Fundamental Control of Low Permeability Sandstone Reservoirs, Sirikit Oil Field Phitsanulok Basin, Thailand

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Abstract

Low permeability and porosity reservoirs were investigated in the Lan Krabu (L and M units) and Sarabop (P sand unit) formations. For this research, core description, poroperm relationships and well log characteristics including mineralogy were considered from available core data in north and south area, Sirikit Oil Field, Phitsanulok, Thailand. In the southern area, there are two good potential reservoirs; P sand and Lower Lan Krabu (LKU-M) units. The best reservoir quality is proximal delta front deposits (P sand unit) in a subaqueous environment. The conglomerate/coarse grained sandstone and laminated siltstone is up to 20-26% porosity and 600-1300 mD permeability. They were deposited with variable slope and energy and become progressively more distal delta front with finer grained and mud lamination. The second best reservoir quality is in distal delta front and mouthbar deposits in the LKU-M unit. It contains distal delta front silt interbedded with sand lenses and mouth bar sandstone with mud lamination and ripples. The mouthbar facies has good reservoir quality with 6-18% porosity and 0.05-40 mD permeability. The lowest reservoir quality is in the northern area reservoir facies that was deposited as crevasse splays in the Middle Lan Krabu (LKU-L) unit. This sandstone with interbedded mudstone facies has 8-11% porosity and low (0.05-0.45 mD) permeability.

Reservoir quality in the southern area is mainly controlled by depositional environment such as variable energy during deposition, clay content, sand body geometry and sedimentary structures. Conversely, the tight reservoirs in the northern area are mainly controlled by deposition and authigenic clay content. Other diagenetic processes, such as compaction, cementation and recrystallization, also degraded porosity.

Keywords: low permeability, crevasse splay, authigenic clay, diagenetic processes

1. Introduction

Sirikit Oil Field is located in the Phitsanulok Basin, the largest non-marine basin onshore in Thailand, which is a major asymmetric half graben formed by Oligocene extension and minor strike slip movement (C & C reservoirs, 2009) that contains 8000 m of Tertiary sediment. Sirikit Oil field is operated by PTTEP (Figure 1) and has produced for more than 30 years. It has not only primary reservoirs but also low quality reservoirs that were discovered with proven oil accumulations in the lower part of the Lan Krabu (L & M units) and Sarabop (P sand) intervals. There are both south (shallow reservoir targets) and north areas (deep reservoir targets). Core and thin section analysis, well log characteristics, mineral analysis and poroperm relationships in low permeability sandstone leads to a better understanding of depositional and diagenesis processes in tight reservoirs in Sirikit Oil Field.

Key objectives of the present study are:

- To determine the cause of low permeability in the north and south of the field
- To identify potential reservoirs from the Lan Krabu (L & M units) and Sarabop (P sand) reservoirs

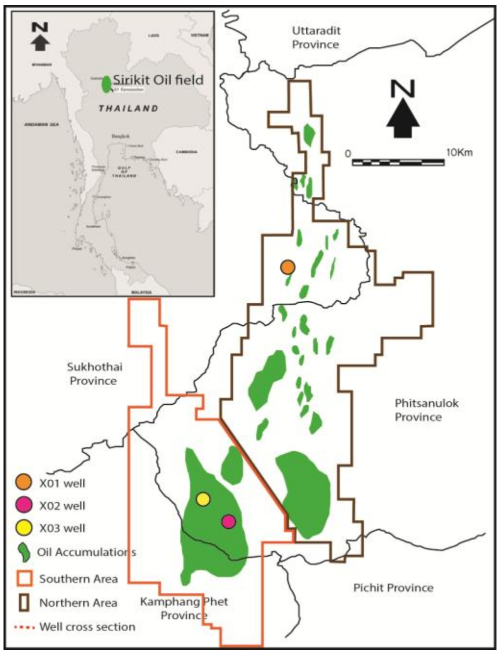

Figure 1: Location map of Sirikit Oil Field

In the southern area, there are large oil accumulations with low permeability in the P sand and LKU-M units with shallow reservoir targets whereas deep reservoir targets represent the LKU-L unit in the northern area. The oil accumulation is based on structure closure.

The Sarabop Formation, P sand interval, is fan deposits along the western fault boundary and more basinward in the Oligocene extensional phase (Figure 2). They are shallow targets (1500-2500 m) in the south.

The Lan Krabu Formation straddles the Oligocene and Miocene boundary. During a time of widespread lacustrine shale deposit across the basin, a series of progradational deltaic tongues were deposited as the Lan Krabu D, K, L and M sand units. They comprise distal fluvio-lacustrine systems which are alternating claystones and thin-bedded sandstones and gravels. For this study Lower Lan Krabu (LKU-M) is in shallow targets (2000-3000 meters) in the south while Middle Lan Krabu (LKU-L) comprises deep targets (more than 3000 m) in the north.

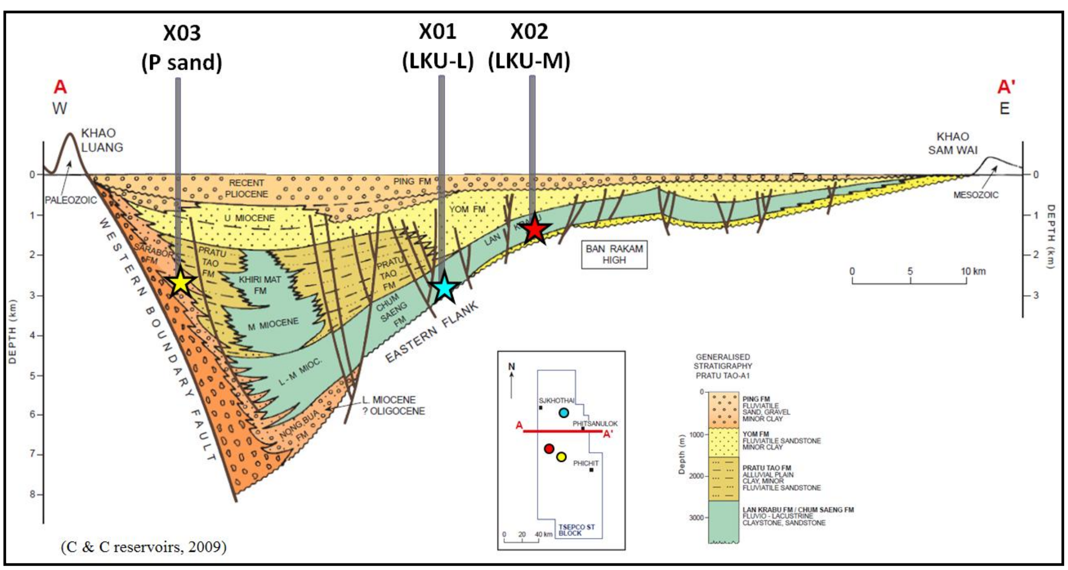

Figure 2. Geometry of sedimentary deposits in a half graben (modified from C&C, 2009)

2. Core and Thin section Analysis

Cores were described from three tight reservoir units at various depths in three wells; LKU-L in X01, LKU-M in X02 and P sand in X03 (Figure 2).

P sand:

Three lithofacies, A, B and C (Figure 3A), are at the base of the stratigraphic succession. Lithofacies A is thick (up to 3-4 m) of massive siltstone with gastropod layers. Poor to fair visible skel-moldic porosity has evidence of carbonate leaching of the original gastropods (Figure 3B). Lithofacies B is conglomerate and coarse grained sandstones that are poor to moderately sorted, sub-rounded to angular and not graded. There is local coarsening upward and visible porosity with hydrocarbon shows.

During a transgressive period, there is a gradual change upward to laminated siltstone lithofacies. Lithofacies C is pale yellowish brown laminated siltstone with dark brown mud laminations, small ripples and black layers of plant debris and coal.

The cored interval consists of a shallowing upward succession deposited in a shallow lacustrine to proximal delta front setting. Good reservoir potential occurs in proximal delta front sandstones deposited by various high energy flow types on relatively steep slopes.

Lower Lan Krabu (LKU-M):

Subaqueous condition observed within three lithofacies; A, B and C (Figure 4A). Begin with Lithofacies A as medium grey fissile claystone and siltstone (up to 9 m thick) with a white gastropod layer at the base which indicated low energy and shallow water deposit. Upward, lithofacies B becomes interbedded with siltstone and mudstone with fine sand lenses and there also is more mud upward. It has a sharp boundary with the underlying thick sandstone and a gradational boundary with an overlying claystone and siltstone facies. Occasionally, Lithofacies C is fine to medium massive sandstone that is sub-round to sub-angular and moderate to well sorted with mud laminations,

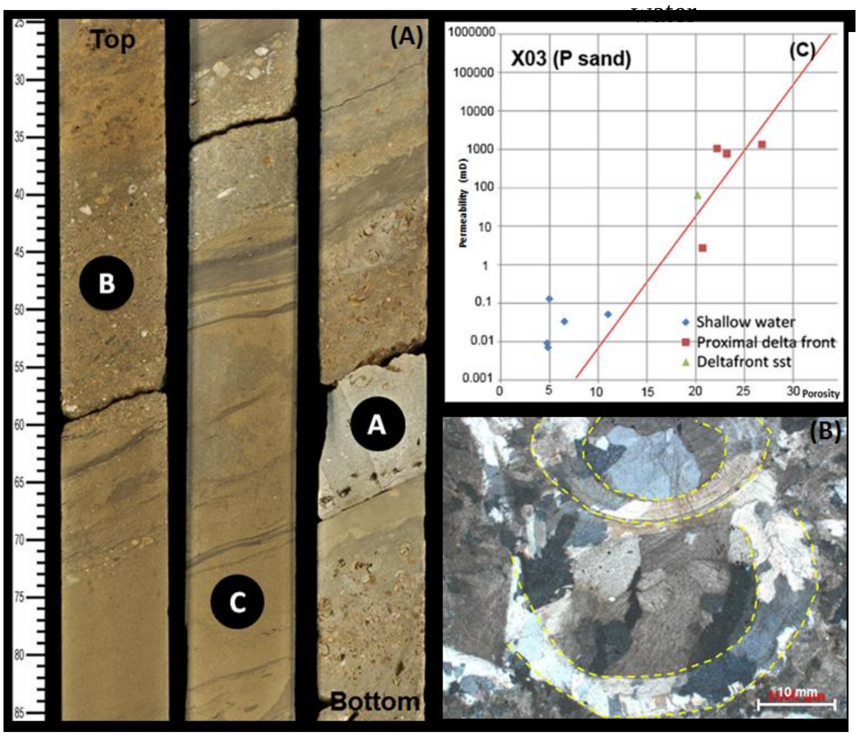

Figure 3. Stratigraphic column of the P sand interval with sedimentary structure and rock characteristic

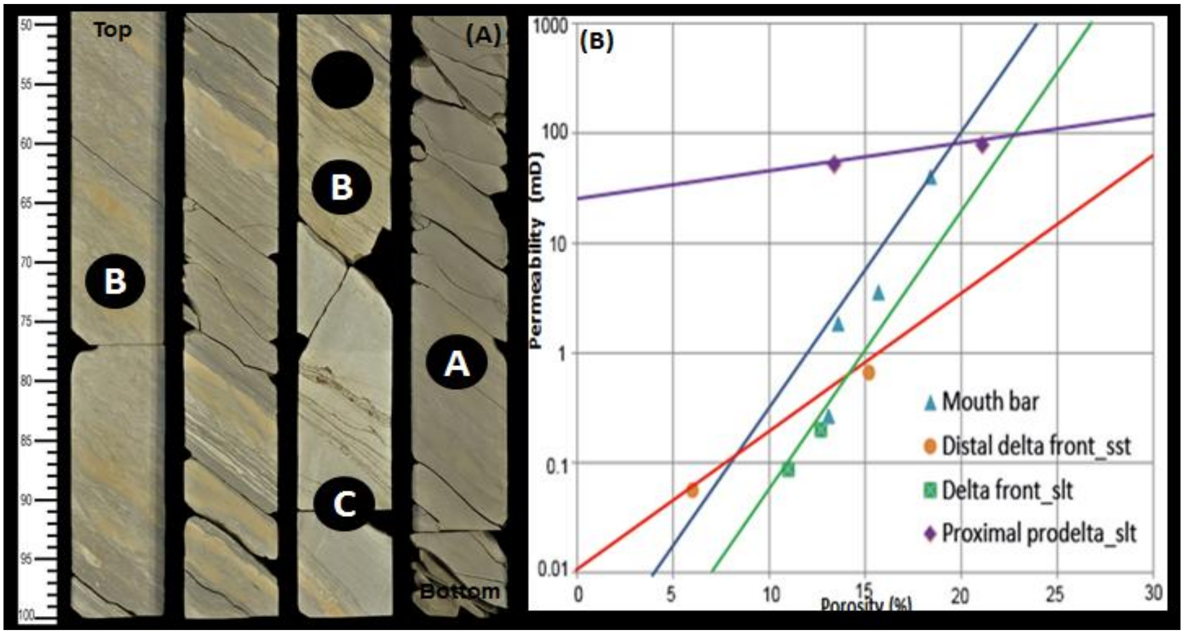

Figure 4. Stratigraphic column of the LKU-M interval with sedimentary structure and rock characteristic

mud ripples and mud and organic matter layers. There are sharp boundaries with underlying and overlying beds. According to color, grain size and sedimentary features, this interval is a deepening upward succession which was deposited in an open lacustrine to proximal prodelta environment.

Two potential tight reservoirs in LKU-M are in sand lenses and massive sands, based on effective porosity and permeability from core plug samples (PTTEP, 2014). A wide range of depositional environments are represented, from sandy mouth bar to muddy prodelta. Reservoir quality varies significantly with depth, sand thickness and sedimentary structures. The massive fine to medium sandstone deposited in the mouthbar facies has 6-18% porosity and 0.05-40 mD permeability. Low permeability is caused by a relatively high mud content. High porosity and permeability values (8-21% and 0.01-78 mD, respectively) were measured in distal delta front sand lenses but they have very limited lateral extent. Although the P sand and LKU-M unit were also interpreted as shallow lacustrine and delta front in the south, they are much different in terms of grain size, sorting, sedimentary features and energy during deposition.

Middle Lan Krabu (LKU-L):

In the northern part of the study area, the deep reservoir targets in the LKU-L unit are relatively more terrestrial deposits than in the southern. There are three lithofacies (A, B and C); lithofacies C is a clearly sub-aerial red and dark grey claystone and siltstone (Figure 5A) while lithofacies A is dominantly thick massive sandstone (up to 3 m) interbedded with mudstone and mud layers.

There is a gradual change upward to the more muddy and silty sands of Lithofacies B that were deposited under lower energy conditions.

In the cored LKU-L interval, there is a fining upward succession which was deposited by crevasse splays on a floodplain. Diagenesis is one factor that reduced reservoir quality in LKU-L. Quartz grains were deformed by mechanical compaction (etched features) and feldspar was partly converted to clay during burial (Figure 5B). More mud layers reduce permeability which affects vertical flow that controls permeability in this lithofacies. The sandstone with clay matrix in lithofacies A and B is low quality with 8-11% intergranular porosity and 0.05-0.45 mD permeability.

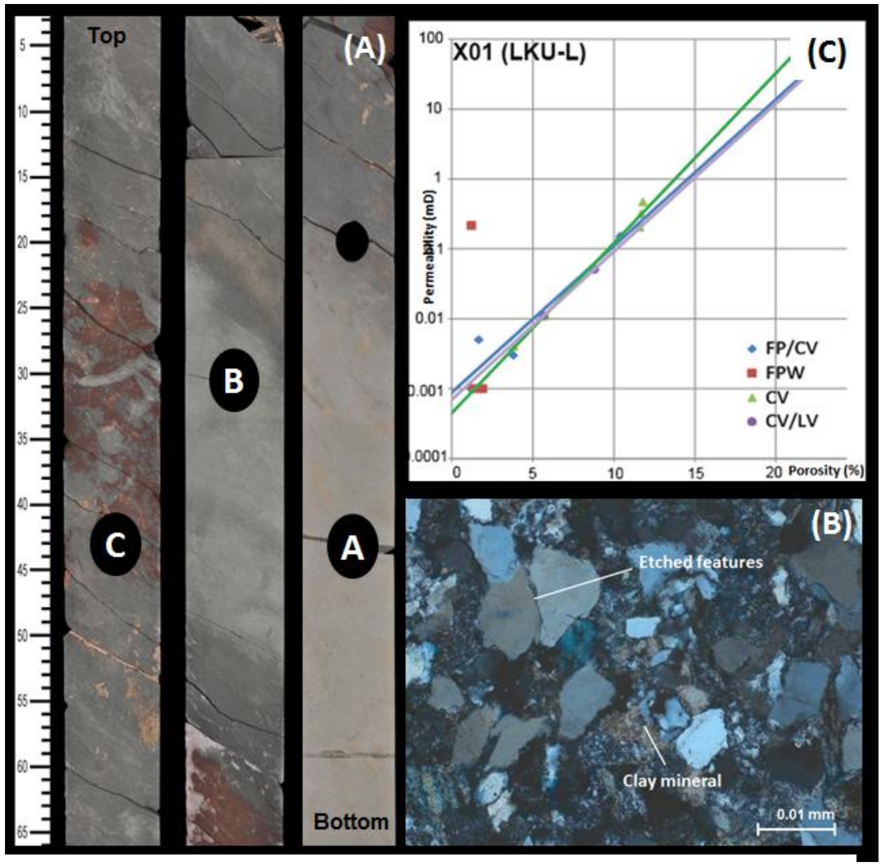

Figure 4. Stratigraphic column of the LKU-Linterval with sedimentary structure and rock characteristic

Based on thin section analysis and sedimentary features, crevasse splay deposits in LKU-L have good reservoir potential. The crevasse splay were deposited in the medial zone and are low energy floodplain splays. Reservoir quality is not significantly different from the surrounding lithofacies (Figure 5C).

3. Poroperm related to reservoir quality

Depositional models are important for predicting the distribution of porosity and permeability within reservoirs. Each core sample typically indicates a direct relationship to a depositional process with its own poroperm relationship (Figure 6).

Different trends based on grain size, sorting, clay content, cementation and compaction are illustrated on Figure 6A.

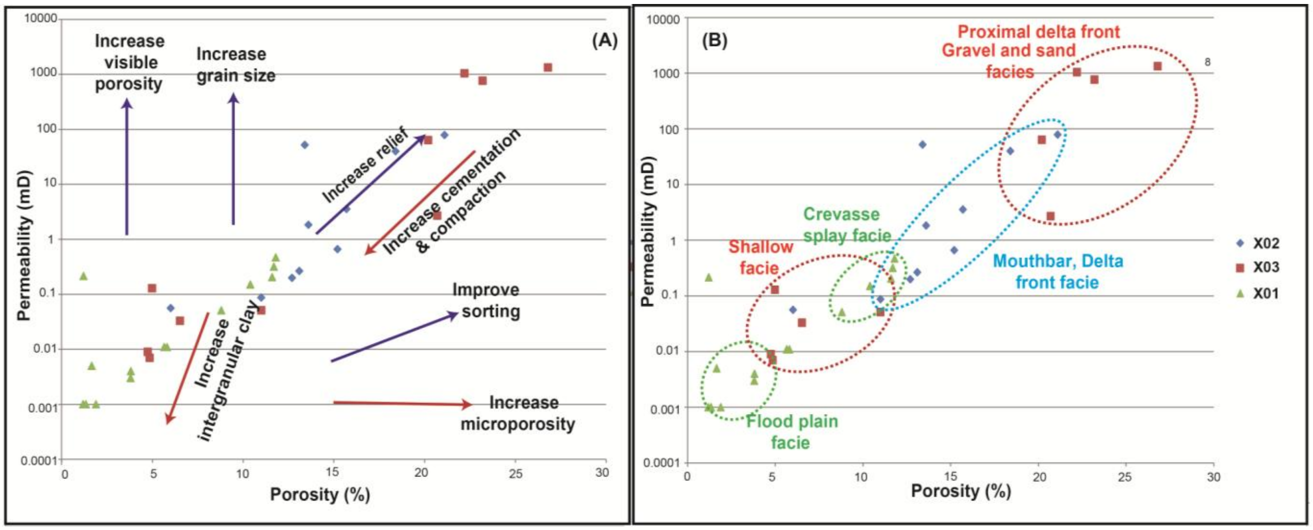

Figure 6. Porosity and permeability relationships with depositional and diagenetic processes

LKU-L in X01 has the lowest reservoir quality of the three cored intervals (Figure 6A and 6B). Crevasse splay facies are nearly identical to shallow lacustrine facies in the south due to abundant, highly compacted clay and silt in the northern deep reservoir targets.

The LKU-M unit in X02 comprises two main reservoirs with a wide range of poroperm characteristics from a wide range of depositional environments, including homogeneous sandstone mouth bar facies and interbedded sandstone and siltstone delta front facies (Figure 6B). They represent the second best reservoir quality in finer sands with more mud. Porosity is 10-20% and permeability is 0.1 to 100 mD (Figure 6A).

The best reservoir quality is in the P sand unit in X03. It is a proximal delta front conglomerate and sandstone facies in shallow reservoir targets in the south.

4. Well log characteristics

Relating the facies interpretation from core to spectral well log data indicates a good correlation with the stratigraphic trend and depositional environment in three cored intervals. The gamma ray log yields the most distinctive log signature for each individual facies. Spectral gamma ray was used to improve lithology determination and shale estimation by analyzing Uranium, Thorium and Potassium contents (Figure 7).

Potassium content is fairly consistent in most shale at 2-3.5%. Thorium is a very good shale indicator that has a constant value in almost all naturally occurring shales, with average values at 12 ppm (8-12 ppm) for typical shales. Thorium also has an affinity for terrestrial clay minerals (Malcolm R., 1996). Th/K ratios (>6 values) occur in three wells, indicating that kaolinite is dominant with high concentrations in the range of 10-30 ppm (AAPG, 1958).

U, Th and K also were used to indicate clay content. In LKU-L, high Th/U ratios represent oxidized floodplain deposits of red and dark grey claystone and siltstone with high gamma ray values. Also, the proportion of Th/K is often related to grain size (Myers, 1987), such as a coarsening upward trend in the P sand alluvial fan.

Gamma ray distribution and log pattern can be separated in the LKU and P sand units and may refer to the different depositional settings, but it cannot identify reservoir quality. High gamma ray values in the P sand may be caused by abundant feldspar, sedimentary structures and clay content. Therefore, estimates of reservoir quality can be provided by core observation of lithology, sorting, grain size and sedimentary features.

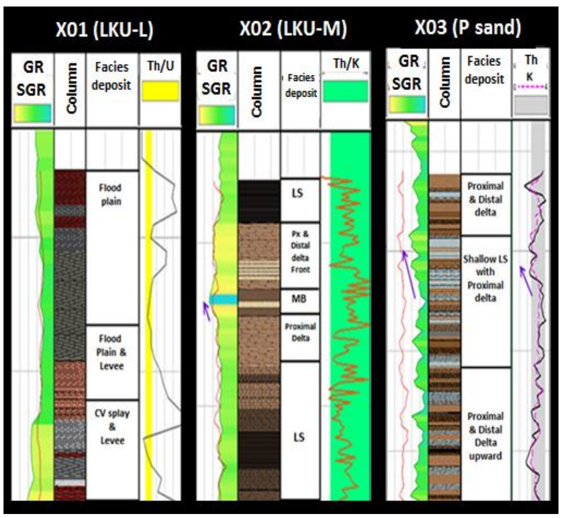

Figure 7. Depositional interpretation from core corresponds with log signatures (Spectral gamma ray)

The well log characteristics of cored units were extrapolated to uncored intervals by broad interpretation of log pattern and gamma ray distribution. The uppermost unit, the PTO Formation, has a serrated cylinder or bell shaped (fining-upward) signature and stacked sands 2-20 m thick in the three wells. It was interpreted as a fluvial system across entire area.

The middle and lower formation can be used to identify different depositional systems. More serrated bell shaped (fining upward) log signatures in the Lan Krabu Formation and an increased sand influx in the middle lacustrine formation imply more terrestrial deposits to the north. However, in the south the middle lacustrine formation is mostly shale and there are more serrated funnel shapes in the lower formation.

5. Petrophysical properties of reservoirs

Depth-related porosity calculated from three porosity logs indicates decreasing porosity with depth with two compaction trends: exponential (normal compaction) and reciprocal (high sedimentation rates). The reciprocal trend decreases quickly with depth at first and then slows to fit a low sedimentation rate (Figure 8).

Petrophysical properties in the P sand indicate a high sedimentation rate that corresponds to its high energy proximal delta front and slope environment. The Lan Krabu (LKU) Formation has a normal compaction trend in the south while the LKU deep (in excess of 3000 mTVD) reservoir targets in the north exhibit burial effects with a high gradient reciprocal trend (Figure 8).

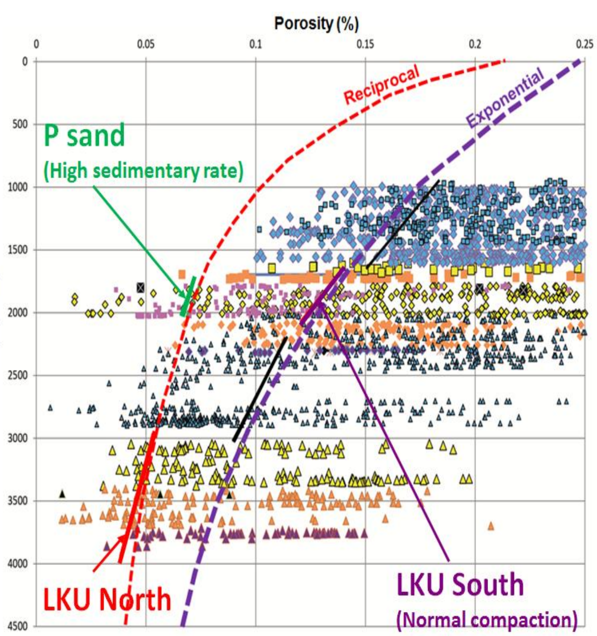

Figure 8. Calculated and cored of porosity versus depth in three wells

6. Discussion

The Lan Krabu fluvio-deltaic system is interpreted to be the primary reservoir in the north and south parts of the Sirikit Oil Field. This research has defined different depositional systems in the north and south that may be due to regional setting because the southern area is near the Western Boundary Fault while the northern area is affected by the Uttradit Fault.

Based on the core descriptions in this research and core analysis (PTTEP, 2012, 2014), the depositional process of the reservoir facies can be correlated with reservoir quality by identifying the sedimentary features and comparing porosity and permeability. This is helpful for understanding the tight reservoirs, improving reservoir characterisation and well planning.

7. Conclusions

Integration of core description, poroperm analysis and well log characteristics determined that low permeability reservoirs are mainly controlled by depositional environment. Diagenetic processes such as recrystallization, cementation and compaction have a minor effect.

The best potential reservoir is the P sand unit in X03, which is a proximal delta front deposit that is not excessively compacted and has a coarser grain size than other units. The second best potential reservoir is the distal delta front and mouth bar deposits in the Lower Lan Krabu (LKU-M) unit in X02. The main cause of low permeability is fine sand with a relatively high proportion of mud. The crevasse splays of the Middle Lan Krabu (LKU-L) unit in X01 have the lowest reservoir potential. Reservoir quality is very low due to abundant clay in highly compacted sands at depths of more than 3000 m.

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