# POROPERM CONTROLS IN THE CARBONATE RESERVOIR IN SIN PHU HORM FIELD, NE THAILAND: USING A COMBINATION OF CUTTINGS, ISOTOPES AND FMI

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## Abstract

Dolomites and silicified fractured and brecciated carbonates of the Pha Nok Khao Formation constitute the main petroleum reservoir in Sin Phu Horm Field. Rapid lateral changes in reservoir quality between nearby wells (less than a km apart) suggest that not only stratabound diagenesis, but also structure associated diagenesis, likely control reservoir properties across the field. Better understanding of the relationships and timings of fracturing and diagenetic evolution, via detailed quantification of many factors that can inhibit porosity loss or enhance porosity is needed to predict reservoir quality in such a complex setting. Even more useful is an ability to relate the various stages of porosity evolution with respect to timing of hydrocarbon migration. hese goals are achieved in this study via the integration of: 1) FMI interpretation (including orientations of open versus closed fractures), 2) petrography and 3) texture-aware isotope determinations. he stable isotope cross plot (carbon – oxygen), define two distinct trends of the diagenesis in the field, which tie to passive margin burial, later followed by uplift driven by Himalayan inversion. Ongoing post-deposition, compaction and pressure dissolution result the calcite cement precipitation and the overall loss of matrix porosity in the mesogenetic realm. he thrusting during Indosinian orogeny likely created an initial fracture porosity in the buried Permian carbonate. From FMI interpretation and petrography, most of the early fractures were filled by calcite cement so the preservation potential of fracture porosity related to burial and the Indosinian orogeny is low. Effective porosity in the Sin Phu Horm reservoir believe to be associated with cooling, fracturing and entry of fluids with isotope signatures interpreted as belonging to the catagenic plot field. his event can be tied to the early telogenetic as deeply circulating meteoric-influenced waters, perhaps mixed with remnant catagenic fluids, entered along fractures with orientations that indicate reactivation of earlier Indosinian features and newly formed fractures with orientations controlled by Cenozoic transtensional stresses. hus catagenic fluid entry occurred sometime during or immediately after the onset of the Himalaya (Paleogene) event. From FMI interpretation, the Cenozoic fracture set shows as open fractures, which increased the effective porosity and permeability in the Pha Nok Khao carbonates to levels where the formerly tight limestone host became a viable (if patchy) reservoir. Poroperm enhancement was especially so in intervals of more brittle response typically associated with zones of more abundant dolomite or silicification. Lastly, based on the successful integration of isotope timing from cuttings and fracture-orientation from FMI, it is highly recommended that future wells in the region are directional and that well directions should be planned to be orthogonal to the main set of Paleogene event-induced fractures.

**Keywords:** Indosinian orogeny, Himalayan event, catagenic, FMI

## 1. Introduction

Sin Phu Horm field in NE Thailand has been producing gas from the Permian carbonates in Pha Nok Khao Formation since 2006. Nine wells have been drilled in the field to date and only half have discovered economic levels of hydrocarbon and are currently in production (Figure 1). The prediction of reservoir quality in the main Permian carbonate reservoirs is difficult in that it requires reliable predictions of the effects of dolomitization, karstification and fracturing on reservoir distribution (Racey, 2011). The apparent random behavior of wells, is believed to be a response to reservoir complexity; as in many reservoirs worldwide, successful development of carbonate reservoirs can be very challenging.

The carbonates in the Pha Nok Kao Formation have very limited remaining matrix porosity, which is locally enhanced by dolomitization and hydrothermal chertification. Open fracture intensity is an important aspect of reservoir performance (Booth and Sattayarak, 2011). Hence, the quality of Sin Phu Horm

Hence, the quality of Sin Phu Horm reservoir is controlled by both diagenetic variability and fracture occurrence. Diagenesis can either reduce or increase porosity and permeability. In general, in most carbonate reservoirs the trend is towards progressive loss of porosity and permeability with increasing time and depth of burial (Scholle, 2003). Fractures can increase porosity and permeability by creating an interconnected fluid flow network. There are both open and closed fractures in the carbonate, closed fracture might be altered by dissolution or cementation during diagenesis. Some fractures were likely first activated during the Indosinian orogeny and may have been reactivated later during Himalayan inversion (Paleogene–Eocene onset), others may have formed after the Indosinian Orogeny. So the prime aim of this study is to answer the question; what is the relationship between fluid evolution and fracturing? This will give a better understand controls on porosity and permeability distribution, diagenetic history and reservoir quality evolution in Sin Phu Horm Field.

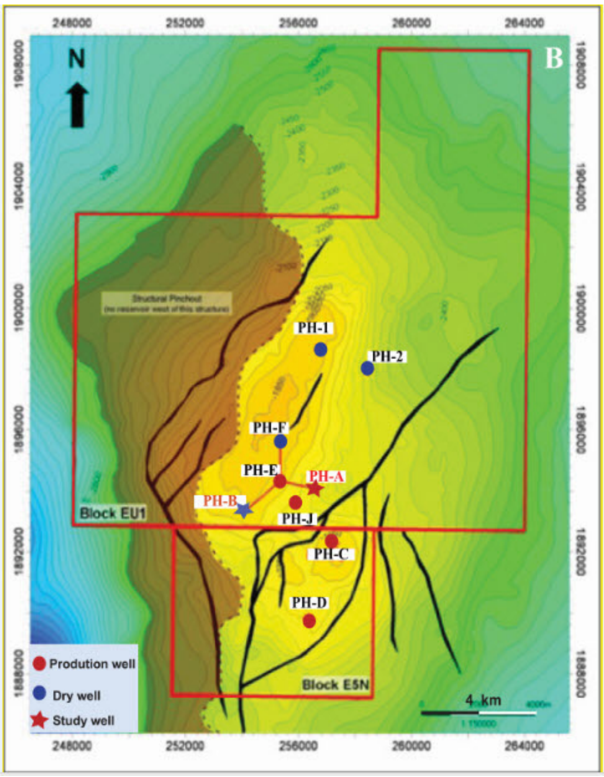



**Figure 1** Location Map of Sin Phu Horm Field.

## 2. Methodology

This research study is done using data from the two wells in Sin Phu Horm Field. Research methodology is separated into 2 approaches. The first approach is image log (FMI) interpretation using Interactive Petrophysics® (IP) software program to identify textural features, fractures and so determine fracture orientation in Pha Nok Khao carbonate reservoir. The FMI interpretation is calibrated with core photos and thin sections in order to identify the textural features and fracture types in the carbonate reservoir, which relate to the various diagenetic processes. The second approach is texture-aware isotopic sampling study integrated with thin section petrography and XRD analysis in order to better understanding diagenetic history. Fifty cutting samples were submitted for stable isotope analysis. The cutting samples were classified based on color, texture and the reaction with HCl acid. Another fifteen groups of rock chips were chosen for petrographic study, via thin section, to define diagenetic timing and porosity modification of the rocks. This was done using a polarizing microscope in order to observe cement morphology, cement distribution patterns and the relationship of grain-cements to compaction in the various chip types (Moore, 2001). The carbonate mineralogies were confirmed by staining of the thin sections and by XRD analysis of a selected subset of samples. Finally all the results of the cuttings study were integrated with the fracture analysis using FMI in order to upgrade current understanding of diagenetic history, porosity evolution, timing of catagenic and structural evolution in carbonates reservoir.

## 3. Results

### 3.1 FMI Interpretation and Core Photo Calibration

The Pha Nok Khao carbonate contains several different fracture types (open fracture, closed fracture and stylolites). There are two main fracture trends developed in this carbonate, which are N-S and NNE-SSW (bedding-parallel frac horizontal stress direction (Shmax), parallel to the fracture is N-S, which is the approximate direction of Shmax during the Indosinian deformation (Morley et al., 2013). The NNE –SSW fracture trend is interpreted to have formed, or have been reactivated, during Cenozoic strike-slip deformation.

Some likely karst features (possible collapse breccia zones) can be seen above and within the weathered zone and within carbonate section of the Pha Nok Khao Formation. The collapse breccias are interpreted to be filled with siliciclastics and in FMI and core are associated with crackle to mosaic textures (Figure 3).

The core and image log comparison was done using available core photos from the in-house core reports. Several different fracture types and carbonate features have been observed in Pha Nok Khao cores from PH-1 and PH-2 wells in Sin Phu Horm Field. Fractures filled with white sparry calcite cement are common in core photos. These textures are consistent with the "resistive or closed fractures" interpreted from FMI in both wells (Figure 3). Because they are cement filled, most of these fractures, observed in core and FMI, are assumed to have very limited associated porosity or permeability. The conductive fractures in FMI were interpreted to be open fractures, which are not easily captured in cored samples. FMI to core photo comparisons were done with care as it was obvious that at times the relevant features were developed at different scales of resolution and present in different intervals in different wells.

### 3.2 Petrographic Study

Cuttings cannot be used to make detailed interpretations of depositional layering and diagenesis, as they are always made up of smeared and mixed lithologies. However, the cutting thin sections do show that cuttings capture a variety of limestone lithologies, along with microfractures and calcite vein fills in varying stages of diagenesis. Two microfacies can be identify from thin sections namely; 1) muddy limestone and 2) packstone. Microfractures cutting through the rock are filled by calcite. Multiphase fractures can be

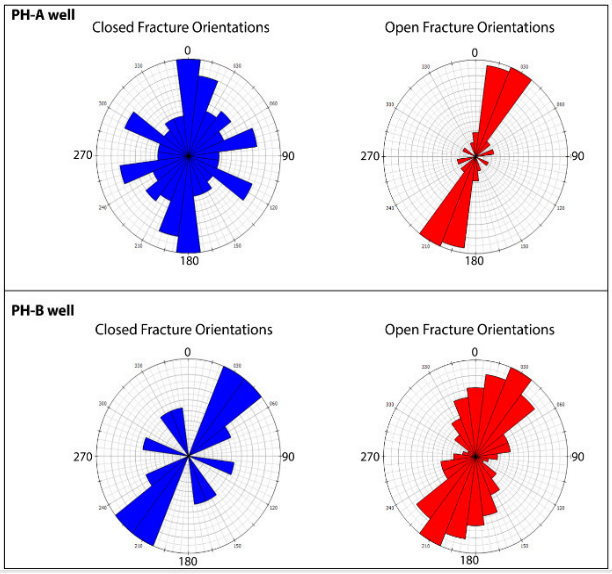


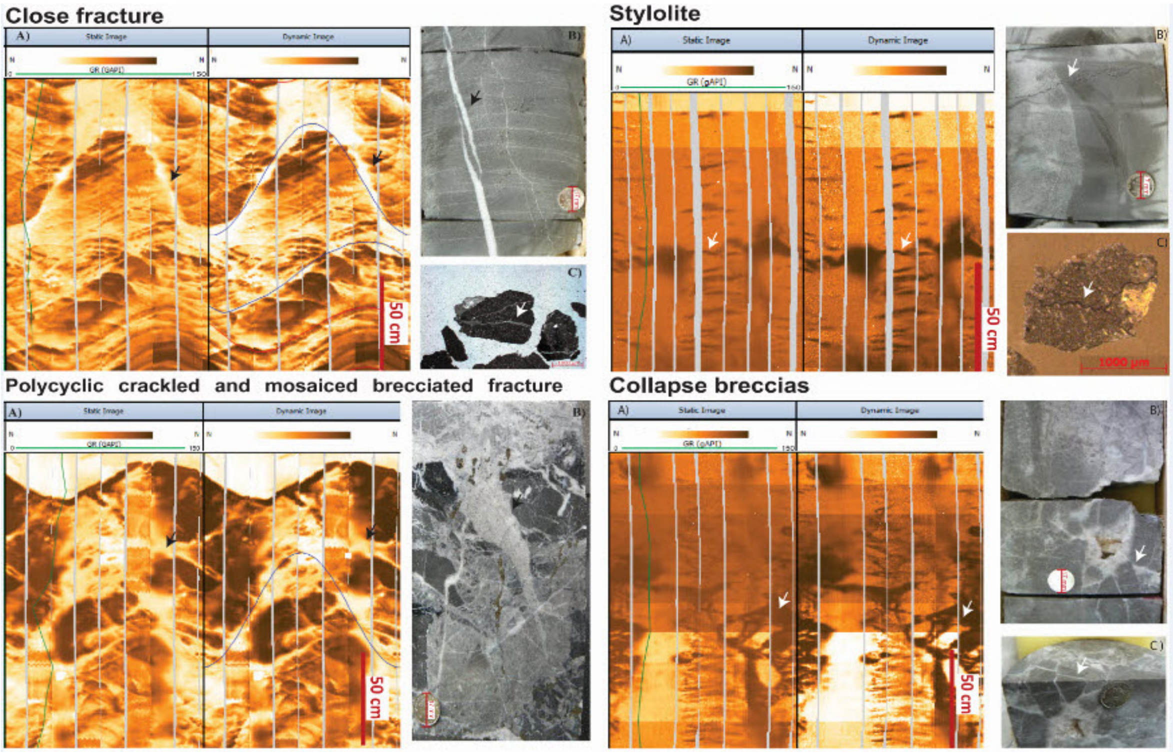

**Figure 2** The Fracture orientation from FMI interpretation.

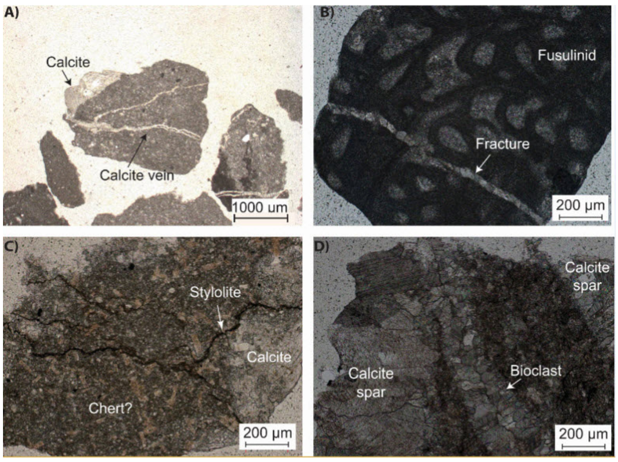
seen in some chips where fractures cross-cut each other (Figure 4). In fracture fills and some bioclast fills, calcite cements show multiple phases of calcite generation and growth into voids. Stylolites can be seen in some chips and show as dark brown colored stylolite layers, typically due to clay-sized residuals (Figure 4C). Petrographic study shows that the reservoir matrix was cemented and recrystallized pervasively, so there is little no primary porosity remaining.

### 3.3 Stable isotope analysis

The $\delta^{18}O$ and $\delta^{13}C$ compositions of Pha Nok Khao samples are plotted in Figure 5, where two trends stand out. One is the burial trend which matches the isotope burial trend as defined for Permian carbonates of central Thailand by Warren et al., 2014. The second trend is cooling/catagenic trend, perhaps related to the effect of uplift and an increasing mixed meteoric source for the carbon in the calcite cements, as was first established by Pantong, 2015.

Trend 1 is the regional burial trend. This trend encompasses most C-O values from limestone, dolomitic limestone and white calcite




fragments with tabular or elongate shapes that are likely came from mesogenetic calcite cements in large pores. Interestingly, within the burial stage plotfield (indicated by the green and pink shading in Figure 5, none of the matrix or cements show the oxygen values more negative than -12‰. The oxygen isotope value of -12‰ was defined by Warren et al. (2014) as the value in the fluid-exchange temperature burial curve describing the end of rock matrix fluid exchange and signposting the time when all effective matrix porosity is lost in Permian carbonates of central Thailand. Values on positive side of -12‰, on the same covariant oxygen-carbon trend, indicate the typical passive margin Indochina burial trend, whereas values on negative side of -12‰ oxygen delineation indicate hotter calcite veins generally sampled in thrust fault damage zone. The Sin Phu Horm carbonates shows typical burial trend values implying that the rocks in this area experienced only normal mesogenetic fluid crossflows during burial and have not seen the hotter fluids related to deformation-induced fracturing across the Indosinian orogeny.

Trend 2 shows a decreasing set of negative oxygen values and an increasingly negative set of carbon isotope values. The decreasing levels of negative oxygen values are interpreted as tied to the cooling temperatures of fluids related to uplift, while the increasingly negative carbon values may indicated the effects of catagenic carbon or an increasingly mixed meteoric source for the carbon, carried in crossflowing deeply-circulating meteoric waters, interacting with both matrix and spar. This trend may be related to the diagenetic event that created/reactivated the fracture system during Himalayan event, which also created the post porosity and permeability storage of hydrocarbon in Sin Phu Horm Field.

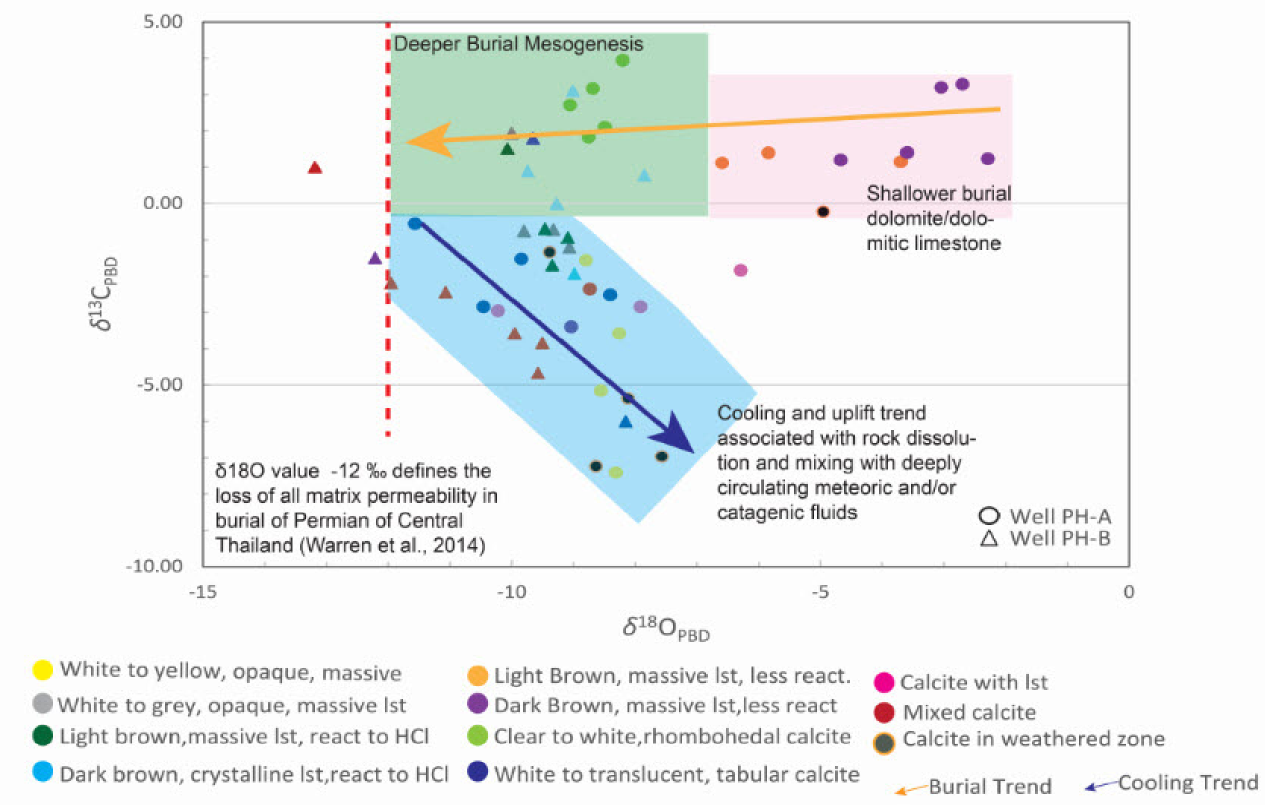



**Figure 5.** C-O isotope plot illustrating sample values from Sin Phu Horm Field. See text for detailed discussion.

## 4. Discussion

The study of texture-aware isotope values in Pha Nok Khao carbonate shows that isotope signatures of the various calcite cements formed at different stages in the burial and uplift history. The carbonate matrix in this area follow the normal burial trend related to compaction and fluid-rock interactions under condition of increasing burial temperatures and is the same isotope trend as seen in the carbonates in Saraburi area documented by Warren et al., 2014. None of the oxygen values are more negative than -12‰ and matrix porosity of the Pha Nok Khao carbonate is low or not preserved. Possible thrusting during the Indosinian orogeny may have created the fracture porosity in the carbonate. Early Mesozoic uplift likely created a weathered zone recognized beneath a subaerial unconformity in the FMI imagery. It would preserve remnant textures in the form of weathering products from the limestone host rock, such as collapse breccia seen in the FMI. From the FMI interpretation, most N-S striking fractures in both wells were since filled with calcite cement. Hence, the preservation potential of fracture porosity formed in the Indosinian orogenic uplift event is low. The effective porosity in the reservoir is believed to be associated with cooling and the catagenic plot field. The cooling (with catagenic influence) plot field, which is clearly seen in the calcite cements in cuttings is interpreted as related to deep meteoric circulation, responding to fracturing and uplifting and driven by Cenozoic transformation.

Uplift-related fluids precipitated a set of calcite cements that define a characteristic meteoric uplift trend associated with cooling temperatures and a later catagenic fluid migration event. Likely, many of these fractures were reactivated Indosinian structures. In terms of porosity and permeability evolution in the Permian reservoir in Sin Phu Horm Field, the isotope study together with FMI interpretation result shows that very low levels or no matrix porosity are preserved in the carbonates in Sin Phu Horm Field. Most structurally-induced fractures formed in the Indonisian orogeny are now cemented. The newly formed or reactivated fractures, which were driven by Cenozoic event, increased the porosity and permeability of the carbonates to become reservoirs. Open fractures show a predominant NNE-SSW orientation and

Phu Horm carbonate.

Within the oxygen-defined burial trend, some Suphanburi samples show somewhat more negative carbon values than Sin Phu Horm, which suggests a more intense catagenic (oxidized-hydrocarbon?) influence on the

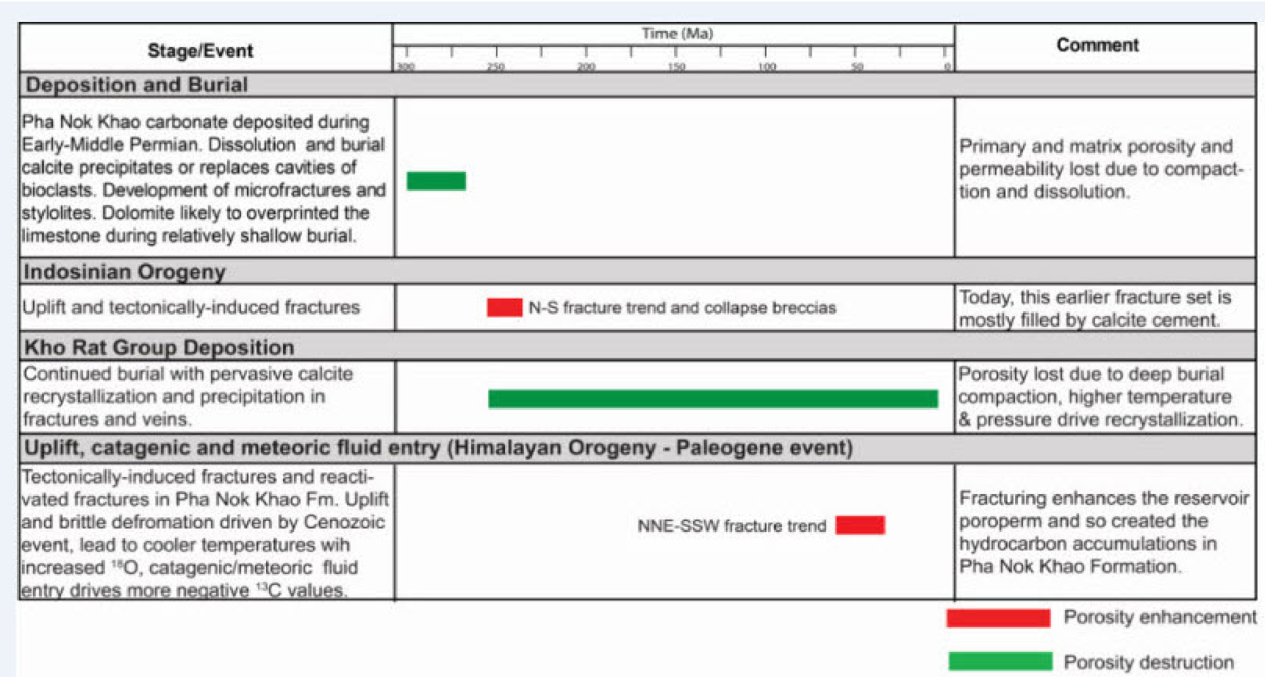



**Figure 6.** Summary of the likely timing of the fracture and poroperm evolution in the study area. See text for detailed discussion.

a higher intensity beneath the capping unconformity and in the dolomite interval. Catagenic fluid entry occurred sometime during or immediately after the Himalaya (Paleogene) event. The summary of timing of fracture and poroperm evolution is shown in Figure 6

## 5. Comparison to carbonate isotope signature with Suphanburi basin

Compared to the Sin Phu Horm carbonate system, the C-O values from subsurface cuttings and outcrops of potential carbonate reservoir in the Suphanburi basin, show an ongoing covariant trend indicative of burial passing into metamorphic deformation (Figure 7). The oxygen isotope values are far more negative than -12‰. These more negative oxygen isotope value indicates that fractured carbonates in Suphanburi basin

experienced higher fluid temperature than Sin carbon values of some Suphanburi Basin calcites. Potential carbonate reservoir intervals in Suphanburi basin are extensively metamorphosed and no primary or matrix porosity remains. Yet, as in Sin Phu Horm field, telogenetic fracturing and karstification tied to the Himalayan (Paleogene) event has enhanced the reservoir quality of an otherwise tight carbonate host.

## 6. Conclusions

The integration of isotope and FMI studies in well PH-A and PH-B improves our understanding of the relationship between fluid evolution and fracturing in Pha Nok Khao carbonate reservoir.

The FMI interpretation shows there are two main orientations to the fracture sets in the field, namely N-S versus NNE-SSW striking sets.

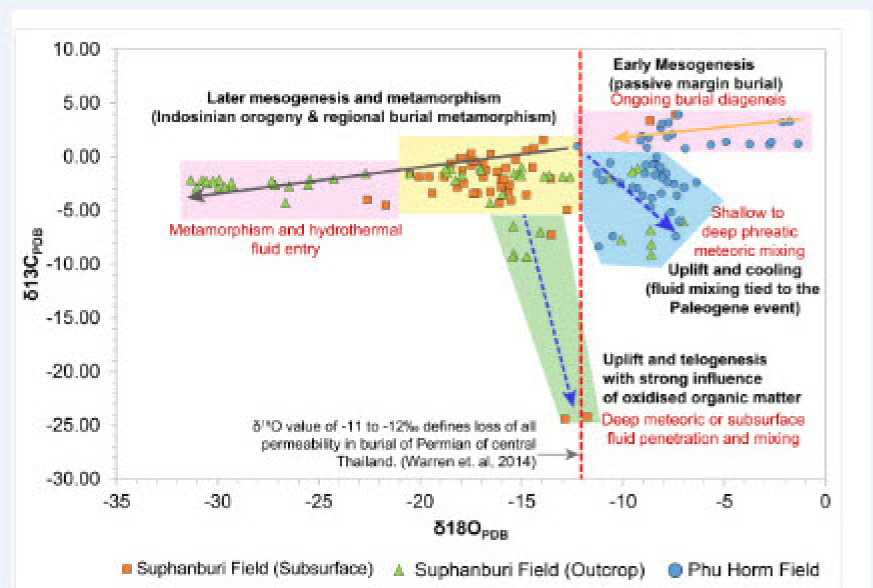



**Figure 7.** C-O stable isotope plot of samples from Suphanburi field and Sin Phu Horm field. See text for detailed discussion.

The N-S fracture set was initiated by stresses likely related to the Indosinian Orogeny and the NNE-SSW set by stresses related to the Himalayan (Paleogene) event, respectively.

Most N-S fractures are now cemented, while the newly formed or reactivated fractures, which were driven by Cenozoic event, are still open or partially open, and likely increase the porosity and permeability of the carbonates to levels where they become viable reservoirs. Stable isotope studies (using texturally-classified) drill cuttings indicates initial passive margin burial (mesogesesis), later followed fracture-controlled entry of fluids that are cooler and possibly with some with catagenic input (early telogenetic). The possible influence of catagenic fluid cements likely occurred sometime during or immediately after the Himalayan (Paleogene) event. In terms of the reservoir quality of this carbonate reservoir, there is only limited or no matrix porosity preserved, due to ongoing mesogenetic calcite cement precipitation. Likewise, the reservoir quality in the potential carbonate reservoirs in Suphanburi field are likely to be controlle by telogenetic fracturing and karstification, tied to the Himalayan (Paleogene) event.

## 7. Recommendations

Based on the successful integration of isotope and FMI studies in Sin Phu Horm Field,future well placement and well directions in the region should be planned to be orthogonal to the Paleogene structural trend, which is NNE-SSW and should scoop the dolomites and fractured intervals immediately below the capping unconformity. This will maximize the intersection of open fractures.

The proposed cooling with catagenic influence hypothesis still need to be tested further by future core-based isotope study.

## 8. Acknowledgements

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