Structural Development of Thrusts, Folds and Fractures in Quarry Exposures of Permian Limestones, Saraburi Province, Central Thailand: Implication for Fracture Reservior Development in NE Thailand

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Abstract

Exposures in two quarries (quarry-1 and 2), Saraburi Province, central Thailand reveal that Permian Limestone folds and thrusts underwent complex deformation related to the Indosinian Orogeny (Late Permian to Early Triassic). Possibly the structural grain was reactivated during Cenozoic time. The deformation history evidenced by outcrop patterns in the study area evolved largely under the influence of (approximately) N – S directed compression. The two largest thrust faults in the study area trend ~ E – W, and dip 35° – 40°. Disharmonic buckle folds, fault – bend fold and detachment fold are present with the main fold axes trending approximately E – W.Two types of fractures are present: unfilled and calcite-filled fractures. Fracture sets can be grouped into two main categories: a) Bedding-orthogonal fractures with consistent trends (longitudinal fractures with E – W trend, transverse fractures with N – S trend and diagonal fractures with NE – SW and NW - SE trends) and, b) Non-orthogonal fractures with bedding showing discrete and isotropic orientations. These fractures tended to progressively develop during folding and thrusting in the core zone of deformation. The high-angle fractures in the fault zone are truncated by a late stage sub-horizontal pressure solution cleavage, which probably developed during loading by a now eroded higher thrust sheet. Stable oxygen and carbon isotope signatures in calcite veins indicate that they are related to tectonism. The calcite veins (Group I),are parallel to thrusting and formed during bedding plane slip, veins precipitated under the influence of fluid circulating through, and released from, the host rock during burial. In contrast, calcite veins of Group II, are present perpendicular andto, or high angles to bedding, they formed from even higher temperature fluids flowing along fractures. All this evidence indicates synchronous calcite growth is related to thrusting. The larger thrust faults appear to have been the focus for the migration of hotter, deeper basinal fluids. Moreover, ferroan-rim calcites in veins indicate late stage precipitation from hot fluids, related to deep burial reducing conditions, with iron probably derived from clay minerals within the carbonates. The fractured Permian reservoirs of the Sin Phu Horm and Nam Phong gas fields in NE Thailand, to the north of the study area in the Khorat Plateau, have proven difficult to understand and predict in term of their reservoir properties. Therefore, the results of this outcrop study are directly applicable to the fractured carbonate reservoirs of this region and elsewhere in SE Asia.

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

1. Introduction

Reservoir evaluation in fold and thrust belts is typically difficult due to significant alteration of the porosity and permeability properties of the reservoir rocks during structural development, which consequently influences fluid migration and accumulation. In this context the fractured Permian reservoirs of the Sin PhuHorm and Nam Phong gas fields in NE Thailand, the Khorat Plateau, have proven difficult to understand and predict (Malila et al., 2008).

Therefore the main objectives of this study are to analyze structural elements in the Permian Limestone outcrop in order to better understand sequential development of structural elements and specifically, to understand the relationship between fold and fault-related fracture zones in a core zone of the thrust-fold belt using measured and sampled field data.

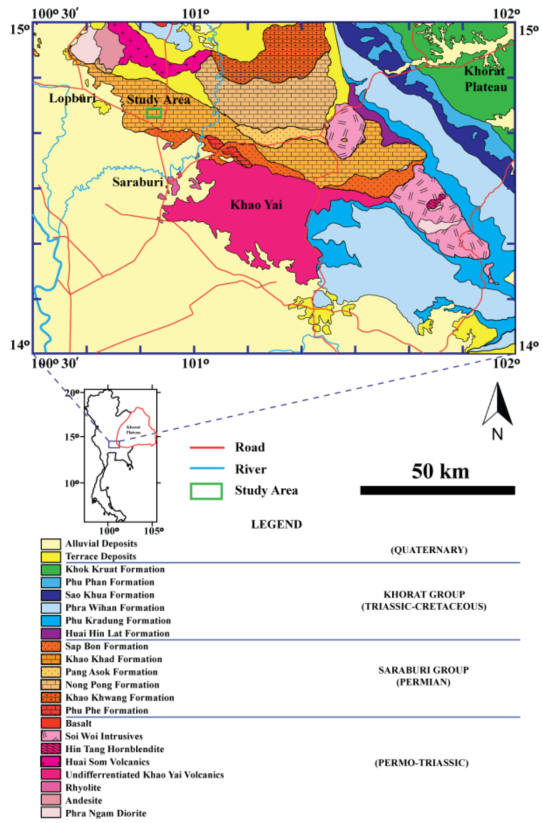

Figure 1. Geologic map of ND 47-8, Pranakhon Si Ayutthaya, central Thailand showing study area location (Modified after Hinthong et al., 1985 and Thambunya, 2007).

2. Method

The study focused on quarry exposures of Permian Limestone in the Na Phralan, Chaloem Phrakiat District, Saraburi Province, central Thailand (Figure 1). The study area is some 0.7km wide, 2.0km long and 175m high. Within the area are five quarries centred on an isolated hill of limestone and two of the quarries are still active. Two of the inactive quarries in the southern and eastern part of the outcrop (here called quarry-1 and 2) were selected for detailed field work.

Structural geometries in the outcrop exposures were measured, photographed and sketched. Samples were then selected for stable isotope measurement, thin section analysis, and XRD determinations. Furthermore, two spectral gamma ray profiles were measured across both quarries and photographs were taken to document and quantify outcrop properties along the gamma transects.

3. Results

3.1 Field Investigation

Figure 2 shows the positions of the two studied, now inactive quarries (quarry-1 and 2), they make up the southern and eastern part of a single hill of Permian limestone. Quarry-1 is around 400m wide and the quarry wall some 130m high, Quarry-2 is approximately 300m wide and 130m high.

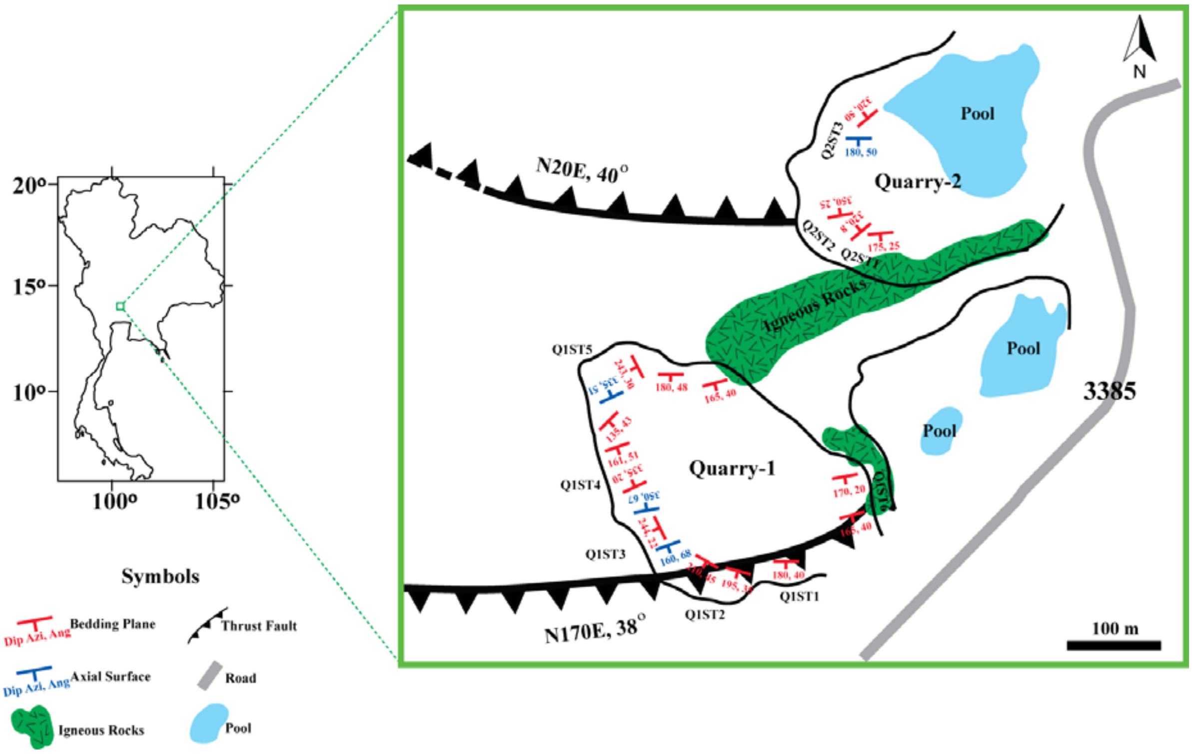

Figure2. Structural map of the study area location (the quarry-1 and 2) at Na Phralan, ChaloemPhrakiat District, Saraburi Province, central Thailand.

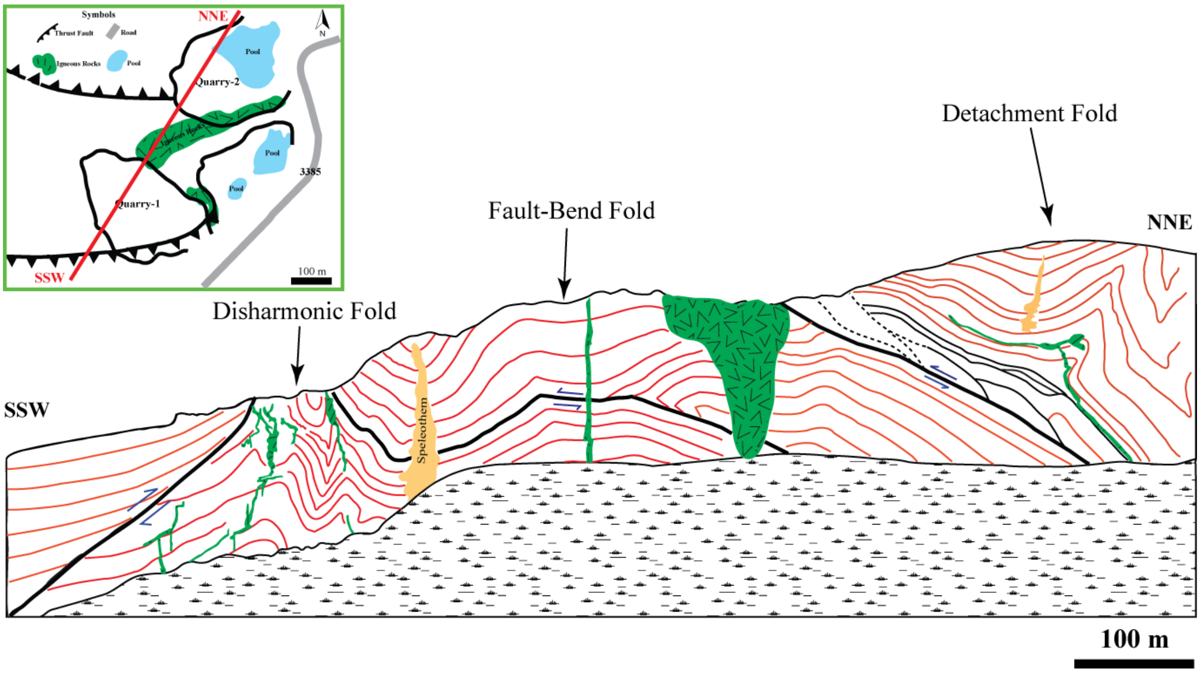

Figure 3. Cross section (NNE - SSW line) showing general structural elements in the quarries. Disharmonic fold (left, below thrust), Fault-bend fold (middle) and Detachment fold (right, above thrust). Green indicates positions of igneous dykes and sills, yellow the position of speleothems (mostly flowstones).

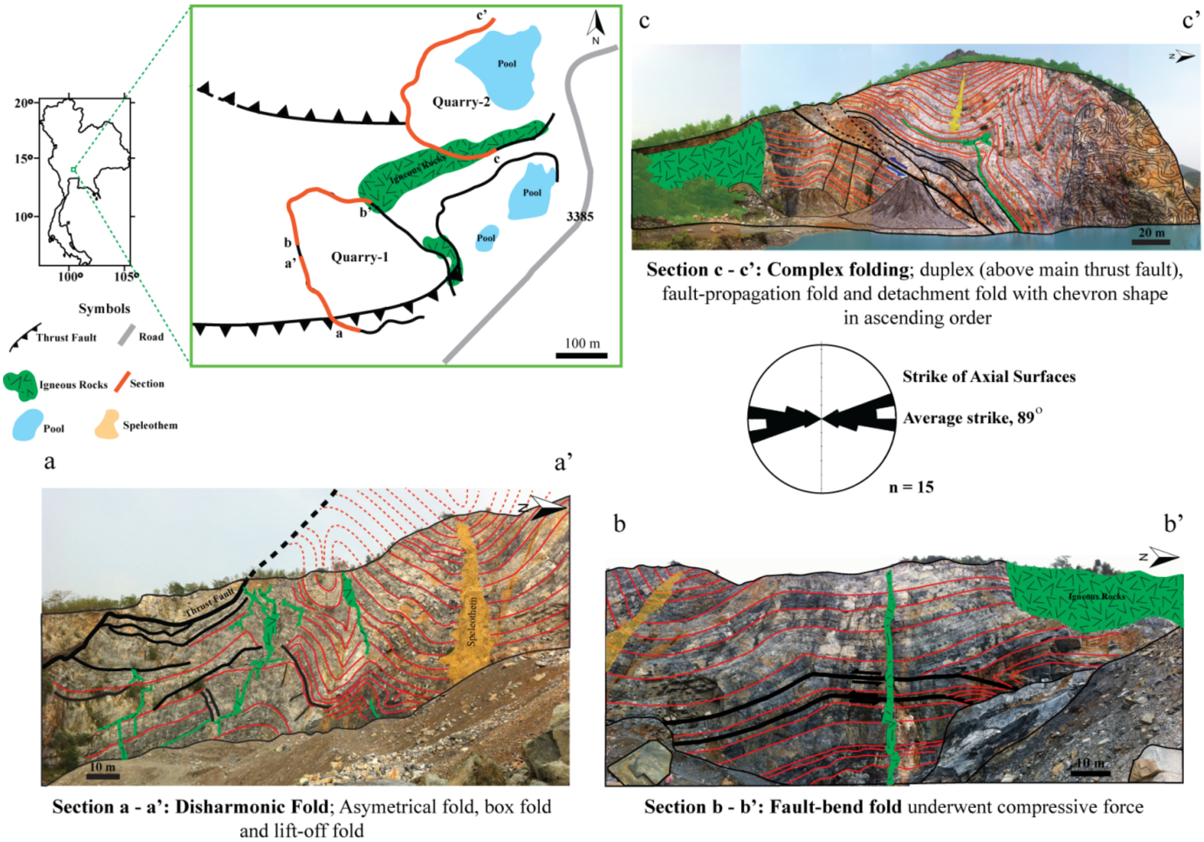

Figure 4. Fold geometries and orientations of the quarry-1 and 2.

Thrust Faults: Two largest thrust faults in the study area trend ~ E – W, and dip 35° – 40° to south in quarry-1, and to north in quarry-2 (Figure 2-4).

Folds: Three major types of thrust-related folds; disharmonic fold, fault-bend fold and detachment fold are observed in both quarries. Fold axes of thrust-related folds trend approximately E – W (Figure 3-4).

Flexural Slip: Folds in both quarries show evidence for flexural slip between bed contacts. The stepping displacement or offsetting of igneous dykes indicates the movement horizons; generally centimetres to meters in spacing offset and filled by bedding-parallel and perpendicular calcite veins. Flexural slip is particularly well developed within finer-grained limestone beds composed of mudstones and fine-grained, thinly bedded units (Figure 3-4).

Stylolites: Stylolites are recognized by jagged planes between two rock units and are thought to be the result of pressure solution, a process that involves dissolution of highly soluble minerals (e.g. calcium carbonate) and the concentration of less soluble minerals (e.g. clay) along the stylolite seam in response to differential stress (Nelson, 2001).

Fractures: Two types of fracture were observed in the field; a) unfilled fractures, which are fractures with no material filling the width between the walls of the fracture, and b) calcite-filled fractures, which are the main fracture type encountered in both quarries.

Bedding: The attitudes of bedding planes are mostly inclined to the south, with various orientations related to the local fold shape

Igneous Rocks: Two types of igneous rocks are present locally in the quarries. The first is fine-grained intrusive igneous rock with andesitic/dioritic composition. The second type is fine-grained intrusive igneous rock with rhyolitic/granitic composition.Intrusive igneous rocks cross cut major structures and indicate they postdate the main structural development, but some also appear to have been offset by late movements on the folds.

3.2 Paleo-stress Analysis

The fault plane and slicken line orientations, including sense of relative motion, are used to calculate the three parameters of paleostress tensors. The calculated stress tensor is characterized as σ_1: 01/007, σ_2: 11/276, σ_3: 79/104. It defines a compressive thrust fault regime and responding to NNE – SSW compression.

3.3 Fracture Analysis

Fracture Orientation

Fracture orientation data were restored to pre-deformation conditions by rotating bedding orientations to horizontal. This shows which of the current fracture orientations can be related to original pre-deformation joint sets. After bedding rotation, fractures can be grouped into two main categories. The first rotated group is composed of bedding-orthogonal fractures, with consistent trends (probably related to pre-deformation or deformation onset stresses) that are longitudinal, transverse and diagonal fractures, while the second group is non-orthogonal to bedding and shows discrete and varied dip angles, with no consistent trend (related to deformation stresses)

Fracture Intensity

The relationship between bed thickness and fracture density shows that thinner beds have higher fracture intensities than thicker beds.

3.4 Shortening Estimation of Detachment Folding

The significant shortening of layers is caused by due to pressure solution and folding mechanism in the core of zone of thrusting and folding.

3.5 Spectral Gamma Ray and X-Ray Diffraction (XRD)

Measured gamma transects show an increase in the Th/U ratio in carbonates in both quarries is an indicator of an increased amount of radiogenic detritus in regions of cataclasis within the zone of thrusting. Similar measurements in wireline logs from the subsurface may indicate zones of thrusting in a carbonate host.

The carbonate rocks of the study outcrop are dominated by calcite with traces of dolomite. The igneous rocks are composed mainly of feldspar, clay minerals (altered from feldspar), and quartz, which are a major components of andesites and rhyolites.

3.6 Micro-scale Study

Lithofacies of Carbonate Rocks

Based on Dunham's classification (1962), the limestone outcrops in quarry-1 and 2 can be subdivided into five lithofacies, namely; bioclastic packstone, bioclastic wackestone, calcisphere wackestone, mudstone and aggregated grainstone (Figure 5).

Diagenetic Features

There are several diagenetic features seen in thin sections such as stylolites, twining and kink bands within calcite vein crystal, deformed and flattened microfossils and micritised grains commonly seen in the more deformed intervals, multiple phases of hot-solution calcite precipitation in vein fills (Figure 5).

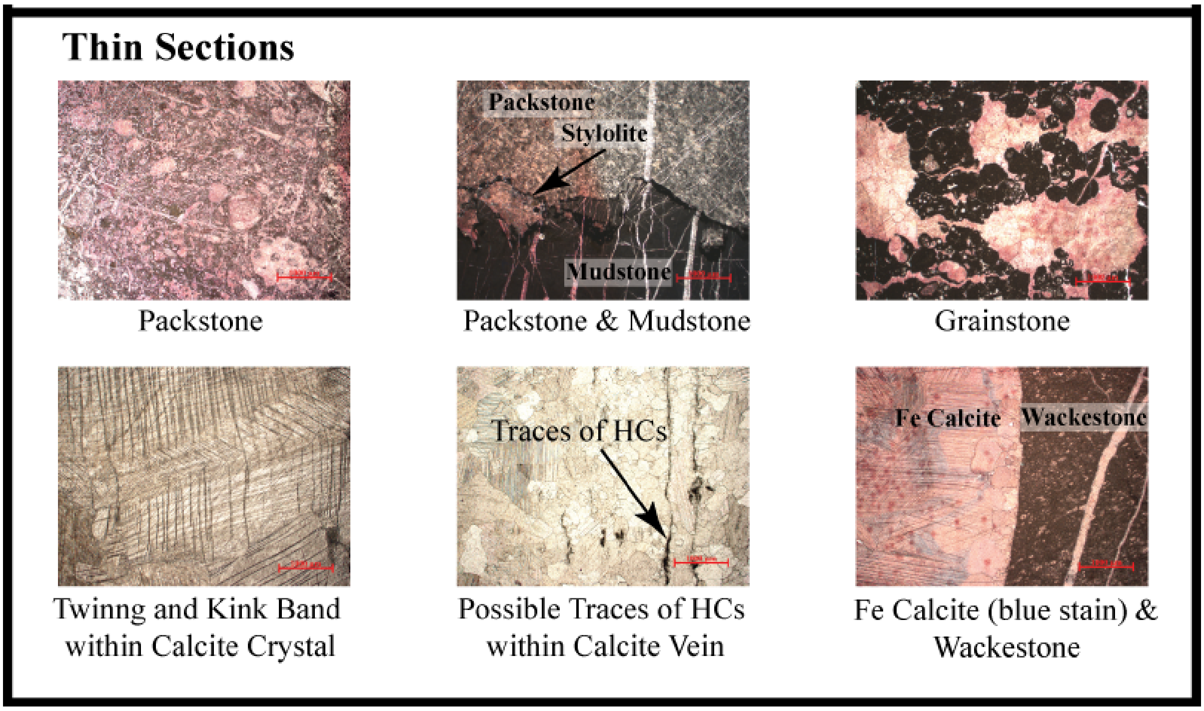

Figure 5. Thin sections of carbonate rocks and calcite veins represented lithofacies and dominant diagenetic features.

3.7 Stable Isotope Analysis

Stable oxygen and carbon isotope signatures in calcite veins indicate that they are related to tectonism. The calcite veins (Group I), are parallel to thrusting and formed during bedding plane slip, veins precipitated under the influence of fluid circulating through and released from the host rock during burial. In contrast, calcite veins of Group II, a present perpendicular and at high angles to bedding, they formed from even higher temperature fluids flowing along fractures (Figure 6). All this evidence indicates synchronous calcite growth is related to thrusting. The larger thrust faults appear to have been the focus for the migration of hotter, deeper basin fluids. Moreover, ferroan-rim calcites in veins (Figure 5, last photo) indicate late stage precipitation from hot fluids, related to deep burial reducing conditions, with iron derived from clay minerals within the carbonates.

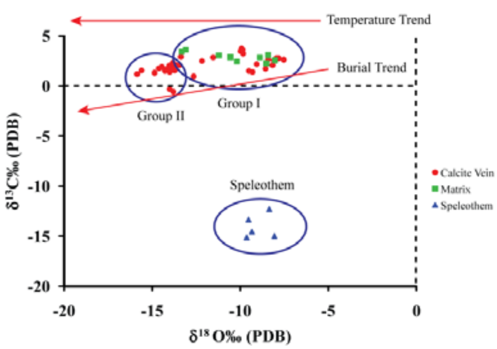

Figure 6. The plot of stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope.

4. Discussion

4.1 Sequential development of the structural elements

The specific mechanisms of structural development involved in the formation of fracture and fault systems in the carbonate outcrops that make up Quarries 1 and 2 are summarized as a conceptual model (Figure 7)

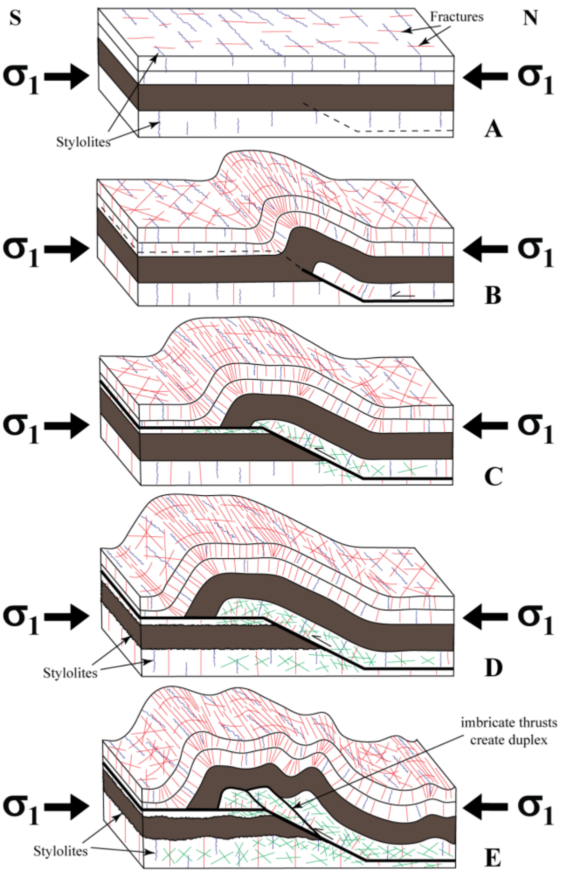

Figure 7. Conceptual model explaining the sequential development of structural elements in the study area.

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

- Hot solutions may be channelized along thrust fault through the generation of micro-cracks and fractures during deformation at high fluid pressures.
- All this evidence indicate simultaneous calcite growth tied to the thrusting and confirms that the associated temperatures in the Group II calcites came from the fault-focused escape of hotter deeper basin fluids.
- The interaction of fold, fault and fracture formation corresponds to fluid migration evidenced by microscopic scale study that identify calcite cements and traces of hydrocarbons in these structures as indicators of fluid migration.

4.3 Implication for timing of structural development correlated to regional tectonic evolution in SE Asia.

- The deformation history evidenced by outcrop patterns in the study area evolved largely under the influence of (approximately) N – S directed compression. This stress regime explains the investigated fault, fold and fracture geometries, and is consistent with other observations in the field including calcite veining and stylolization.
- Fine-grained intrusive igneous rocks encountered at the outcrop appear to be relatively late event. There is a distinct possibility that a major uplift event may have occurred in the study are in Cenozoic time during the collision of India and Eurasia (Himalayan Orogeny) and that the cross cutting igneous features seen in the quarries are younger that the Indosinian orogeny. However, age dating of these igneous rocks is needed in order to help determine timing of deformation in the thrusting and folding in this area. (it is planned to test this hypothesis with a set of K-Ar dates on the intrusives, but this analysis could not be completed in the short 4-month time frame of this current research project).

4.4Implications for fracture reservoir in NE Thailand in term of fluid pathways

- There may be two possible mechanisms driving the filling sequence of calcite cement and possible hydrocarbons. The first possibility is that the veins periodically re-opened (hydro fractured?) and so allowed hydrocarbons and hot fluids to migrate along the vein, which was subsequently deformed by further shear. Alternatively, the vein may have been reactivated during shear and so allowed hydrocarbons and hot fluid to infill along the vein at the same time as shearing occurred. Hydrocarbons may have migrated through the connected network of veins and fractures to concentrate in areas of sheared fractures and so moved further into the localized areas that had increased connectivity. These structural elements were then pathways for fluid flow within potential reservoir rocks.

5. Conclusions

- The limestone is comprised of bioclastic packstone, calcisphere wackestone and mudstone underwent progressive deformation.

- The major thrust faults trend more or less E – W dip 35^o – 40o to the south in quarry-1 and to the north in quarry-2, while the fault slip data indicate a compressive thrust fault regime with NNE – SSW compression.

- The lithified limestone intervals show flexural slip occurred on discrete movement horizontal between bed contacts marked by calcite-fibre sheets or polished surfaces and offset veins.

- Two types of fractures were observed; unfilled and calcite-filled fractures showing various present-day orientations with respect to folding shape and local compressive stress. These fractures can be grouped into two main categories: a) Bedding-orthogonal fractures with consistent trends (longitudinal fractures with E – W trend, transverse fractures with N – S trend and diagonal fractures with NE – SW and NW - SE trends) and, b) Non-orthogonal fractures with bedding showing discrete and isotropic orientations, possibly due to isotopic compressive stress and indicated by inconsistent fracture trends. The former fracture sets tended to develop during early stages of folding. After that during more intense deformation, folding developed related to pervasive thrusting and the later fracture set simultaneously developed.

- Measurement of fracture intensity shows that thinner beds produce a higher number of fracture densities than thicker beds.

- The proposed mechanisms of fold, fault and fracture formation are also responsible for creating flow pathways in a potential analog for fractured Permian Limestone reservoirs.

- The results of this outcrop study are directly applicable to the fracture carbonate reservoirs of this region and elsewhere in SE Asia.

6. Acknowledgments

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