POROPERM CONTROLS IN OUTCROP ANALOGS FOR "ORDOVICIAN" FRACTURED CARBONATE RESERVOIRS IN THE SUPHANBURI BASIN,WESTERN THAILAND

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Abstract

Ordovician carbonate outcrops in Suphanburi Province, region of western Thailand are composed of highly metamorphosed carbonates. Previously these rocks were mapped as Ordovician limestones. The lithologies are actually composed of a variety of "Mylonitic marbles," based on the classification of protolith, texture and mineral composition. The dominant fracture orientation is NW-SE in the studied outcrops. Stable isotopic study focused on calcite-filled fractures (with different orientations) along with calcite-vein cements in various metamorphosed hosts in variably deformed and thrusted Ordovician carbonates of the Thung Song Group. Samples were collected in quarry faces across three areas. Stable isotope crossplots of carbon and oxygen (C-O), using texture-aware isotope samples, define variable, but related, fluid-cement histories. The covariant C-O stable isotope plotfields indicate two trends. The first is a very hot fluid system tied to late mesogenetic/metamorphic alteration driving thermal re-equilibration in calcite cement matrix and in calcite filled fractures with NW-SE and NE-SE trends. These are likely orogenic responses driven by the Indosinian (Triassic) orogeny.nThe second trend or plotfield indicates a diagenetic overprint seen in the latest calcite cements from speleothems and calcite filled N-S trending fractures. These samples occur in an uplifted telogenetic setting, driven by Cenozoic tectonics and isostatic uplift. The two distinct C-O signatures suggests a secondary porosity potential, which can be useful as an analogy in subsurface investigations via the integration of values from equivalent drill cuttings, fracture orientation measurements from open hole logs, and identification of unconformities in seismic images. Such integration will better define likely zones of porosity development in possible "uplift plays" in this carbonate unit in the subsurface in the nearby Suphanburi Basin.

Keywords: Metamorphism, Marble, Fractures, Speleothem

1. Introduction

A need to better understand the "basement" came out of an unexpected hydrocarbon intersection located well below the Tertiary-age target in an exploration well drilled in the western part of Suphanburi Basin in 2015. The result suggested oil was present in the "basement" in a possible secondary target hosted in a carbonate reservoir interval. Historically, all reservoir targets in this basin are focused in clastic plays in the Tertiary basement fill. Hence, this new success spotlighted the need for a better understanding of the nature of the "basement" carbonate.

Primary porosity in ancient carbonate reservoirs can be completely lost during burial in the diagenetic realm. This is less likely in siliciclastic reservoirs, which tend to partially preserve primary porosity (Ahr, 2008). So, developing an understanding of poroperm evolution and the relationship between fracture orientations, fluid crossflow and tectonic uplift event are necessary to identify and develop most carbonate reservoirs. Fluid flow and fluid rock interactions in carbonates in fold and thrust belts are also of considerable interest when building a better understanding of their structural and tectonic development, as well as an understanding of evolving fluid distributions and poroperm changes in relation to mineral exploitation and the trapping of hydrocarbons.

Syntectonic veins record evidence of changing fluid flows and sources during deformation and uplift, while fracture orientation studies provide important data about the stress and strain states during episodes of deformation and uplift (e.g. Lacombe, 2010; Beaudoin et al., 2011; 2012) as well as information about the origin and temperature of the fluids (e.g. Hudson, 1977; Dietrich et al., 1983; Kirschner et al., 1995; Beaudoin et al., 2011; Lacroix et al., 2014).

Outcrops of what were mapped as Ordovician limestone in quarries (DMR, 2014) located about 10 km to the west of outcropping edge of Suphanburi Basin were chosen as to analog for the nature of the carbonate basement in the basin. In terms of lithology and color of rock samples from initial review, there are notable similarities between outcrop and cutting samples. Therefore, the detailed study, as mentioned, in these carbonate outcrops are crucial in developing a better understanding of potential reservoir character. However, the “basement” carbonate studied in outcrop in this report, and in the subsurface by Taweepornpath-omgul (2016), are made up of various types of metamorphosed carbonates of likely amphibolite-grade marbles (R. Searle, pers. com.), The units are incorrectly mapped as Ordovician limestones in the region west of the Suphanburi Basin.

Three outcrop areas were selected for study via detailed field work in Suphanburi Province, Western Thailand (Figure 1). All exposures are in abandoned marble quarries, mostly mapped as Ordovician Tha Ma Nao limestone, with a small part mapped as Cambrian-Ordovician marble in the southern part as shown in Area 1 and Area 2 (Figure 1). These two areas are about two km apart, where Area 3 is approximately 27 km to the north.

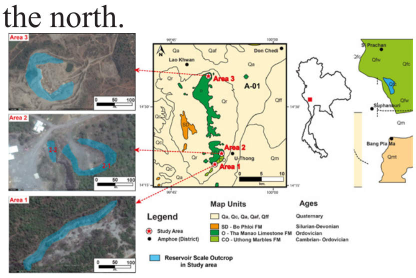

Figure 1: Geological map of Suphanburi area, Thailand (DMR, 2014) showing the study area locations.

In general, studies of fluid flow evolution can enhance our ability to better predict the subsurface distribution of hydrocarbons in reservoirs with porosities and permeabilities that are affected by burial, uplift, deformation and metamorphism.

The purpose of this study is to understand the main diagenetic/metamorphic controls affecting porosity and permeability in potential “basement” carbonate reservoirs and so better predict reservoir properties and locations of further secondary targets in the future wells that insect the “basement” of the Suphanburi Basin.

2. Geological setting

The study area is located in Suphanburi province, western Thailand, which is a part of the highly deformed as Thai-Malay Mobile Belt stretching from northern Thailand to Sumatra in the south (Figure 2a). This area was formed by the collision of the Shan-Thai and Indo-China continental plates, during late Paleozoic to early Mesozoic (Ueno and Charoentitirat, 2011). The Indochina continental block was extruded to the southeast during the India and Eurasia plate collision, with the movement of the Indochina continental block relative to the Shan-Thai continental block being accommodated by strike-slip along the Thai-Malay Mobile Belt (Polachan et. al, 1991).

The Suphanburi basin is a response to tectonic elements that created a number of north trending pull-apart basins between the Three Pagodas and Mae Ping dextral strike-slip faults (Figure 2b; Polachan and Sattayarak, 1989). That is, the basin is one of seven major Cenozoic north trending, pull-apart basins in the Thai-Malay Mobile Belt, (i.e., Phitsanulok, Phetchabun, Nang Bua, Suphanburi, Mae Sod, Kamphaeng Saen and Ayutthaya). These basins formed in the Late Oligocene in response to the collision between the India and Eurasia plates and the resultant strike-slip displacement between the Shan-Thai and Indochina continental blocks.

3. Metamorphism

Clearly carbonate outcrops in study area are located in a highly deformed area (Figure 3) and have experienced massive tectonic overprints. Based on field observations, solid evidence of rock textures such as foliation, augens, porphyroblasts and porphyroclasts, show that these carbonate outcrops have been highly

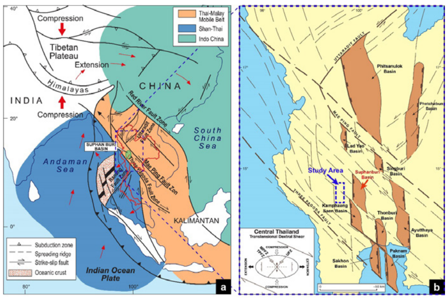

Figure 2: (a) Tectonic framework of India and SE Asia (Polachan et al., 1991). (b) Major tectonic elements of Thai-Malay Mobile Belt in central Thailand showing the development of north trending pull-apart basins between the Three Pagodas and Mae Ping dextral strike-slip faults (Polachan and Sattayarak,1989).

metamorphosed. These textures and other high temperature and pressure features were observed throughout all three areas during field work. Clearly, these rock are metamorphics, rather than sedimentary rocks, as mapped (Figure 1). The widespread nature of these metamorphic rocks was a surprise when relevant outcrops were first visited in the early stages of this study. Consequently, before proceeding to the petrographic and isotopic results, a metamorphic framework needs to be discussed and an appropriate broad-spectrum set of rock names defined. In general, the classification of metamorphic rocks is based on mineral assemblage, texture, protolith, and bulk chemical composition of the rock (Bucher and Grapes, 2011). Each of these parameters will be further discussed, and after integrating results of field work, thin section and XRD analyses, we will summarize how these metamorphic rocks that are the "basement" carbonates should be classified.

There are four major types of metamorphism, as summarized below;

3.1 Dynamic metamorphism (Figure 3a)

Dynamic metamorphism occurs as a result of mechanical deformation, as when two bodies of rock slide past one another along a fault zone. Heat is generated by the friction of sliding in such a shear zone, and the rocks tend to be mechanically deformed, being crushed and pulverized by the shearing. Cataclastic metamorphism is not very extensive and is typically restricted to narrow zones where intense shearing occurred (Mibei, 2014).

3.2 Contact metamorphism (Figure 3b)

Contact metamorphism occurs adjacent to igneous intrusions and results from high temperatures associated with the igneous intrusion. Since only a small area surrounding the intrusion is heated by the magma, metamorphism is restricted to the zone surrounding the intrusion, called the contact aureole. Outside of the contact aureole, the rocks are little affected by the intrusive event. The grade of metamorphism increases in all directions toward the intrusion. Because the temperature contrast between the surrounding rock and the intruded magma is larger at shallow levels in the crust where pressure is low, contact metamorphism is often referred to as high temperature, low pressure metamorphism. The rock produced is typically a fine-grained rock that shows no foliation, and is called a hornfels (Mibei, 2014).

3.3 Hydrothermal metamorphism(Figure 3c)

Rocks that are altered at high temperatures and moderate pressures by hydrothermal fluids are hydrothermally metamorphosed. This is common in basaltic rocks that generally lack hydrous minerals. The hydrothermal meta morphism results in alteration to such Mg-Fe ch hydrous minerals as talc, chlorite,serpentine, actinolite, tremolite, zeolites, and clay minerals. Rich ore deposits are often formed as a result of hydrothermal metamorphism (Mibei, 2014).

3.4 Regional metamorphism (Figure 3d)

Regional metamorphism occurs over large areas and generally does not show any relationship to igneous bodies. Most regional metamorphism is accompanied by deformation under non-hydrostatic or differential stress conditions. Thus, regional metamorphism usually results in metamorphic rocks that are strongly foliated, such as slates, schists, and gneisses. The differential stress usually results from tectonic forces that produce compressional stresses in the rocks, such as when two continental masses collide.

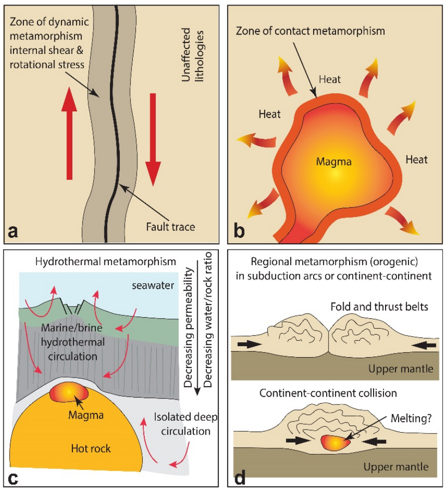

Figure 3: The four major types of metamorphism (after Warren, 2016).

Thus, regionally metamorphosed rocks occur in the cores of fold/thrust mountain belts or in eroded mountain ranges. Compressive stresses result in folding of rock and thickening of the crust, which tends to push rocks to deeper levels where they are subjected to higher temperatures and pressures (Mibei, 2014).

4. Methodology

Across all three areas, fracture and calcite vein orientations were measured and samples were collected based on various rock textures and vein orientations. Furthermore, metamorphic evidence was photographed and documented. Then, samples were selected as representatives of each area rock properties and prepared for stable isotope measurement, thin section analysis, and XRD identification.

Stable isotope samples were collected using a dental technician's drill to extract calcite powders from calcite vein with different orientations and nearby carbonate matrix showing various rock texture was also sampled. All carbonate mineralogies were confirmed by staining of quarry face slabs, by stained thin sections and with XRD analysis. Staining showed dolomite was not present in significant amounts in any of the carbonate rocks sampled. All drilled powders were prepared and analyzed for oxygen isotope ($\delta^{18}O$) and carbon ($\delta^{13}C$) values, using standard techniques as outlined in Allegre (2008). Staining techniques for calcite, dolomite and ferroan carbonate minerals follow the methods outlined in Hitzman (1999).

The diagenetic terms eogenetic, mesogenetic and telogenetic follow the usage of Choquette and Pray (1970) and imply early marine-influenced, burial and uplift-related pore waters, respectively. However, as these rocks are highly metamorphosed, telogenesis (uplift-related) is the most relevant term in terms of any diagenetic discussion. Metamorphism has largely obliterated eogenetic and early to mid mesogenetic textures. The term late mesogenesis, as used in this study, encompasses the metamorphic burial realm.

5. Results

5.1 Overall Geological and Fracture Document

5.1.1 Area1: Late Mesogenesis and Altered Metamorphics

Area 1 is an abandoned quarry located in the south of the study area (Figure 1). The quarry is about 350 m wide, and 25 m approximately high. In general, two main lithologies crop out, based on rock texture and appearance, namely marble and an overlying schist unit (Figure 4a). Mostly, fracture orientations in this quarry follow a NW-SE trend with two dip azimuths, as westerly directions which are plotted in red and easterly direction, which are plotted in yellow (Figure 4a, 4b). Lithology of the lower unit is combination of medium- to dark-grey, fine- grain matrix, marble. Rock texture shows foliation, which is uncom-mon for most marbles developed from clean limestones. This suggest an impure protolith, with silicate minerals such as micas and clays in the precursor rock composition (Figure 5a). Porphyroclast textures, indicating the sense of shear were found in some parts of Area 1 and are mainly found in rocks affected by dynamic meta morphism (Figure 5b). Furthermore, segregation made up of quartzose layers that run parallel the banding of marble can be found throughout the outcrop and likely indicate a more siliciclastic protolith (Figure 5c). Overall calcite veins were associated with two fracture trends, namely major NW-SE and NE-SW orientations (Figure 5c, 5d, 6a). In addition, the upper unit that crops out

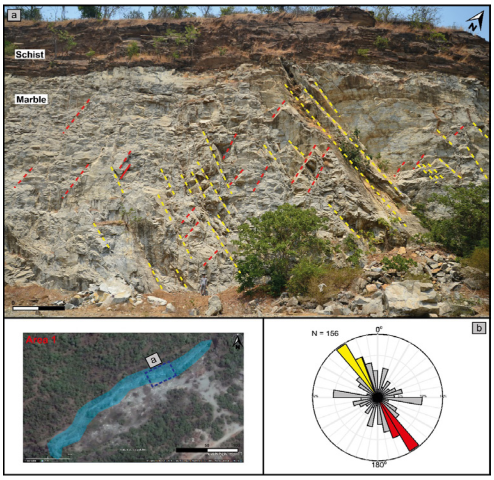

Figure 4: Mosaic photo of abandoned quarry in Area 1. (a) Two lithologies an overlying schist and a lower marble show two major fracture trends. (b) The result of fracture orientations in Area 1 show a major NW-SE orientation with two different dip azimuths.

in the upper part of the quarry face is classified as schist, which is characterized by a "scaly" schistose texture, which caused by orientated platy micas (Figure 5e).

Typical samples, on the basis of various textures and calcite filled fracture trends in Area 1, were collected for thin section analysis, XRD identification and stable isotope measurement. With respect to the orientations measured in a quarry face, there are some constraints (bias) in measurements of the NE- SW trending fractures, given the similarity of this measurement to the orientation of the quarry face (Figure 6a and 7a). This means there are lesser numbers of measured fracture data available for this trend.

Nevertheless, appropriate samples can be taken for slabbing, with the understanding that the same slab faces are used for thin section and associated isotope work (Figure 6b and 7b). Photomicrographs of thin section illustrate most of the marble is made up of compact finely-crystalline calcite, with some dispersed and some layered quartz in the matrix. The calcite lens texture seen in outcrop and thin section is a meshwork combination of deformed calcite crystals and quartz (Figure 6c, 7c). The boundary portion between calcite and quartz composition in a calcite vein are subject to random changes from any position and cannot be clearly distinguished in the field by the human eye or using HCl acid. It is only visible in thin section and suggest stress growth shadows were present in the metamorphic realm as this meshwork texture formed (Figure 7c, 7d; Hobbs and Ord, 2015).

5.1.2 Area 2: Uplift and Telogenesis

Area 2 is another abandoned quarry located about two km north-east of Area 1. (Figure 1). There are two subareas in area 2 used for field work investigation (Figure 1). Subarea 2-1 is about 50 m wide and 18 m high. The dominant fracture orientation in this quarry is NNW-SSE with two dip azimuths; a SWW direction represent in red and a NEE direction shown in yellow (Figure 8a, 8b, 8c). In terms of rock texture, foliation occurs throughout the quarry (Figure 9a, 9b, and 9c). This strongly suggests regional metamorphism has overprinted this area. In addition, segregations of quartzose material are larger than seen in Area 1 (Figure 9d). These more quartzose zones show internal fracture sets because of inherent rigidity, compared to surrounding calcitic (marble) matrixes, which are more ductile and show foliated textures.

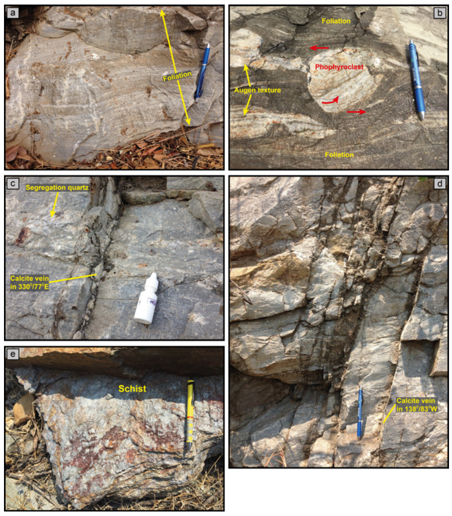

Figure 5: Outcrop characteristics in Area 1 (a) Example of marble showing foliation. (b) Porphyroclast texture indicates sense of shear related to dynamic metamorphism. (c) Calcite-filled vein with NW-SE fracture trend cutting through segregated quartzose and calcitic matrix banding. (d) Calcite-filled NW-SE trending fracture. (e) "Slaty" schistose texture caused by platy mica layering indicative of a schist.

In Area 2, only N-S trending fractures

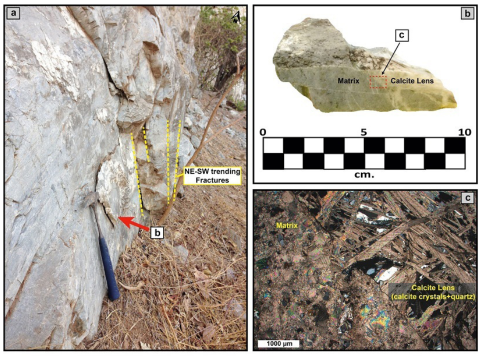

Figure 6: Outcrop characteristics in Area 1 (a) Calcite-filled NE-SW fracture orientation. (b) Slab face used for thin section and stable isotope work (c) Boundary between marble matrix and calcite lens meshwork in photomicrograph

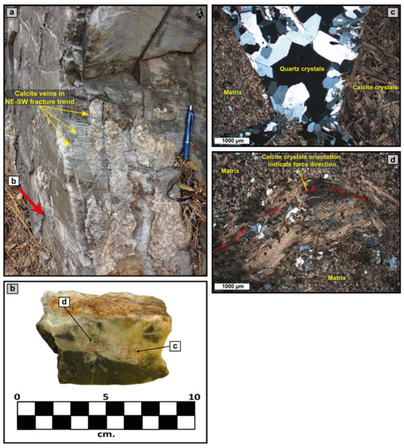

Figure 7: Outcrop characteristics in Area 1 (a) Calcite-filled veins with NE-SW fracture orientation (note b-horizontal slickensides). (b) Slab face used for thin section and stable isotope work (c) Marble with fine-crystalline matrix and calcite lens meshwork (calcite crystals and quartz) as seen in photomicrograph. (d) Calcite crystal meshwork orientations in photomicrograph indicate evolving stress directions at the time of vein growth.

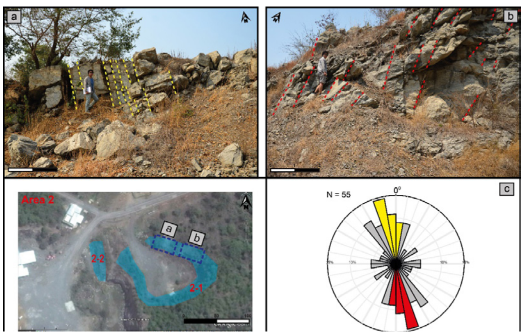

Figure 8: Outcrop characteristics in Area 2 (a) Dominant NNW-SSE trending fracture set with east dipping azimuth. (b) Dominant NNW- SSE fracture trending set with a west-dipping azimuth. (c) The compilation of fracture orientation measurements in Area 2 shows a major NNW-SSE orientation with two different dip azimuths.

occur as quartz- and calcite-vein filled fractures (figure 10a, 10b). The slab face of the sample shows lenticular lens-like shapes or augens (Figure10c). Rotation of augens during growth, due to shearing, leads to sigmoidal inclusion trails and augen tails at different levels in the external foliation. Photomicrographs show syntaxial vein growth or edge inward of quartz growth (Figure 10d). In addition, calcite crystals meshworks (stress shadows) are associated with some parts of the quartz vein fill (Figure 10e). Microfractures cut through these meshwork calcite crystals in some parts of the quartz veins.

Subarea 2-2 is located some 50 m to the west of Subarea 2-1 (Figure 2). This subarea contains secondary (diagenetic-telogenetic) crystalline deposits of calcium carbonate ($CaCO3$) precipitated in cavities from meteoric water. They are a response to dilute aqueous solutions entering to a cave or fissure and define various types of "speleothem" textures including stalactites, stalagmites, flowstones, breccias and soils (Figure 11a, 11b). Away from the speleothem contact, typical foliated textures remain in marble matrix of the country rock.

Area 2-2 contains a larger-scale solution feature which has been partially filled by speleothem structures (Figure 12a). The orientation of this solution valley follows a N-S trend. The rock sample collected for slabbing from the cemented wall of this feature shows various clasts in a fine-grained red calcitic matrix (Figure 12b). Different color banding in adjacent layered metamorphic rock matrix are the result of assorted mineral and crystal size distributions. Most are calcite crystals with some associated quartz, as in Area 2-1. The dark bands represent finer mineral crystals compared to light bands (Figure 12c). Clasts deposited in the speleothem breccia are combinations of marble matrixes, calcite crystals and quartzose material. Furthermore, late calcite (telogenetic) cement has grown at the edge some clasts in the speleothem breccia and filled in microfractures and microvugs about individual clasts (Figure 12d, 12e, 12f).

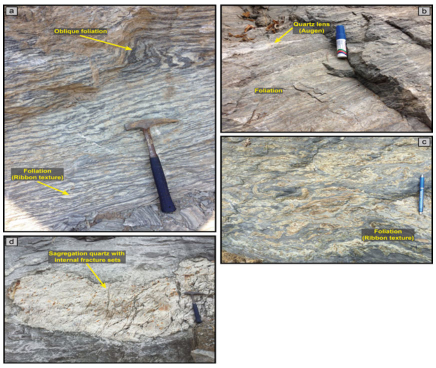

Figure 9: Outcrop characteristics in Area 2 (a) Oblique foliation suggesting the sense of shear. (b) Small quartzose lens compared with surrounding foliated calcitic matrix. (c) Highly deformed matrix as shown in ribbon texture. (d) Brittle fracture sets observed in segregations of quartzose material which indicate a more rigid response compared to the surrounding calcitic matrix.

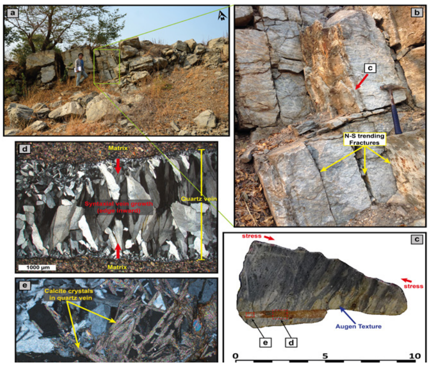

Figure 10: Outcrop characteristics in Area 2 (a) Illustration of the dominant NNW-SSE fracture orientation in Area 2 (b) Mix of quartz and calcite veins in a N-S trending fracture. (c) Slab face showing vein cuts through an augen-textured matrix. (d) Syntaxial vein growth of quartz. (e) Calcite meshwork crystal associations in a quartz vein, with a later microfracture cutting through meshwork crystals.

Figure 11: Outcrop characteristic in Area 2 (a) Outcrop cut illustrating open solution fissures were partially filled with speleothems in Subarea 2-2 (b) Another speleothem sample attached to foliated marble.

5.1.3 Area 3: Late Mesogenesis and Metamorphism Altered

Area 3 is a large abandoned quarry located some 27 km north of Area 1 and defines the northern end of study area (Figure 1). This quarry is 250 m long and 60 m high at its highest point (Figure 2). Overall, fracture orientations in this quarry show a NW-SE trend, with a westward dip shown in red (Figure 13a, 13b, 13c). As in area 1 the orientations of the main quarry face make it difficult to measure many NE-SW trending fractures. Consequently, there are fewer measurements of this fracture trend in the compiled data. In terms of lithology, this area is similar to Area 1 and Area 2 and is dominated by marble. Foliation is the most common texture seen in the quarry walls.

Zones of augen texture are scattered throughout the quarry, as in Area 1 (Figure 14c, 14d). Calcite veins in Area 3 can be seen in the dominant trend fractures, as in Areas 1 and 2 (Figure 14d, 14e). Quartzose segregations in Area 3 are well developed and somewhat larger than seen in Areas 1 and 2. These large quartzose segregations are parallel to the banding of marble, possibly indicating more quartzose beds in the protolith compared to areas 1 and 2 (Figure 14a). Numerous “conjugate fracture” sets occur in the quarry walls in Area 3 (Figure 14b).

Samples were collected from both calcite veins and quartz veins that filled in the dominant NW-SE trending fractures, typically with a part of attached matrix. Vein and matrix were used for thin section analysis, stable isotope measurement and XRD identification (Figure 15a, 15b, 15c). Photomicrographs illustrate different crystals sizes cause the banding or foliation (the dark bands are made up of finer crystals compared to lighter-colored bands) with layering sometimes emphasized by aligned platy minerals e.g. biotite (Figure 15d). In addition, it can be noticed that crystals were deformed into more flattened shape. The reoriented flattened and elongated minerals are now aligned in planar arrangements with each other, parallel along their long axes.

As a result, matrix has squeezed mineral crystals aligned parallel to biotite platess, which indicate the dominant stress direction. Furthermore, microfractures cutting through calcite crystals are seen in some quartz veins

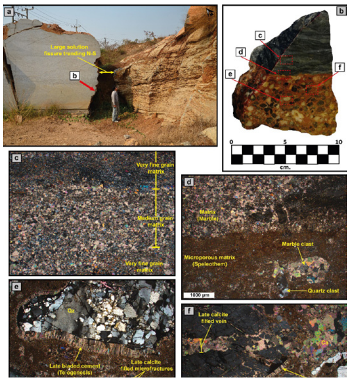

Figure 12: Outcrop characteristics in Area 2 (a) Large (meter-scale) N- S trending solution valley partially filled with speleothems in Subarea 2-2 (b) Slab face of a speleothem sample. (c) Various mineral grain sizes create different color bands as thin section seen in marble matrix outcrop. (d) Microporous matrix in a speleothem thin section. (e) Typical thin section late-stage bladed telogenetic calcite cement lining the edge of clasts (f) Thin section late-stage telogenetic calcite cement fill in microfractures in a clast.

(Figure 15e).

5.2 Fracture Orientation and Calcite-Fill Summary

Overall, all three areas show a similar dominantly NW-SE fracture trend. Nevertheless, Area 1 and Area 2 have a dominant mean dip azimuth that is easterly, but in Area 3 the dominant mean dip azimuth is westerly (Figure 16). As illustrated earlier, due to the prevailing orientation of the quarry faces, it can be difficult to measure fracture sets with NE-SW orientation as there are fewer suitable data sites for this trend, so there is a data baias due to quarry facealignments. In general, calcite-filled fractures show a NW-SE orientation across three areas. Subsidiary calcite-filled NE-SW trending fractures are only seen in Area 1, similar calcite-filledsubsidiary fractures with a N-Strend are only seen in Area 2. Furthermore, microfractures that cut through calcite crystal meshworks associated with quartz veins also were observed in these N-S and NW-SE fracture orientation (Figure 10e, 15e).

5.3 Stable Isotopes

All carbon and oxygen isotope values (C-O) from all three areas are compiled and plotted in a single crossplot showing distinct but related C-O covariant trends (Figure 17). The two obvious trends are, 1) the late mesogenesis (metamorphic) burial trend which is shown across C-O crossplots of Area 1 and Area 3 samples. 2) a telogenetic (uplift-related) meteoric mixing trend which is clearly seen in the C-O crossplots of Area 2 samples. Within the late mesogenesis trend, values from all three areas overlap in the upper part of the crossplot (indicated by light purple and light orange plot points in Figure 17).

This is to be expected as it is the result of regional deformation with rock-fluid interactions that drive C-O re-equilibration. It occurs wherever the rocks experienced late mesogenetic/ metamorphic re-equilibration- related hot fluid crossflows of highly metamorphosed fluid, all of which are defined by increasing temperature (highly negative oxygen values). It seems that some less- negative calcite cements and marble signatures in all three areas overlap the thermal regime of calcite veins formed from thrust-related veins precipitated from hot confined fluids in veins and fractures in the Saburi region to the east and driven by the Indosinian orogeny (Warren et al., 2014). The most negative oxygen isotope values seen in the thrust vein calcites of the Saraburi region by Warren et al (2014) show $\delta^{18}O$ values in the range -12 to -20 ‰, which are related to deep burial and tied to the Indosinian Orogeny.

In the hot tectonic vein calcite plots of the current study area the measured oxygen values are much more negative than this, and thermal trends of Areas 1 and 3 show consistent overlapping values in each color shaded area (Figure 17). This implies a similar temperature regime across both areas with metamorphic temperatures that are isotopically much hotter than those preserved in Permian carbonates of the Saraburi area. In the study area the oxygen values show a transition from temperatures overlapping the thrust zone vein cement range, as preserved in the Saraburi region, ($\delta^{18}O$ ~ -12 to -20 ‰) and shown in light purple zone into a zone with much more negative (hotter fluid) oxygen values that range up to ~ 32‰, illustrated by the orange-shaded area in Figure 19. Most of the samples plotted in this orange-shaded zone come from calcite veins, although some samples came from the

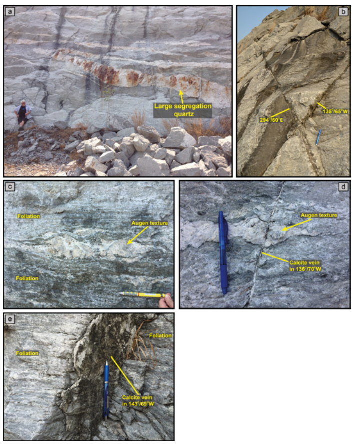

Figure 14: Outcrop characteristics in Area 3 (a) Large quartzose segregations align parallel to the banding in the marble. (b) Conjugate fracture set with a NW-SE trend. (c) Augen texture within the surrounding foliated marble matrix. (d) Calcite-filled NW-SE fracture, cutting through lenticular eye-shaped segregations of the augens, which are mostly made of quartzose material. (e) Another example of cross-cutting calcite veins showing the dominant NW-SE orientation

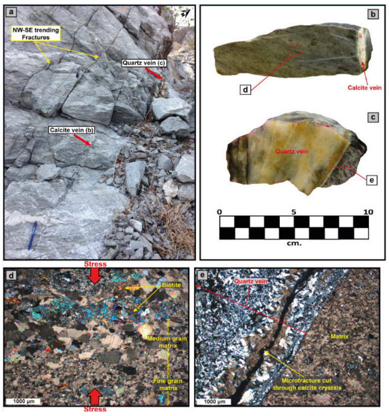

Figure 15: Outcrop characteristics in Area 3 (a) Both calcite veins and quartz veins show the dominant NW-SE trending fracture trend. (b), (c) Slab face samples of calcite veins and quartz veins with attached matrix. (d) Photomicrograph showing banding in marble is caused by combination of different crystal sizes and aligned platy minerals, mostly biotite. (e) Microfracture cutting through, with calcite crystals precipitated within a quartz vein.

wherever the rocks experienced late mesogenetic/ metamorphic re-equilibration- related hot fluid crossflows of highly metamorphosed fluid, all of which are defined by increasing temperature (highly negative oxygen values). It seems

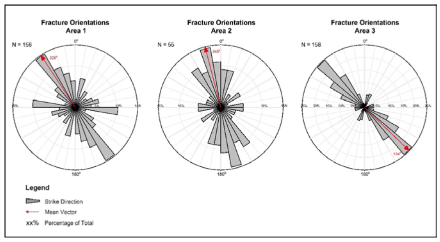

Figure 16: Rose diagrams showing fracture orientations by area.

that some less- negative calcite cements and marble signatures in all three areas overlap the thermal regime of calcite veins formed from thrust-related veins precipitated from hot confined fluids in veins and fractures in the Saburi region to the east and driven by the Indosinian orogeny (Warren et al., 2014). The most negative oxygen isotope values seen in the thrust vein calcites of the Saraburi region by Warren et al (2014) show $\delta^{18}O$ values in the range -12 to -20 ‰, which are related to deep burial and tied to the Indosinian Orogeny.

In the hot tectonic vein calcite plots of the current study area the measured oxygen values are much more negative than this, and thermal trends of Areas 1 and 3 show consistent overlapping values in each color shaded area (Figure 17). This implies a similar temperature regime across both areas with metamorphic temperatures that are isotopically much hotter than those preserved in Permian carbonates of the Saraburi area. In the study area the oxygen values show a transition from temperatures overlapping the thrust zone vein cement range, as preserved in the Saraburi region, ($\delta^{18}O$ ~ -12 to -20 ‰) and shown in light purple zone into a zone with much more negative (hotter fluid) oxygen values that range up to ~ 32‰, illustrated by the orange-shaded area in Figure 19. Most of the samples plotted in this orange-shaded zone come from calcite veins, although some samples came from the metamorphosed marbles. Most of the samples in the cooler (purple-shaded) area come from marble matrixes not veins. The dichotomy in temperatures (purple versus orange shaded plotfields) implies the hotter vein fills may be related to out-of-sequence hydrothermal water crossflows.

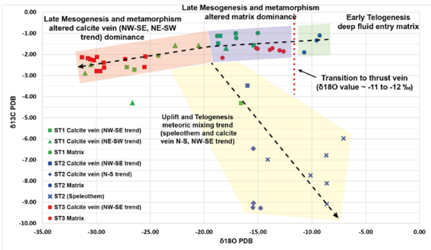

Figure 17: C-O isotope plot illustrating sample values from Areas 1, 2 and 3.

In addition, many of the hotter calcite vein fills in the Suphanburi region are interpreted as derived from out-of-sequence hydrothermal fluids. These fluids are much hotter than any of the fluids phases in the Saraburi area (c.f. Warren et al., 2014). The contrast in oxygen values (and hence relative temperature) between vein calcite and adjacent metamorphic marble-matrix calcite especially in area 3) suggests these hotter temperatures at the time of fluid entry were perhaps hydrothermally driven into crosscutting fractures created by, or reactivated by, the stresses imposed by the Himalayan event (red symbols in Figure 18). These very hot hydrothermal fluids are likely related to the deep regional nature of the Three Pagoda fault zones. The similarity in vein temperatures in the study area and the Three Pagoda fault damage zone is seen in the overlap of C-O plotfields with respect to late stage Himalayan (Paleogene) fluids, as documented by Nazrul (2015). Oxygen values of the late stage veins in both areas indicate hot fluids at the warmer end of a transition from temperatures overlapping the thrust zone vein cements, as preserved in the Three Pagodas fault damage zones ($\delta^{18}O$ ~-18 to -23 ‰) shown by cluster 3 values (emphasized by light yellow shading in Figure 18).

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The cooling trends seen in the Suphanburi region relates to the speleothem- influenced zone that is sampled in Area 2-2, where a meteoric water signature is superimposed on the uplifted metamorphics (yellow and green shaded areas in Figure 17). 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 resulting meteoric mixing trend, as seen in Figures 17 and 19, is an example of the subsurface combination of infiltrated rainwaters with more deeply circulated telogenetic fluids that have dissolved shallow uplifted metamorphic carbonates.

Prior to uplift, these carbonates had highly negative oxygen values indicating the rocks were once situated in the late mesogenesis (metamorphic) zone. The mixing- field calcites, precipitated by mingling of these two fluid sources, is mostly shown as a light yellow zone (Figures 17 and 19). This trend of decreasingly negative oxygen and increasingly negative carbon values implies precipitation from waters that are cooler (less negative oxygen values), with increasing contributions of soil gases in the in shallow meteoric waters, indicated by increasingly negative carbon values (Figure 19). Nonetheless, there is likely a separate meteoric field to this main mixing trend field. It is indicated by decreased negative oxygen isotope values in the range ~ - 9 to -11 ‰

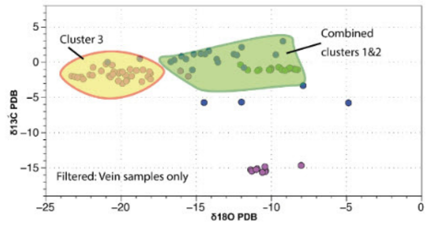

Figure 18: C-O isotope plot shows likely hot fluid equivalent to those in "out of-sequence" Suphanburi calcite veins (figure 20). These fluids are defined by cluster 3 in samples collected from the Three Pagoda fault damage zone (from Nazrul, 2015).

but little-changed negative carbon values, defined by three data points in C-O plotfield (blue points with green background in Figure 17 and 19). These points sampled marble matrix in Area 2-2 and are distinct from the plots typical of the speleothem-influenced zone (illustrated by point c in Figure 12b). The low $\delta^{18}O$ values, compared to the other marble matrix samples across from Areas 1 and Area 3 come from samples collected from metamorphic matrix in positions located only a centimeters from the contact between matrix and a nearby speleothem calcite (Figure 12b, 12c). The lack of a more negative shift in the carbon values from these three samples is interpreted to indicate alteration calcite precipitated in the early state of telogenesis, when somewhat cooler deep phreatic fluids first penetrated the matrix along a nearby Himalayan fracture. This happened deep in the telogenetic zone (bathyphreatic entry) at a time and depth that was well before any calcite precipitation from shallow soil-gas-rich meteoric waters. That is, these three samples from Area 2, defined by the green shaded plot field in Figures 17 and 19, indicate calcite alteration and crystallization at a time and location well prior to uplift into the active meteoric circulation zone. There, its shallower pore water precipitates have a significant soil gas contribution and hence more negative carbon values, as well as more positive (cooler temperature) oxygen values.

And so, the seperation into two isotope values plotfields in calcite veins in NW-SE trend suggest early infiltration of deeply circulating meteoric-phreatic in uplift telogenesis was then focused into a series of calcite-filled N-S trending fractures, that later widen and were associated with speleothem deposits (Figure 19).

6. Conclusions

Fieldwork documented foliation, augen texture, and porphyroclast texture throughout the study area. These rocks are not Ordovician limestones but metamorphosed carbonates from a protolith of as yet unknown age. Furthermore, photomicrographs show numerous aligned platy minerals e.g. biotite, as well as reformed crystals that a superimposed stress field forced into more flattened shape. These reoriented, flattened and squeezed minerals indicate superimposed shear at the time of crystal growth and recrystallization with different crystals sizes causing the laminar banding in matrix. Likely, many episodes of banding do not indicate original sedimentary layering. Mineral composition in the rock matrix, as identified from staining and XRD shows calcite dominance across the study area, followed by quartz (see Appendix A). Inaddition, increasingly negative $\delta^{18}O$ values form a covariant C-0 stable isotope trend show increasing temperature and the effects of pervasive metamorphic alteration, superimposed on a carbonate dominated protolith of unknown age.

As a result, variably "mylonitic marble" is the interpreted name as being most representative for outcrop in all three carbonate quarries. This is based on likely protolith, as well as ambient metamorphic texture and mineral composition. Hence, stratigraphic chart referred to geological map of Suphanburi Province (DMR, 2014), (Figure 1) is modified as shown in Table 1.

The dominant fracture trend in this study area is NW-SE (Figure 16). Calcite veins in NW-SE and NE-SW fractures were most likely crystallized during late burial mesogenesis (up to amphibolite-grade metamorphism). During later uplift telogenesis, calcite filled N-S trending fractures and speleothems formed and clearly illustrated as a separate C-O plotfield.

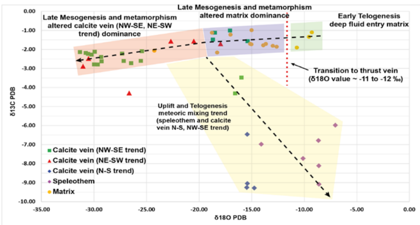

Figure 19: Filtered C-O covariant isotope plot illustrating sample values classified by sample categories.

AGE	DMR, 2014			BUNPITAKSAKUL, 2016		
	GROUP	FORMATION	DESCRIPTIONS	AGE	FORMATION	DESCRIPTIONS
QUATERNARY			Alluvial fan, sandstone interbedded claystone, siltstone interbedded limestone nodule, gravel and sand.			
ORDOVICIAN	Thung Song	Tha Ma Nao Limestone	Thick bed to massive limestone, recystallized to marble and laminated calc-silicate.	Age Unknown	Likely Uthong Marble equa-valent	Mylonitic marble with equigranular texture, foliated, augen and porphyroclastic texture are common, occasional mica schist, rarely fault breccia.
CAMBRIAN - ORDOVICIAN		Uthong Marble	Marble with sugary texture, quartz schist, mica schist, occasional dolomite.			

Table 1: Stratigraphic chart comparison of Suphanburi Province.

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