

Lithofacies and depositional environment of D sequence, Upper Oligocene formation of Gao field, Cuu Long basin from well log data

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Abstract: *The D sequence, Upper Oligocene formation is the main target for petroleum exploration and exploitation activities at GAO field in Cuu Long basin. The study primarily uses well log and core samples data from exploration wells in the area to investigate the lithofacies and depositional environment. Shale, sandstone and volcanic material were identified in the gamma ray log. Base on variations in lithology as indicated by well log response, the D sequence can be divided into three members (D1, D2, and D3 sub-sequences), which were deposited in fluvial to lacustrine environments. The shapes of the gamma ray signature of D2 sub-sequence are serrated funnel, bell and cylindrical reflected sediment deposited in a mouth bar and a distributary channel environment. Sedimentary structure characterized by parallel ripple cross-bedding, with occasional weak cut cross-bedding or small lenticular features. Meanwhile, sediments of D1 and D3 sub-sequences were deposited in a distal lacustrine environment, characterized by saw tooth features, indicating thick layers of lacustrine shale interbedded with thin shore face sand layers*

Keywords: *lithofacies, depositional environment, well log, core sample, D sequence, Upper Oligocene*

1. Introduction

In petroleum exploration tasks, well log data are commonly used for lithology identification, formation evaluation, and well correlation. Especially, well log interpretation plays a crucial role in the study of lithofacies and depositional environments, particularly in clastic reservoirs. In many cases, core samples, which provide direct insight into subsurface geology, may not be available; therefore, wireline logs become the primary data source for geological interpretation. By utilizing various well logs, such as gamma-ray, spontaneous potential, resistivity, neutron, density, and sonic logs, geoscientists can interpret characteristics of lithofacies, including grain size, mineral composition and sedimentary structures. Relating these features to the processes that produced them is the basic method used by geoscientists for interpreting the depositional environment of the sedimentary basin, because different physical, chemical, and biological processes would display for the distributions of grain size and sedimentary structures that characterize deposited sediment. As a result, well log analysis has become an indispensable tool for geologists seeking to interpret lithofacies, depositional environments, and predict the potential of reservoirs in hydrocarbon exploration. In this study, the authors also use core sample data as clues to determine the depositional environment and cross-check it with interpretation results from well log data to provide a consistent assessment of the depositional environment of the D sequence, Upper Oligocene, Cuu Long basin.

Among all well logs, geoscientists usually utilize gamma ray (GR) and spontaneous potential (SP) logs for classifying lithofacies and determining the depositional environment. The gamma ray log is the most widely used log for facies analysis and depositional environment interpretation because it shows a wide variety of shapes, greater definition, and more character. The variation in gamma ray log characteristics can be used to interpret grain size and depositional energy. Coarse-grain sand, which is deposited in high-energy environments, will have a low gamma ray value, while fine-grain shale will have a high gamma ray value. An abrupt change in gamma ray log response is interpreted as being related to sharp lithological breaks

associated with unconformities and sequence boundaries (Nwagwu et al., 2019; Dalrymple & Choi, 2007; Delfiner et al., 1987;).

2. Geological background

The GAO field is located in block X on the southeastern margin of the Cuu Long Basin, offshore on the Vietnamese continental shelf . It is regarded as a field with significant potential for oil and gas accumulations/deposits. The petroleum system in this field has been confirmed to contain all essential elements: source rock, reservoir, cap rock, trap, and possibility of migration. The source rocks are composed of shale from the Upper Oligocene and Lower Miocene sedimentary, while the reservoirs consist of fractured granitoid basements and sandstones from the Early Oligocene to the Early Miocene. The caprocks consist of shale layers from the Con Son, Bach Ho, Tra Tan, and Tra Cu formations, as well as Rotalia shale within the Bach Ho formation. Potential traps are mainly structural, stratigraphic, or a combination of both, and were predominantly formed during the syn-rift and early post-rift periods. The formation of these traps occurred before the migration of hydrocarbons, which created favorable conditions for effective hydrocarbon entrapment. The stratigraphic column shows that the study area comprises pre-Cenozoic basement rocks and Cenozoic sedimentary formations from the Oligocene, Miocene, and Pliocene-Quaternary periods, including the Tra Cu, Tra Tan, Bach Ho, Con Son, Dong Nai, and Bien Dong formations. D sequence is the member of the Tra Tan formation, Late Oligocene (Fig. 1) (Chuc Nguyen et al., 2019; Nguyen Huy et al., 2018).

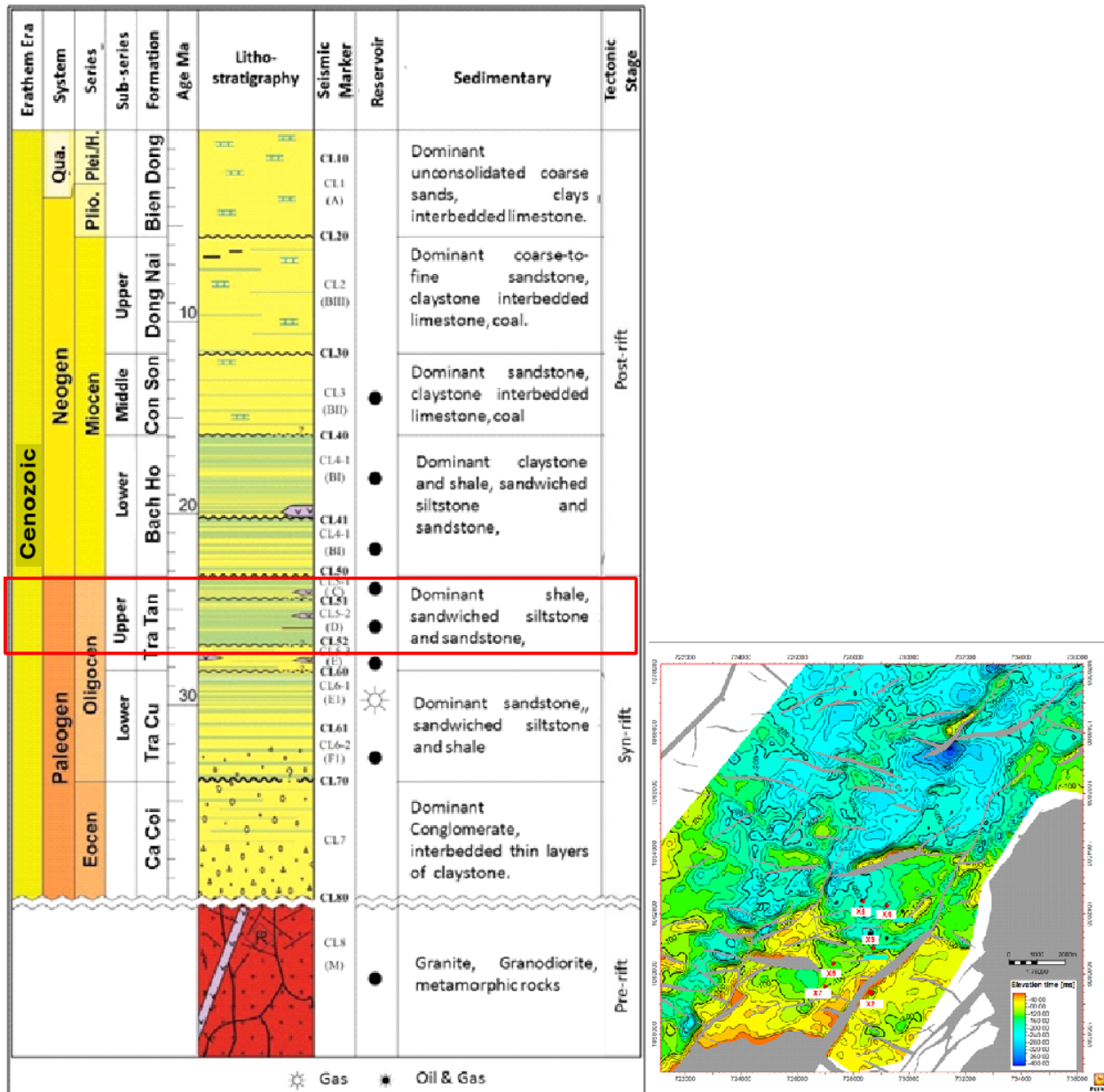


Fig. 1. Stratigraphy of the Cuu Long basin with tectonic phases (modified from Tran and Phung 2007; Morley et al. 2019), displaying sequences D (Tra Tan Formation) and locating wells in the study area

The Cuu Long basin is the oval-shaped, early Tertiary rift basin, located on the southern continental shelf of Vietnam. It is separated from the Gulf of Thailand basins to the west by the Khorat High and from the Nam Con Son basin to the southeast by the Con Son swell. The geological evolution of the Cuu Long basin can be divided into 3 episodes: pre-rift (Pre-Tertiary), syn-rift (Eocene to Oligocene), and post-rift (Miocene - Present) (Schmidt et al., 2019). The pre-rift period was marked by widespread magmatic activities, which led to the formation of the crystalline basement for the basin. During the Oligocene, syn-rift basins were initially filled with coarse-grained alluvial and fluvial sand-dominant sediments, represented by the F and lower E sequences. In the Late Oligocene, the lacustrine environment became dominant, leading to the formation of the E and D shale sequences, which serve as the primary source rocks for the basin. A compressional phase in the Late Oligocene caused the basement to be fractured, leading to the formation of folds and reverse faults, which are observed throughout much of the basin. The post-rift phase begins in the Early Miocene, from which point the whole basin enters the thermal sag phase, dominated by

fluvio-marine to shallow marine environments (Chuc Nguyen et al., 2019; Kieu & Dung, 2018; Nguyen Huy et al., 2018; Tran et al., 2017).

3. Materials and Methodology

In this study, the primary data source is a dataset of well logs from 14 wells, used to identify the lithofacies and depositional environment of the D sequence in the Upper Oligocene formation of the Gao field. However, data only from five wells (X3, X4, X5, X6 and X7) were included in this paper due to the restricted data-sharing policy of the providing organization (Fig. 1). Core sample data from wells X4, X6, and X7 were also used to interpret the depositional environment of the D sequence. Additionally, the study also incorporates biostratigraphy and thin-section petrography data from wells in the Gao field to support and compare the interpretation results for the D sequence's depositional environment.

Gamma ray log was used to identification of lithology. Gamma ray log records the radioactivity of the sedimentary layers pierced by the boreholes. Shale lithology is usually associated with high gamma ray and sandstone lithology is associated with low gamma ray value (Majid et al., 2017; Nwagwu et al., 2019). The higher levels of radiation in shale are caused by absorption of thorium by clay minerals, the potassium content of clay minerals (principally illite), and uranium fixed by associated organic material. By contrast, sandstones have low levels of radioactivity, although numerous exceptions occur. Sources of gamma radiation in sandstone can often be attributed to clay minerals, potassium feldspars (in arkosic sandstones), micas (in micaceous sandstones) or heavy minerals (such as zircons). Therefore, geoscientists can use gamma ray log data to determine grain size and subsequently infer the flow energy corresponding to the depositional environment.

In terms of depositional environment, the shape of the gamma-ray curve is one of the most basic and widely used tools in petroleum exploration (Cant, 1992; M, Okosun, Goro, & Baba, 2019; Nwagwu et al., 2019; Mene & Okengwu, 2020). The five most common pattern of the gamma ray log are funnel, bell, cylindrical, symmetrical and serrated shapes (Fig. 2) and they are as follows:

Funnel shape: This curve could reflect coarsening upward which is an indication of a lithology change from shale to sand and it is gradual upward decrease in gamma ray response. This is a cleaning up trend and a sign of increasing depositional energy. This type of curve is common inferred depositional environments in crevasse splay, mouth bar, delta front, shore face, or it may be change from clastic to carbonate deposition.

Bell shape: This is fining upward trend and it represents a gradual upward increase in gamma response. It is the prograding process and indicates the lithology change from sand to shale. This shape also represents for fluvial point bar, deltaic distributaries, proximal deep sea setting, tidal point bar environments.

Cylindrical/Blocky shape: This type is characterized by sharp boundaries at the upper and bottom boundaries with relatively consistent gamma log value which indicate uniform lithology. It is also referred to as an aggrading process. This curve is typically observed in fluvial channel sands reef, tidal sands and prograding delta distributaries.

Symmetrical shape: This type of trend is linked to a gradual decrease followed by a gradual increase in gamma values. It indicates the progradation and retrogradation of clastic sediments.

Serrated/ Saw tooth shapes: This type is characterized by fluctuating gamma ray value, which indicated a mixture of various grain size of sand and shale lamination within the lithology. This pattern typically signifies fluvial floodplains, mixed tidal flats, and debris flow depositional environments.

GR Log Pattern	Cylindrical/ Boxcar	Funnel	Bell	Symmetrical	Serrated/Irregular
GR Trend					
Sediment Supply	Aggrading	Prograding	Retrograding	Prograding & Retrograding	Aggrading
Depositional Environment (Common)	Fluvial channels, Carbonate shelf, Reef, Submarine canyon fill, Prograding delta distributaries, Aeolian dunes, evaporite fill of basin	Crevasse splay, River, Mouth bar, Delta front, shoreface, Submarine fan lobe	Fluvial Point bar, Tidal point bar, deep tidal channel fill, Deltaic channels, proximal deep sea settings, Tidal flats	Reworked offshore bar, regressive to transgressive shore face delta,	Fluvial flood plain, Storm dominated shelf, mixed Tidal flat, Debris flow, Canyon fill, Deep marine-slope

Fig. 2. Common sedimentological facies associated with various gamma-ray log shapes. Modified after (Cant, 1992; Nwagwu et al., 2019)

4. Results
Lithofacies

The gamma ray values range from 0-150 API units. If the measured signal shifts to the left (low GR values), it indicates sand, whereas a shift to the right suggests shale. The gamma ray logs for D sequence from 5 wells showed sandstone (in yellow) and shale (in green), interbedded with thin layers of siltstone (Fig. 3). In the study area, volcanic materials were encountered in several wells, most notably in wells X5 and X7. These occurrences show significant variations in well log curves, such as density and sonic (with RHOB curve tending to increase and DT decreasing, while the GR values are relatively low).

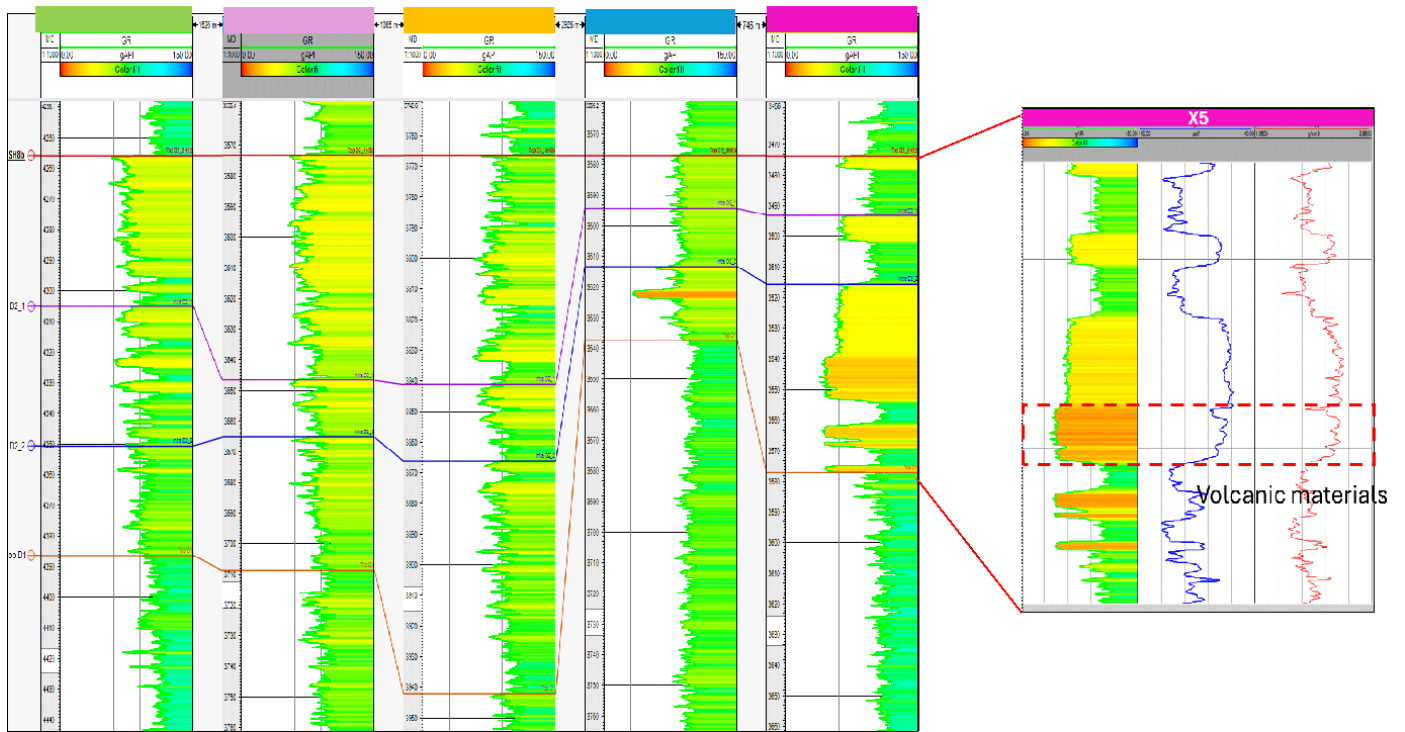


Fig. 3. Lithofacies of D sequence identify from gamma ray log indicate sedimentary include shale, sand and volcanic material

Depositional environment

Previous research results also proved Cuu Long basin developed through different climate condition. Cycles of alternating long periods of wet and dry climate extend or shrink the water covered area of the lake (Tran et al., 2017). Base on variations in lithology as indicated by well log response, the D sequence can be divided into three members (D1, D2, and D3 sub- sequence). The sedimentary environment of three sub- sequence is also controlled by changes in water level due to the climate and shelf bottom due to tectonic activities. The first stage is characterized by a distal lacustrine setting resulting from basin extension and rifting. The second stage recorded a period of gradual fall in the lake water levels, leading to the forming of mouth bars and distributary channel sandstones, which act as importance reservoirs of GAO field. The final stage of Upper Oligocene sedimentation is marked by a deep lacustrine environment, when the lake water level increased again, forming thick layer of shale in the whole area of block X. The shale layers in D1 and D3 serve as an effective source rock for hydrocarbon generation in the study area.

D1 sub-sequence

The variations in climate, in addition to plate tectonic activities, can significantly impact synrift sedimentation (Lambiase & Morley, 1999). In Cuu Long basin, fault activities during the syn-rift period created half-grabens that were filled with alluvial fan sediments of the E sequence. In the initial stage, the sediment supply was limited. Additionally, over an extended period of wet climate, the water level in the eastern sub-basin of the Cuu Long Basin rose, causing the lake to expand. This environmental shift led to the accumulation of fine-grained (shale-rich) sediments over the previously deposited coarse-grained layers. The biostratigraphy analysis results show that the D1 sub-member is characterized by a typical fossil assemblage, mainly including *Botryococcus spp.*, *Pediastrum spp.*, *Bosedinia infragranulata*, *Potamogeton spp.*, and many autochthonous fossils deposited in a freshwater lacustrine environment (Fig. 4). This is also a common characteristic of the Eocene-Oligocene lacustrine sediments of the Cuu Long basin (Hoang Dam & Thi Tham, 2022; Mai Hoàng, Nguyễn Thị, & Nguyễn Hoài, 2018).

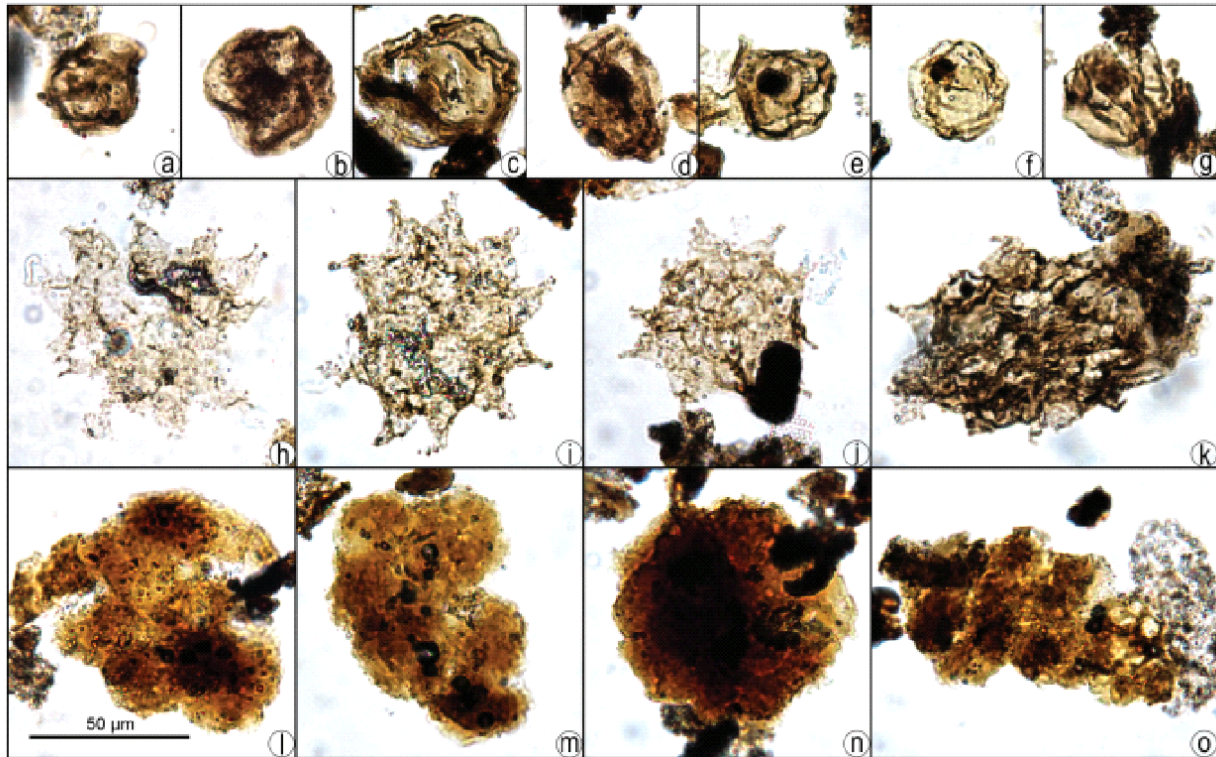


Fig. 4. The fossil assemblage characterizes a freshwater lacustrine environment; (a-g) - types of Bosedinia ring-shaped algae fossils; (h-k) groups of Pediastrum green algae fossils; (l-o) groups of Botryococcus green algae fossils (Mai Hoàng et al., 2018)

The lithological composition of the D1 sub-member is primarily fine- to medium-grained interbedded sandstone and shale beds. The sandstones are primarily categorized as arkosic, mainly composed of quartz with minor feldspar and granite fragments. The trend of the gamma ray curve in this D1 sub-member is the serrated shape gamma ray log motif revealed the deposition of heterolithic mixture of various grain size sediments. High gamma-ray values (ranging from 85 to 150 API) in shale formations associated with fluvial floodplains reflect distal lacustrine environment (Chow et al., 2005; Mene & Okengwu, 2020). These shale layers are relatively thick and are widely distributed across the wells in Block X (Fig. 5), serving as the source rock for hydrocarbon generation in prospective traps within the study area. D1 sub-member also records the presence of thin-bedded shoreface sandstones, resulting from gravity-driven flows (hyperpycnal flows, turbidites, etc.) in deep lacustrine environments during flooding (Aird, 2019; Shanmugam, 2021). The shoreface facies, characterized by relatively small wave amplitudes, abundant vegetation, and numerous insect burrows, consequently reduces the quality of the reservoir (Majid et al., 2017; Syah Putra et al., 2021). Additionally, in thin-section petrography samples from the lower part of D1 sub-member, the development of zeolite minerals was observed (Fig. 6). The zeolitized cementation or partially replaces some of the feldspar grains leads to a significant reduction in intergranular pores, which degrades reservoir quality.

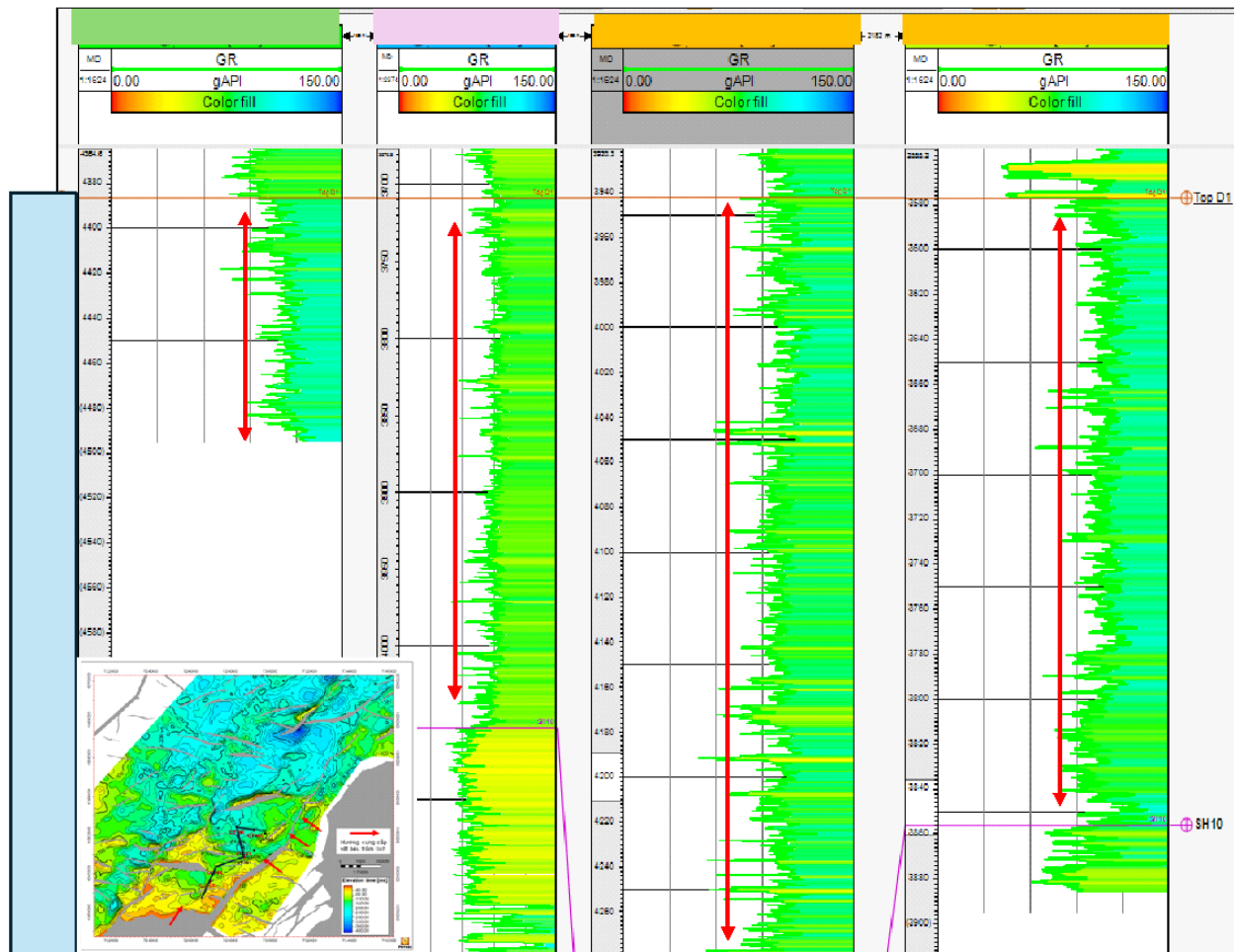


Fig. 5. Gamma ray log shape trend saw tooth reflected distal lacustrine depositional environment

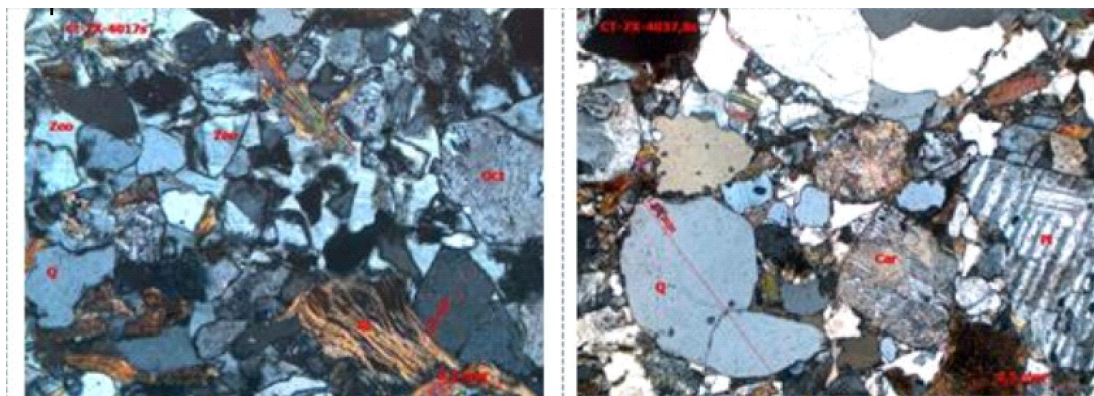


Fig. 6. Characterization of material composition of sandstone in upper Oligocene sediments, well X7 at intervals of 4017-4037m

D2 sub- sequence

During dry climate periods, the lake's water retreated and filled only the small area. The uncovered area became fluvial depositing place for near-source sediments and subsequently evolved into reservoirs (Mene & Okengwu, 2020; Nwagwu et al., 2019; Tran et al., 2017). According biostratigraphy, this D2 sub-sequence is characterized by a decrease in the fossils *Pediastrum spp.* and *Bosedinia infragranulata*. The main fossil assemblage consists primarily of *Botryococcus spp.*, *Botryococcus braunii*, *Pediastrum spp.*, *Leiosphaeridia spp.*, *Micrhystridium spp.*, and *Tasmanites spp.* The shape of the gamma ray log at the lower part of the D2 sub-sequence is primarily funnel-shaped (coarsening upward), characteristic of sediments formed in mouth-bar environments. Meanwhile, the gamma ray log shapes at the upper part of the D2 sub-sequence are cylindrical and bell-shaped, reflecting distributary channel (Fig. 7). Thus, during this period, the dominant depositional environment is fluvial.

The trend of the gamma ray log shape in the D2 sub-sequence also indicates a change in sedimentary facies between wells. For example, the lower part of the D2 sub-sequence in wells X3, X4, and X6 shows a funnel shape, while wells X5 and X7 exhibit a blocky shape (Fig. 8). This variation is due to the sedimentary characteristics during this period were controlled by the fall in lake water levels and the change in shelf bottom (due to the heterogeneity in fault intensity, sediment input direction, and subsidence caused by extension and compaction processes). In a fan delta, sediment is transported from the high-energy channels that carry sand, silt, and clay from source (Con Son and Soi swell) enters the lacustrine environment (standing water) leading to a significant reduction in flow velocity. As the main channels reach the delta front, they distribute sediments into multiple smaller channels or distributaries, which fan out as they approach the water body. The rapid decrease in energy causes the heavier, coarser-grained sediments to settle out quickly, while finer-grained sediments are carried further into the water. As a result, the formation of mouth bars, which is characterized by a coarsening-upward sequence, indicating progressive deposition during flood events. Over time, these sand bodies grow and extend outward, creating potential hydrocarbon reservoirs characterized by good reservoir quality with high-quality porosity and permeability (Keighley et al., 2021; Olariu et al., 2010; Tye & Hickey, 2001; Wang, 1992). The interpretation of well log data from 6 wells in the GAO field shows that the sandstone reservoirs in the D2 sub-sequence have moderate to high reservoir quality (neutron porosity, NPHI: 14-25%, transit interval time, DT: 80-92 $\mu\text{s}/\text{f}$, bulk density, RHOB: 2.3-2.4 g/cm^3) and high resistivity values ranging from 10 to 30 Ohm.m. The well log interpretation indicates that the sandstone reservoirs of the D2 sub-sequence have an effective thickness ranging from 3 to 10 m, shale volume between 6% and 22%, porosity from 13% to 21%, and oil saturation between 40% and 60%. However, a few thin sandstone layers in the wells, with low DT values ranging from 57 to 63 $\mu\text{s}/\text{f}$, are considered tight sandstones, lacking reservoir potential.

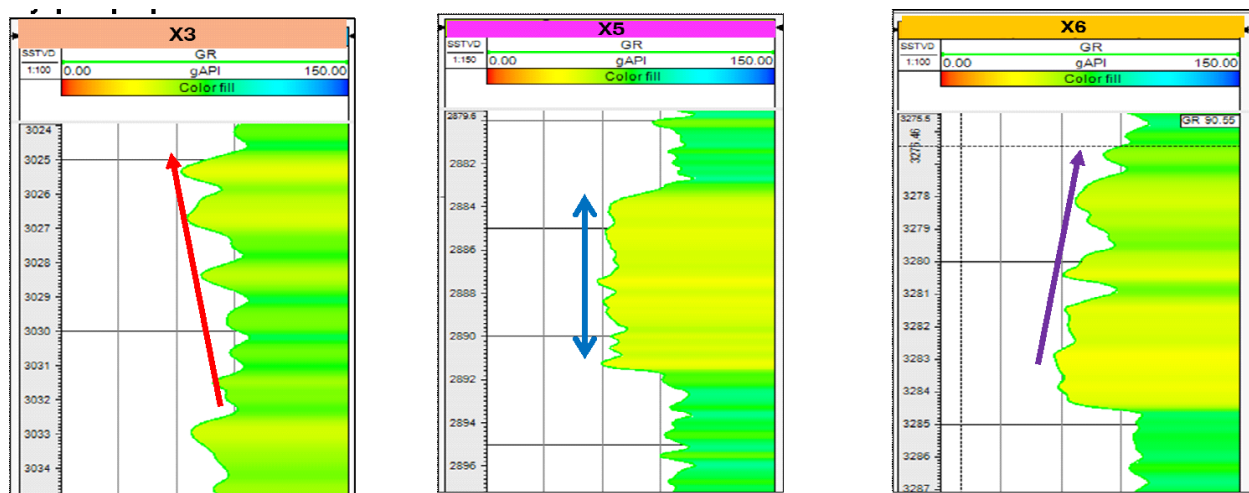


Fig. 7. Gamma ray log patterns characterize the depositional systems in the study area

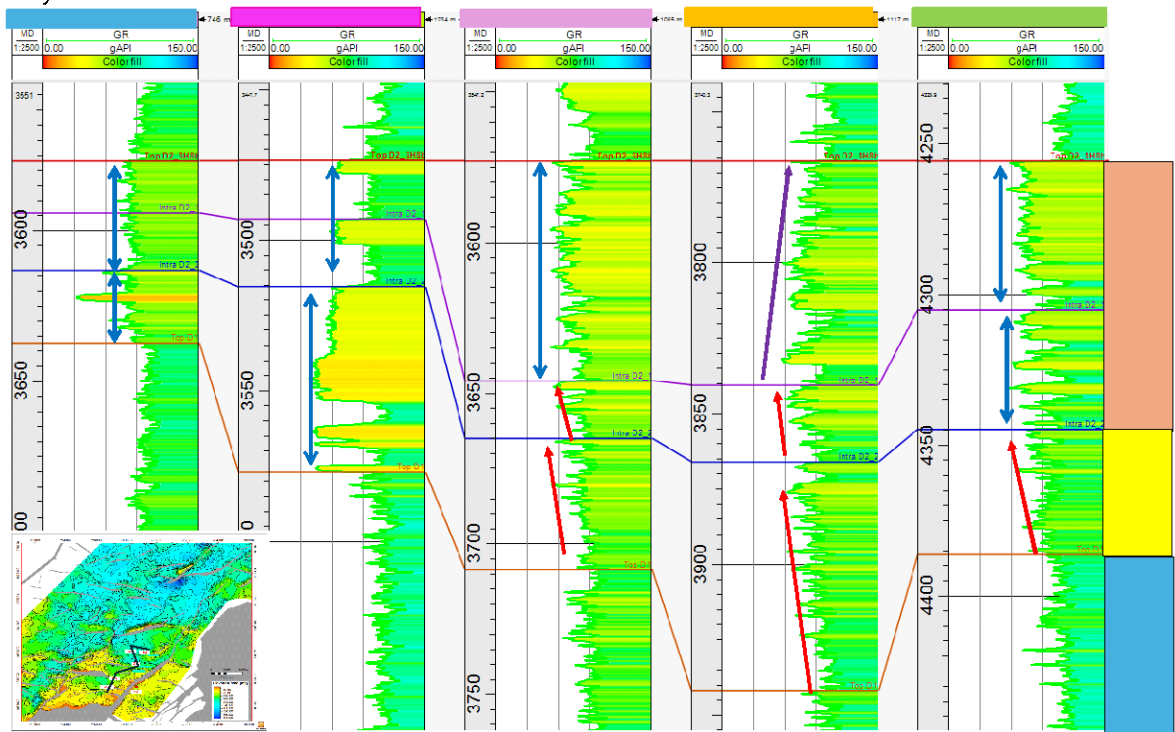


Fig. 8. Gamma ray log shapes showing the fluvial deposited environment dominated in D2 sub-sequence in wells of GAO field

The core samples (well X4 and X6) and sidewall core sample (X7 well) show that the lithological composition includes sandstone, siltstone, argillite shale, and clay limestone, interbedded with thin layers of eruption products. The sandstones have gray, light gray, and dark-brownish gray colors due to irregular oil saturation, primarily exhibiting a blocky structure with uncertain thick layering. Some samples display a thin layering structure characterized by parallel ripple cross-bedding, with occasional weak cut cross-bedding or small lenticular features (Figs 9 and 10). The texture of the rocks in this sub-member varies from layer to layer, ranging from fine-grained to small- and medium-grained, and includes irregular coarse-grained sandstone with small amounts of gravel and clay-silty materials, moderately to poorly sorted. The sandstones are mostly classified as arkose grading and graywacke-arkose. Siltstone and argillaceous shale are present in smaller proportions. The mineral composition of the rock is rich in quartz and feldspar (averaging 55.2% and 15%, respectively), with fewer lithic fragments (granitoid, siliceous, quartzite, etc.). The moderate to good roundness (So: 1.6-2.2) and sorting (Ro: 0.4-0.6) indicate that the sedimentary material originates from magmatic sources and has been transported relatively far from the source (Con Son and Soi swell). These characteristics suggest that the sandstones in this sub-sequence were formed in a distributary channel or mouth bar in the deltaic plain area, under conditions of unstable current energy due to changes in tidal rhythms, seasonal variations, and alterations in the shelf bottom caused by river bed movements.

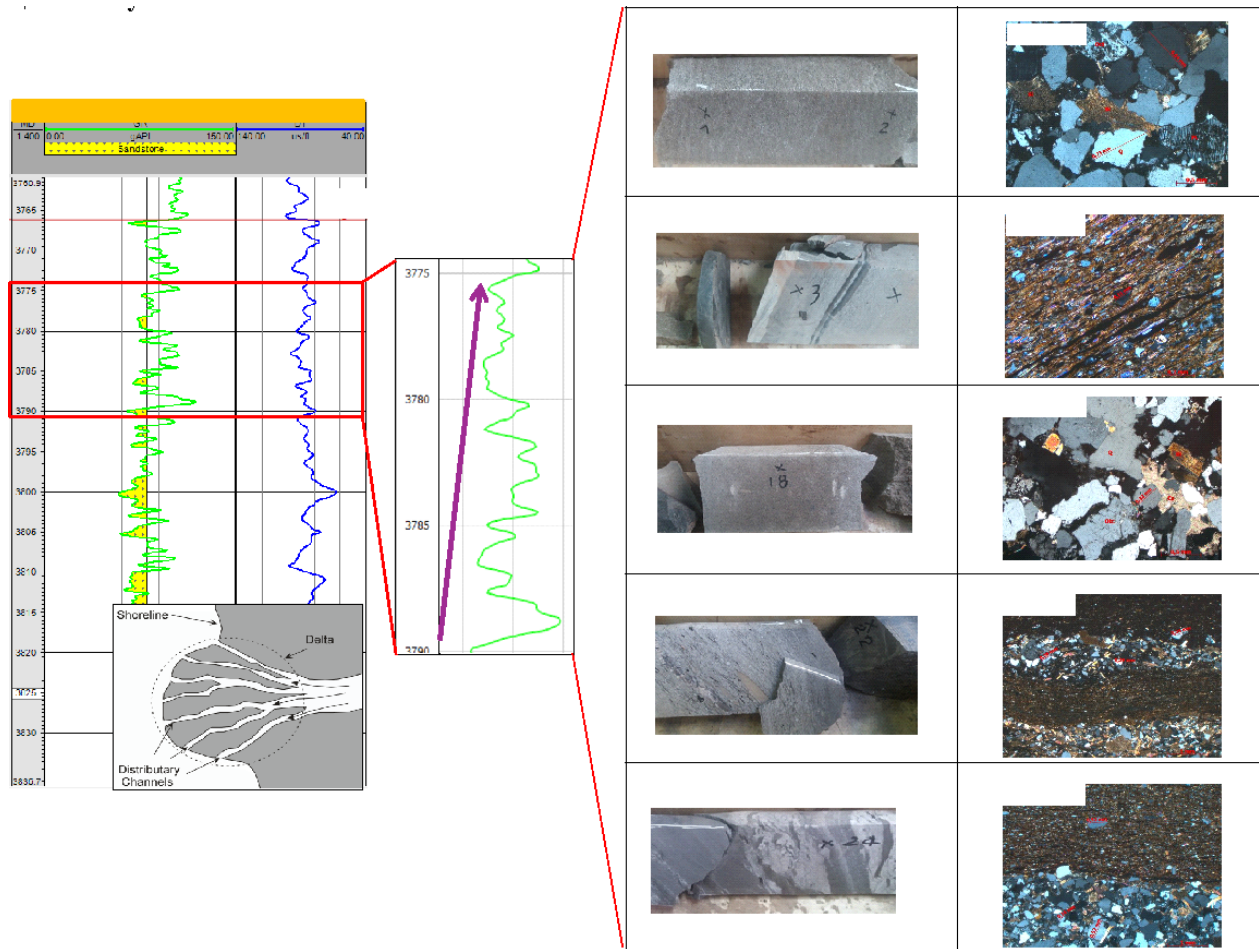


Fig. 9. Textural and structural characteristics of core samples of well X6, D2 sub-sequence of Upper Oligocene formation, 3780.5- 3785.45 m interval

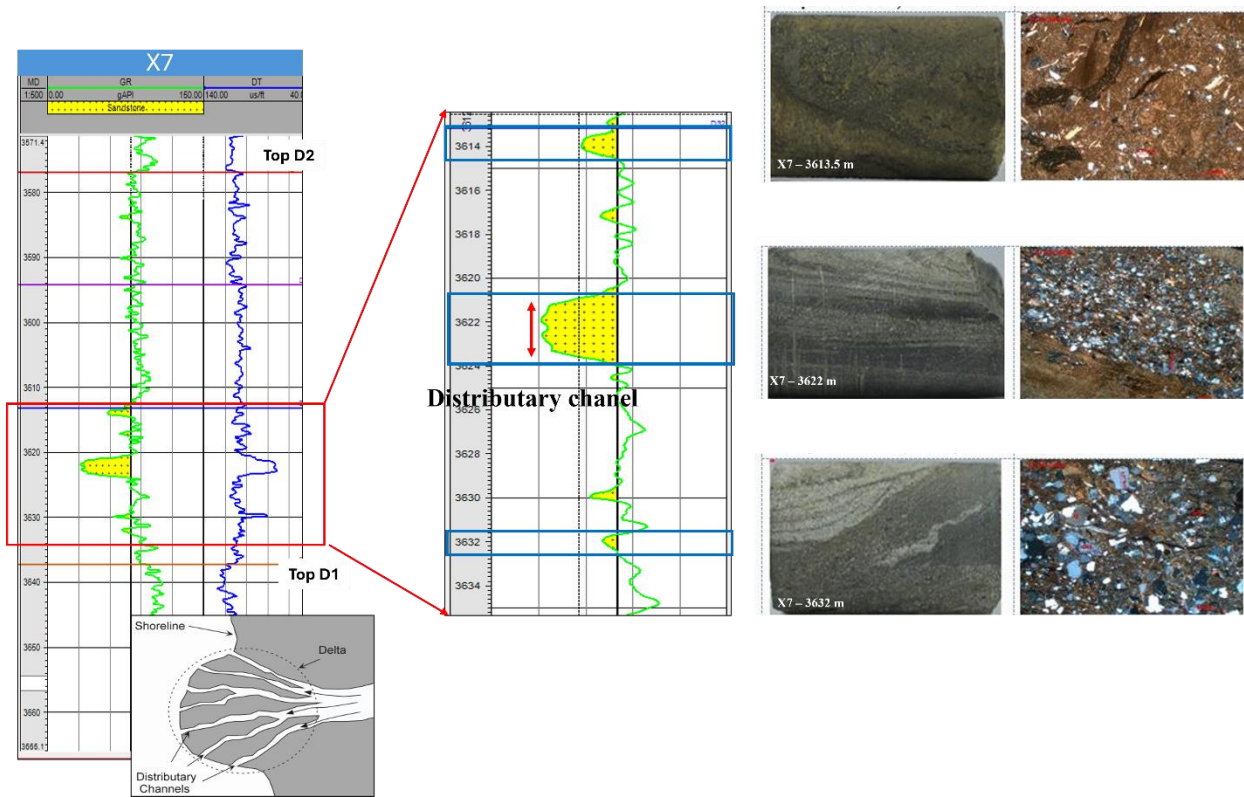


Fig. 10. Textural and structural characteristics of sidewall core samples of well X7, D2 sub-member of Upper Oligocene formation, 3613.5-3632 m interval

The results of thin-section petrographic analysis, core and side wall coresample descriptions of the D2 sub-member from the wells in the GAO field also provide similar interpretations regarding the sedimentary deposition environment. The reservoirs were mainly formed in Distributary channel environment (X5 and X7) and mouth bar environment (X3, X4 and X6, which are characterized by high-quality reservoir properties (Fig. 11). The sedimentary facies in this formation were mainly transported from the Southeast, primarily from the Con Son swell, with a minor contribution from the South from the Soi swell.

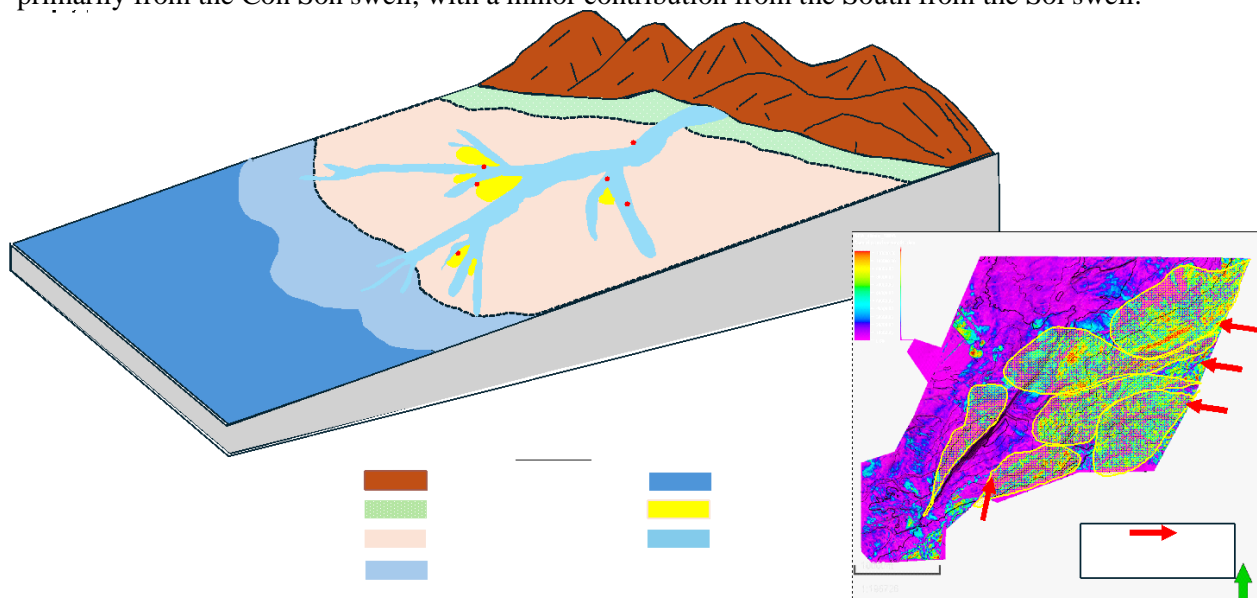


Fig. 11. Block diagram showing a generalised depositional model of D2 sub-sequence for a lacustrine delta front

D3 sub-sequence

D3 sub-sequence formed during long periods of wet climate, the lake covered area spread out facilitating lacustrine facies deposition. It is easily noticeable that the sand-shale ratio varies significantly within this D3 sub-sequence. The lower part consists of thin sand layers interbedded with shale, while the middle and upper part mainly comprise thick layers of shale, indicating the dominance of a deep lacustrine environment in this stage. The lacustrine environment developed strongly, characterized by the presence of thick shale deposits reaching hundreds of meters, with a stable gamma ray trend (90-115 API). According to wireline data, there are thick sand deposits found at the bottom of the distal lacustrine formed by underwater currents that transported sediments from the coastal plain to the lacustrine, leading to the formation of turbidite deposits or distal fan systems. Because these deposits were transported far from the sediment source with moderate flow energy, the sorting and roundness of the grains were relatively good, which resulted in favorable reservoir characteristics. For example, in the interval from 3675-3754 m in well X6, there are several sandstone layers interbedded with thin shale layers that exhibit potential reservoir (Fig. 12).

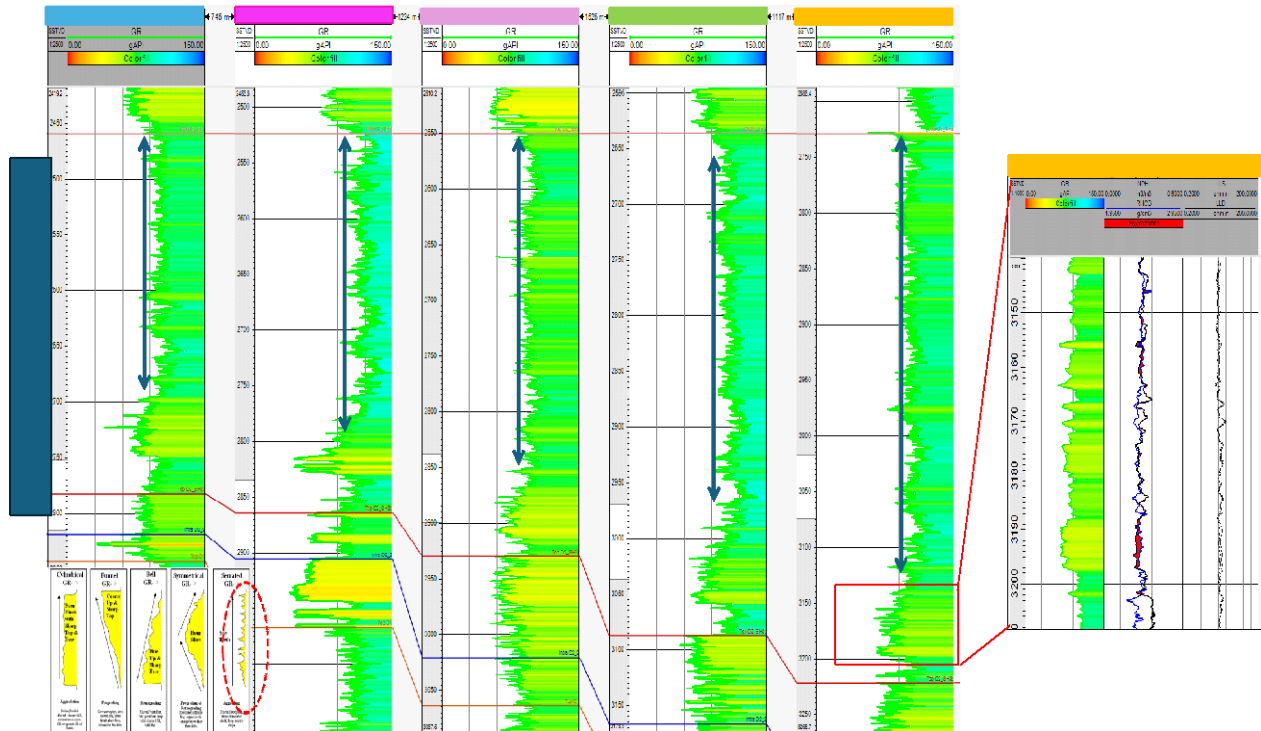


Fig. 12. Gamma ray log shapes showing the distal lacustrine deposited environment dominated in D3 sub-sequence in GAO field

5. Conclusion

The depositional environment of D sequence is dominated by fluvial to distal lacustrine facies. Sediment supply is mainly from Con Son swell in the southeast and minor from Soi swell in the south part.

The depositional environment of the main reservoirs of D sequence (D2 sub-member) varies between wells. Sandstone reservoirs of well X5 and X7 characterized by distributary channel, meanwhile reservoirs of well X3, X4 and X6 deposited in mouth bars environment.

The shoreface sandstone of D1 sub-member also considered potential reservoir. However, the porosity of these reservoirs is reduced due to the compression process due to the proximity to the sediment provenance area.

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