STRUCTURAL DEVELOPMENT OF THRUSTS, FOLDS AND FRACTURES IN QUARRY EXPOSURES OF PERMIAN LIMESTONES, PAK CHONG, NAKHON RATCHIMA PROVINCE, CENTRAL THAILAND: IMPLICATION FOR FRACTURED RESERVOIR DEVELOPMENT IN NE THAILAND

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Abstract

Detailed field study and laboratory analysis show Permian carbonates in Pak Chong, Nakhon Ratchasima Province are deformed into folds and thrusts by N - S compressional stress during the burial stage (Indosinian Orogeny). This created a series of calcite-filled E - W fractures, and related features, via transpressional stress. After that, tectonic reactivation during the Cenozoic created a set of N - S fractures. These N - S fractures are widespread at the reservoir scale and tend to be partially to completely open fractures.

This structural evolution, as mapped in the field, is supported by stable isotope measurements (carbon and oxygen) of vein-filling calcites, which show a clear temperature and time-relation separation along the same burial trend into: Group I: cooler and shallower; defined by pervasive fluid crossflow in the matrix, driving ongoing calcite cementation and isotope re-equilibration in the matrix and in early fractures, and, Group II: hotter and likely deeper; indicates fault- and fracture-focused calcite precipitation. By this burial stage the matrix is largely impermeable due to pervasive calcite cementation and stylotitisation, which had shut down matrix fluid flow, so that fluid flow was confined to tectonically activated fractures and faults.

This temperature-related bipartite isotope trend refines the earlier isotope burial trends established by Ampaiwan (2011) and Thanudamrong (2011), who studied structural and diagenetic evolution in the same folded and thrusted formation (Khao Khad Formation), but at different locations in Central Thailand. In combination, this study and the previous two, have now established a reliable stable isotope-derived burial trend in Central Thailand (made up of more than 250 isotope pairs). It can be used as a yardstick to test and compare other isotopic analyses conducted in Permian carbonates of Thailand. Much of the earlier work in Thailand has interpreted stable isotope values in various spar cements as indicators of meteoric or mixing zone diagenesis.

The model of structural evolution, fracture development and sequential calcite precipitation, as defined in this study, can now be used to refine our understanding of fluid flow evolution in fractured reservoirs hosted in Permian carbonates in gas and oilfields; such as Sin Phu Horm and Nam Pong gas fields in NE Thailand and Nang Nuan field in offshore Thailand.

Keywords: Permian limestone, fractured reservoir, Khao Khad Formation, stable isotope, structural evolution, fluid flow evolution

1. Introduction

Economic levels of porosity and permeability in fractures in carbonate reservoirs are well documented worldwide, but the structural mechanisms that drive this process are poorly understood and complicated. This is especially so for fracture mechanisms related to thrusts, folds and fractures. Nowadays, folded and fractured carbonate reservoirs are widely exploited in the Zagros Mountains. But in Thailand there has only been limited exploration success exploring in folded and fractured Permian carbonates in the Khorat Plateau area. Malila et al., (2008) notes that "the fractured Permian reservoirs of the Sin Phu Horm and Nam Phong gas fields in NE Thailand have proven difficult to understand and predict". So studying the structural development of thrusts, folds and fractures that outcrop in central Thailand will help better understand the structural mechanisms in fractured Permian carbonate reservoirs of NE Thailand and perhaps elsewhere in SE Asia

2. Methods

The research methodology is subdivided into field study and laboratory analysis.

The actively quarried limestone hill that is the focus of this study, was mapped and geological information documented by taking photos, sketching structures, taking structural-related orientation measurements, and collecting samples at representative stations for laboratory analysis (figure 1). At each station, detailed basic geological data such as rock type, bedding and fracture style, vein type and orientation were noted and detailed fracture data was measured, at some stations spectral gamma ray measurements as points or traverses were collected. The detail of each data type is shown below;

Geological data: Rock type, texture, diagenetic features, strike and dip of beds, bed thicknesses, fracture spacings, fault and fold orientations, and slickenside orien-tations.

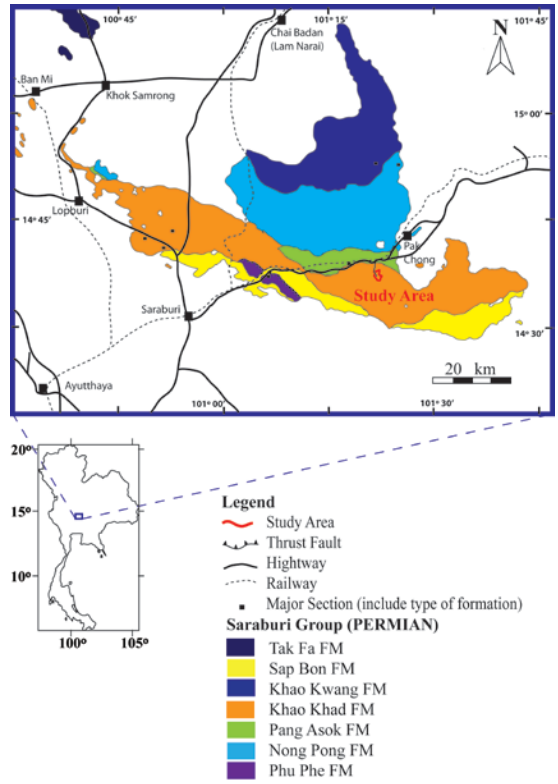


Figure 1. Geologic map of Saraburi Group (Permian) in Saraburi area, Thailand. Modified from Ueno and Charoentitirat (2011) with adding Study area location by using topographic map No. Pak Chong, Thailand 5238 II L 7018 Edition 1-RTSD for reference.

Fracture data: Strike, dip and fracture type (unfilled or mineral- filled)

Spectral gamma ray: Measurement of Uranium, Thorium and Potassium contents in limestone and veins

All measured field data as fault, fold, and fracture geometries were plotted on ster-onets and Wintensor was used for palaeostress analysis of fault kinematic data. Rep-resentative rock samples were chosen for thin sectioning and petrographic analysis, some samples were also submitted for semi-quatitative XRD determination. . In addition 58 samples that were representative of all calcite vein directions, faults lithology end members were run to determine stable oxygen isotope (δ^{13}O) and carbon (δ^{13}C) values. The isotope samples were collected using a carbide-tipped dental technician's drill and analysed in the Isotope lab at Monash University in Australia. Samples were prepared and analysed using standard techniques, as described in Allegre (2008). Integration of the field and laboratory results were used to better define the relation-ship between fluid flow and structural evolution in the study area.

3. Results

3.1 Field Investigations

Bedding: The bedding thickness measurements in the quarry show parallel bedding that varies from 0.5 m to 4 m. In pit A & B, bedding strikes N150^{o} and dips 15^{o}-20^{o} to north - east with the consistent dips reflecting a low degree of faulting and folding. Deformation becomes more intense in the centre of the pit, where folded beds strike E-W and typically exhibit high dips of 60^{o}-80^{o}, predominantly to the south. In the southern part of the pit C deformation is again reduced in intensity and bedding strikes N20^{o}-30^{o} with 20^{o}-30^{o} dips to south-east

Reverse faults (thrust faults) and flexural slip: Two major parallel thrust faults occur in pit C, where relatively thick calcite veins occur, with slickensides that are present discontinuously along the thrusts. The southern major thrust fault is oriented N85^{o} (E-W) 60^{o}south, with N-S trending, dip-slip slickenlines. The central thrust is oriented N83^{o}. Calcite veins occur parallel with bedding in the limestones. Black organic shales were commonly observed associated with the folds, and indicate the occurrence of flexural slip during folding.

Folding: Changing bed orientations indicate significant folding in the middle of quarry. The detail of this folding was not completely measured because the beds were less visible in some parts of the folded wall that were not accessible. The bedding dip in this fold was N90^{o} (E-W) strike direction with 60^{o}-80^{o} dip to south and fold axis was approximately in an E-W direction. There are 2 minor folds along slip bedding formed under the same compressional stress that created thrust folding and fault-bend folds.

Stylolites: There were 2 types of stylolites in the quarry; 1) associated with fractures and 2) not associated with fractures. The stylolite not associated with fractures formed during burial or uniaxial compaction, while those associated with fracture formed under the combination of maximum principle stress and minimum principle stress, which created tension gashes, or with unloading fractures which can be associated with stylolites

Fractures: There are open fractures and calcite-filled fractures present in the quarry. Open fractures strike N-S and dip 60^{o}-90^{o}, while another set of steeply dipping fractures trend NE-SW. The highest bench of the quarry, showed fractures filled with coarse layered calcite cement with textures that initially suggested a speleothem-type fill.

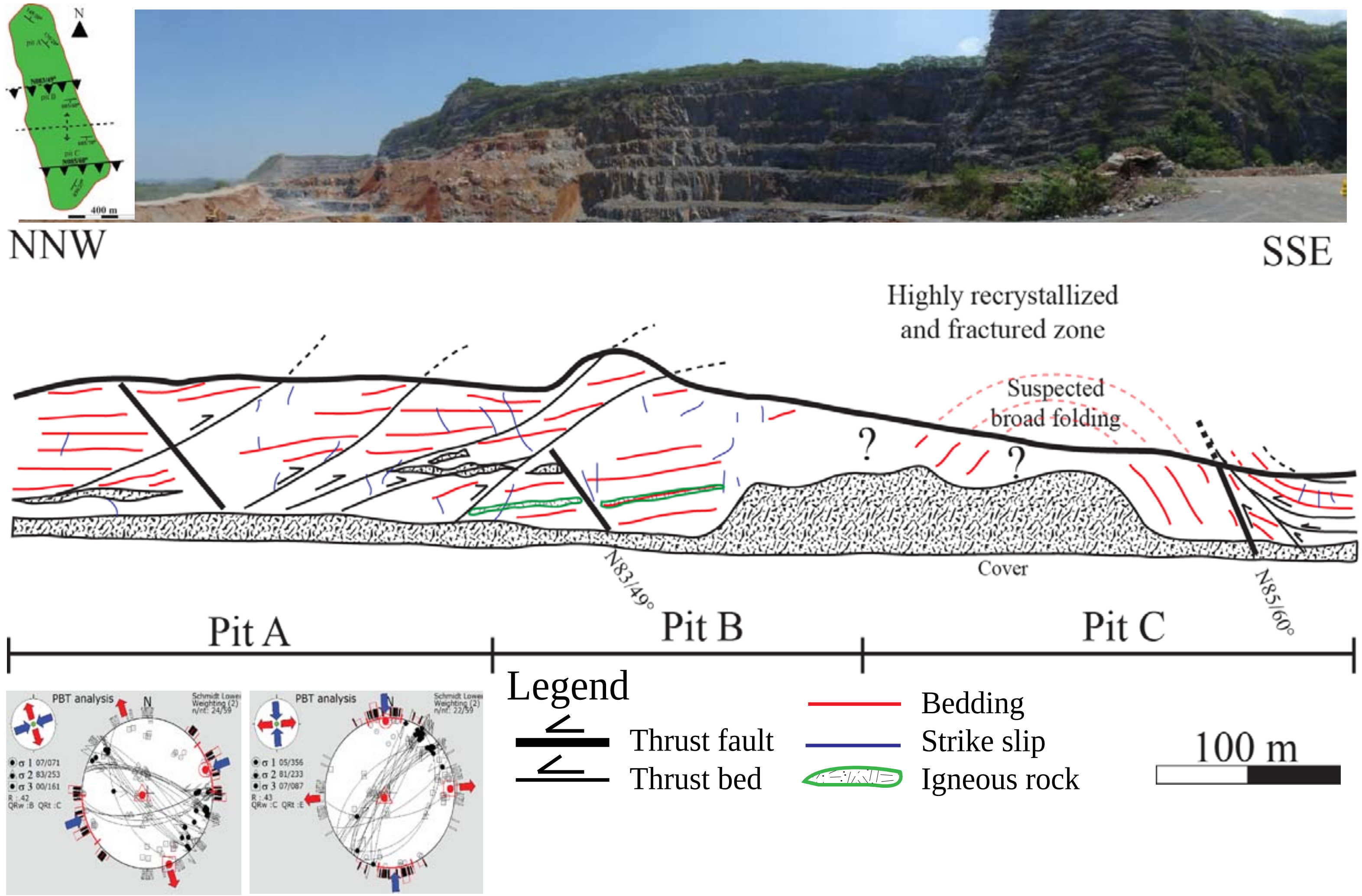


Figure 2. Cross section (NNW - SSE line) showing mapped structures in the quarry and location of igneous rocks. In the middle part between pit B and C, was a high re-crystallized and fractured zone, which largely destroyed bedding orientation and structures. and the palaeostress analysis with N-S and ENE-WSW results.

Isotope data (section 3.5) however, showed this fill was a late fill, with distinct isotope character to the karst-related veining and dissolution features observed and sampled elsewhere in the quarry. Most of calcite-filled fractures show E-W strike directions with dips of around 60^{o}. However, other fractures that trend (N-S, N100^{o}) are also present and trend to dip steeply. Cross-cutting relationships indicate the N-S trend was younger than the E-W trend and the N-S set is the one most commonly dominated by open fractures (figure 2).

3.2 Paleo-stress Analysis

The results give 2 sets of outputs as reverse fault; The ENE-WSW compression thrust regime are σ1: 07/071, σ2: 83/253 σ3: 00/161. The N-S compression thrust regime are σ1: 05/356, σ2: 81/233 σ3: 07/087.

3.3 Spectral Gamma Ray and X-ray Diffraction (XRD)

Spectral Gamma Ray;

Measurement in vertical direction was performed to check responses to the lithology. A minor shift of trend of total gamma ray is seen in the lower part compared with upper part with an increase in U and total gamma the lower part, as seen in figure 2a. Study of the outcrop shows this is a response to increase levels of organics in the lower part.

Measurement in horizontal direction was performed across a thrust and part of a fold in the east wall of pit C in order to test any influence of the opened-fracture zone on gamma values. Measurements show a spikier and perhaps slightly higher overall gamma value curve in the more highly structured zone. This spikier curve probably indicates the presence of shale smears or clay infillings in the opened fractures. In the subsurface, the spikes could also indicate water, minerals, or hydrocarbons once filled the opened fractures (figure 2b).

X-ray Diffraction (XRD);

The XRD results were match to thin sections. The carbonate rocks in the quarry are mostly limestones dominated by calcite with trace or accessory dolomite. Minor dolomite is present in calcite veins. The igneous rock

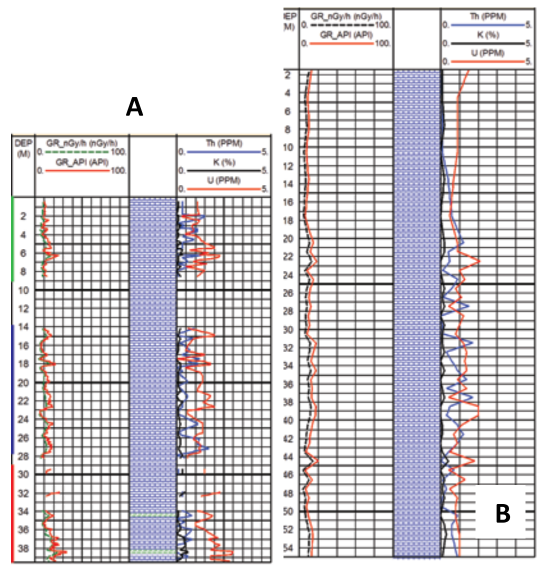


Figure 3. a) the vertical direction of spectral gamma ray measurement. b) the horizontal direction of spectral gamma ray measurement.

sampled consists of dominant plagioclase with sub-dominant chlorite, with accessory quartz, and a trace of mica. Thus the igneous composition is andesite.

3.4 Lithofacies and Diagenetic Features

Lithofacies; The classification of lithofacies in the quarry is based on Dunham (1962), there are three lithofacies present: packstone, wackestone, and mudstone.

Diagenetic Features; Many diagenetic features were observed in the outcrop and thin section, including stylolites, and twinning, The calcite crystal growth preserved the indicators of: tectonic deformation, multiple phases of hydrothermal solution throughflow, vugs and micro-vugs and tectonic shortening of calcite veins.

3.5 Stable Isotope Analysis

Group I is a combination of vein calcite and mostly matrix samples, which is interpreted as formed at lower temperature (less negative oxygen values) than Group II samples, in part based on plot fields of Nelson and Smith, (1996). This plot field can be inferred to be indicative of calcite precipitated while the carbonate rock matrix was not completely cemented during earlier burial, when there was ongoing rock-fluid re-equilibration of the rock matrix.

Group II is a group of mostly vein calcites that were precipitated in a possibly deeper and certainly hotter subsurface environment than Group I samples. This is indicated by more negative oxygen and carbon values of Group II. At this stage of the burial cycle, the isotope data suggest the adjacent carbonate rock matrix was fully was

fully cemented by the end of the Group I burial trend so the matrix could no longer re-equilibrate by rock-pore fluid interaction. Hotter fluids of Group II then flowed through opened fractures and precipitated as Group II vein calcites, while the tight matrix values of Group I were unaffected by this more structurally focused fluid flow. This clear separation between the hotter focused (and possibly derived from a more deeply buried system) vein calcites of Group II contrast with a more pervasive set of matrix isotope values shown by Group I, which indicate the preservation a rock-matrix re-equilibration series related to ongoing burial (figure 4).

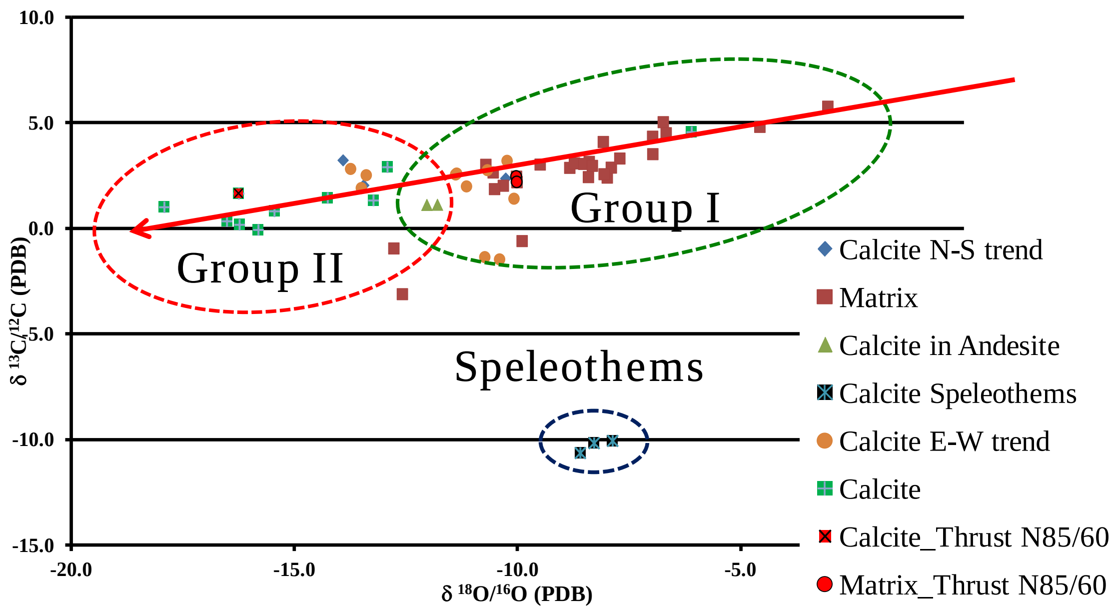
3.6 Fracture Analysis

Fracture orientations;

The E-W fractures formed during burial and are related to folding and thrusting. Ongoing burial conditions dominated, when both E-W and N-S trending fractures were filled by calcite. After that there was later(?) tectonic activity thatformed open fracture sets, with mostly N-S trends. This later event may have occurred during Cenozoic uplift and erosion as the N-S trend is sub-parallel to the modern maximum horizontal stress direction (Tingay et al., 2010). It probably reactivated along a structural grain preserved in the older cemented fracture sets.

Open Fracture Intensity;

The average fracture density is 1:1, which is to say each one meter tends to have one fracture intersect. There are also some areas of higher open fracture density, which are related to a combination of transverse fractures and conjugate sets. From the measurement data, the average distance of open fractures is 0.8-1.0 meter but in more highly fractured zones this reduces to 0.3-0.5 meter.



Group I: Matrix is permeable and requilibrating to increasing burial temperature
Group II: Calcite is focused into veins and faults, matrix is not involved (tight)

Figure 4. Isotope results in Khao Khad formation in different area Oxygen and carbon stable isotope results for 58 samples from Pak Chong, Nakhon Rachasima Province.

4. Structural Evolution and Implications

4.1 Sequential Development of The Structural Elements

Paleostress analysis (section 3.2) and structural trends indicate a phase of N-S compressional stress. This is consistent with structures observed in Saraburi and the Siam Cement Quarry, and interpreted as representing Indosinian I age (Early Triassic) structures.

The study area lies north of the Khao Yai Fault, which forms the northern boundary of a belt of several ENE–WSW trending fault splays which are thought to link with the Mae Ping Fault further south (Ridd and Morley,2011). The Mae Ping Fault is interpreted as a left-stepping, sinistral complex fault zone that splays at large scale in Eastern Thailand. It is one of a number of folds and faults that caused exhumation of the Permian limestones on the eastern margin of the Khorat Plateau. Apatite fission track data indicate that exhumation began during the earliest Palaeogene (Ridd and Morley, 2011). Possibly, the late NW-SE to E-W sinistral faults that affect the quarry correlate with Palaeogene sinistral motion along the Mae Ping Fault. An ENE-WSW compressional stress direction from palaeo-stress analysis has been calculated for these (figure 5).

4.2 Implications for fractures reservoir in NE Thailand

Many observations and results in the quarry and surrounding areas can be used as analogues to fractured reservoirs in NE Thailand;

1. The stable isotope results in this work and in Saraburi and Siam Cement Quarries clearly show that most calcite-filled fractures follow a consistent burial trend. It implies that during evolving stages of

deformation the larger thrusts have tapped deeper, hotter fluid throughflows. The smaller cooler earlier fracture sets formed when the rock matrix was still permeable (figure 4).

2. A brecciated vein fill, which was initially thought to be possibly speleothem – related, because of its N-S trend, is actually filled by calcite associated with relatively hot fluids, as discussed in section 6. The vein fill is relatively late in the tectonic history and indicates a pulse of hydothermal fluid circulating in the basin. Possibly this is associated with the strong recrystallisation seen in the centre of the quarry, which is probably related also to hydrothermal fluids.

3. Intense, N-S trending open fractures affect the quarry. This fracture orientation has also been observed in Saraburi. The fractures post-date all deformation in the quarry and are presumably Cenozoic in age. They may have formed during uplift and erosion of the Khorat Group during the Palaeogene when the Permian limestones were exhumed.

4. The final phase of calcite cementation occurred during late karstification when faults and fractures were exploited as fluid conduits for modern meteoric waters, in some places they were filled by calcite speleothem cements, and in others infiltrated by surface-derived red clays.

For some types of reservoir development, porosity creation due to leaching by hot hydrothermal fluids could be important. Older calcite filled veins could become partially opened as a result of this leaching. The N-S open fractures could also be an important factor for creating permeability.

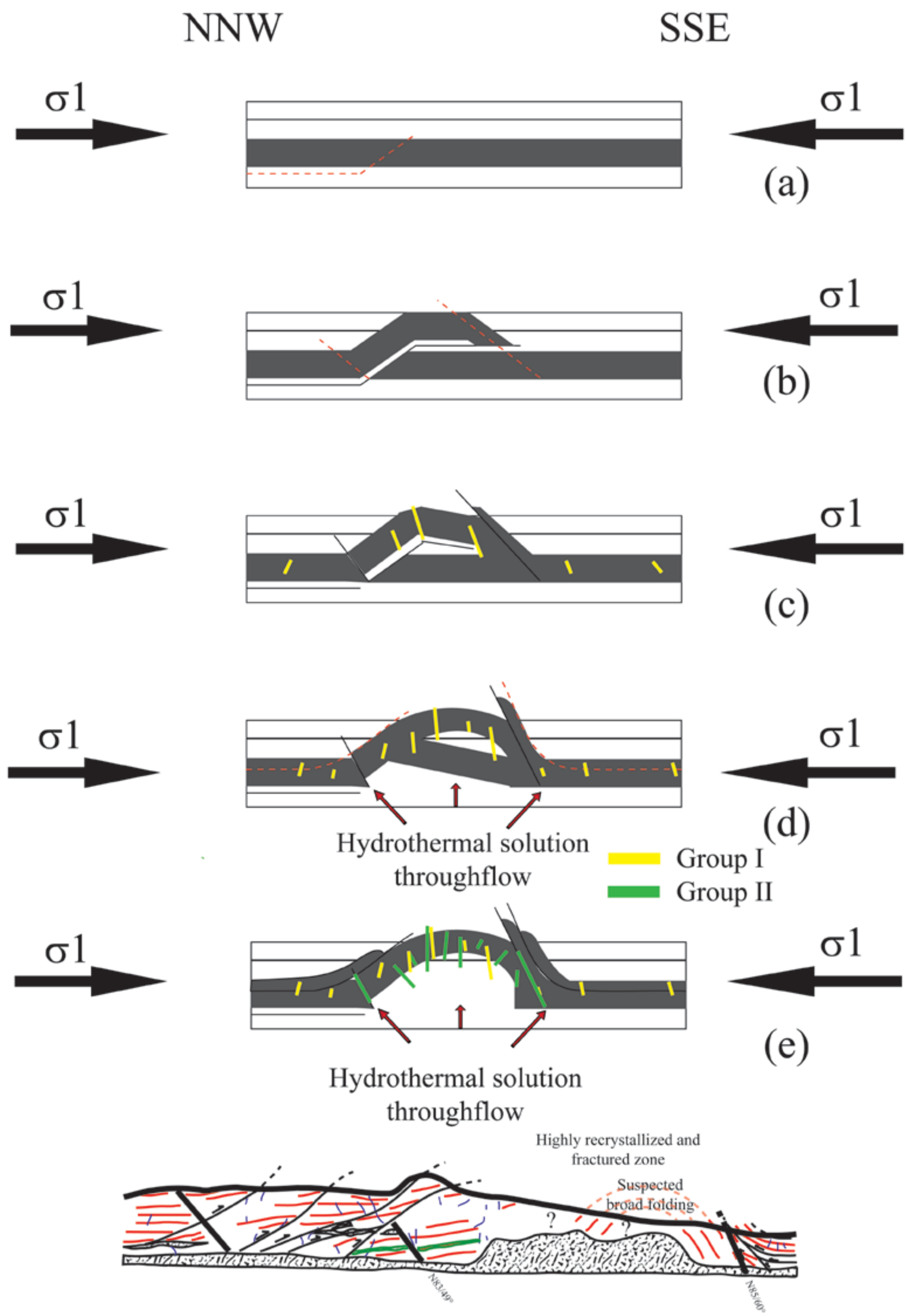


Figure 5. Conceptual model explaining the structural development in the quarry.

5. Conclusions

1. The trend of the major thrust fault is N85/60^{o} located in pit C, and the lesser thrust fault, located in pit B, trends N83/49^{o}.

2. The two main fracture sets in the quarry are; E-W calcite-filled fractures and N-S sub-vertical open fractures.

3. The NE-SW trending sinistral strike-slip faults present in the quarry may have formed at the same time as the E-W thrusting and folding, or they may have formed somewhat later. Both are associated with a similar N-S maximum horizontal stress orientation.

4. Transpressional stress with a WSW-ENE maximum horizontal stress orientation (strike slip) created the E-W to NW-SE trending sinistral strike-slip faults that cross-cut older structures (1 and 2 above).

5. Fluids within the fractured network precipitated calcite that filled fractures and in the earlier stages of burial evolution, when the matrix was still permeable, also formed re-equilibrated calcite cements in the matrix (both reduced effective porosity). There are 2 calcite groups based on isotope results; Group I calcites formed during thrusting and folding and Group II calcites after complete cementation of the matrix.

6. The N-S open fractures are sub-parallel to the modern maximum horizontal stress and probably formed during Cenozoic uplift and erosion.

7. The Khao Khad Formation is dominated by diagenetic features formed during the burial stage.

8. A regional isotope-defined burial trend for Khao Khad Formation has now been established in Central Thailand.

9. Based on regional considerations the E-W fractures and folds formed during Indosinian I (Early Triassic). The E-W to NW-SE ternding fractures could have formed either during Indosinian II or Palaeogene transpressional deformation, or both.

10. Post Indosinian I deformation hydrothermal fluids caused extensive recrystallization in the centre of the quarry, and perhaps the associated fluids caused the thick brecciated veins (Isotope Group II) seen in the northern part of the quarry.

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