World Journal of Advanced Research and Reviews

eISSN: 2581-9615 CODEN (USA): WJARAI

Cross Ref DOI: 10.30574/wjarr

Journal homepage: https://wjarr.com/

(Research Article)

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Lithofacies and depositional environments in the Saltpond Basin of Ghana: A well log analysis

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World Journal of Advanced Research and Reviews, 2025, 26(01), 2997-3008

Publication history: Received on 07 March 2025; revised on 16 April 2025; accepted on 18 April 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.26.1.1287

Abstract

This study employs geophysical logs to interpret lithofacies and depositional environments within Ghana's Saltpond Basin, complementing the region's predominantly surface-based analyses. Gamma ray (GR) and spontaneous potential (SP) logs were used to identify sand, shaly sand, and shale lithologies, while resistivity, bulk density, and sonic logs further refined lithological characterization. The well section was divided into seven electrofacies units based on distinct log responses and motifs. GR log motifs and facies sequences were analyzed to interpret depositional environments, which were identified as fluvial, shallow marine, and deltaic, consistent with known regional facies patterns. This study confirms the reliability of well logs for lithofacies and depositional environment interpretations, particularly in the absence of core samples

Keywords: Lithofacies; Depositional Environment; Geophysical Logs; Saltpond Basin; Fluvial Environment; Shallow Marine Environment; Deltaic Environment

1. Introduction

Depositional environments play a fundamental role in determining the physical, structural, and chemical properties of sedimentary rock formations. Understanding these environments is essential for reservoir modeling and petroleum exploration, as it aids in facies distribution analysis and hydrocarbon assessment.

Core samples provide the most reliable source of depositional environment data, offering insights into grain size, sedimentary structures, and mineral composition. However, obtaining core samples is often expensive and impractical. As an alternative, well logs—such as Gamma Ray, Density, and Resistivity logs—can be used to interpret lithofacies and depositional environments in the absence of core data.

This study aims to provide lithofacies and depositional environment interpretations from well log data from the Saltpond Basin using the Interactive Petrophysics (IP) software.

The objectives of the study are:

- To identify various lithologies and lithological characteristics from the well logs.
- To identify facies sequences from the SP and GR logs.
- To determine depositional environments.

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The well data analyzed in this study comes from the Signal 13-2 well in Ghana's Saltpond Basin. While previous studies on the basin have primarily relied on surface geological analysis, this research contributes to subsurface characterization by applying geophysical logs to lithofacies interpretation. The results of this study will serve as a cost-effective approach for evaluating depositional settings in other underexplored or data-limited sedimentary basins

2. Material and methods

2.1. Study Area and Geological Setting

The Saltpond Basin, commonly referred to as the Central Basin, is one of Ghana's four sedimentary basins, covering an area of approximately 12,294 km^2. According to Bansah et al. (2014), only 205 km^2 of this area lies on land, with the remaining 12,089 km^2 situated offshore, of which about 95% is in shallow water. The basin is located along Ghana's Atlantic Coastline, between the Accra-Keta Basin to the east and the Ivory Coast/Tano-Cape Three Points Basin to the west, stretching from Sekondi-Takoradi in the west to the coastal region of Winneba in the east.

The Saltpond Basin lies within the northwestern part of the Gulf of Guinea, alongside the Ivory Coast/Tano-Cape Three Points Basin, the Accra-Keta Basin, the Benin Basin, and the Dahomey Embayment. These basins have been modified by wrench tectonics and consist of rocks ranging from the Ordovician to the Holocene. (Brownfield and Charpentier, 2006).

Sedimentation in the Saltpond Basin is said to have commenced before the opening and expansion of the Atlantic Ocean, as well as the divergence of the African and South American plates (Heine and Brune, 2014). The pre-rift sedimentary rocks, which predate the Middle Albian, were deposited conformably and, in their undisturbed state, mirrored the seafloor profile upon which they were laid down, before the opening of the Equatorial Atlantic (Brownfield and Charpentier, 2006; Aryeetey, 2014). As lithospheric stretching triggered by convective mantle currents continued, brittle fractures developed in the paleocontinental crust, resulting in fault blocks such as grabens and horsts within the Paleozoic sediments (Aryeetey, 2014).

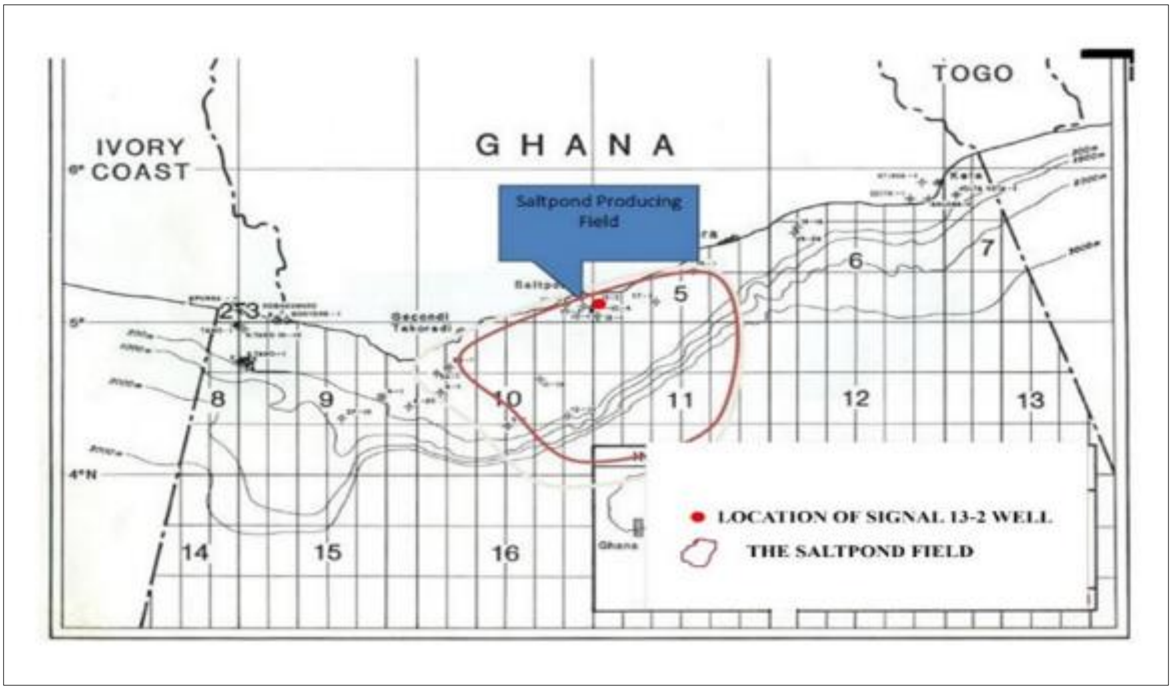

Figure 1 The Location of the Saltpond Basin showing the Signal 13-2 well with a red dot. (Modified after Aryeetey, 2014)

The basin is characterized by Precambrian basement rocks, which are overlain by Ordovician to Silurian rocks, followed by Devonian and younger sands and shales of shallow marine environments (Bansah et al., 2014). A seven-formation stratigraphic framework has been proposed for the Saltpond Basin based on lithofacies and depositional conditions, including the Ajua Shales, Elmina Sandstone, Takoradi Sandstone, Takoradi Shale, Effia Nkwanta Beds, Sekondi Sandstone, and Essikado Sandstone (Asiedu et al., 2005). These formations belong to the Sekondian Group, which is approximately 1,200 km thick and rests unconformably on the Birimian Supergroup of the Paleoproterozoic age.

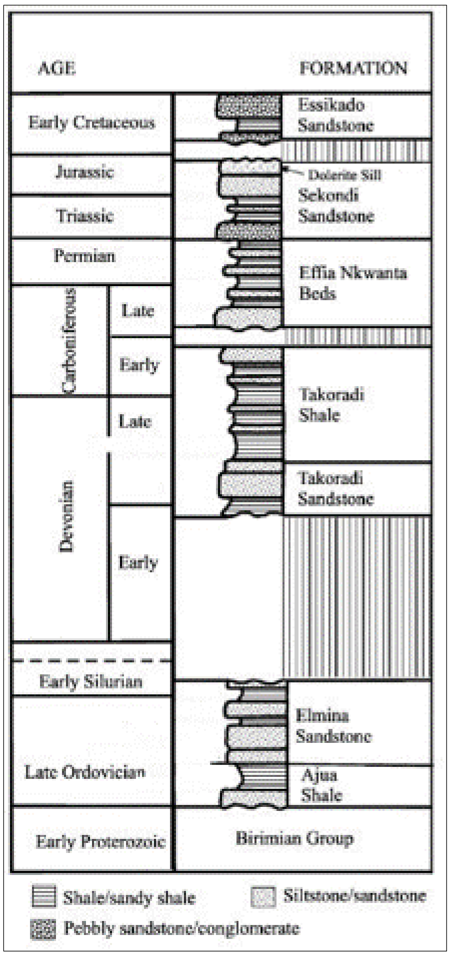

Figure 2 A Chart Showing the Chrono-Stratigraphy of the Saltpond Basin (Modified after Bar and Riegel, 1980; cited in Asiedu et al., 2005)

Previous structural and paleontological examinations (Asiedu et al., 2005; Bansah et al., 2014) based on facies characteristics observed in outcrops have shown the depositional environments of the Sekondian Group as non-marine to shallow marine.

2.2. Data acquisition and processing

Well log data from the Saltpond Basin of Ghana were analyzed and interpreted to identify the Lithofacies and depositional environments present. The well logs were obtained from the Signal 13-2 well, with no core data available. The dataset includes Gamma Ray (GR), Spontaneous Potential (SP), Bulk Density (RHOB), Sonic (DT), and Resistivity logs at various depths of investigation: Shallow (CILD), Medium (MLD), and Deep (ILD), covering a depth interval from 570 ft to 9,000 ft.

The composite well data was processed using Interactive Petrophysics (IP) Software (Figure 3). The software enabled detailed analysis and interpretation of the various well logs to identify lithofacies and depositional environments.

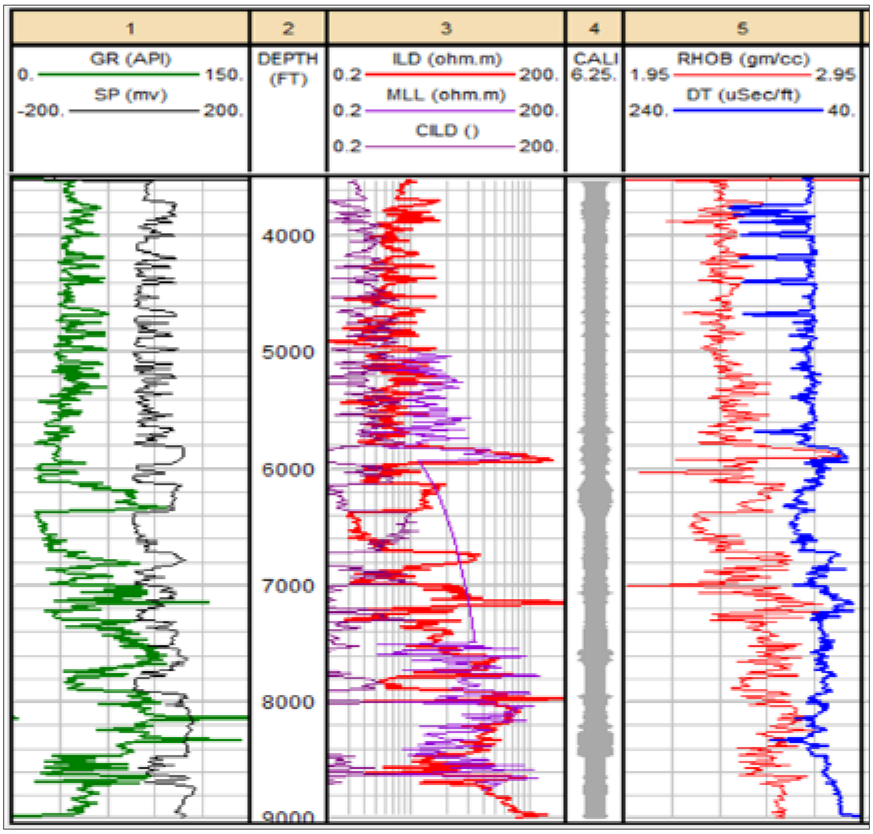

Figure 3 Well Logs Displayed in IP as Composite CPI Log Plot

2.3. Lithofacies Interpretation

2.3.1. The Gamma Ray (GR) and Spontaneous Potential (SP) Logs

The Gamma Ray (GR) and Spontaneous Potential (SP) logs were used mainly for differentiating lithologies. The GR log, which measures the natural radioactivity of formations (Ellis et al., 2008), was used to distinguish between shales and sandstones. High GR values generally indicate shale, while low GR values indicate sandstone, siltstone, or carbonate.

The SP log, which records the natural electrical potential differences between the wellbore fluid and the surrounding formation (Marini et al., 2015), was employed to infer permeability and lithology. Fine-grained sediments like shales show a rightward deflection, while coarse, permeable sediments like sand exhibit a leftward deflection. Intervals where the SP curve deflected left, combined with low GR readings, indicated permeable sand beds. However, rightward SP deflections with low-permeability sands were also observed, influenced by salinity contrasts (Marini et al., 2015).

2.3.2. Resistivity Logs

The study utilized three resistivity logs: Deep Resistivity (ILD), Medium Resistivity (MLD), and Shallow Resistivity (CILD). Emphasis was placed on the Deep Resistivity (ILD) log as it most accurately represents the true resistivity of the formation. Although resistivity logs are primarily used as fluid indicators, they were also employed to support lithological interpretation. High resistivity readings, often indicating fluid-filled or impermeable zones, were used to infer zones with very poor permeability (Low et al., 2021).

2.3.3. The Sonic (DT) and Bulk Density (RHOB) Logs

The Sonic (DT) and Bulk Density (RHOB) logs were plotted on the same track. The Sonic log was used to identify the presence of pore fluids and infer porosity (Mabrouk et al., 2015), while the Bulk Density log measures matrix density and pore fluid density. These two logs are especially useful in detecting hydrocarbon-bearing zones and identifying low porosity within sandy intervals (Silva et al., 2019).

3. Theory/Calculation

3.1. Rationale for Log Motifs and Environment Interpretation

The interpretation of depositional environments is based on the analysis of gamma ray (GR) log motifs as patterns that reflect variations in lithology and sedimentary structures. These patterns were interpreted in comparison to well-established models that represent a set of depositional settings (Cant, 1992; Miall, 2022). The models include cylindrical or blocky shapes, bell shapes, funnel shapes, bow or symmetrical shapes, and irregular/serrated shapes.

The motifs identified from the GR curve were correlated with the appropriate depositional environments.

3.1.1. Cylindrical/Blocky Motif

This motif is characterized by consistent GR readings with abrupt top and base boundaries, indicating relatively uniform lithology. In the Saltpond Basin, this motif could be associated with fluvial channel or tidal sand deposits, consistent with previous studies identifying braided river systems and distributary sands within the Sekondian Group (Cant, 1992; Rider, 2002). This interpretation aligns with findings of massive coarse sands dominating the basin's stratigraphy (Asiedu et al., 2005).

3.1.2. Bell-Shaped Motif

Bell-shaped motifs exhibit a fining-upward sequence, with GR values increasing upwards, reflecting a lithological transition from coarser to finer sediments. This motif is commonly associated with fluvial point bars, tidal point bars, or deltaic distributaries. In the Saltpond Basin, this pattern would represent depositional settings such as fluvial meandering systems or transitional deltaic environments (Cant, 1992; Rider, 2002).

3.1.3. Funnel-Shaped Motif

Funnel-shaped motifs display a coarsening-upward sequence, where GR values decrease upwards. This pattern is indicative of environments such as delta fronts, shallow marine systems, or shoreface deposits. These settings correspond to progradational sequences observed in the basin's lithofacies (Asiedu et al., 2000; Shabeer and Sarfaz, 2016).

3.1.4. Bow/Symmetrical Motif

The bow or symmetrical motif is characterized by GR values that increase and decrease symmetrically within an interval, suggesting balanced depositional processes. This motif often represents offshore environments with relatively consistent sedimentation rates, such as offshore bars or wave-dominated tidal flats (Cant, 1992; Rider, 2002).

3.1.5. Irregular/Serrated Motif

Irregular or serrated motifs are marked by fluctuating GR values, representing interbedded sand and shale intervals. These motifs are linked to mixed depositional settings such as fluvial floodplains, tidal flats, or debris flows. The variability in GR readings indicates repeated depositional events, likely influenced by changes in sediment supply or energy conditions. In the Saltpond Basin, these motifs could suggest dynamic depositional environments with episodic sedimentation (Cant, 1992; Mene and Okengwu, 2020; Rider, 2002).

These motifs are reliable indicators of depositional environments as consistent and established geological models. By analyzing these log patterns in conjunction with lithological characteristics, this study effectively delineates depositional settings and confirms the utility of well logs for subsurface geological interpretation in the absence of core data.

3.2. Identification of facies sequences

Both the SP and GR logs are recognized for their utility in identifying facies sequences. However, in this study, greater emphasis was placed on the GR log due to its higher degree of character and repetitiveness (Rider, 2002). The GR log curve was analyzed to identify facies sequences at various depth intervals, providing key insights into the sedimentary architecture of the basin.

3.3. Depositional environment interpretation

The depositional environments were interpreted by analyzing the curve shapes of the GR and SP logs at different intervals. Although both logs are suitable for this purpose, the GR log was emphasized due to its superior character compared to the SP log. The identified motifs were used to infer depositional environments. The well section was divided into distinct lithofacies units, facilitating easier interpretation and analysis. The identified lithologies, combined with facies sequences, provided a comprehensive framework for interpreting the depositional environments, as certain lithologies and sequences are characteristic of specific depositional settings.

4. Results

Lithologies were identified and color-coded on the GR curve. Various facies sequences were identified from the GR curve. The log motifs were examined, and the facies sequences and log motifs were applied to interpret the depositional environments for the lithofacies units generated.

4.1. Lithology Interpretation

Three lithologies were identified from the well logs: coarse sand, shaly sand, and shale. On the GR log, coarse sand intervals were colored yellow, shaly sands were marked in chocolate brown, and shale intervals were represented in black (Figure 4). Coarse sand was observed to be the dominant lithology, which is consistent with findings that the Sekondian Group (Saltpond Basin) is dominated by sandstones (Asiedu et al., 2005). An anomaly was observed between the depths of 5804 ft and 5940 ft (Figure 4, within the blue mark), showing the presence of an intrusive volcanic rock (Rider, 2002).

4.2. Facies sequences

Seven electrofacies units (A to G) were identified from the GR log (Figure 5). Each of them was characterized by unique lithological characteristics and facies sequences. They are each also expressed as GR log shapes/motifs. Electrofacies A and B had a cylindrical log motif. Electrofacies C, F, and G possessed a bell-shaped motif. Eloctrofacies D and E had a funnel-shaped motif.

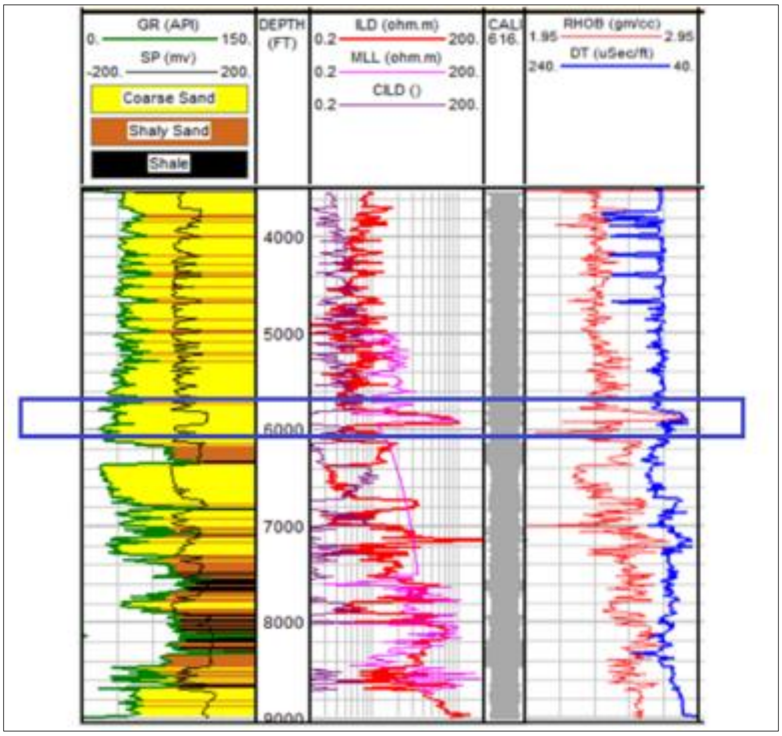

Figure 4 Identified Lithologies Color-coded on the GR-Log. Yellow intervals represent sands, chocolate-brown represents shaly sands, and black represents shale. The interval marked with the blue box represents the predicted depth location of the dolerite sill

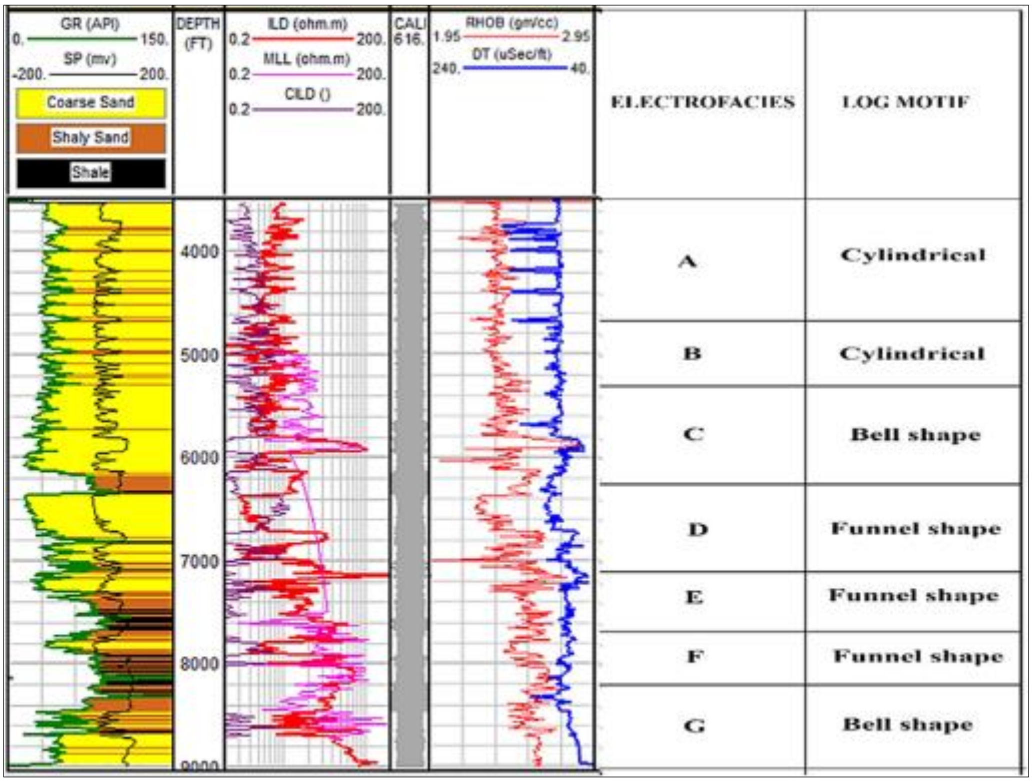

Figure 5 The Electrofacies units and their Log Motifs. Each unit (A to G) represents an interval with a distinct log motif used to interpret the depositional environment

5. Discussion

5.1. Lithology Interpretation

From the well logs (GR, SP, Resistivity, RHOB, and DT) (Figure 4), the dominant lithology identified was coarse sand, which confirms the dominance of sandstone within the Sekondian Group, as noted by Asiedu et al., (2005). Coarse sands were recognized by low API values on the gamma ray (GR) log, ranging between 0 and 50 API. Shaly sands were identified in the 50-80 API range, while shale exhibited values between 80-150 API.

An anomaly detected between the depths of 5804 ft and 5940 ft was identified as volcanic and intrusive based on the combination of log readings in that interval. The GR log indicated lower readings, suggesting low radioactivity, typically associated with sandstone. However, the SP log displayed a rightward deflection, and the Resistivity log exhibited extremely high values, indicating an impermeable formation. The Bulk Density and Neutron logs further supported this interpretation, showing very high readings, suggesting a dense rock with significant hydrogen content, likely in the form of chemically bound water (Rider, 2002).

This volcanic and intrusive material was interpreted as the dolerite sill intruding the Sekondi Sandstone, as previously documented by Asiedu et al., (2005). This structure indicates post-depositional tectonic and magmatic activity that disrupts depositional continuity and modifies the mechanical properties of the host rocks, such as reducing porosity and permeability through compaction and thermal alteration. The sill creates localized barriers or pathways for fluid migration, influencing reservoir connectivity and providing insights into the tectonic evolution and magmatic history of the Saltpond Basin (Ogata et al., 2014; Wilson et al., 2022).

5.2. Interpretation of Electrofacies and Log Motifs

Seven electrofacies units (A to G) were identified (Figure 4) based on their lithological characteristics and log motifs. Identifying the dolerite sill determines where the Sekondi Sandstone may be found in the well section. According to surface facies analysis (Asiedu et al., 2005), the dolerite sill intrudes into the Sekondi Sandstone formation. However, the precise depth of the Sekondi Sandstone and other formations in the Saltpond Basin could not be determined without seismic and additional well data.

Figure 6 shows the interpreted depositional environments for the various electrofacies and log motifs.

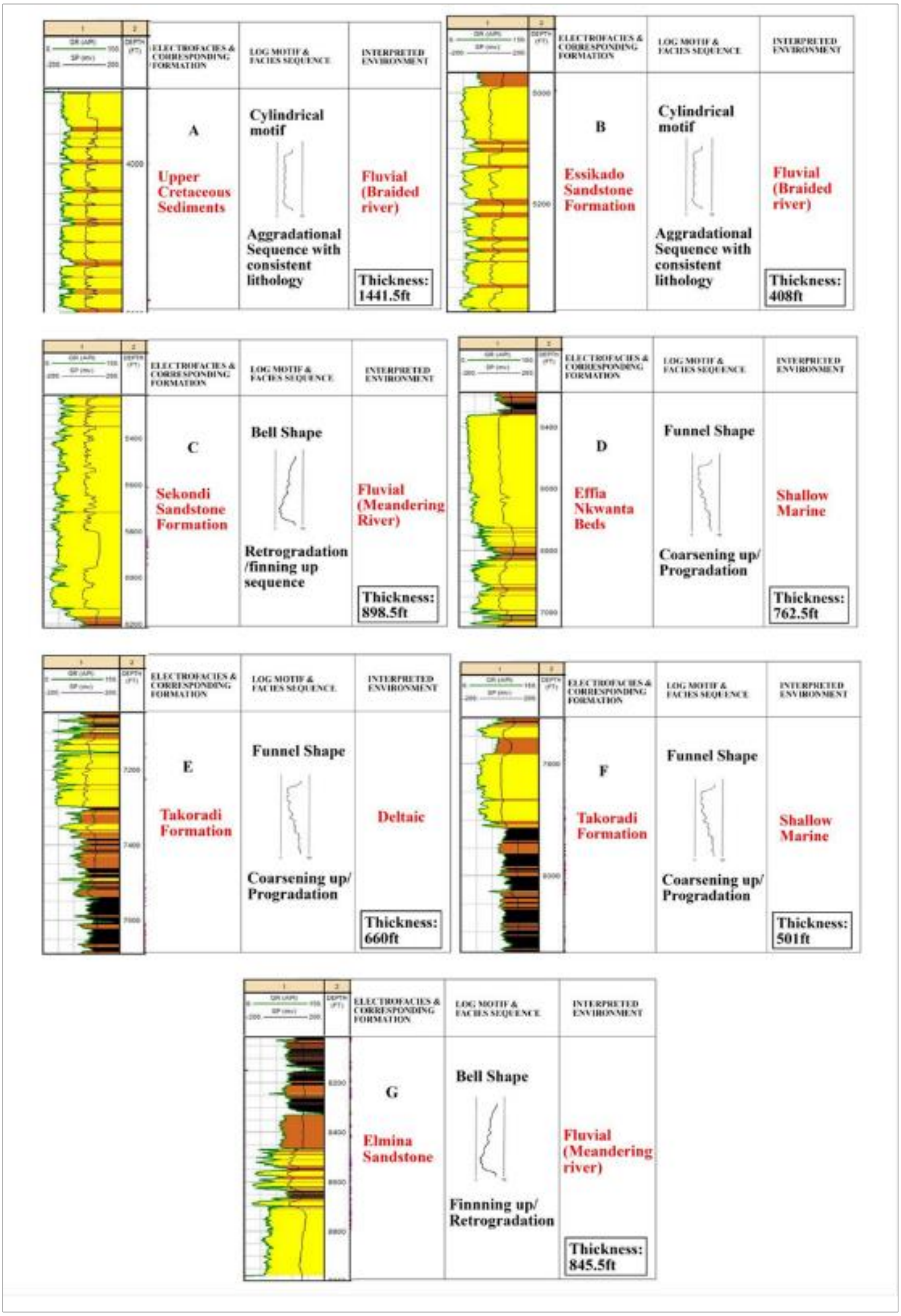

Figure 6 Analysis of Electrofacies and Log Motifs for Depositional Environment Interpretation. Units A and B were interpreted as Fluvial braided river, C and G are Fluvial meandering river, D and F are Shallow marine, and E is Deltaic

5.2.1. Electrofacies A

This unit extends from a depth of 3523 ft to 4974.5 ft, covering a thickness of 1451.5 ft (~442 m). It is characterized by massive coarse sands with intermittent thin shaly sand beds. The log motif exhibited by this unit is cylindrical/blocky, with abrupt top and base boundaries and consistent gamma ray (GR) readings, indicating uniform lithology (Cant, 1992; Rider, 2002). Due to the consistently low GR values indicating a coarse sand sequence without significant fine-grained sedimentation, this unit was interpreted as a Fluvial (braided river) environment, which is a stable high-energy environment (Asquith and Krygowski, 2004; Rider and Kennedy 2011).

5.2.2. Electrofacies B

This unit extends from 4974.5 ft to 5382.5 ft, with a thickness of 408 ft (~124 m). Similar to Electrofacies A, the lithology is dominated by coarse sands with occasional thin shaly sand beds. The log motif is also cylindrical/blocky with sharp top and base boundaries and very consistent GR readings, signifying uniform lithology (Cant, 1992; Rider, 2002). This unit's depositional environment was likewise interpreted as Fluvial (braided river).

5.2.3. Electrofacies C

This unit covers a thickness of 898.5 ft (~274 m), from 5382.5 ft to 6281.0 ft. It is characterized by massive coarse sands showing a fining-upward grain size sequence. The log motif is bell-shaped, with an abrupt lower boundary and a gradual upward increase in GR values. Though this motif is typically associated with fluvial point bars, tidal point bars, or deltaic distributaries (Cant, 1992; Rider, 2002), for a fining upwards sequence that is highly dominated by sand without any significant shows of shale, the depositional environment was interpreted as Fluvial (meandering river) (Posamentier and Walker 2006, Rider and Kennedy 2011).

5.2.4. Electrofacies D

Extending from 6281.0 ft to 7043.5 ft, this unit is 762 ft (~232 m) thick. It is dominated by coarse sand at the top, transitioning into finer shaly sand beds towards the middle and base, exhibiting a coarsening-upward facies sequence. The log motif is funnel-shaped, characterized by an abrupt top boundary and increasing GR readings towards the bottom (Cant, 1992; Rider, 2002). This motif is indicative of environments such as shallow marine, crevasse splay, river mouth bars, delta fronts, or shore faces (Cant, 1992; Shabeer and Sarfaz, 2016). The depositional environment was interpreted as Shallow Marine as the coarsening-up sequence is relatively cleaner with just a few fine sediment interruptions, reflecting a prograding marine environment where sediment supply builds outward over time (Asquith and Krygowski, 2004; Cant, 1992).

5.2.5. Electrofacies E

This unit extends from 7043.5 ft to 7703.5 ft, with a thickness of 660 ft (~201 m). Coarse sand occupies the upper part, while the middle consists of shaly sands, and the base is shale. A coarsening-upward sequence is observed. The log motif is funnel-shaped, with an abrupt top and increasing GR readings from top to bottom (Cant, 1992; Rider, 2002). This motif is commonly associated with shallow marine, crevasse splay, river mouth bar, delta front, or shoreface environments (Cant, 1992; Shabeer and Sarfaz, 2016). The depositional environment was interpreted as Deltaic since the coarsening-up sequence is characterized by a more irregular GR pattern, characteristic of interbedding deltaic sediments (Asquith and Krygowski, 2004).

5.2.6. Electrofacies F

Covering the interval from 7703.5 ft to 8116.0 ft, this unit has a thickness of 501 ft (~153 m). The dominant lithology is shaly sands with thin interspersed coarse sand beds. A coarsening-up sequence is observed here, with coarse sands transitioning to finer-grained shaly sands towards the bottom. The log motif is funnel-shaped, showing an abrupt top boundary and a gradual increase in GR readings towards the bottom (Cant, 1992; Rider, 2002). The depositional environment is interpreted as Shallow Marine as such upward transition from shale to sand is commonly associated with lower shoreface to upper shoreface settings (Rider and Kennedy, 2011).

5.2.7. Electrofacies G

This unit extends from 8116.0 ft to 8663.0 ft, covering a thickness of 845.5 ft (~258 m). It is shaly at the top, with alternating shaly sand and sand beds in the middle, and coarse sands at the base, displaying a fining-upward sequence. The log motif is bell-shaped, with an abrupt base boundary and increasing GR readings toward the top. This motif is commonly associated with deltaic distributaries, tidal point bars, or fluvial point bars (Cant, 1992; Rider, 2002). The depositional environment is interpreted as Fluvial (meandering river) because the base coarse sand fines upward through shaly sand and sand in the middle to shaly deposits at the top, and that is characteristic of lateral point bar deposition as a river loses energy, moving outwards from its main channel so that progressively finer sediments are deposited upward (Asquith and Krygowski, 2004).

5.3. Assumptions

5.3.1. Lithology and Depositional Environment Interpretation

The interpretation of lithofacies and depositional environments relied on analyzing well logs (gamma, SP, resistivity, density, and sonic log). In the absence of core samples, it was assumed that these log readings accurately reflected lithological changes, consistent with established models from similar sedimentary basins (Rider, 2002).

Additionally, the study assumes that the depositional environments inferred from log motifs correspond to those identified through surface facies analysis in the Saltpond Basin (Asiedu et al., 2005). This reliance on surface studies provided a framework for validating subsurface interpretations. However, the absence of seismic data introduces a degree of uncertainty regarding spatial continuity, with interpretations limited to the vertical resolution provided by the well logs.

5.3.2. Identification of dolerite sill

The log readings observed between 5804 ft and 5940 ft were assumed to indicate the dolerite sill intruding on the Sekondi Sandstone. This interpretation aligns with previous studies documenting similar intrusions (Asiedu et al., 2005). Without direct core data, this identification is based on the correlation of well log responses with expected lithological characteristics.

6. Conclusion

This study has demonstrated the effectiveness of well log analysis in evaluating depositional environments and lithofacies, even in the absence of core or seismic data. Through the well log analysis of the Signal 13-2 in the Saltpond Basin, lithology, and facies sequences, were successfully identified, enabling the interpretation of depositional environments. The logs revealed that coarse sand is the dominant lithology, as supported by literature. Other lithologies identified include shaly sands and shale. Additionally, the dolerite sill within the Sekondi Sandstone interval was detected through log analysis. This is consistent with previous studies.

A total of seven electrofacies units were identified from the well section, each characterized by distinct log motifs and facies sequences. The depositional environments interpreted from these electrofacies units include fluvial (braided river), fluvial (meandering river), shallow marine, and deltaic settings. These interpretations align with the environments suggested by surface facies analyses in the literature.

It is recommended that future studies incorporate core data and other well sections from the basin to further refine the identification of lithological characteristics. This will enable more accurate stratigraphic correlations and help confirm the interpretations of depositional environments derived from well log analyses.

Compliance with ethical standards

Acknowledgments

The authors acknowledge the Petroleum Commission of Ghana for providing the well log data used in this research. We also express our gratitude to the Department of Earth Science, University of Ghana, for granting access to the workstation essential for this study. Finally, we sincerely thank Dr. Y. A. Boakye-Ansah for proofreading the manuscript in preparation for publication.

Disclosure of conflict of interest

No conflict of interest to be disclosed.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used OpenAI's ChatGPT in order to improve the language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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