. Fractures and faults

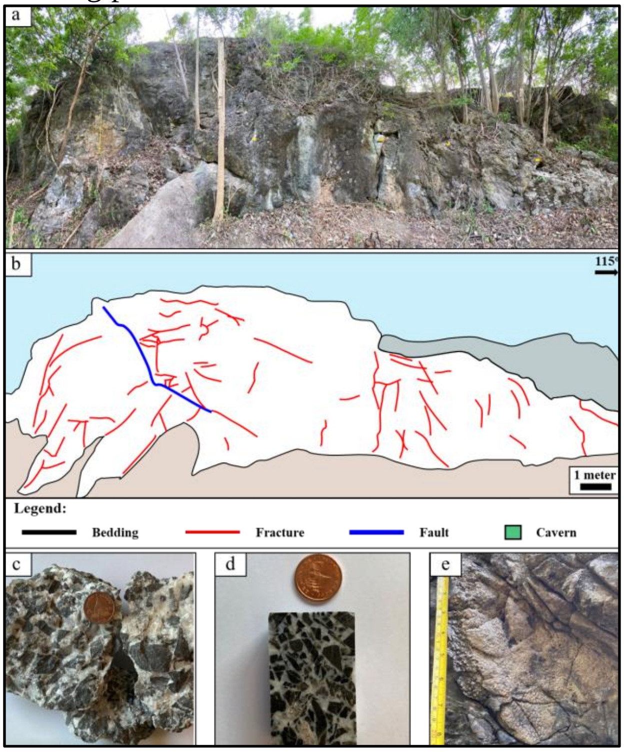

Figure 4. a) Geological overview of outcrop 1. b) Outcrop panorama sketch illustrating the bedding and structural features. c and d) Brecciated limestone [a hand-specimen sample for c and a rock slab sample for d] composed of broken fragments of limestone, cemented by calcite. It is suspected that the breccia results from the in-situ collapse. e) Fossils of colonial corals characterised by a bee hive feature.

are also commonly observed within this cave. It can be observed that the fractures are dense toward the front of the cave. Bedding trends have a main direction of NNW-SSE direction with consistently moderate angle, and dip to a south-west direction, while the fractures and calcite veins show a main trending of ENE-WSW direction.

The sixth outcrop-station F (Latitude: 17° 32’ 73” N., Longitude: 102° 02’ 57” E.) is located in Phu Lek-B area. This outcrop is characterized by massively fractured dolomite. The outcrop is also marked by 2 m wide and 3 m height cave, caused by dissolution. Many speleothems are formed inside the cave. The elephant-skin textures are commonly developed on the outcrop. Both opened and filled fractures are recorded at this site, and show trends of ENE-WSW and NNE-SSW.

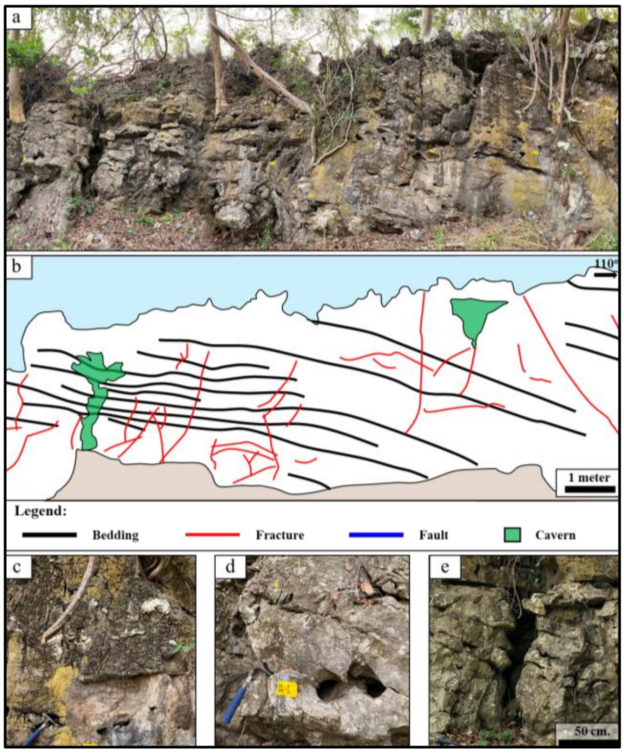

Figure 5. *a) Geological overview of outcrop 4. b) Outcrop panorama sketch revealing the bedding and structural features. c) Weathered surface of the dolomite exposed as an elephant-skin surface texture. d) Outcrop exposure showing solution vugs. e) A small cavern related to fracturing and dissolution.*

The final outcrop-station G (Fig. 6a) (Latitude: 17° 33’ 55” N., Longitude: 102° 01’ 13” E.) is located in the Phu Pha Phi Thon area. This outcrop is roughly 1.3 km to the northwest of the Phu Lek area. The outcrop is represented by thin- to thick light grey limestone made up of about 5 m thick interval (Fig. 6b). Bedding is noticeably recognizable in this area (Fig. 6c), and its orientation trend is ESE-WNW (Fig. 6d), and others two fracture trends are oriented in NNE-SSW and ENE-WSW (Fig. 6e).

2.3 XRD and XRF

Nineteen XRD and XRF samples were collected and analysed as the same sample set to confirm geochemical compositions. The sample lists, including results of XRD and XRF are presented in Tables 1 and 2, respectively. The samples were divided into two categories; (A):

samples from various locations, which were aimed to confirm existing of dolomite mineral

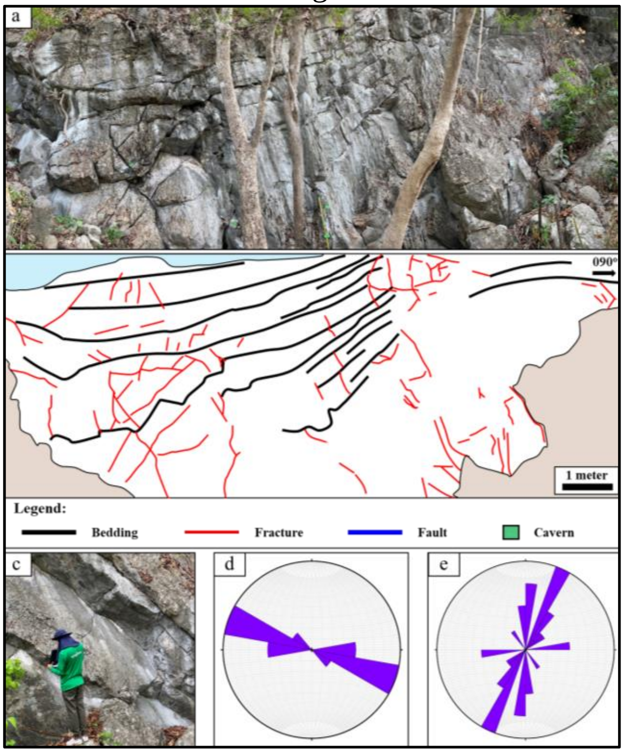

Figure 6. a) Geological overview of outcrop 7. b) Outcrop panorama sketch representing the bedding and structural features. c) Thick bedded light grey limestone showing a remarkable bedding feature with fractures. d) A rose diagram plotting the bedding orientation in an ESE-WNW direction. e) A rose diagram displaying three major trends of calcite veins and fractures (NNE-SSW, N-S and ENE-WSW).

in the outcrops and to differentiate dolomite mineral from calcite mineral, and (B): samples from a single outcrop, where is the third outcrop-station C were proposed to test how fractures impact to rate of dolomitization.

For XRD results, they are matched with the lithofacies distribution, mentioned in the field study results. Dolomite is significant mineral for almost entire of the study area, but exception of the Phu Pha Phi Thon area, dominated with calcite mineral. The sample number 1, taken from the limestone facies in the Phu Lek-A area, is mainly composed of calcite rather than dolomite. Co-dominant between dolomite and calcite is observed in the sample number 15, which is picked up from the Tham Erawan-B area. Quartz was occurred as an accessory mineral in a sample, collected from the Phu Pha Phi Thon area.

Table 1. XRD results, showing the semi-quantitative mineralogy from the samples.

Sample Number	Location	Relative Abundance form XRD		
		Calcite $CaCO_3$	Dolomite $CaMg(CO_3)_2$	Quartz SiO_2
1	Phu Lek-A	D	SD	
2	Phu Lek-A	A	D	
3	Phu Lek-A	A	D	
4	Phu Lek-A	Tr	D	
5	Phu Lek-A	Tr	D	
6	Phu Lek-A	Tr	D	
7	Phu Lek-A	Tr	D	
8	Phu Lek-A	SD	D	
9	Phu Lek-A	Tr	D	
10	Phu Lek-A	A	D	
11	Phu Lek-A	A	D	
12	Phu Lek-A	Tr	D	
13	Phu Lek-A		D	
14	Phu Lek-A	A	D	
15	Tham Erawan-B	CD	CD	
16	Phu Lek-B	Tr	D	
17	Phu Pha Phi Thon	D		A
18	Tham Wang Thong	A	D	
19	Tham Wang Thong	SD	D	

Semiquantitative Abbreviations	
D	Dominant. Used for the component apparently most abundant, regardless of its probable percentage level.
CD	Co-dominant. Used for two (or more) predominating components, in roughly equal amounts.
SD	Sub-dominant. The next most abundant component(s) providing its percentage level is judged above about 20.
A	Components judged to be present between the levels of roughly 5 and 20%.
Tr	Trace. Components judged to be below about 5%.

Table 2. XRF results, illustrating the quantitative values of elemental composition from the samples.

Sample Number	Location	XRF: Elemental Composition (%)		
		Calcium, Ca	Magnesium, Mg	Silicon, Si
1	Phu Lek-A	38.6	4.39	
2	Phu Lek-A	24.8	13.4	0.1
3	Phu Lek-A	23.8	13.4	
4	Phu Lek-A	23.5	13.8	0.6
5	Phu Lek-A	24.1	14.0	
6	Phu Lek-A	25.0	14.0	
7	Phu Lek-A	24.2	14.3	
8	Phu Lek-A	26.2	12.4	
9	Phu Lek-A	24.3	14.1	
10	Phu Lek-A	25.0	13.6	
11	Phu Lek-A	25.9	12.7	
12	Phu Lek-A	23.9	13.9	0.4
13	Phu Lek-A	23.2	13.9	
14	Phu Lek-A	23.9	13.7	
15	Tham Erawan-B	30.7	9.7	0.4
16	Phu Lek-B	23.8	13.8	
17	Phu Pha Phi Thon	40.3	0.6	1.3
18	Tham Wang Thong	24.2	13.6	
19	Tham Wang Thong	26.4	12.5	1.7

Cell-colour scale with percent range						
<1%	>1-5%	>5-10%	>10-15%	>15-25%	>25-30%	>30%

The category B samples were from the outcrop-station C. The samples were collected to observe a degree of dolomitization in outcrop scale. It is expected that dolomitization might be related with main fracture and/ or zone of intense fractures. The results indicate a slightly variation in mineralogy. Dolomite is dominant mineral for every sample, but the semi-quantitative amounts of calcite have a range from trace to accessory. This calcite shows increase trend, approaching to a main fracture of the outcrop.

The XRF results were illustrated the values of Magnesium (Mg), which were accordant with the XRD results. It was helped to confirm the XRD results, that rate dolomitization in the category B samples has a negligible variation in outcrop scale.

2.4 Petrography

Constituents. Original skeletal and non-skeletal limestone grains can be identified from the limestone and the partially dolomitized limestone units. These grains are predominantly peloids and foraminifers (Figs. 7a, b and c). However, the grains in the crystalline dolomite unit are unable to be determined, because their internal features are destroyed by dolomitization and not preserved. Matrix predominantly consists of finer crystalline matrix dolomites and occasionally micritic calcite matrix. Common types of cements are fracture-filling cement and pore-filling cement. These spaces are mainly filled with calcite and dolomite (Fig. 7d). There is a minor appearance of cements from quartz (Figs. 7e and f) and opaque metalliferous minerals.

Dolomite texture and diagenetic. Dolomite is developed as well-preserved fabric dolomite; original grains maintain their shapes and poorly-preserved fabric or fabric destructive dolomite. The fabric of original allochems of the precursor limestone has been destroyed by dolomitization. Types of dolomite crystal shapes consist of unimodal planar-e (euhedral) to planar-s (subhedral) (Fig. 8a), unimodal nonplanar-a (anhedral) crystals (Fig. 8b) and non-planar saddle dolomite (Fig. 8c) with brownish interior crystal colours. Planar dolomite is characterised

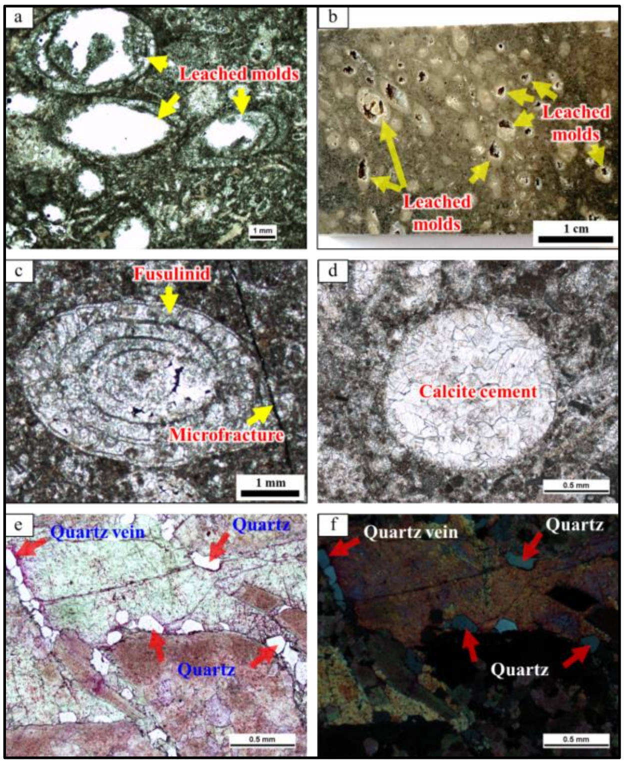

Figure 7. *Dolomite constituents. a) Photo-micrograph of partially dolomitized fusulinid fossils, which replacive dolomite crystals are corroded by dissolution. b) Rock slab photograph showing dolomitized fusulinid grains are progressively leached, from partial molds to complete molds. c) Photomicrograph of partially dolomitized fusulinid fossils showing rhombohedral crystals of dolomite with intercrystalline pores. d) Photomicrograph of pore-filling calcite cement inside a crinoid mold. e) and f) Photomicrographs of fracture-filling quartz cement (red arrows) under plane-polarized light and cross-polarized light, respectively.*

by rhombic-shaped crystals, planar compromise boundaries with many crystal-face junctions. This dolomite is cloudy centred and clear-rimmed crystals (Fig. 8d). Non-planar dolomite is recognised by its boundaries between crystals, which are curved and have coarser crystal size as well as strong undulose extinction. Most of the crystals show a turbid colour and cleavage traces (Fig. 8c). The levels of replacement have variation ranging from mimetic to obliterated (mosaic or sucrosic). There are few grains replaced as mimetic dolomite (thin-film replacement) (Fig. 8e), which the original texture is preserved. Fracture filling dolomites (Fig. 8f) and void filling dolomites (Fig. 9b) are

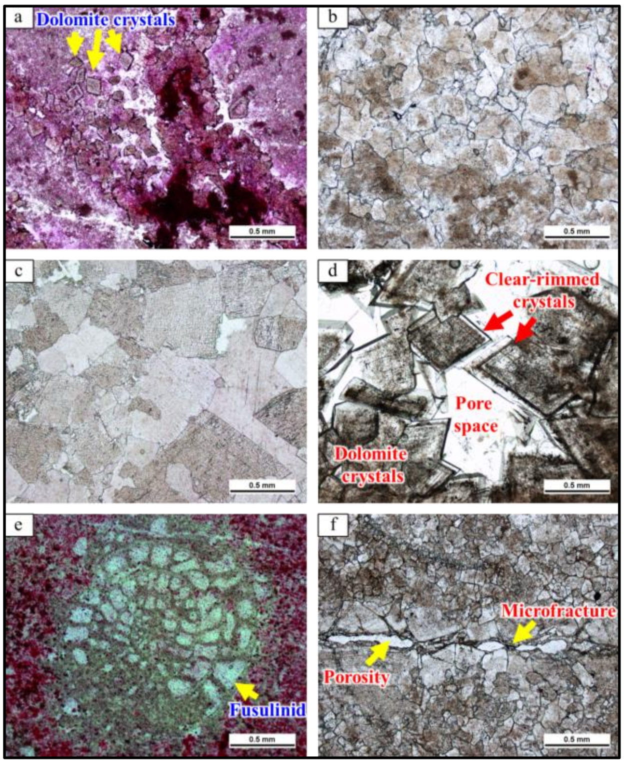

Figure 8. *Photomicrographs of a) Micritic dolomited limestone stained with Alizarin Red S. Dolomite crystals are unimodal and planar-e crystals. b) Nonplanar anhedral dolomite crystals. c) Nonplanar saddle dolomite showing curved crystal faces. d) Rim overgrowths lining pore-filling dolomite cement and crystals are euhedral rhombs. e) Mimetic replacement of a foraminifer. This thin section is stained with Alizarin Red S. f) A partially filled fracture (lining in E-W direction) with planar-s dolomite.*

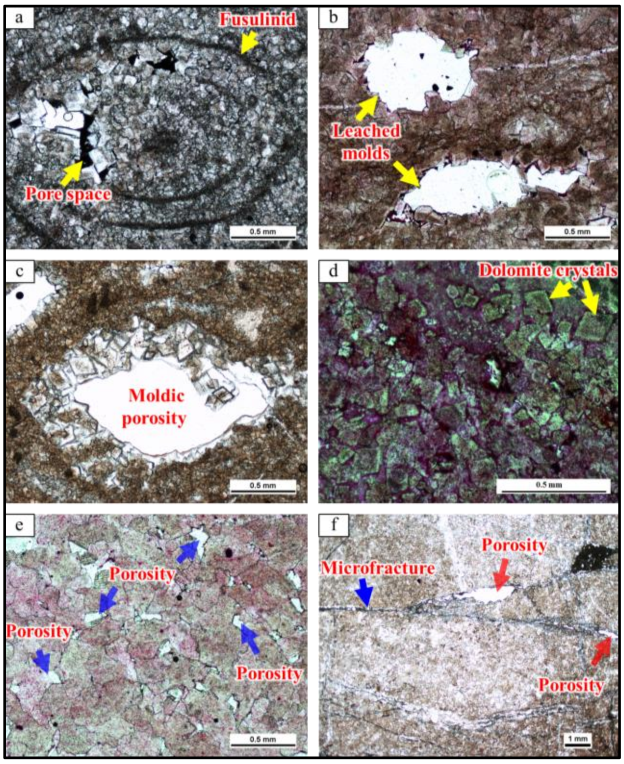

Figure 9. *Photomicrographs of a) A partially dolomitized fusulinid fossil. The grain is replaced by dolomite rhombs. b) Dissolution pores are partially filled by dolomite cement. c) Crystal growth cementation in moldic pore filling dolomite. d) Planar dolomite porphyrites in dolomized limestone showing intercrystalline pores between crystals. e) Intercrystalline pores (blue arrows) at crystal junctions. f) Pores related to fractures (red arrows).*

commonly observed. Many pre-existing calcite veins are locally replaced by dolomite (Fig. 8f). They are characterised by a polymodal planar-e to planar-s microcrystalline appearance.

Pore types. Three pore types can be classified from the thin sections: (1) dissolution pores, such as fusulinid pores (Figs 7a and 9a), moldic pores (Figs. 9b and c), which are the dissolution of unstable allochems, resulting in moldic porosity and intergranular dissolution pores, which mainly include the selective dissolution of early calcite. Vug porosity typically forms irregular shaped cavities up to 0.5 cm in size. (2) Intercrystalline pores (Figs. 9d and e) normally appear as fine crystalline dolomites, formed by dolomitization. (3) Fracture pores can be observed in the samples. The identified fractures are opened to semi-filled with calcite cement, but the opened fractures are the dominant ones (Fig. 9f). Overall, partially dolomitized limestone unit gives the highest estimation of visible porosity.

Fracture. There is more than one episode of tectonic events, observed from many thin sections. Cross-cutting veins with different orientations (Fig. 10d) can indicate different stages of fluid evolution with varying paleo-stress. Investigation with a microscope can be distinguished these fracture styles. Completely closed and partially opened fractures can be observed from the thin sections. The completely closed fractures are filled by combinations of dolomite crystal and calcite cement. Partially opened fractures occur as patchy voids with clear crystal rims (Fig. 8d).

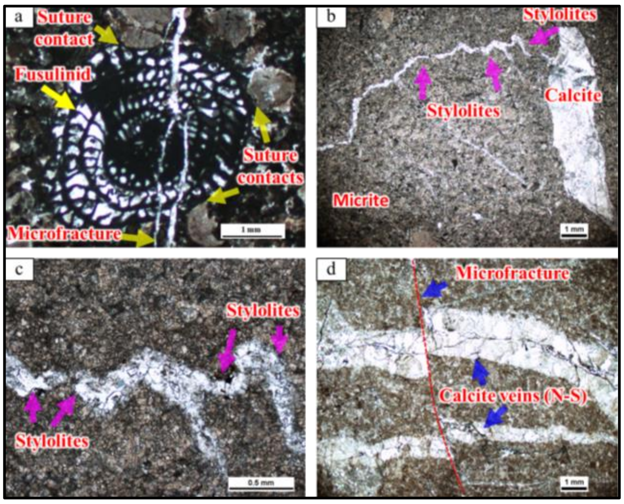

Figure 10. *Photomicrographs of a) Packstone showing grain-grain sutured contacts (yellow arrows) between a fusulinid grain and crinoid grains. Microfractures pass through the fusulinid grain. b and c) Microstylolites (pink arrows) are dissolved before precipitation of calcite cement in the later phase. d) The cross-cutting calcite veins where sub-horizontal older veins are truncated by sub-vertical fracture. The calcite veins are in N-S direction.*

Microscopically, they show sutured contacts between grains (Fig. 10a) driven by compression as well as extensional fractures. Stylolites, caused by chemical compaction can be seen in the thin sections from Tham Erawan-B area. These stylolites are suspected to have been dissolved, and primary filled materials were leached out. In later stage, calcite cement was precipitated along stylolites (Figs. 10b and c). In some samples, extensional fracture of N-S trend was cut by either NE-SW or ENE-WSW trends (Fig. 10d).

3. Discussion

3.1 Fracture system

Four trends of fractures were developed in the study area. These orientations consist of (1) NE-SW; (2) N-S; (3) ENE-WSW; and (4) NW-SE. The fractures of NE-SW and N-S trends are the most prevalent among all the fracture trends in the area. Tectonically, these trends correspond to the Indosinian event since they are nearly perpendicular to the E-W maximum stress of the compressional regime present during the event (Kongchum, 2018). Based on the cross-cutting calcite veins, mentioned in the petrographic result (Fig. 9d), the calcite-filled fractures were cut by other trends of opened fractures. Therefore, the NE-SW and N-S trends fracture trend developed prior to the ENE-WSW and NW-SE fracture trends. These two later trends can be referred to the reactivation and uplift driven by the distal effects of the Himalayan orogeny.

It is observed that the NW-SE fracture trend aligns with the fold axial planes of nearby folds and parallel with the strikes of nearby faults. Furthermore, there is one major syncline running through the study area, and the NW-SE fracture trend is also parallel with the axial plane of this structure (Fig. 2). Based on the observation, the Tham Erawan Mountain is located in NW limb of the syncline is interpreted as the Tham Erawan Mountain, while the Phu Pha Phi Thon mountain is in another limb of the syncline, oriented in E-W direction. The Phu Lek area is located around the hinge zone of the syncline.

3.2 Impact on reservoir character

The primary porosity of the precursor limestone was entirely obliterated by dolomitization and cementation processes. Porosity is therefore reliant on the secondary origin and comprises vuggy, moldic, fracture and intercrystalline types. From the petrographic study, vuggy and moldic porosities are common in the partially dolomitized limestone unit as well as in the crystalline dolomitized limestone unit. In limestone unit, the visible porosity is ranging from poor to fair, which is in the form of unfilled microfractures dolomite unit. The intercrystalline porosity seems to be more apparent in the partially and vuggy porosity. The partially dolomitized limestone unit has the best visible porosity among the lithofacies units in the study area. Its overall visible porosity is fair to good, while the visible porosity in crystalline dolomite unit, including saddle dolomite is fair.

For porosity with the addition of other diagenetic and tectonic factors, the overall effective porosity will be more increases. Multiple fracturing stages occurred in the study area. Fracture porosity is possibly created by deformation during the Indosinian orogeny.

This porosity is obviously filled by calcite cement. According to field surveys, the orientation data associated with this event is mainly from calcite veins. The fracture porosity, generated in the Indosinian orogeny has a low chance for preservation potential. On the other hand, there is fracture porosity reactivated during Himalayan orogeny. The enchantment of effective porosity and permeability is caused by this tectonic event. In the Sin Phu Horm field, there is evidence that the effective porosity driven by Himalayan orogeny relates to the deep meteoric uplift or cooling temperature and later catagenic fluid migration event (Promsen, 2016). In addition, the uplift during this telogenetic stage can increase the porosity by creating vuggy / cavern porosity. Dissolution of the limestone allows on-going water entry, joining up along the expanding fractures and joints that further enhanced the porosity (Yingyuen, 2013).

4. Conclusions

This research combined field works, laboratory analyses and literature reviews of the Nam Maholan carbonate outcrops in order to provide evidences concerning lithofacies distribution, dolomite texture, fracture system and the impact on reservoir character.

The study area is geologically situated on a syncline lining in a NW-SE direction. There are three lithofacies units consisting of a limestone unit, a partially dolomitized limestone unit and a crystalline dolomite unit. Two groups of fracture trends are recognised, which were developed in different tectonic events. The first group is the NE-SW and N-S trends related to Indosinian Orogeny. The second set is in the ENE-WSW and NW-SE directions, associated with Himalayan orogeny. Dolomitization occurred locally in four areas, comprising the Phu Lek area, the Tham Wang Thong, the Tham Erawan-B area and Phu Rang area. Three types of dolomite textures were identified, and they include unimodal planar-e to planar-s, unimodal nonplanar-a crystals and nonplanar saddle dolomite. In areas proximal to the hinge zone of the syncline, the nonplanar saddle dolomite is dominant among replacive dolomite textures, whereas the texture in distal areas far away from the hinge zone is predominantly unimodal planar-e to planar-s.

The reservoir quality of the studied thin sections relied on the vuggy, moldic, intercrystalline, fracture porosities. The partially dolomitized limestone unit exhibited the best visible porosity. The effective porosity and vuggy/ cavern porosity could be enhanced by tectonic influence during Himalayan orogeny.

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