



Depositional Facies Influence on Reservoir Heterogeneity in The Balikpapan Formation, Lower Kutai Basin: Insights Well Log

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ABSTRACT - This The Balikpapan Formation in the Lower Kutai Basin hosts a complex assemblage of fluvial-to-deltaic reservoir facies whose heterogeneity significantly influences reservoir quality and connectivity. This study integrates well-log interpretation, electrofacies classification, and quantitative petrophysical evaluation from six wells to assess the stratigraphic controls governing reservoir distribution. Three main facies associations are identified: channelised sandstones, mouth-bar to delta-front, and prodelta. Proximal channel sands exhibit the highest porosity (18–30%) and permeability (5–40 mD), but their limited lateral continuity results in poor interwell connectivity. Mouth-bar and delta-front sands display moderate porosity (12–25%) and permeability (<1–30 mD) and form laterally extensive, sheet-like bodies that enhance reservoir connectivity under increasing tidal influence. Thick prodelta mudstones act as regionally extensive vertical seals. The stratigraphic framework is characterised by repeated upward-coarsening parasequences bounded by marine flooding surfaces, reflecting alternating phases of delta progradation and transgression. These results demonstrate that depositional processes and stratigraphic architecture are the primary controls on reservoir heterogeneity in the Lower Kutai Basin.

Keywords: Lower Kutai Basin, facies, Balikpapan Formation, reservoir, well log.

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INTRODUCTION

Reservoir quality and heterogeneity in clastic sedimentary systems are fundamentally governed by the nature and distribution of depositional facies. Variations in grain size, sedimentary structures, bed geometry, and stacking patterns impose strong controls on porosity–permeability architecture, ultimately influencing fluid flow behaviour and hydrocarbon recovery efficiency. In many deltaic to shallow-marine successions, these facies transitions are often complex, laterally discontinuous, and difficult to predict solely from outcrop or core data. As a result, well-log analysis has become a critical tool for delineating facies variability and interpreting reservoir heterogeneity in subsurface settings Chambers & Daley 1997; Husein & Lambiasi 2013; Jamaluddin et al., 2023.

The Lower Kutai Basin in eastern Kalimantan represents one of Southeast Asia's most prolific Tertiary petroleum provinces, characterised by thick, rapidly deposited syn-rift and post-rift clastic sequences Chambers & Daley 1997; Allen & Chambers 1998; Cibaj et al., 2007. Within this basin, the Balikpapan Formation hosts a diverse range of fluvial–deltaic to shallow-marine deposits whose reservoir characteristics remain insufficiently constrained. Previous studies have highlighted the influence of high sedimentation rates, active tectonics, and accommodation changes on stratigraphic architecture in the Lower Kutai Basin; however, the direct relationship between depositional facies and reservoir heterogeneity within the Balikpapan Formation has received limited attention Bachtiar et al., 2013; Jamaluddin et al., 2024a.

Understanding how depositional processes shape reservoir properties in this formation is particularly essential due to its increasing significance in regional hydrocarbon exploration and field development strategies. Well-log signatures offer a continuous, high-resolution dataset for recognising facies transitions, predicting reservoir quality, and refining stratigraphic models where core availability is limited. By integrating gamma-ray, resistivity, density, and neutron log

responses, it is possible to evaluate lithological variability, identify electrofacies, and characterise vertical and lateral heterogeneity across the reservoir intervals.

Unlike previous studies that primarily focused on lithofacies description or single-well analysis, this study integrates electrofacies classification and quantitative petrophysical evaluation across multiple wells to constrain the stratigraphic controls on reservoir heterogeneity and connectivity in the Balikpapan Formation. This study investigates the extent to which depositional facies control reservoir heterogeneity in the Balikpapan Formation, utilising well-log–based facies analysis to elucidate internal architectural patterns and reservoir distribution. The results provide new insights into the subsurface stratigraphy of the Lower Kutai Basin and contribute to more robust reservoir prediction and development workflows in similar clastic depositional systems.

The stratigraphic framework of the Lower Kutai Basin is dominated by thick Neogene clastic successions deposited during rapid subsidence and sustained sediment input from the hinterland. Within this framework, the Balikpapan Formation occupies a key position in the Middle–Upper Miocene stratigraphic interval, overlying the older fluvio-deltaic units and underlying younger coastal to shallow-marine sequences associated with continued Mahakam Delta progradation (Figure 1a) Hutchison 1989; Metcalfe 2011; Jamaluddin et al., 2023; Jamaluddin et al., 2024b. Regionally, the Balikpapan Formation is composed of a vertically stacked succession of sandstone, siltstone, and mudstone intervals that collectively represent a spectrum of deltaic to nearshore depositional environments. The lower part of the formation is typically dominated by fine-grained mudstones and heterolithic beds interpreted as prodelta to distal delta-front deposits. These units commonly exhibit upward-coarsening motifs, reflecting gradual shoaling as delta lobes advanced basinward Metcalfe 2011; Friederich et al., 2016; Permana et al., 2018; Hall & Nichols 2002. The middle portion of the formation contains the most significant

reservoir-prone intervals. It is characterised by medium to thick-bedded sandstones associated with distributary channels, mouth bars, and wave-modified delta-front settings (Oktaviyani et al., 2022). Sedimentary structures including cross-bedding, hummocky cross-stratification, and sharp-based erosional contact surfaces are frequently observed in core and are well expressed in well-log signatures through blocky to bell-shaped gamma-ray responses Selley 1978; Serra 1990; Euzen & Power 2014. These sand-rich intervals are interbedded with mudstones and siltstones that record episodic abandonment, channel-margin deposition, and offshore suspension settling, creating a highly heterogeneous reservoir architecture (Satyana et al., 1999). The upper part of the Balikpapan Formation exhibits an increased influence of coastal and shallow-marine processes. This interval contains laterally extensive shoreface sandstones intercalated with offshore-transition mudstones. Upward coarsening shoreface successions are commonly capped by marine flooding surfaces, indicating repeated shoreline transgressions linked to relative sea-level fluctuations in the region (Hall, 2002; 2012).

Stratigraphically (Figure 1b), the formation is bounded by regionally correlatable flooding surfaces that serve as key markers for high-resolution sequence stratigraphic interpretation. These surfaces delineate parasequence sets that represent cycles of progradation, retrogradation, and aggradation driven by the interplay of sediment supply and accommodation changes Cibaj et al., 2007; Riadi & Lambiasi 2015.

The internal stratigraphic complexity of the Balikpapan Formation particularly the distribution of high quality sandstone bodies within finer-grained intervals highlights the need for integrated well-log, core, and seismic analysis to accurately characterise reservoir heterogeneity Marshall et al., 2015; Oktaviyani et al., 2022; Ronlei et al., 2025.

The research area focused on the Balikpapan Formation in the Lower Kutai Basin, East Kalimantan, Indonesia, where the formation is mainly composed of deltaic to shallow-marine siliciclastic deposits consisting of interbedded sandstones, siltstones, shales, and coal layers that indicate deposition under fluctuating marginal-marine conditions during the late Neogene (Jamaluddin et al., 2023).

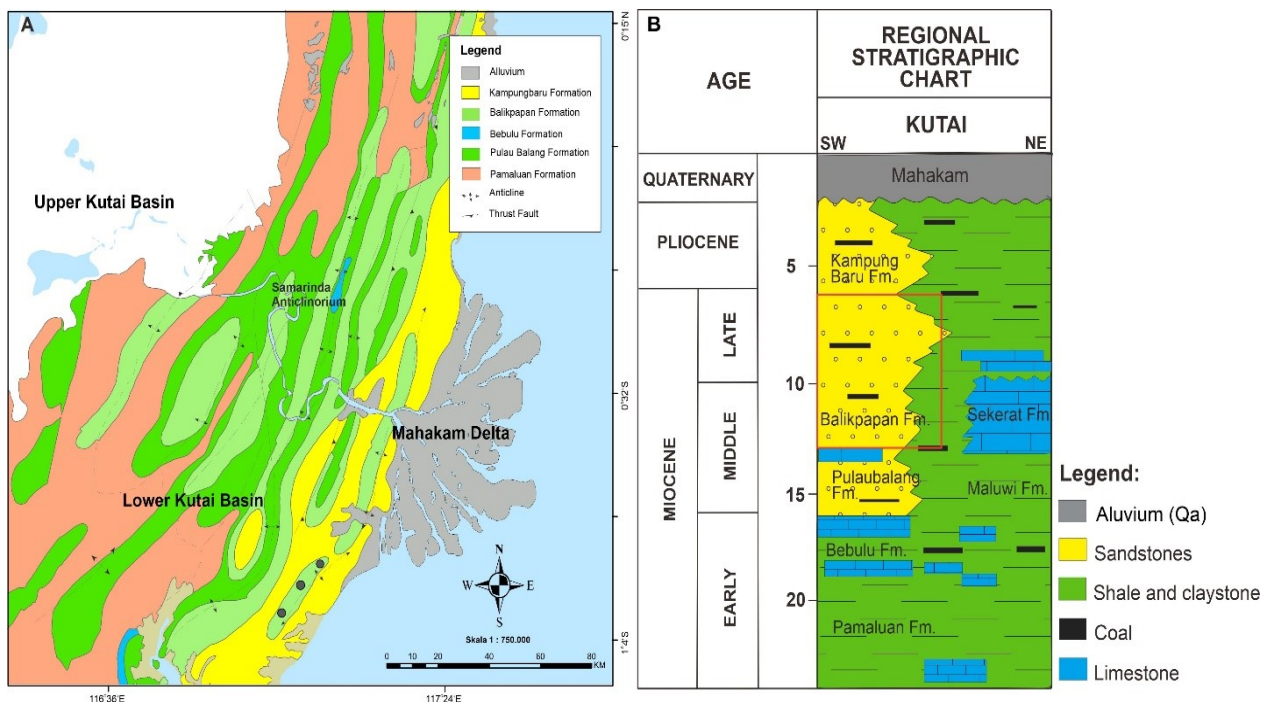


Figure 1. (a) Geological map of the Kutai Basin showing the distribution of the major stratigraphic formations. The black dot indicates the location of the studied well. (b) Regional stratigraphic chart illustrating the Miocene–Pliocene succession from southwest to northeast (modified from Satyana et al., 1999; Jamaluddin et al., 2023).

METHODOLOGY

This study integrates well-log interpretation, electrofacies classification, and petrophysical evaluation to quantify the influence of depositional facies on reservoir heterogeneity within the Balikpapan Formation (Figure 2). A dataset comprising six vertical wells (WHD-1 to WHD-6) located in the central sector of the Lower Kutai Basin was analysed. Each well contains a suite of wireline logs including gamma ray (GR), resistivity (RT), density (RHOB), neutron porosity (NPHI), and sonic (DT) logs.

Initial preprocessing involved depth matching, environmental correction, and quality control to ensure log consistency across all wells. Spurious spikes, washout-affected intervals, and tool malfunction zones were identified and removed through a combination of cross-plot inspection and curve normalisation. All logs were calibrated to a uniform baseline to minimise inter-well variability caused by differing acquisition conditions.

Electrofacies interpretation using gamma-ray (GR) logs relies on log motifs, stacking patterns, and GR responses to infer depositional facies. GR logs record natural radioactivity in API units (0–150 API), where high API values reflect shale-rich lithologies and low values indicate sand-dominated intervals. Common GR motifs include cylindrical,

funnel, bell, bow, and irregular are used to distinguish fluvial, deltaic, and shallow-marine depositional settings in the subsurface (Selley 1978; Nazeer et al., 2016).

Shale volume, porosity, and water saturation were calculated to quantify reservoir quality within each facies. Shale volume (V_{sh}) was estimated using linear equation to accommodate varying maturity levels of the formation. Total porosity (Φ_T) was derived from density–neutron cross-plots, while effective porosity (Φ_E) was computed after correcting for clay-bound water using standard volumetric models. Formation water resistivity (R_w) was determined from Pickett plot analysis using intervals of clean water-bearing sands. Water saturation (S_w) was calculated using the Indonesia equation, with parameters optimised for local reservoir conditions.

A detailed well-to-well correlation was constructed to evaluate lateral facies variability and reservoir continuity. Key stratigraphic markers, flooding surfaces, and upward-coarsening or upward-fining trends were traced across the six wells. Correlation panels generated within the petrophysical software provided visualization of facies distribution and internal heterogeneity at the reservoir scale.

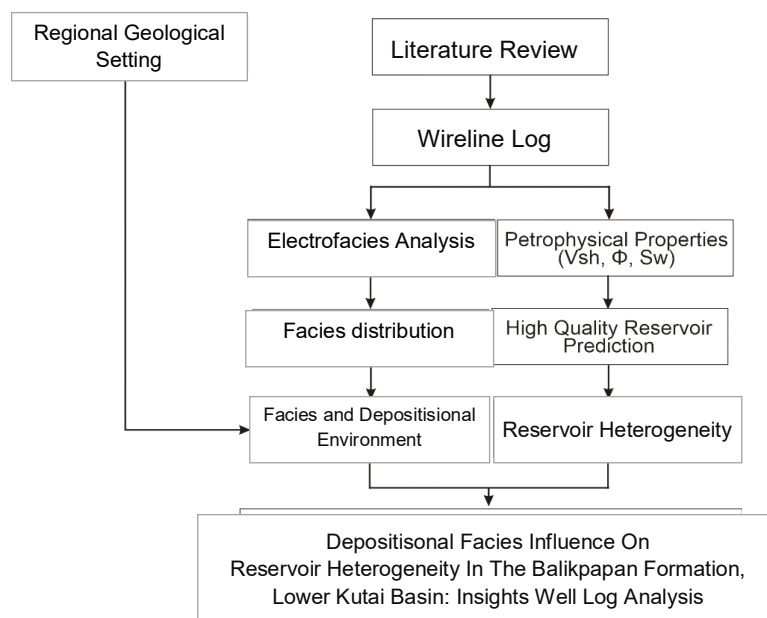


Figure 2. Integrated workflow for electrofacies interpretation and petrophysical evaluation of the Balikpapan Formation, Lower Kutai Basin

RESULT AND DISCUSSION

Log-based facies distribution

To better constrain the vertical facies variability and depositional dynamics, gamma-ray log motifs from multiple wells were carefully examined. These log signatures reflect characteristic grain-size successions and sedimentary processes within the Balikpapan Formation. The identified motif types are summarised in Figure 3. The gamma-ray log motifs documented in the Balikpapan Formation provide essential insights into the sedimentation dynamics governing its fluvio-deltaic architecture. The dominance of funnel-shaped patterns reflects multiple episodes of progradation driven by high sediment supply and sustained fluvial input, consistent with an active delta-front environment during relative sea-level fall. In contrast, the bell-shaped motifs mark intervals of waning flow and reduced sediment delivery, capturing the transition toward more accommodation-dominated settings such as abandoned channels, estuarine backfilling, or reworked mouth-bar successions during transgressive phases. The cylindrical log shapes indicate periods of relatively stable hydraulic conditions, likely representing aggradational channel fills or distributary systems that maintained persistent sediment flux across the delta plain. The presence of symmetrical shaped signatures highlights the imprint of tidal modulation, suggesting that portions of the Balikpapan depositional system operated under mixed fluvial-tidal influence typical of the central Kutai deltaic regime. Collectively, these motifs reveal that sedimentation in the Balikpapan Formation was

governed by the interplay between fluvial processes, tidal reworking, and relative sea-level oscillations, producing a vertically heterogeneous stacking pattern that records the cyclicity of regressive–transgressive deposition.

To further refine the interpretation of log-based facies distribution, gamma-ray log motifs were systematically analysed across the studied wells (Figure 4). These motifs reflect characteristic vertical grain-size trends and depositional processes, where funnel-shaped patterns indicate coarsening-upward successions related to progradational delta-front deposits, bell-shaped motifs represent fining-upward channel or distributary-fill sequences, cylindrical motifs suggest relatively uniform lithology associated with aggradational conditions, and symmetrical patterns record alternating energy fluctuations within transitional depositional settings.

Building upon these motif-based interpretations, an integrated analysis of gamma-ray logs from well WHD-1, WHD-2, and WHD-3 was conducted to reconstruct the vertical facies architecture and stratigraphic stacking patterns of the Balikpapan Formation. The vertical succession reveals repeated regressive–transgressive cycles developed within the fluvio-deltaic system. Regressive phases are characterised by upward-coarsening trends, reflecting progressive shoreline progradation and increased sand dominance, whereas transgressive phases display upward-fining trends, indicating landward shoreline retreat and enhanced shale deposition under relatively lower-energy conditions. The correlation of these log signatures

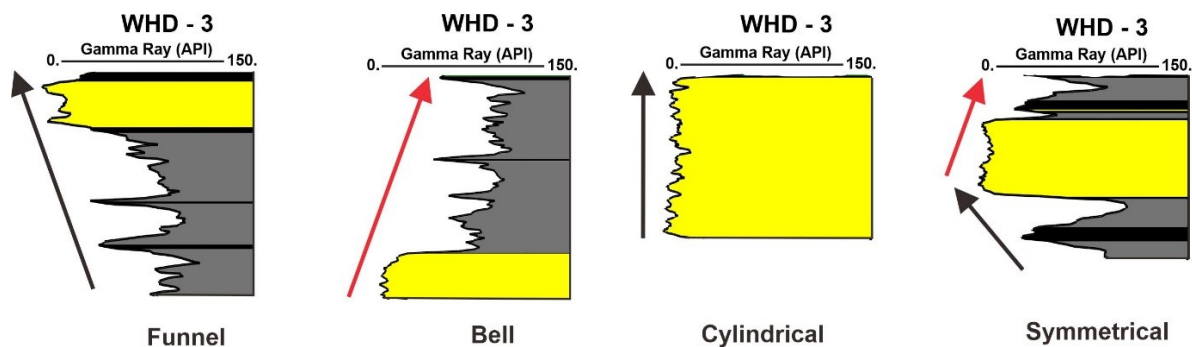


Figure 3. Gamma-ray log motifs identified from well in the Balikpapan Formation, Lower Kutai Basin, illustrating four characteristic shapes: (a) funnel, (b) bell, (c) cylindrical, and (d) symmetrical patterns

across the three wells demonstrates laterally persistent stratigraphic cyclicity, suggesting that relative sea-level fluctuations exerted a primary control on sediment dispersal, accommodation space, and facies stacking within the Balikpapan fluvio-deltaic succession.

Facies a channelised sandstones

The gamma-ray and lithology log depicts a thick sandstone interval defined by a blocky, cylindrical GR motif, indicating a relatively homogeneous, sand-dominated package typical of a

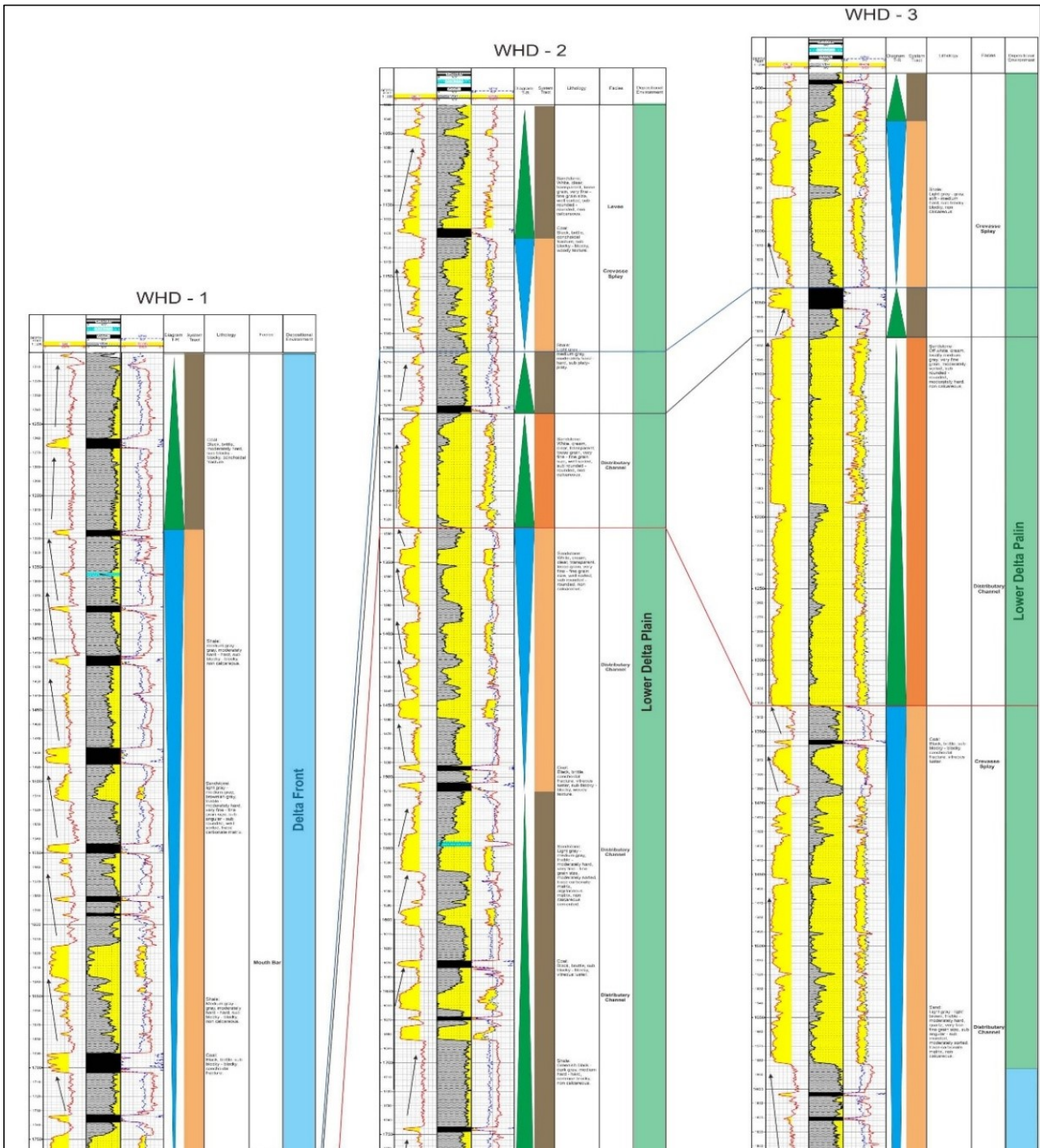


Figure 4. Gamma-ray logs from well WHD-1, WHD-2, and WHD-3 were interpreted to delineate regressive–transgressive cycles developed within the fluvio-deltaic successions of the Balikpapan Formation.

distributary-channel deposit. The channelized sandstone facies is characterised by blocky to funnel-shaped gamma-ray motifs, elevated resistivity, and consistently high porosity, with thicknesses ranging from 6 to 18 m. The low and consistently uniform gamma-ray values reflect minimal clay content and a sharp contrast with adjacent muddier facies, suggesting deposition under sustained high-energy fluvial conditions. Lithological attributes white to cream coloration, very fine to fine grain size, excellent sorting, and sub-rounded to rounded grain morphology support interpretation of a traction-dominated sediment supply capable of efficiently winnowing fines. The absence of calcareous material further points to a siliciclastic-dominated fluvial system with limited marine influence. Collectively, these characteristics are consistent with a well developed distributary-channel sandstone within the Balikpapan Formation, representing one of the most reservoir-prone facies due to its high textural maturity, uniform internal architecture, and potential for elevated porosity and permeability. The log response and representative interval of this facies are illustrated in Figure 5.

Facies B – mouth-bar and delta-front sandstones

expressed as funnel-shaped/upward-coarsening GR trends that are laterally persistent across the transect and form the most regionally continuous and laterally connected reservoir sheets. The mouth-bar and delta-front sandstones represent the most laterally extensive and internally organised reservoir units within the correlated interval. In the log panel, these facies appear as funnel-shaped or gently upward-coarsening gamma-ray (GR) trends, transitioning from moderate GR values at the base to cleaner, lower GR values near the top. This motif reflects a classic progradational energy gradient in which fine-grained suspension fallout is progressively overlain by coarser traction deposits as the delta lobe advances basinward. The resistivity logs typically increase upward in parallel with the GR trend, indicating improved grain sorting, reduced clay content, and greater hydrocarbon saturation potential toward the top of each mouth-bar cycle.

Laterally, these units correlate exceptionally well across all six wells, forming sheet-like sand bodies that extend over significant distances, in contrast to the discontinuous and incised geometry

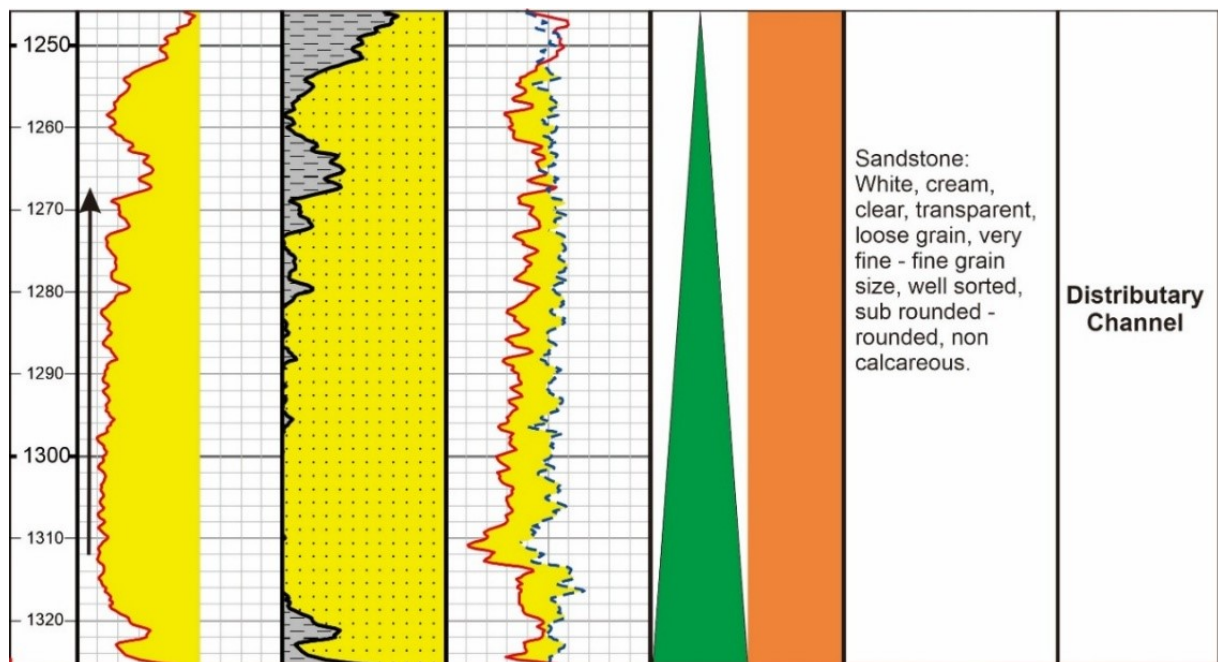


Figure 5. Gamma-ray and lithology log showing a thick sandstone interval characterised by a blocky (cylindrical) GR motif, interpreted as a distributary-channel deposit.

of distributary channels. The correlation lines linking these sand packages are smooth, nearly horizontal, and uninterrupted, demonstrating that mouth-bar sands preserve a high degree of spatial continuity - a defining characteristic of wave - or mixed-energy delta-front systems. This continuity suggests deposition in a lower-gradient, moderately energetic environment just seaward of the distributary channel mouths, where sediment dispersal occurs through deceleration and lateral spreading of the outflow plume.

The log panel exhibits a classic upward coarsening motif, defined by moderate to high gamma-ray values at the base transitioning upward into cleaner, sand-rich intervals, which is diagnostic of mouth-bar progradation. The alternation of light- to medium-gray shale with increasingly sand-dominated packages reflects episodic sediment delivery at the river mouth, where fluctuating flow energy governs the deposition of fine-grained topset muds and progressively cleaner foreset sands. The sandstone

units very fine to fine grained, moderately to well sorted, and lightly cemented suggest traction-dominated deposition under decelerating currents as distributary-plume energy dissipated seaward.

The slightly serrated GR patterns and intercalated shale streaks indicate intermittent suspension fallout and periodic waning-flow events, consistent with the dynamic nature of river-dominated delta fronts. Increased resistivity and porosity within the upper sandstone portions further support a transition toward better-developed mouth-bar reservoirs. However, the vertical juxtaposition of sand-rich and mud-rich layers introduces moderate reservoir heterogeneity, with mud-prone intervals acting as internal baffles. The log response and facies characteristics are illustrated in Figure 6, supporting interpretation of a well-developed distributary-channel sandstone within the Balikpapan Formation and highlighting its strong reservoir potential due to high textural maturity and favourable porosity-permeability.

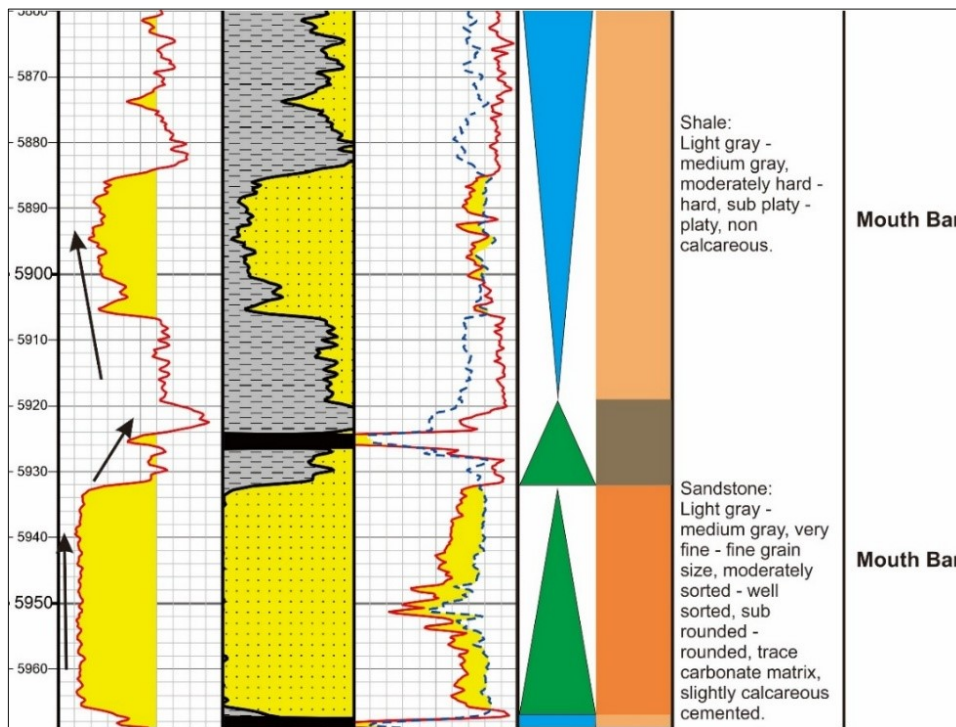


Figure 6. Gamma-ray log responses illustrating a mixed sandstone-shale succession interpreted as mouth-bar deposits within the Balikpapan Formation.

Petrophysical properties

The analysis of petrophysical data from the Wahid field, encompassing wells WHD-1, WHD-2, and WHD-3, reveals a compelling interpretation of the reservoir characteristics, lithology, porosity, and hydrocarbon saturation, consistent with a high-quality shaly-sand system. The distribution of key petrophysical parameters is illustrated in Figure 7.

Histograms of the primary reservoir parameter (likely V_{Sh}) across all three wells show a multi-modal distribution, suggesting significant heterogeneity and the presence of multiple lithofacies or distinct flow units, particularly in WHD-1 and WHD-2. The mean values indicate moderate to good overall reservoir potential. The neutron-density cross-plots, colored by volume of

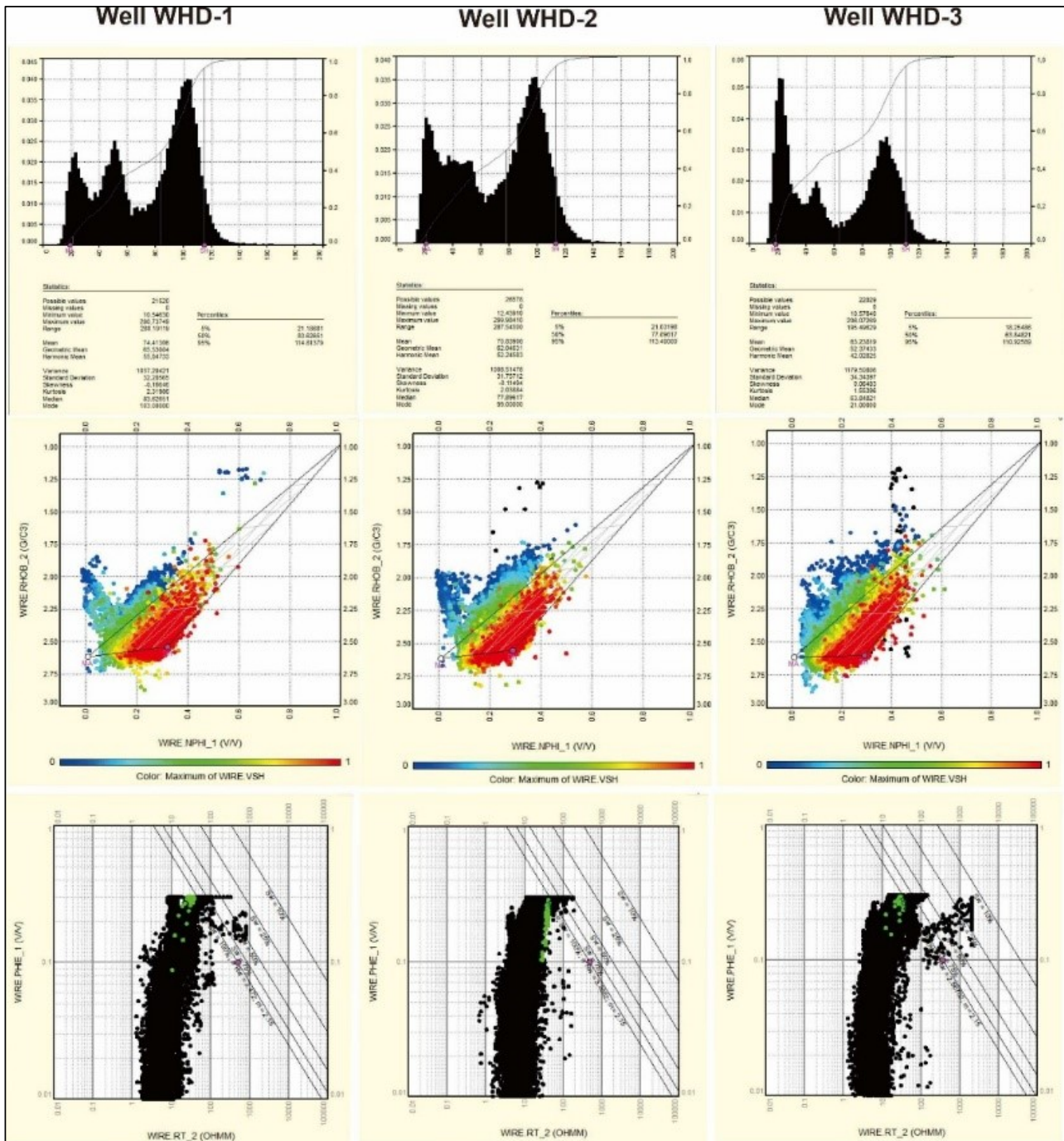


Figure 7. Petrophysical characterization of Wahid field wells (WHD-1, WHD-2, and WHD-3).

Shale confirm the dominant lithology as shaly-sandstone. The bulk of the low- V_{sh} data (interpreted as reservoir rock) aligns closely with the Sandstone trend, exhibiting a substantial range of porosity. Points migrating toward the upper-left of the plot, characterised by high V_{sh} (green/blue/black), are identified as non-reservoir shales or tight streaks.

Critically, a large portion of the reservoir data deviates strongly to the right of the $S_w = 100\%$ line, indicating high true resistivity (R_t) at a given porosity, a definitive signature of hydrocarbon presence. These high R_t data points consistently fall below the $S_w=50\%$ curve and extend into the $S_w=25\%$ saturation zone, confirming the existence of excellent pay zones with high hydrocarbon saturation.

The reservoir intervals in all three wells exhibit porosities reaching approximately 0.30 v/v, with corresponding resistivities often exceeding 100 ohm-m in the hydrocarbon column. While WHD-3 suggests a slightly tighter overall matrix as evidenced by its histogram distribution, the presence of highly resistive, high-porosity points ensures its categorization as a productive reservoir. The integration of these logs highlights the Wahid field as a heterogeneous shaly-sand reservoir characterised by good to excellent porosity and high hydrocarbon saturation.

The WHD-1 well exhibits a vertically heterogeneous fluvio-deltaic succession dominated by mouth-bar and distributary-channel sand bodies, interspersed with crevasse-splay and levee deposits. Mouth-bar intervals typically show moderate shale content (V_{sh} 0.10–0.35) and fair

porosity (18–27%), but permeability is highly variable (1–38 mD), reflecting textural heterogeneity and early diagenetic modification. Distributary-channel deposits constitute several thick, laterally amalgamated sand packages with lower shale content (V_{sh} 0.01–0.06), higher porosity (27–29%), and consistently excellent permeability (36–56 mD), indicating their role as the primary reservoir fairways in the well. These channel sands also exhibit very low water saturation (S_w 65–99%), suggesting vertically connected fluid pathways (Table 1).

Crevasse-splay intervals display moderate V_{sh} (0.15–0.32) and lower porosity (21–24%), with permeability ranging from 0.3 to 64 mD, implying thin, heterogeneous, and locally compartmentalized reservoir zones. Levee facies have the highest clay content (V_{sh} 0.26–0.31), lowest porosity (10–13%), and poor permeability (<2 mD), reflecting their function as internal baffles restricting cross-flow. The overall reservoir architecture in WHD-1 is therefore governed by the juxtaposition of high-quality channel-belt sands against moderately productive mouth-bar sandstones, with crevasse splays and levees acting as heterogeneity elements influencing vertical connectivity (Table 1).

WHD-2 is characterised by a thicker and more continuous sand-dominated succession compared with WHD-1, with distributary-channel and mouth-bar systems comprising the majority of the penetrated interval. Distributary-channel units show broad variability in shale content (V_{sh} 0.04–0.25) and maintain moderate-to-good porosity (23–29%) with permeability mostly in the 20–55 mD range, indicating well-preserved fluvial–deltaic

Table 1. Average Reservoir Properties per facies (well WHD-1)

| Facies | Avg. V_{sh} (v/v) | Avg. Porosity (%) | Avg. S_w (%) | Avg. Perm. (mD) | Reservoir quality |
|----------------------|---------------------|-------------------|----------------|-----------------|-----------------------------|
| Distributary Channel | 0.046 | 26.8 | 92.4 | 36.1 | Excellent; clean, proximal |
| Mouth Bar | 0.178 | 18.8 | 92.2 | 16.7 | Moderate; variable clay |
| Crevasse Splay | 0.214 | 17.4 | 94.5 | 7.2 | Poor–moderate; heterolithic |
| Levee | 0.172 | 17.6 | 94.3 | 10.0 | Tight; non-reservoir |
| Tidal Channel | 0.239 | 13.8 | 100 | 0.9 | Poor; distal tidal mud-rich |

Table 2. Average reservoir properties per facies (well WHD-2)

| Facies | Avg. V _{sh} (v/v) | Avg. Porosity (%) | Avg. Sw (%) | Avg. Perm. (mD) | Reservoir quality |
|----------------------|-------------------------------|----------------------|----------------|--------------------|--------------------------|
| Distributary Channel | 0.061 | 25.9 | 89–95 | 38–52 | Very good |
| Mouth Bar | 0.083 | 24.5 | 90–99 | 20–30 | Good; cleaner than WHD-1 |
| Crevasse Splay | 0.221 | 14–17 | 100 | 3–6 | Poor; water-prone |
| Levee | 0.260 | 11–13 | 100 | 1–2 | Tight |

channel belts. Mouth-bar deposits are abundant and reveal a mixed reservoir character: some intervals contain clean, well-sorted sandstones ($V_{sh} < 0.10$; PHIE 25–27%; Permeability 30–40 mD), while others exhibit more argillaceous textures (V_{sh} up to 0.38) with reduced porosity (18–22%). These variations reflect progressive progradation and abandonment phases during mouth-bar accretion (Table 2).

Tidal-channel deposits appear intermittently and show elevated shale content (V_{sh} 0.16–0.40) with porosity around 18–24%, reflecting bidirectional flow reworking and enhanced mud drapes, resulting in permeability typically <25 mD. Crevasse-splay and levee facies consistently show high V_{sh} (0.24–0.42), lower porosity (16–23%), and restricted permeability (<15 mD), functioning as heterogeneities and barriers within the reservoir. Compared to WHD-1, the WHD-2 well preserves more continuous high-quality sand bodies, suggesting a more proximal position along distributary channels and mouth-bar complexes (Table 2).

WHD-3 displays a thick delta-plain to delta-front succession dominated by amalgamated distributary-channel systems, representing the highest reservoir quality among the three wells. The channel deposits are characterised by very low shale content (V_{sh} 0.10–0.19), good porosity (24–27%), and excellent permeability (36–62 mD), indicating well-developed, laterally connected channel sand bodies. Crevasse-splay units show moderate V_{sh} (0.10–0.24) and slightly lower porosity (23–27%), with permeability varying from 32 to 54 mD, suggesting more heterogeneous but still productive thin sand sheets. Levee intervals at the upper section of the well exhibit higher shale content ($V_{sh} \sim 0.15$) and lower porosity (25–26%),

but permeability remains relatively high (up to 46 mD), reflecting sandy levee deposits typical of a high-sediment-supply distributary system (Table 3). The overall vertical stacking in WHD-3 indicates repeated deposition of thick, amalgamated channel belts separated by thin overbank and splay deposits. Compared with WHD -1 and WHD-2, WHD-3 clearly represents the most favorable reservoir zone, with thicker, cleaner channel sandstones and superior permeability (Table 3).

Depositional controls on reservoir architecture

The reservoir architecture across the WHD-1 to WHD-3 well corridor is fundamentally governed by the spatial and temporal organization of delta-front to delta-plain depositional processes (Table 4; Figure 8). The reservoir quality classification referred to in this section follows the criteria of Koesoemadinata (1980) and is based on integrated petrophysical parameters, including shale volume (V_{sh}), porosity, permeability, and water saturation. The distribution of high-quality reservoir units is primarily controlled by the palaeogeographic position of each well within the fluvial–deltaic system and the dynamics of sediment supply, accommodation creation, and channel migration. WHD-1, positioned more proximally toward the distributary-channel belt, is dominated by thick, blocky sandstone successions with low V_{sh} and consistently high porosity–permeability, reflecting deposition from high-energy channelized flows with limited marine influence. These conditions promoted the development of vertically amalgamated channel bars and mouth-bar complexes, generating a laterally continuous, high-quality reservoir framework.

Table 3. Average reservoir properties per facies (well WHD-3)

| Facies | Avg. Vsh (v/v) | Avg. Porosity (%) | Avg. Sw (%) | Avg. Perm. (mD) | Reservoir quality |
|----------------------|----------------|-------------------|-------------|-----------------|----------------------------------|
| Distributary Channel | 0.110 | 24.9 | 86–93 | 22–36 | Moderate; more distal than WHD-1 |
| Mouth Bar | 0.229 | 17.6 | 90–99 | 8–20 | Highly variable |
| Tidal Channel | 0.210 | 21.9 | 82–95 | 18–35 | Moderate; tidal influence strong |
| Crevasse Splay | 0.255 | 17.9 | ~100 | 2–5 | Very poor |
| Levee | 0.311 | 11.6 | ~100 | 1.1 | Tight |

Table 4. Summary of petrophysical properties by depositional facies in the Balikpapan Formation

| Facies | WHD-1 | WHD-2 | WHD-3 | Interpretation |
|----------------------|--------------|---------------|--------------------|--------------------------------------------|
| Distributary Channel | Best quality | Good-moderate | Moderate | Declining fluvial influence basinward |
| Mouth Bar | Moderate | Best quality | Most heterogeneous | Marine/tidal reworking increases basinward |
| Tidal Channel | Minor | Rare | Dominant | Shows strong tidal regime in WHD-3 |
| Crevasse Splay | Occasional | Moderate | Frequent | Floodplain increases basinward |
| Levee | Present | Present | Present | Overbank muds consistent across wells |

In contrast, WHD-2 is situated in a more intermediate setting where fluctuating energy conditions produced a mosaic of mouth-bar, tidal-channel, and crevasse-splay deposits. The reservoir quality in this well is more variable, as reflected by moderate Vsh, mixed log motifs, and heterolithic textures that developed during rapid facies shifts driven by channel bifurcation, bar progradation, and intermittent tidal reworking. WHD-3, positioned furthest basinward, captures the highest degree of marine influence, with heterolithic tidal-flat and distal mouth-bar facies dominating. Increased shale content and more isolated sand bodies reduce reservoir connectivity in this distal zone, reflecting deposition under lower-energy conditions, higher accommodation, and more frequent abandonment phases

Overall, the reservoir architecture is strongly facies-controlled, where the best reservoir intervals are associated with proximal distributary-channel and mouth-bar deposits, characterised by thick, laterally extensive sandstone bodies with high porosity and permeability. Basinward, reservoir

quality deteriorates due to increased heterogeneity and compartmentalization driven by tidal processes, mud encroachment, and the presence of thinly bedded mixed-energy facies. These depositional controls create a predictable trend of reservoir quality decrease from WHD-1 → WHD-2 → WHD-3, with heterolithic tidal facies acting as internal baffles that segment the reservoir into multiple flow units. This stratigraphic and architectural framework highlights the importance of deltaic geomorphology particularly channel avulsion, bar migration, and tidal modulation in shaping sand-body connectivity and controlling fluid flow behaviour within the reservoir system.

The integrated stratigraphic and petrophysical evaluation indicates that reservoir distribution within the Balikpapan Formation is predominantly controlled by the interaction between fluvio-deltaic depositional processes and relative sea-level fluctuations. The study successfully meets its objective by delineating facies-controlled reservoir architecture and quantifying the key parameters governing reservoir quality and heterogeneity.

Depositional Facies Influence on Reservoir Heterogeneity
 in The Balikpapan Formation, Lower Kutai Basin: Insights Well Log Analysis (Farida et al.)

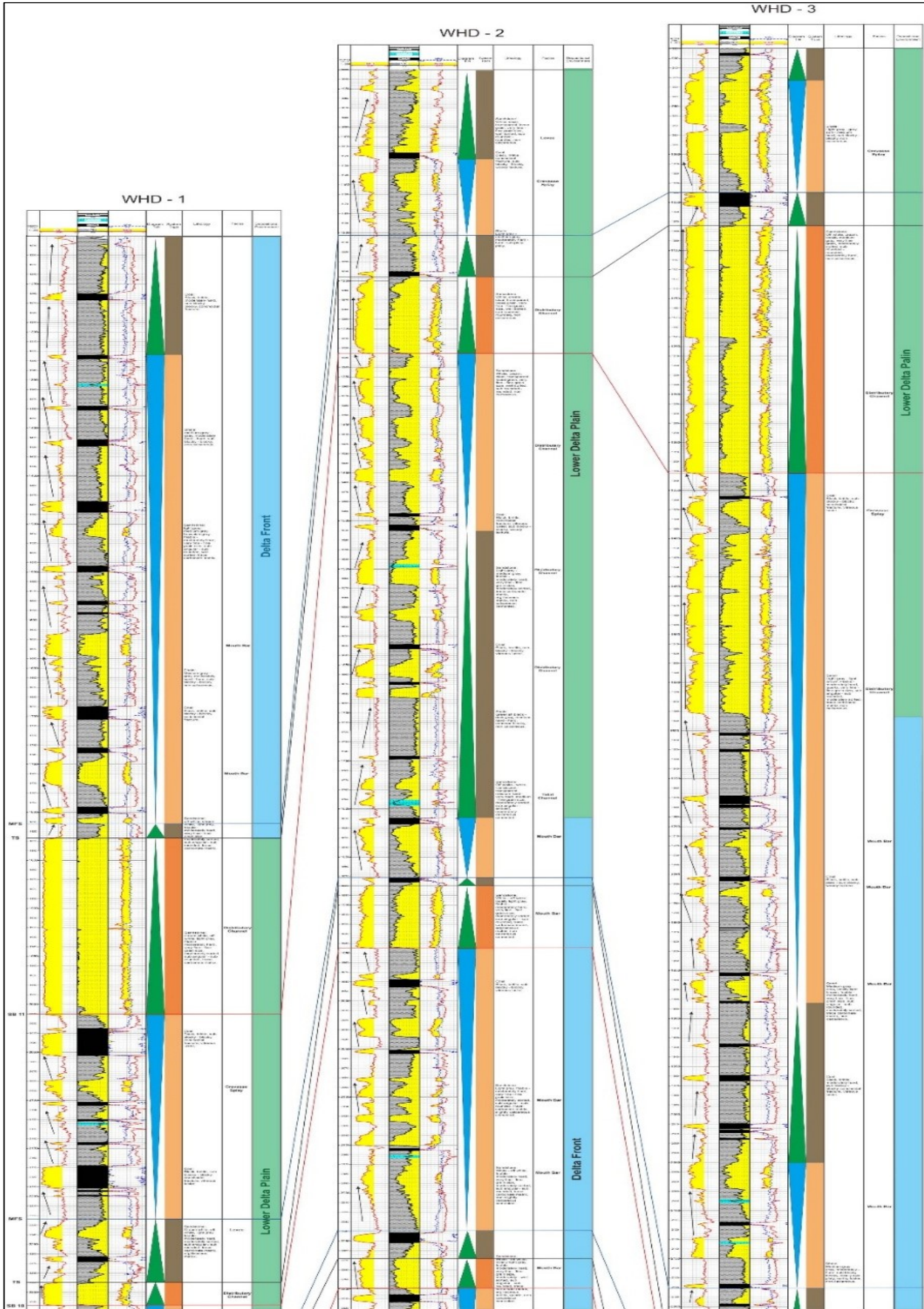


Figure 8. Reservoir heterogeneity and facies variability in the research area.

High-quality reservoir intervals are mainly associated with distributary-channel and mouth-bar sandstones deposited during regressive phases, characterised by high porosity and permeability, low shale volume, and relatively low water saturation. In contrast, transgressive and more distal heterolithic deposits form internal baffles that reduce vertical and lateral reservoir connectivity. These findings directly address the problem outlined in the Introduction by clarifying the geological and petrophysical controls on spatial variability of reservoir quality across the WHD-1 to WHD-3 corridor.

The results are consistent with established depositional models of the Lower Kutai Basin, where proximal channelized and mouth-bar deposits form the principal reservoir framework, while tidal and heterolithic facies contribute to reservoir compartmentalization. Nevertheless, this study provides a more integrated log-based facies and petrophysical characterization, improving prediction of reservoir quality trends from proximal to distal settings. Some limitations were encountered, including limited core calibration and the vertical resolution constraints of well-log data, which may affect fine-scale facies discrimination and permeability estimation. Future work should incorporate additional wells, higher-resolution sedimentological data, and, where available, seismic stratigraphic interpretation to better constrain sand-body geometry, connectivity, and dynamic reservoir performance. Collectively, the results offer a predictive framework for understanding reservoir architecture and heterogeneity in fluvio-deltaic systems of the Balikpapan Formation.

CONCLUSION

The analysis of well logs from WHD-1, WHD-2, and WHD-3 demonstrates that depositional facies exert a primary control on reservoir heterogeneity within the Balikpapan Formation, Lower Kutai Basin. Mouth-bar facies are characterised by relatively low shale content (Vsh 7–35%), moderate to high effective porosity (PHIE 11–36%), and variable water saturation (Sw 10–100%), with permeability ranging from 1 to 37

mD, indicating localized moderate- to high-quality reservoir zones. Distributary-channel deposits show lower shale volumes (Vsh 2–20%) and higher permeability (locally up to 282 mD), forming the principal pathways for fluid flow and contributing to significant lateral variability in reservoir performance. Levee and crevasse-splay deposits display intermediate reservoir quality with moderate porosity and shale content, commonly acting as internal baffles that segment otherwise continuous flow units. Tidal-channel deposits, although thinner and less laterally extensive, introduce additional vertical heterogeneity due to variable petrophysical properties. Collectively, the spatial distribution, stacking pattern, and cross-well correlation of these facies demonstrate pronounced lateral and vertical reservoir heterogeneity, confirming that depositional architecture is the dominant control on reservoir quality and connectivity within the studied interval.

Despite these findings, several aspects remain beyond the scope of this study. The analysis is primarily based on well-log interpretation with limited core calibration and without seismic-scale stratigraphic constraints, which may affect detailed characterization of sand-body geometry and connectivity. Future research should integrate higher-resolution sedimentological data, additional wells, and seismic stratigraphic analysis to better constrain reservoir architecture, quantify connectivity, and improve prediction of dynamic reservoir behaviour. Such integrated approaches would further refine understanding of heterogeneity and fluid-flow distribution in fluvio-deltaic reservoirs of the Balikpapan Formation.

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GLOSSARY OF TERMS AND SYMBOLS

| Terms & Symbols | Definition | Unit |
|-----------------|---------------------------------------------------------------------|-----------|
| Vsh | Shale volume in the rock interval, derived from gamma-ray log | % |
| PHIE | Effective porosity contributing to fluid flow | % |
| Sw | Water saturation, fraction of pore volume filled with water | % |
| NTG | Net-to-gross ratio, thickness of reservoir sand over total interval | – |
| GR | Gamma-ray log measurement, used to distinguish shale vs. sand | API units |
| k | Permeability, ability of rock to transmit fluids | mD |

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