An integrated isotope-based fluid evolution and rock typing study, based on well cuttings and outcrop in Permian and Triassic successions of central and north east Thailand.

ABSTRACT

An isotope-based (^{18}O and ^{13}C) study was used to describe how rock-fluid interaction is impacted by structural and diagenetic processes in a succession of Permian platform carbonate and Triassic siliciclastics and volcanics in central and NE Thailand. Previously completed isotope studies have described fluid evolution resulting from structural and diagenetic processes within outcrops of Permian platform carbonates. This study is the first to extend this isotope-based fluid evolution application from outcrop analog to the un-cored well bore. Permian platform carbonate outcrops and Triassic non-marine clastic outcrops were used as analogs for the subsurface, in a well that had penetrated a well-known Triassic volcanic formation, a shaley carbonate, and then an extremely hard unnamed "conglomerate" section. The mudlog interpretation for this well placed its base in a subthrust Permian sequence; however, analysis of the stable isotope spread in the lower part of this well indicates a C-O isotope plotfield that is not usually associated with subthrust Permian carbonates in Thailand. This study aimed to explain this anomaly and expanded the use of stable isotope analysis via determinations on selected well cutting samples and by examining the isotope signatures of shalier, as yet under-studied "off-platform' Permian carbonates.

1. Introduction

Stable isotope analysis was utilized to better describe the fluid evolution of Permo-Triassic sediments on the western edge of the Khorat Basin in NE Thailand, via sampling a combination of well cuttings and outcrop. The isotope signature was recorded as a function of depth in the subsurface and the isotope signature was also analyzed for select rock samples from the outcrop analogs in a number of quarry walls. Based on the isotope data and in conjunction with other analysis, it appears that hot, carbonate-carrying fluids were expelled from organic-rich shales. Isotope analysis also indicates that the fluid did not migrate far before precipitating as carbonate cements and replacements. The results of the study are consistent with an interpretation for a shaley, low permeability limestone deposited distal to the carbonate platform and subjected to late diagenesis. This paper is the next step in testing the utility of isotopes on cuttings outside of the work that is already done in Permian shelf limestones in Thailand (Warren et al., 2014). The study also tests the utility of isotope profiling as an aid in defining drilling targets and their attainment utilizing diagenetic signature in structurally complex and geologically complex subsurface settings. For this study, Permian and Triassic outcrops were used as analogs for an exploration well targeting a platform carbonate and siliciclastics along the western boundary of the Khorat Basin.

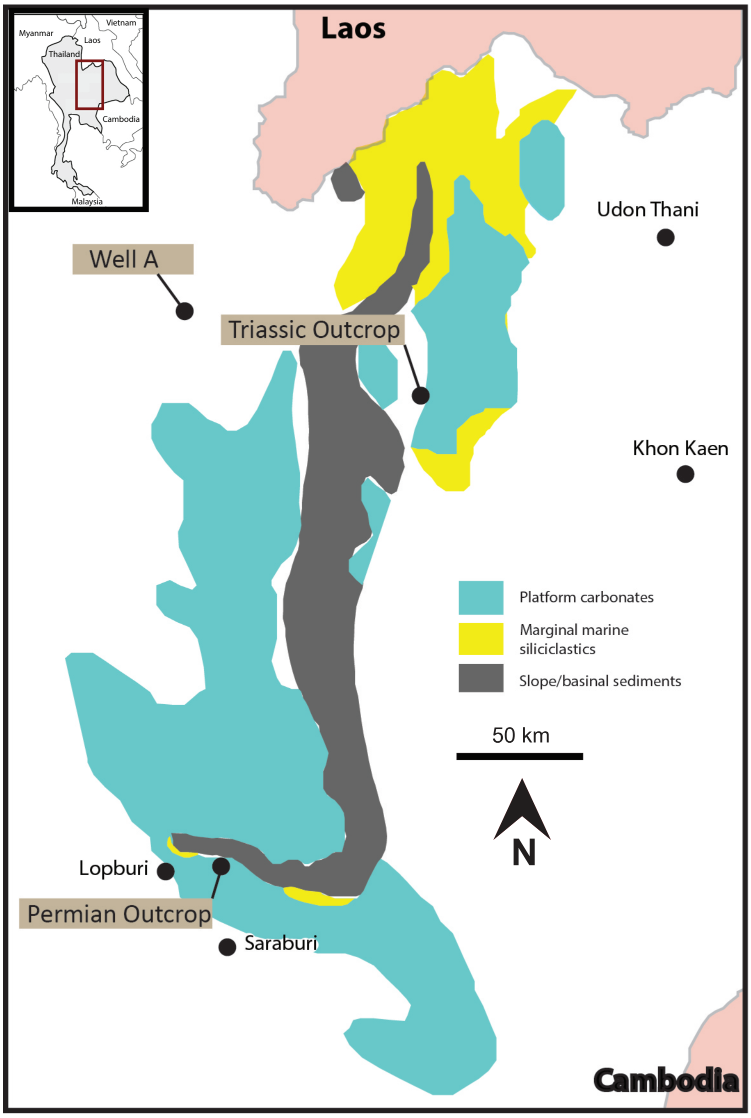

Figure 1: Permian and Triassic outcrop and Well A locations.

2. Geological Setting

Depositionally for this area of NE Thailand, the Permian has been found to be predominately marine facies and the Triassic tends to be non-marine facies. The study area has a complex geological history, which has been covered extensively in previous papers (summarized in Morley, 2011). Within the scope of this study, it has been recognized that the collision of two continental blocks, the Sibumasu and Indochina blocks, impacted the structural geology of this area of SE Asia including Thailand. The Khorat Basin, contained entirely in the Indochina block, is bowl-shaped with thrusting around the edges. The active tectonic setting implies the study area has likely been subject to compressional and tectonically driven cross-flows of various diagenetic fluids (Warren et al., 2014).

The well data analyzed for this study came from drilling operations that targeted a sub-thrust middle Permian platform carbonate, the Pha Nok Khao formation. However, operations had encountered a volcanic interval above and a hard conglomerate section below the shaley carbonate bearing formation. From that data, it was inconclusive and could be debated whether the shaley carbonate was the Permian Pha Nok Khao formation with material introduced from a later volcanic event, or if this interval was instead a continuation of the Triassic with a section of limestone. Therefore, both Permian carbonate and Triassic volcanic/conglomerate outcrops were chosen as analogs to compare and help to interpret the well data. The relative locations of the outcrops and the well are shown in Figure 1.

3. Methodology

Stable isotope (^{13}C and ^{18}O) analysis has been established as a method to identify changes to the rock/fluid interaction over time. The impact to the isotope signatures can be tied to fluids creating cements indicative of different diagenetic processes; increasing negative ^{13}C isotope values can be due to organic content in fluids and increasing negative ^{18}O isotopes can be due to higher temperatures. Starting with an assumption of stable isotope values at the time of deposition, the change to the isotope signature can be used to infer the fluid evolution. The isotope analysis presented in this paper is part of a larger study on the diagenetic and structural signatures of the carbonates found in Thailand; therefore an effort was made to use methodology consistent with this previous work as described in Warren et al., (2014). Texture-aware ^{18}O and ^{13}C isotope sampling as described in Allegre, (2008) was performed on rock samples and were classified and analyzed according to matrix or cement sample points. Thin sections were analyzed from selected outcrop and well cuttings samples; staining techniques for carbonate minerals followed the methods described in Hitzman, (1999). Results and discussion of the tests based on this methodology are provided in the following sections.

4. Results and Discussion

Observations and results of the stable isotope and thin section analysis for the rock and well cuttings samples are described and interpreted in the folowing sections for the outcrops and the well, respectively.

4.1 Permian Outcrop

The Permian outcrop study was comprised of three sites; lower, middle, and upper sections east of Lopburi. The lower section was heavily folded shale, the middle section (Figure 2) was layered shale with a dike cutting through the bedding, and the upper section was layered shale with a dolerite sill. The middle section also contained the thin limestone bed (Figure 3) which was used as an analog for the shaley limestone observed in the well. Calcite veins with no obvious fracture orientation were observed in the rocks throughout the outcrop. Thin section analysis indicated ferroan carbonate content in the cements and amorphous black material (possible bitumen) was also consistently observed in the calcite cements throughout the outcrop. For samples taken in close proximity to the dike, the sample matrices were observed to change from brown to a brownish pink color and although field tests for carbonate were positive, the brownish pink matrices were flagged for low carbonate content in the subsequent isotope analysis. Within the limestone section, deformed and broken crinoids and bivalve debris was observed in a rudstone with no visible bedding.

From the results of the isotope analysis within the limestone section, individual samples showed vein cements had slightly more negative ^{18}O and ^{13}C values than the rock matrix adjacent to the sampled veins. This vein-matrix isotope relationship was consistent throughout the outcrop. In addition, the ^{13}C isotope values became less negative in individual samples as the sampling progressed higher in the limestone section. This shift is likely due to less organic-rich fluids or

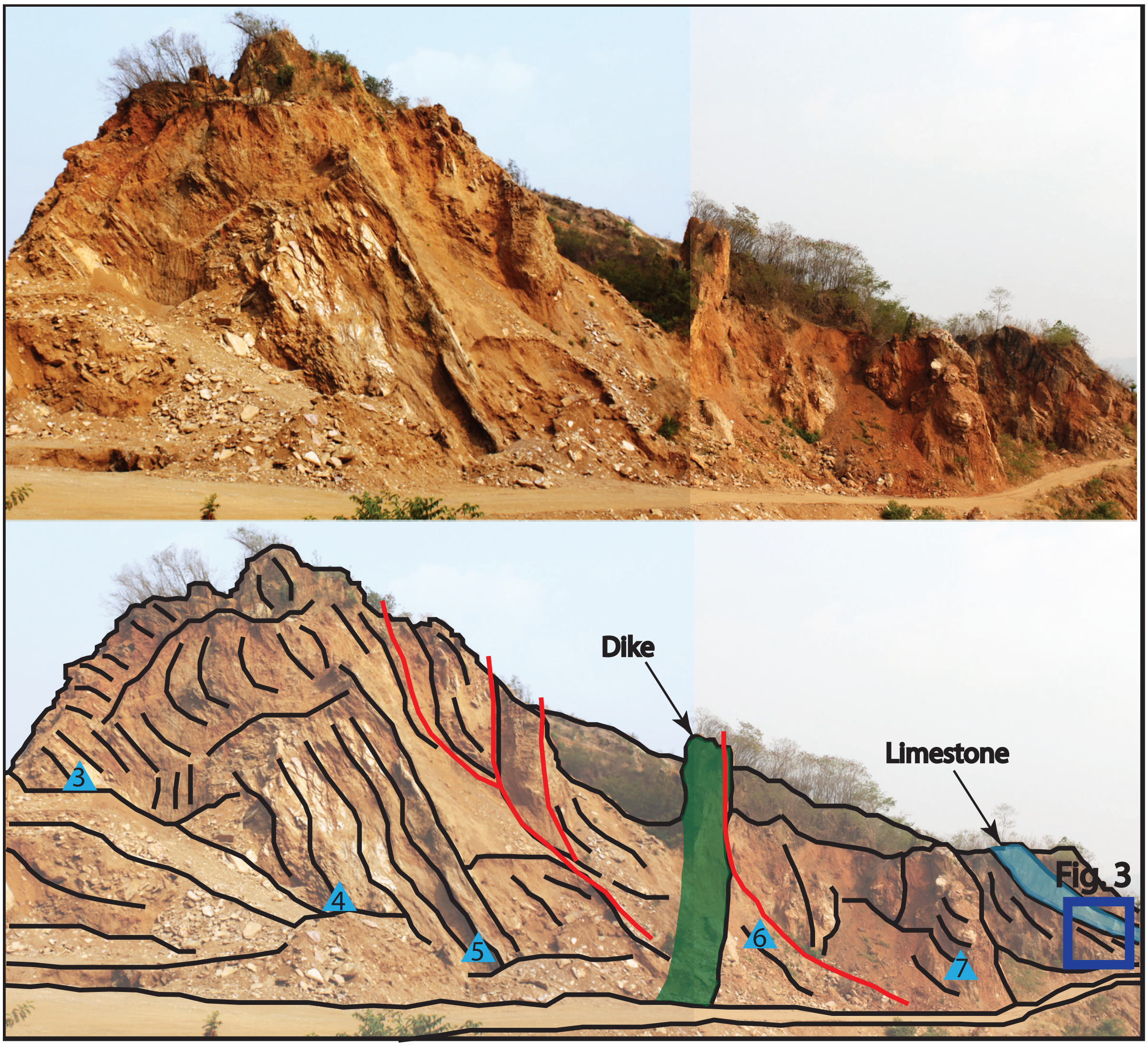

Figure 2: Permian outcrop Middle Section showing bedding, thrusts, and sample locations.

a less reductive diagenetic environment, possibly related to porosity and permeability contrast between the limestone and adjacent shales, as the units were flushed by mesogenetic fluids. This interpretation is consistent with the thin section analysis, which showed a continuation of the reduction of organic material and less ferroan calcite cements compared to the shales found in the lower and upper sections of the outcrop.

Based on the isotope and thin section evidence, the interpretation was that the organic-rich shales were folded and squeezed; expelling organic-rich carbonate containing fluids which then precipitated in the adjacent veins. Samples taken in close proximity to the dike and sill appear to shift to increasingly negative ^{18}O isotope values; likely influenced from the heating of the fluids by volcanics.

4.2 Triassic Outcrop

Triassic outcrops located west of Khon Kaen were studied as a possible analog for the volcanic and conglomerate intervals observed in the well log. Four sites collectively showed sandstone

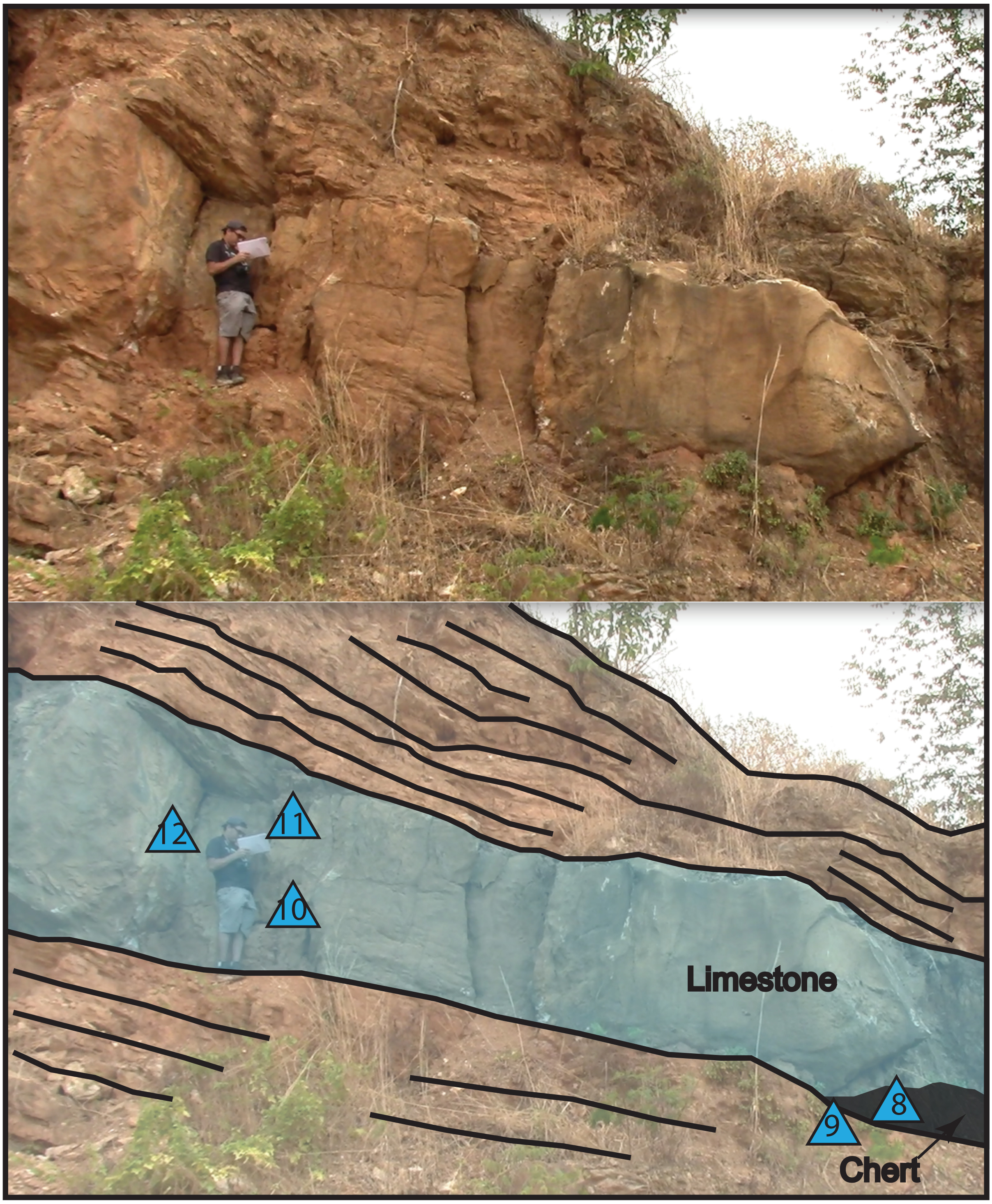

Figure 3: Permian outcrop middle section showing limestone with sample locations.

containing volcanic material overlain by alternating sections of bedded and non-bedded black shale overlain by a conglomerate section interbedded with shales. Due to time restrictions for this project, isotope and thin section analysis from the Triassic outcrop was not available for comparison to the well.

4.3 Well A

The original mud log interpretation was that the interval of thin siltstone and limestone beds

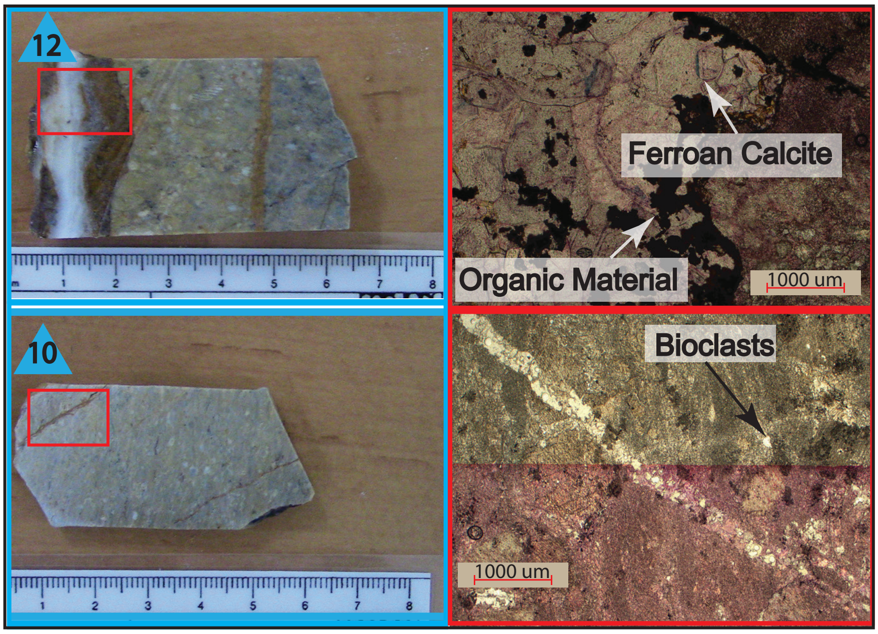

Figure 4: Limestone samples and thin sections.

encountered was the Permian Pha Nok Khao formation. However, additional investigation was warranted since a thick section of hard conglomerate was encountered below the carbonate and such a unit is not documented in the current Permian stratigraphy of NE Thailand.

Isotope analysis on carbonate content for well cuttings all the way to the surface is shown in Figure 5. The blue shaded area represents the Pha Nok Khao from the mud log interpretation. Thin sections from well cuttings were analyzed from the Pha Nok Khao and from the lower conglomerate interval

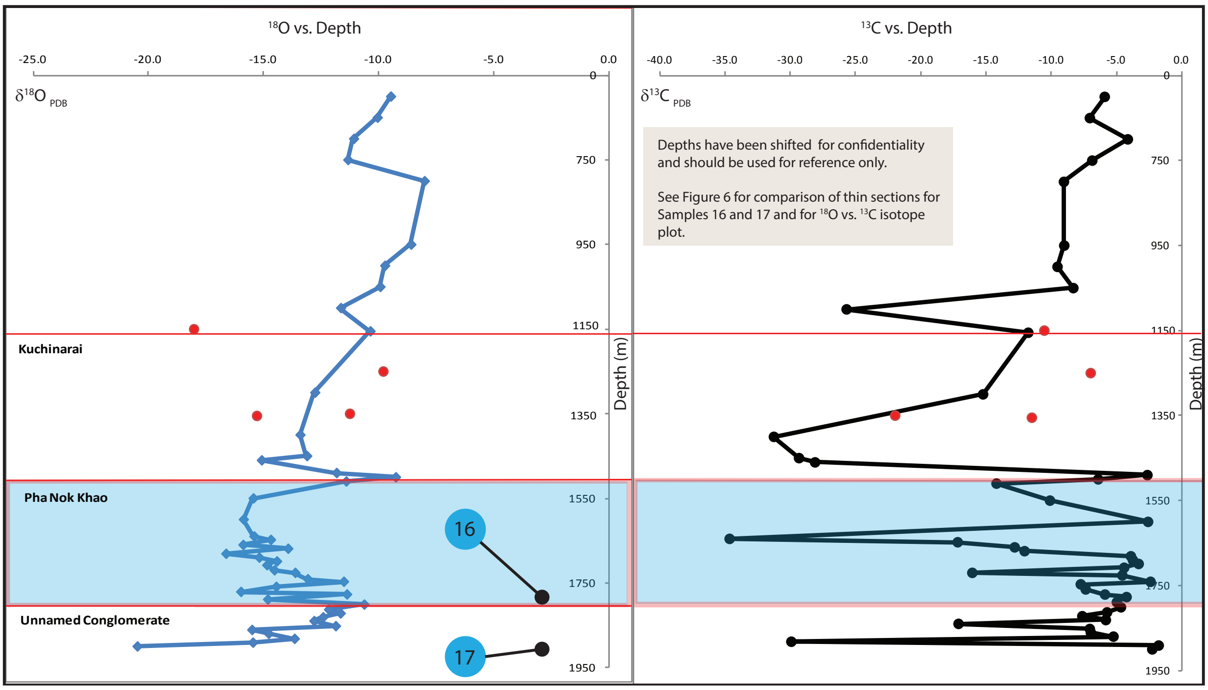

Figure 5: Subsurface 13C and 18O isotope analysis vs. depth.

and are presented in Figure 6. For the Pha Nok Khao the thin section contained angular fragments; late calcite cements, possible organic material, and included sandstone. The conglomerate thin section contained angular shards of glass-like material (volcanic?). Sandstone, volcanic, and bioclast fragments were cemented together. No obvious crinoid or fusilinid fragments,

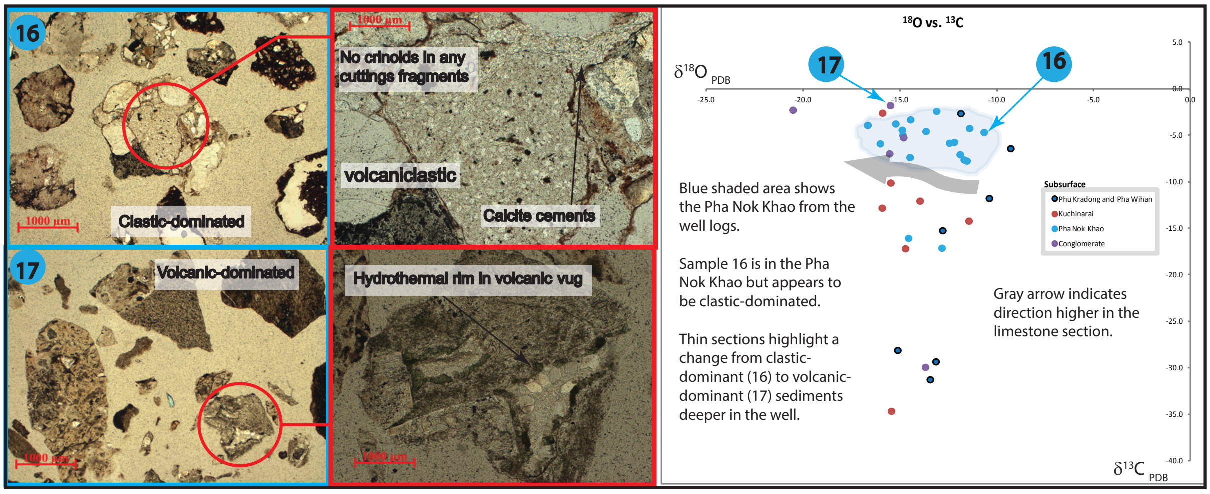

Figure 6: Thin section analysis and isotope plot for Well A.

which typify the Permian carbonates of Thailand and were observed in the Permian outcrop in this study, were found in any of the thin sections made from cuttings. The carbonate present in the chips comes from either veins, or finer-grained, typically micritic muds or shales.

Permian carbonates typically exhibit a burial trend; a range of increasing negative ^{18}O isotopes (approximately -5 to -10) resulting from re-equilibration of ^{18}O isotopes as the fluids in the rocks heat up with burial and precipitate as carbonate cements (Warren et al., 2014). This trend continues until the rock poroperm is restricted by the increasing carbonate cement content. If the platform was subjected to later structural deformation, a jump in negative oxygen isotope values would be observed as this later hotter fluid migrated into the fractures and veins and precipitated as calcite cement with a more negative ^{18}O signature. This isotope signature shown by the green shaded area and gray arrow in Figure 7 is based on the rock-fluid interaction for a Permian carbonate and has been well established by more than 300 isotope samples (Warren et al., 2014). A plot of the isotope signature from a different Permian platform carbonate adjacent to the study area (Pagocho MSc. provided in Figure 7) provides another example of this typical signature. For comparison to the subsurface data from this study, the Permian Pha Nok Khao from the mud log is shown shaded in blue. The Pha Nok Khao from the mudlog deviates noticeably from this expected isotope signature with the cluster of data points shifted toward more negative values for both ^{18}O and ^{13}C. From the thin section analysis; the angular volcanic and sandstone fragments observed in the cuttings were not consistent with the carbonates observed in the Permian outcrop thin section for this study.

5. Conclusions

This study utilized an integrated isotope-based fluid evolution study to provide a geological interpretation for subsurface sediments previously interpreted as a Permian platform carbonate intersection in NE Thailand. The bulk of previous isotope studies were focused into Permian "on-platform" carbonates and signatures associated with Indosinian thrusts that deform these carbonates (Warren et al., 2014). Based on the data from those studies, isotopic signatures have

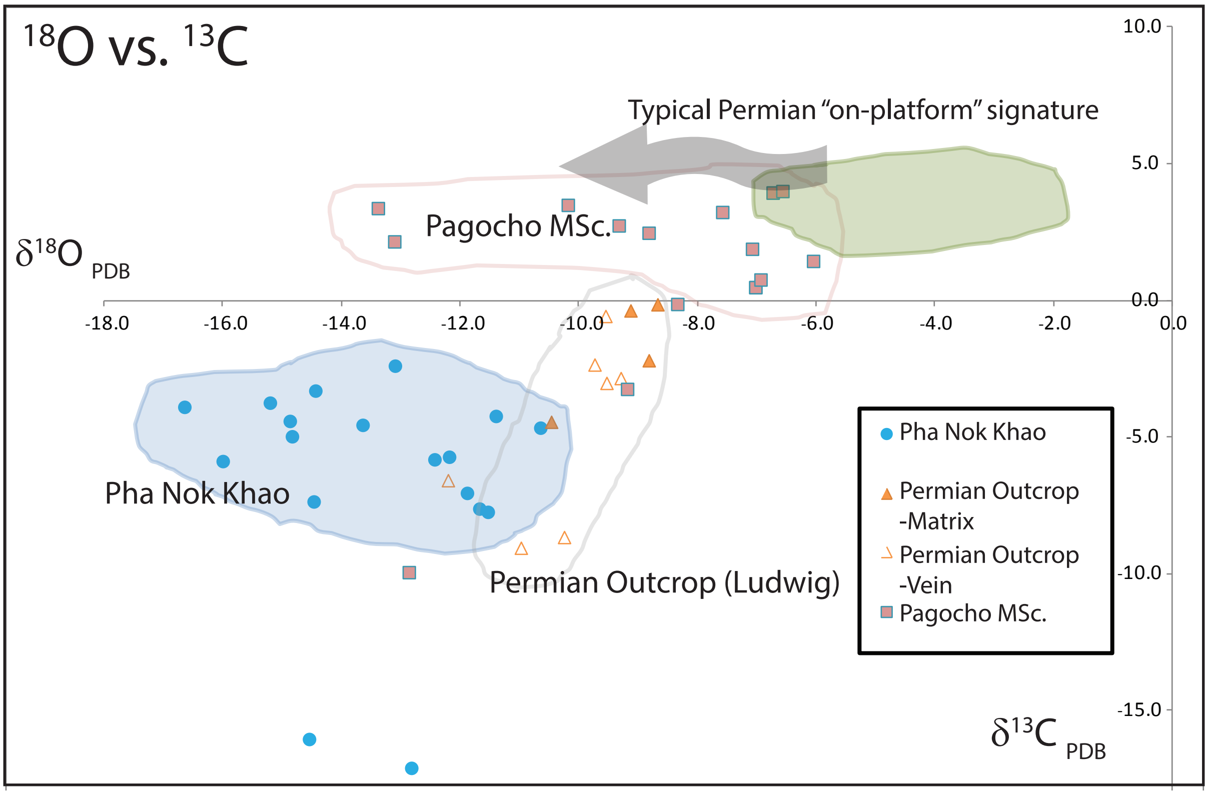

Figure 7: Isotope analysis comparison plot.

been established for a platform carbonate and the effects of diagenetic and structural processes on those signatures. This study provides value by extending the application to "off-platform" Permian carbonates and thus expands the coverage of the larger ongoing study. It also utilizes these isotopic results to determine the fluid evolution in what has been earlier interpreted as age-equivalent sub-thrust subsurface sediments.

The Permian outcrop examined in this study was deposited basinal to the carbonate platform edge. This off-platform, distal depositional interpretation is consistent with the predominantly shaley carbonates observed in outcrop. However, there is a deviation from the typical burial trend (increasing negative ^{18}O with nearly constant ^{13}C) observed in the on-platform studies referenced from the literature. Off-platform, the trend from this study showed a greater negative ^{13}C isotope range, likely due to the greater organic content in the shale and the propensity of shale-dominated sediment piles to act more like a closed hydrologic system, due to the inherent lower permeabilities throughout the burial cycle. This is indicated by the relatively small change in isotope signatures between samples in different locations and also the small shift in isotope signatures when comparing the matrix and calcite vein results of an individual sample. That is, isotope results from the outcrop study indicate that the rock-fluid interaction was part of a mostly closed hydrologic system in which increasingly warmer organic-rich mesogenetic fluids were expelled from the shales. The carbonate dissolved in the fluid precipitated as calcite cements after relatively short migration distances, thereby stunting the subsequent fluid evolution, which was apparent in the isotope signatures of on-platform studies.

For the subsurface interpretation, the conglomerate encountered below the limestone formation (Permian Pha Nok Khao from the mud log interpretation) was problematic and presented con-

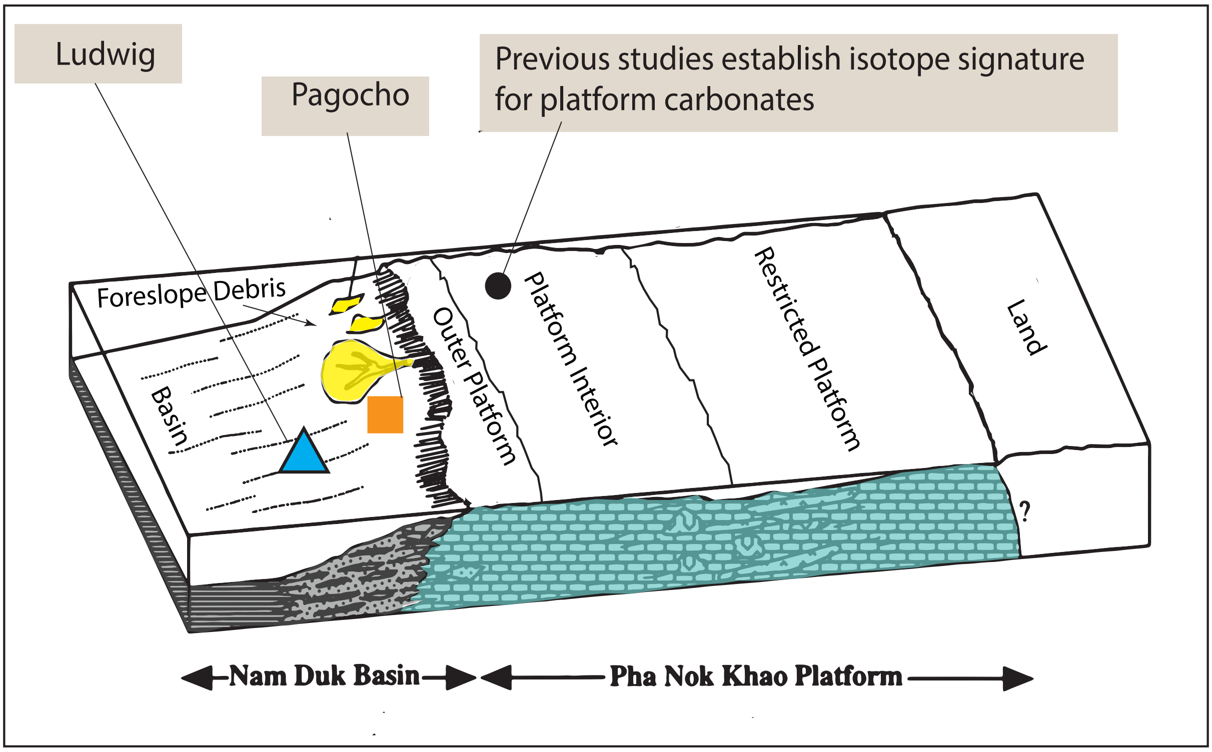

Figure 8: Relative study locations.

flicting geological interpretations. It is less probable and there has been little evidence of Permian volcanic/conglomerate formations in NE Thailand; therefore the possible interpretations were examined based on this premise and assessed as more or less likely. One interpretation is that the limestone formation encountered in the studied well was a Permian carbonate but it had been thrust over a Triassic volcanic/conglomerate. However, an isotope signature consistent with thrusted carbonates exhibits a hydrologic contrast evident from the isotopic signature of calcites which continue to evolve under the influence of increasingly hotter fluids (Warren et al., 2014). These thrust indicative signatures were not observed in the well cuttings; therefore the subsurface isotopic data does not appear to penetrate a thrust so the Permian limestone based on this scenario is less likely. This interpretation is also supported by thin section analysis of the relevant cuttings, which contain no fusilinid or crinoid fragments. The volcanic/conglomerate section in the subsurface is more analogous to the Triassic outcrop section, which includes conglomerates and sandstones containing volcanics; there was nothing comparable to this in the studied Permian outcrop. The limestone above the conglomerate also differed from the Permian outcrop under thin section analysis as the limestone in the well cuttings contained evidence of associated volcanism. Furthermore, the isotopic signature of the subsurface limestone was not consistent with the typical Permian platform isotope signature detailed from previous studies. Even taking into account the possible potential shifts to the isotopic signature proposed in this study due to the effects of organic material or proximity to volcanics, the isotopic signature of the subsurface limestone section is shifted negatively and the fluids never started in the typical range expected for Permian marine carbonates. Based on this evidence, while it cannot be concluded that shaley limestone and the conglomerate are Triassic, it is more likely that the studied well did not penetrate the Permian.

Going forward, it is recommended that this study expand the coverage of the carbonates analyzed including the Pha Nok Khao. The limits of the current stable isotope application for Permian carbonates should be tested to confirm the application is effective in describing the fluid evolution further out on the platform and if this application would be effective for clastic-dominant geology that contains minimal carbonate cements. Additional reference points are needed to confirm the validity of using stable isotope analysis on well cuttings to determine if the isotope signatures obtained are of sufficient quality and are analogous to the original rock matrix-carbonate cement.

6. Acknowledgements

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