DIAGENESIS AND PETROPHYSICAL ROCK-TYPE STUDY OF OLIGOCENE BERAI CARBONATE PLATFORM IN “KX-1” WELL, CENTRAL KALIMANTAN: IMPLICATIONS FOR DEPOSITIONAL AND RESERVOIR MODELS

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Abstract

The “K” Oligocene carbonate platform is located in Upper Kutai Basin, interpreted as an isolated rimmed platform atoll system within a non-reservoir lagoonal environment in the central platform interior. Previous wells were drilled in the eastern rim tested significant volumes of gas. However, the KX-1 well which was drilled to test the western rim of the atoll also discovered gas with a pressure gradient indicating a similar spill point to the eastern rim. Integrated core and wireline log study of the KX-1 exploration well reveals that “K” carbonate platform developed in a land-attached setting in a semi-enclosed embayment without raised rims, under oligophotic conditions, related to encroaching clastic influx points from the North and Southwest. Interlayered reservoir-quality grainstone and packstone units developed across the platform interior as sand shoals with significant lateral extents, suggesting pressure communication in the saddle area between the rimmed margins. Economic porosity is present with average of 5.5%, as secondary porosity generated by: (1) matrix-specific intercrystalline microfractures, and (2) microporosity via non-fabric selective burial leaching and dolomite replacement. Isotope signatures of uplift may relate to tectonically induced microfractures that are associated with burial leaching and dolomite replacement in the platform interior. The microfractures are a response to funneling and leaching fluid pathways connected to the platform margin through a continuous permeability zone. These findings open up a new exploration and development paradigm by identifying new elements as target criteria in Oligocene carbonate platform : (1) Layered grainstone units with extensive lateral continuity in the platform interior setting, (2) Structural overprints that can create combination traps, thus extending the play-type target from what was previously a strict “reefal build-up” poro-perm model.

Keywords: carbonate platforn, oligophotic, land-attached, interlayered grainstone reservoir, microfractures.

1. Introduction

The “K” Field which is located in the Upper Kutei Basin was discovered in 1985 by UNOCAL, and a significant volume of gas has been tested from Oligocene Berai carbonate platform sediments. Several exploration and appraisal wells have been drilled and cored to characterize this gas field, and previously interpreted as aggradational reefal build-up forming atoll geometry in an isolated rimmed platform system (Saller et. al., 1996, 2002) (Figure 1).

However, the KX-1 exploration well drilled recently by Salamander Energy in 2013 has recovered important datasets, which include core and wireline logs that imply a different depositional and diagenetic model from the previous interpretation. Based on the new well data, the main purpose of this study is as follows; (1) integrate this new data to re-interpret depositional and diagenetic history, (2) classify the petrophysical rock-types via core and wireline study, and (3) discuss the results with respect to regional geology and its implications with respect to paleogeography and reservoir facies geometry.

2. Methods

Detailed core analysis and integrated wireline log interpretation are the main tools of this study. The study is based on core and digital log datasets from the KX-1 exploration well supplied by Salamander Energy. The study interval focuses on the Upper Berai Formation, a continuous conventional core from 2651 – 2687 m, with total length of 36m was described in the KX-1 well. Core plugs were taken on average every 5 cm in zones of detailed interest, which recovered 70 samples that were analyzed using petrographic, RCA (Routine Core Analysis), and XRD (X-Ray Diffraction) techniques in order to document the type and distribution of grain sizes, microfossils, diagenetic styles, mineralogy, and poro-perm values. In order to better interpret the controls on likely burial cements and better define the diagenetic history, 59 pulverized samples were taken of limestone bioclasts, carbonate matrix, and calcite filled veins and submitted for carbon (δ13C) and oxygen (δ18O) analysis.

Petrophysical rock-typing is conducted by establishing the link between geological core-based facies and the wireline log responses, so making it possible to extend an electrofacies interpretation into the uncored section of the well.

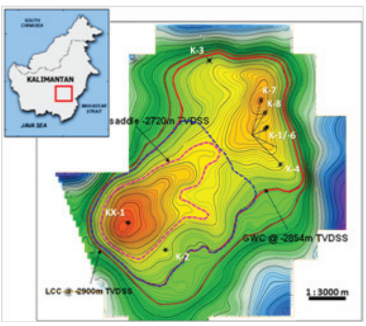

Figure 1. Location of the study area and depth structure map of the “K” Field

3. Integrated Core Study

3.1 Litho- & Biofacies Analysis

Lithofacies analysis was based on several key observations from KX-1 well, including; sedimentary texture and structure, grain type, facies boundary, diagenesis, and pore type.

The resulting description of the limestone core has been subdivided into 5 (five) lithofacies: (1) Dark/Light Grey Foramol Floatstone, (2) Buff-coloured Pack/Floatstone, (3) Light Grey Echinoid Pack/Grainstone, (4) Light Brown Bioclastic Wacke/Packestone, (5) Dark Brown Bioclastic Pack/Grainstone.

Biofacies subdivisions mostly conforms to lithofacies character, with exceptions related to localized patches of mud baffling or low-permeability streaks. Abundance levels display some fluctuations, which correlate with lithofacies changes, possibly tied to variable biogenic production, local paleo-bathymetry, and the varying levels of terrestrial or volcaniclastic input that changed on the paleo-ocean clarity.

The large benthic forams (LBF) are an important constituent in much of the core, especially in the highly cemented units (i.e. Dark/Light Grey Foramol Pack/Floatstone facies). LBF richness is also interpreted as a proxy for the oligophotic zone. Based on core observation and core-plug petrographic modal analysis, the typical Neoge-nereef core framework builders, such as massive aligned Porites sp. and Astreopora sp.,were rare to absent in the cored section. Rather, in coral-rich intervals, shapes varied from branching in lower parts of a unit to domal and digitate-branched structures in the upper part, indicating relatively low energy-levels and reduced light penetration (oligophotic zone). Apparent “deepening”-upward trend possibly relates to high influx of terrestrial run-off and/or volcanism that increased sediment content in the water column, which in turn created temporary oligophotic conditions. The occurrences of non-carbonate and volcaniclastic materials are confirmed by petrography and XRD analysis.

The cored interval shows at least 2 cycles related to energy-turnaround from rapid-“deepening” to slower-“deepening” rate, which are often capped by good reservoir quality litho-facies. A cycle starts with deposition of thin buff-coloured Pack/Floatstone facies that mark onset of substrate destabilization and high terrestrial run-off with gradual thickening upward trend as the oligophotic condition progress, this is interlayered with Dark Brown Bioclastic Pack/grainstone facies, which fills in subsequent accommodation space during periods of slower-“deepening”. This is proven by the positive correlation between quartz mineral fluctuation and LBF abundance, which relates to the increased clastic influx that drives oligophotic conditions that in turn favor to the LBF habitat.

In periods of transgression or stillstand, echinoid-rich Light Brown Bioclastic Echinoid Pack/Grainstone facies begin to develop as sand-shoal layers in “shallow” euphotic subtidal settings, possibly linked or storm-sourced from coral-rich patch reefs that developed in deeper photic zone. The grain-dominated lithofacies (i.e. Light Brown Bioclastic Echinoid Pack/ Grainstone and Dark Brown Bioclastic Pack/ Grainstone), show generally high abundance levels of echinoderms, red algae, and smaller benthic forams throughout the cored interval. This indicates high levels of photosynthesis by stenohaline biota living in the euphotic zone. Bioerosion is interpreted to be the main contributing factor to the generation of grain-dominated units on the platform, as evidenced by frequent appearances of abraded shells and abundance of echinoid fragments on the grainstone – packstone accumulations. In this setting, sea urchins (echinoidea) are the main agent capable of significant bioerosion. Grain-dominated lithofacies groupings are considered to be important reservoir quality zones and likely developed as sand shoal interlayers in the platform interior (Figure 2).

These results indicate that major carbonate contributors to the KX-1 area were benthic forams and coralline algae, both inhabitants defining a foramol facies, which was deposited in relatively low energy condition on a land-attached platform setting. The increasing-upward trend of LBF abundance is consistent with apparent “deepening”-upward trend in the cored interval. The LBF-dominated facies is typically highly cemented and represents the main framework builder in this part of the platform. Such bioherm can be classified as matrix-supported cluster reefs, which typically form low-relief patch reefs morphology in modern analogs (Riding, 2002). The Oligocene era records a global climate transition from greenhouse to icehouse climate characterized by relatively warm, aragonite seas which are favorable for foramol facies development, particularly in SE Asia (Wilson, et. al., 2005).

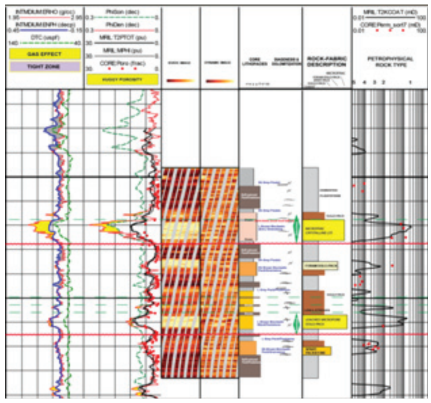

Figure 2. Core to wireline log tie showing major petrophysical rock types (PRT)

3.2 Stable Isotope Analysis

Stable isotope values reflect rock-water interactions and fluid evolution during progressive carbonate rock cementation, re-crystalization, and re-equilibration of $CaCO_3$ minerals in a higher temperature regime (during burial), and other post-depositional factors that control composition of $\delta^{13}C$ and $\delta^{18}O$. This is particularly useful for carbonate reservoir characterization in defining and understanding the various diagenetic stages and the relationships to porosity development via observation of trends/clusters.

Based on observed trend and textural attributes, the C – O plot can be broken into 3 trends, which relate to: (1) meteoric mixing, (2) burial, and (3) uplift.

The meteoric mixing trend is characterized by increasingly negative O isotope followed by slightly more negative C isotope on samples of calcitized coral and calcite cement in vugs. In parallel with this trend are the samples of stylolitized dark carbonaceous clay seams, a strong affinity with the meteoric mixing trend suggest that stylolitized clay seams possibly originated from terrestrially derived mud, or represent the highly insoluble fraction within the platform.

The burial trend is characterized by increasingly negative oxygen isotope values possibly related to elevated temperatures of the burial fluid which gradually produced a more diagenetically stabilized calcite matrix and foram mold fills. The C – O signature beyond the boundary of an δ18O value of -7.12 ‰ PDB in only seen in clear calcite vein and dolomite concretionary patches. These textures likely represent the influx of deep burial leaching fluids derived from compacting basinal shales. Slightly negative C isotope value which skew the trend also supports an interpretation of a closed hydrologic system, where fluid is supplied by increasingly warm, organic-rich, catagenically influenced fluids that were expelled from maturing basinal shales.

The uplift trend is characterized by a trend shown by the gradual increase in O isotope values, which is obvious in cements in some fractured samples. This trend represents the latest-stage of diagenetic solution circulation of diagenetic solution circulation in the well and characterized by a gradual decrease of burial fluid temperature and increasingly negative C isotope value (-4.13‰ PDB). One interpretation is that this diagenetic fluid came from deep regional groundwater circulation with a groundwater head generated by the uplifted Kuching Ranges. Alternative interpretation is that this fluid came from renewed circulation through organic-rich shale, driven by the inversion process (Figure 3).

An interesting set of relationships emerges when correlating the isotope analysis with the rock-fabric. Of particular interest is the "uplift" trend, which was observed in several samples of calcite cement within fractures that apparently represent points from zones with better reservoir quality. This relationship will be discussed in more detail in the following chapter on rock-fabric classification.

3.3 Petrophysical Analysis

This analysis is done in two parts, first relating rock property measures to core-based observations (or rock-fabric classification), followed by upscaling these relationships to wireline properties that have relevance to intervals outside the studied core.

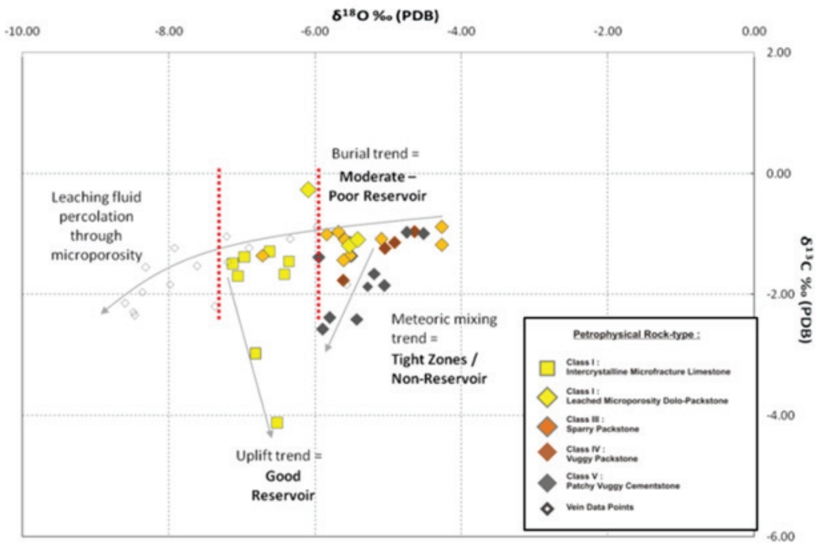

Figure 3. Plot-field showing diagenetic rock-fabric calibration with stable isotope values

Initial crossplot of all data distribution of measured core plug poro-perm relationship from the KX-1 well is scattered and shows no clear relationship. However, the high proportion of poor data measurement due to induced fractures created by the plugging process obscures the actual poro-perm trends in a global crossplot and gives an outcome that is largely unrelated to subsurface condition. Petrographic observation was also utilized to search for visible induced fractures on RCA samples to help filter the poro-perm data to give more reliable values. When filtered poro-perm data is overlain with core-defined lithofacies there is good correlation that shows the hybrid controls of deposition, diagenesis, and fracturing on the measured poro-perm distribution.

Based on thin section observation, pore-type in the cored section is mainly classified as intercrystalline porosity, which can be further sub-classified according to bioclast- and matrix-type modifiers. Some localized visible porosity present as moldic and enlarged vug can be seen in highly cemented zones, however they are typically poorly-connected pores. Visible fragments of large coral seemed to be pervasively calcitized suggesting negligible intra-coralline vuggy porosity. Facies and diagenetic modifiers control the properties of secondary porosity in the core. Measured porosity from core plugs data (a total of 103 samples), range from 1.0 to 7.7 % (average 1.8 %) and measured permeabilities range from 0.036 to 3.12 md. The highest measured porosity (7.7%) in the KX-1 core came from the Light Brown Echinoid Grainstone facies at 2661.2 m (Figure 4).

The economic porosity that is present in the drilled portion of "K" platform is present as secondary porosity, mostly in form of intercrystalline microfractures and microporosity,

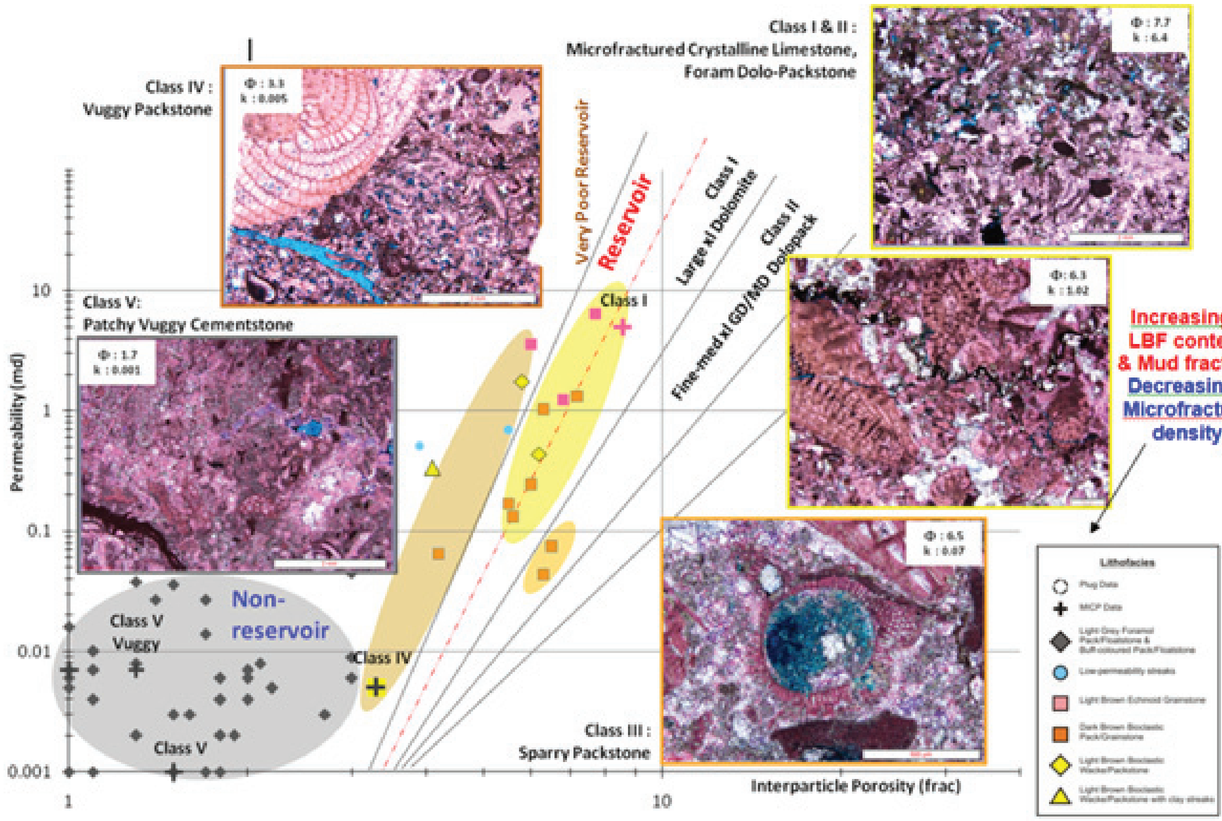

Figure 4. Poro-perm plot tied to rock-fabric classification

with a distribution that partially conforms to the original depositional fabric. Note, lime mudstone microporosity in SE Asian region is known to be capable of forming a reservoir and able to produce gas (Longman, M.W., 1993). However, the presence of low-permeability streaks (e.g. facies change/mosaic distributions), LBF bioclast effects, and heterogeneous matrix-types constitute the main factors for potential flow barriers during diagenesis and may negate the effect of porosity-enhancing diagenetic processes. These effects will impact on gradual/localized quality decline in parts of the reservoir tank or waste zones.

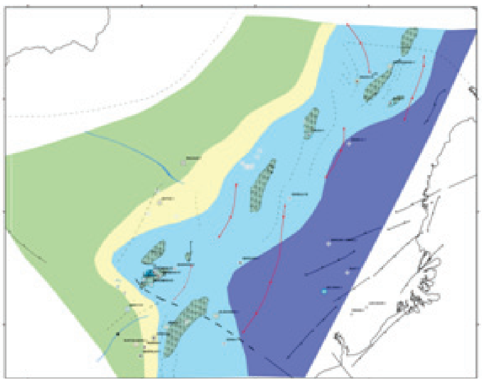

Figure 5. Revised paleogeographic model: land-attached platform. Red box indicate research location

4. Results & Discussion

4.1 Revised Paleogeography Model

This study has two key-findings in that impact on current depositional models in the region: (1) Large Benthic Forams (LBF) or foramol assemblage are main bioherm builders, and (2) Persistent clastic influx into the platform indicates a land-attached settings with nearby clastic influx points affecting the extent and quality of carbonate platform development. The alternation of highly cemented floatstone and grainstone shoal environments indicates that the general facies mosaic is not entirely random, but maybe influenced by significant fluctuation of siliciclastic influx. Facies contacts between each succession are generally sharp to abrupt, thus forming a crude stratification or layering. Conspicuous buff-layers marks possible sequence boundaries that can be correlated confidently between wells.

These lithofacies and biofacies characteristics formed depositional cycles that can be tied into wireline and FMI log signatures and used to predict electrofacies. The lack of typical aggradational massive bright zone FMI signatures and a predominance of "deeper" lagoonal environment signatures infer that the KX-1 well is located within the platform interior, however the integration of core description corroborated by electrofacies interpretation permits a reconstruction of a possible alternative paleogeographic model of the "K" platform. The "K" carbonate platform developed as an open internally-bedded platform, in a land-attached setting, located in a semi-enclosed embayment (Figure 5). In such a restricted setting, the carbonate platform was likely protected from the Indonesian Throughflow current and more influenced by low-energy, tide-dominated processes. Coral-rich patch reefs possibly developed on the northwest flank of the platform, away from the sediment plume emanating from a major deltaic lobe. Periodic storms and transgressive events, promote higher energy setting and bioerosion of the local patch reefs that supplied coarse-grained sediment that extending into platform interior as shoal complexes. Based on regional compilation, there is several fluvial input points that shed clastic material sourced from the hinterland and encroaches the "K" platform position from the North and SW direction (Witts, 2012).

4.2 Diagenesis and Implication to a Reservoir Model

This study shows that despite an overall compaction effect, different matrix types have different responses to burial and some unit tend to host new diagenetic pathways for subsurface fluid flow that can lead to secondary porosity generation.

The current study shows significant events generating secondary porosity occurred during deep burial environment to uplift stages, and recognizes an additional pore-enhancing diagenetic mechanism which is related to "matrix-specific intercrystalline microfractures". Integrated stable isotope analyses tied to rock texture has allowed interpretation of post-depositional fluid evolution. Previous studies have not recognized the influence of the active tectonic setting in the construction of a reservoir model, core data from KX-1 well penetrated reservoir zones consisting: microfractured grainstone shoals, and leached packstones in the platform interior setting. This shows that the control of economically important secondary porosity is related to: (1) late-stage burial leaching and, (2) intercrystalline microfracturing generated by younger tectonic overprints (e.g. uplift trend) and possibly associated with the Oligo-Miocene inversion event (Figure 6).

The matrix-specific intercrystalline microfractures typically develop in the echinoid-rich grainstone lithofacies, which typically characterized by syntaxial calcite overgrowths. This imply relatively rapid cementation that have occluded the entire primary depositional pore space. Furthermore, a single crystal echinoderm grain is less susceptible to replacement. This is considered as negative factor that downgrades the reservoir potential in this zone. However, wireline log and core plug RCA apparently confirm this zone as possessing the highest reservoir quality. Petrographic observations show distinct brittle intercrystalline microfractures and associated large dolomite crystals (isotopically late stage), possibly precipitated during deeper burial from warmer fluid crossflow. Poro-perm plots indicate this zone is controlled by the large-size crystal permeability field of Lucia (1995) which possibly related to connected intercrystalline fracture pore spaces in the matrix. Such extensive distribution of brittle intercrystalline microfracture is possibly promoted by pervasive recrystallization of both matrix and grains by syntaxial calcite overgrowth, which then encouraged extensive stratabound brittle fracture development during tectonic uplift. Tectonically-induced diagenetic event may also enhance the pre-existing secondary porosity which was generated by earlier- processes associated with a deep-burial environment, such as burial leaching and microporosity.

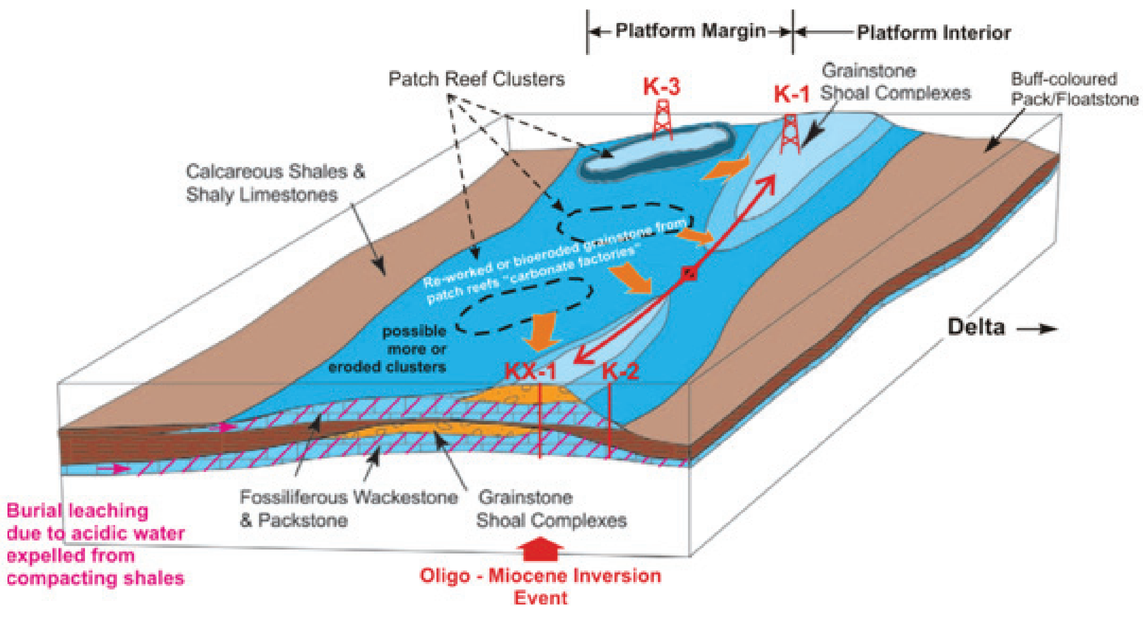

Figure 6. Reservoir Porosity and Permeability Distribution Model of "K" Carbonate Platform

5. Conclusion

This study shows that complex carbonate reservoirs can only be resolved by integrated core analysis with wireline log analysis, and most importantly this must be based on reliable and valid datasets. Basic data filtering of unreliable core plug poro-perm data points proved to be a major contributor to the outcomes in this study.

Comprehensive core description utilizing lithofacies, biofacies, XRD, supported by wireline log data shows that the "K" carbonate platform is carbonate platform developed in a land-attached setting, within a low-energy, semi-enclosed embayment. It was a bedded open platform without significant development of an elevated reef rim. The revised platform model implies more extensive reservoir quality grainstone and packstone units are present across the platform interior. These formed stacked layers of carbonate sand shoals that represent deposition during high-energy storm or transgression events separated by muds.

Petrophysical rock type study integrated with stable isotope analysis show reservoir quality poro-perm classes are generated as secondary porosity during burial-compaction and uplift diagenesis, which relate to; (1) matrix-specific intercrystalline microfractures, and (2) microporosity formed by non-fabric selective burial leaching and dolomite replacement. A modified diagenetic model predicts that burial leaching and dolomite replacement in platform interior is plausible via funneling and channelized leaching fluid pathways reaching from the platform margin through continuous permeability zones into platform interior.

These findings open up new exploration and development paradigms by identifying new elements as targeting criteria in Oligocene carbonate platform, namely: (1) Layered grainstone units with extensive lateral extents in the platform interior setting, (2) Structural overprints to create combination traps, thus extending targets from strict "reefal build-up" into diagenetically altered zones in the platform interior.

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