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Facies Interpretation from Well Logs: Applied to Calub–Hilala Field Within Ogaden Basin, Ethiopia

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Highlights

- Characterizing the Karro formations (Calub sandstone, Bokh shale, Gumburo sandstone, and Adigrat sandstone);
- Analyzing the overlying Lower Jurassic to Upper Cretaceous formations, namely Hamanlei carbonates (Lower Hamanlei limestone, Middle Hamanlei dolomite, Upper Hamanlei limestone), Urandab shale, Gebredare limestone, Gorrahei gypsum, and Mustahil sandstone regarding the thickness, spatial (lateral) continuity point of view;
- Modeling facies patterns based on log outlines.

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Abstract

The lithofacies and environments of deposition interpretations of the Calub–Hilala field toward the central trough of Ogaden Basin were analyzed, and geophysical well logs from three deep exploration wells, namely Calub-1, Bodle-1, and Hilala-2, were used. A methodology was piloted in establishing the sedimentary facies, their successions, and environments of deposition. Gamma-ray, neutron, sonic, and resistivity logs were used for lithologic and depositional environment identification. An attempt was also made to identify formation tops and well-to-well lithostratigraphic correlation basing gamma-ray log trends and correlate with the cored interval of the wells for lithological comparisons. Lithofacies interpretation was carried out with Schlumberger's Petrel software, version 2009. Correlation techniques were conducted to delineate the subsurface trends of these facies with electrofacies to compare facies interpretation results that were implied using the wireline log signatures.

Ten formations, namely Calub, Bokh, Gumburo, Adigrat, Transition, Hamanlei (Lower, Middle, and Upper), Urandab, Gebredare, Gorrahei, Mustahil, and five log facies, namely a cylindrical-shaped log trend representing aeolian, i.e., braded fluvial, a funnel-shaped facies representing a crevasse splay, a carbonate, shallowing upward sequence and shallow marine sheet sand, a bell-shaped facies representing transgressive marine shelf, a symmetrical-shaped facies representing sandy offshore, and an irregular shaped facies representing fluvial floodplain, were recognized. The environments of deposition delineated for the study area are alluvial and transgressive–regressive marine.

Keywords: Bokh, Calub, Hamanlei, Hilala, Ogaden Basin

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1. Introduction

Ethiopia's sedimentary regions embrace five distinct basins: the Ogaden Basin, the Abay (Blue Nile) Basin, the Mekele Basin, the Gambela Basin, and the Southern Rift Basins. From the five sedimentary basins, the Ogaden Basin, which is the main focus of this study, is located in the Somali Plateau, Southeast of Ethiopia between latitudes 4° and 8°N and longitudes 40° and 48°E (Figure 1). Purcell (1979) and later Worku et al. (1992) reported that the Ogaden Basin was initiated in the Late Carboniferous to Permian when rifting occurred widely across Pangaea. The deep Adigrat sandstone and Hamanlei limestone are the primary exploration target formations in prospective areas within Ogaden Basin (Hunegnaw et al., 1998). According to a study by Weber (1971), sediments in different paleo-environments display characteristic log motifs; as a result, borehole logs are widely used to interpret sedimentary facies. According to Gluyas et al. (2004), from the combined core description and wireline log data, it is commonly possible to generate a series of log facies, and such log facies may be used to describe the paleo-depositional environment of a cored and logged interval. Therefore, this study aimed to identify facies associations and the Paleo-depositional environment of the Calub–Hilala area within Ogaden Basin. An attempt was also made to establish sedimentary facies and stratigraphic successions from the well-log responses. Gamma-ray log data used in the current study were analyzed mainly to distinguish between shale and non-shale (or sandy) compositions. Conventionally, a gamma-ray (GR) log is primarily used to detect the presence of radioactive materials that make up clay particles in shales. The gamma-ray (GR) log is commonly referred to as the "shale log" (Kenneth and Allan, 2003; Ellis and Singer, 2007). The GR log was displayed in two narrow columns for measured depths (MD), and the log track was recorded in standard American Petroleum Institute (API) units. The scale of 1–150 API was used to accommodate the typical response range of the gamma-ray log data.

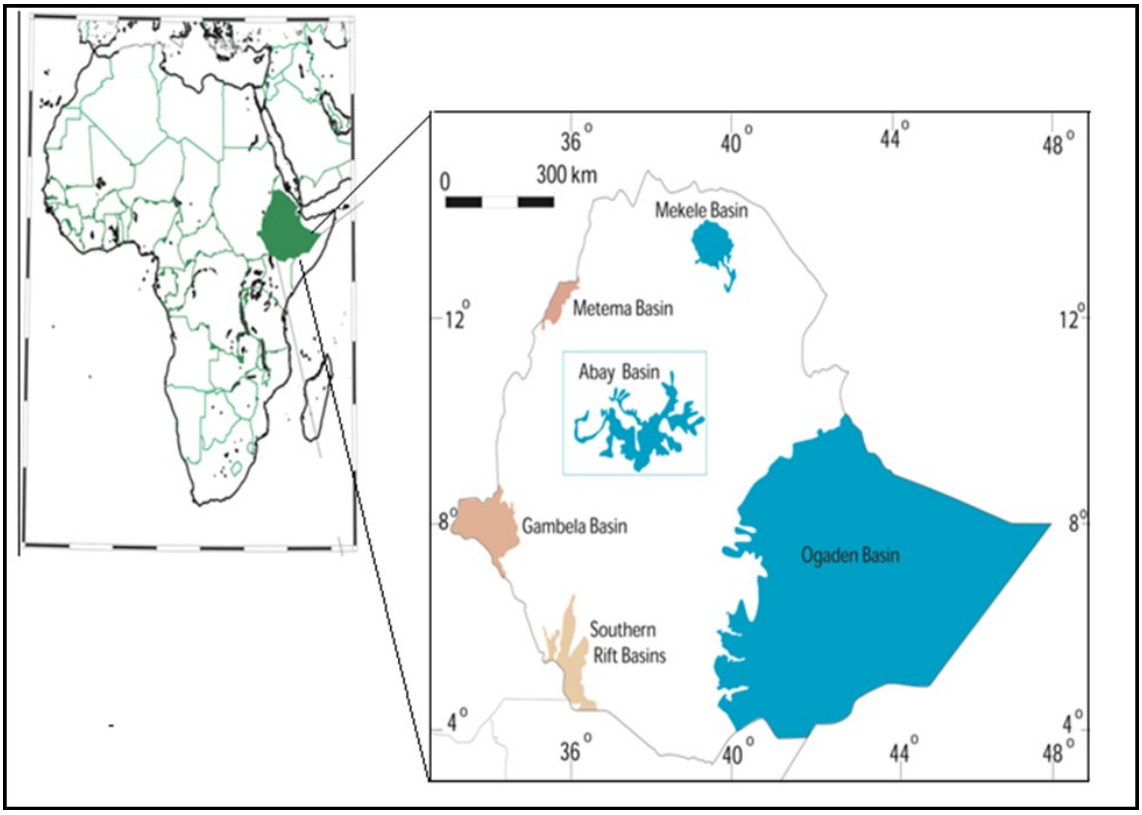

Figure 1
Location Map, Ogaden Basin Ethiopia (Modified After Ministry of Mines, 2011).

2. Location of the study area and aerology

The study area is an onshore field situated in the central and southern part of Ogaden Basin, Ethiopia (Figure 1). Clift (1956) first described the Ogaden Basin as the sedimentary province of the Ogaden district and delimited by the 44º 20'E meridian at the gently dipping cuesta of upper Cretaceous continental sandstones, which excluded the entire western sub-basin area from the basin and was probably based on early reports of a thin, mainly nonmarine, sedimentary sequence in the western area (Daniel, 1943; Murdoch, 1947a). The sedimentary history of Ogaden Basin commenced in the Upper Paleozoic, probably in the Permian. At that time, Africa was part of Gondwanaland, and the southern shore of the Tethys Ocean extended down the current east coast of Africa and provided access for marine waters far into the ancient landmass. Marine Permian sediments are well documented in Madagascar (Radelli, 1975), over 1500 km from the main ocean area. This Permian rifting has been viewed as the rift-stage basin of the Eastern Africa continental margin (Purcell, 1976b) and is described in detail by Kazmin and Purcell (1979). The work of Purcell (1979) reported that the Ogaden Basin is estimated to have a maximum sediment thickness (at deeper parts) of 10 km at the central and southwestern part of the basin and total areal coverage of about 35,0000 km^2. Gebreyohannes (1984) reported on the stratigraphic succession of the Upper Second and Third Order Tributaries of Wabi Shebelle River, the stratigraphic sequence of Ogaden Basin, which is considered a central sedimentary basin in Ethiopia with possible hydrocarbon resources, and focused on three major formations: Permo-Triassic (Karoo), which is of fragmentation of Africa/Madagascar/Indo–Australian blocks and initiation of the Indian Ocean; Upper Jurassic–Cretaceous, developed from the progressive opening of Indian Ocean and Rifting along the Central African Shear Zone; and the Tertiary formations within the basin and adjacent areas related with the breakup of Afro–Arabian plate, Opening of the Red Sea and Gulf of Aden and Development of East African rift system. The Karoo sediments (Late Paleozoic to Early Jurassic) of the Ogaden Basin, Ethiopia, are considered the oldest sediments and occur only in the subsurface.

Furthermore, the basal Calub sandstone consists of arkosic and lithic conglomerate and sandstone of alluvial fan origin. It is overlain by lacustrine shale, siltstone, and minor sandstone of the Bokh shale. The remaining two formations have a transitional boundary. The Gumburo and Adigrat sandstones are fluviatile quarzitic sandstone deposited by braided and meandering rivers. Karoo sedimentation took place within an extensional rift before becoming progressively more widespread during the deposition of the Gumburo and Adigrat sandstone (Beicip, 1998). The Permo-Upper Cretaceous Ogaden Basin formations included Calub, Bokh, Gumburo, Adigrat, Hamanlei, Gebredare, Gorrahei, Mustahil, and Ferfer formations (Figures 2 and 3). The Karro formations considered the oldest formations within the basin include Calub sandstone, Bokh shale, Gumburo sandstone, and Adigrat sandstone, unconsolidated to the slightly consolidated paralic siliciclastic sequence of the sandy unit with minor shale intercalations of about 969 m thick. An upward increase in the sand content was observed on sand-dominated formations of Calub, Gumburo, and Adigrat.

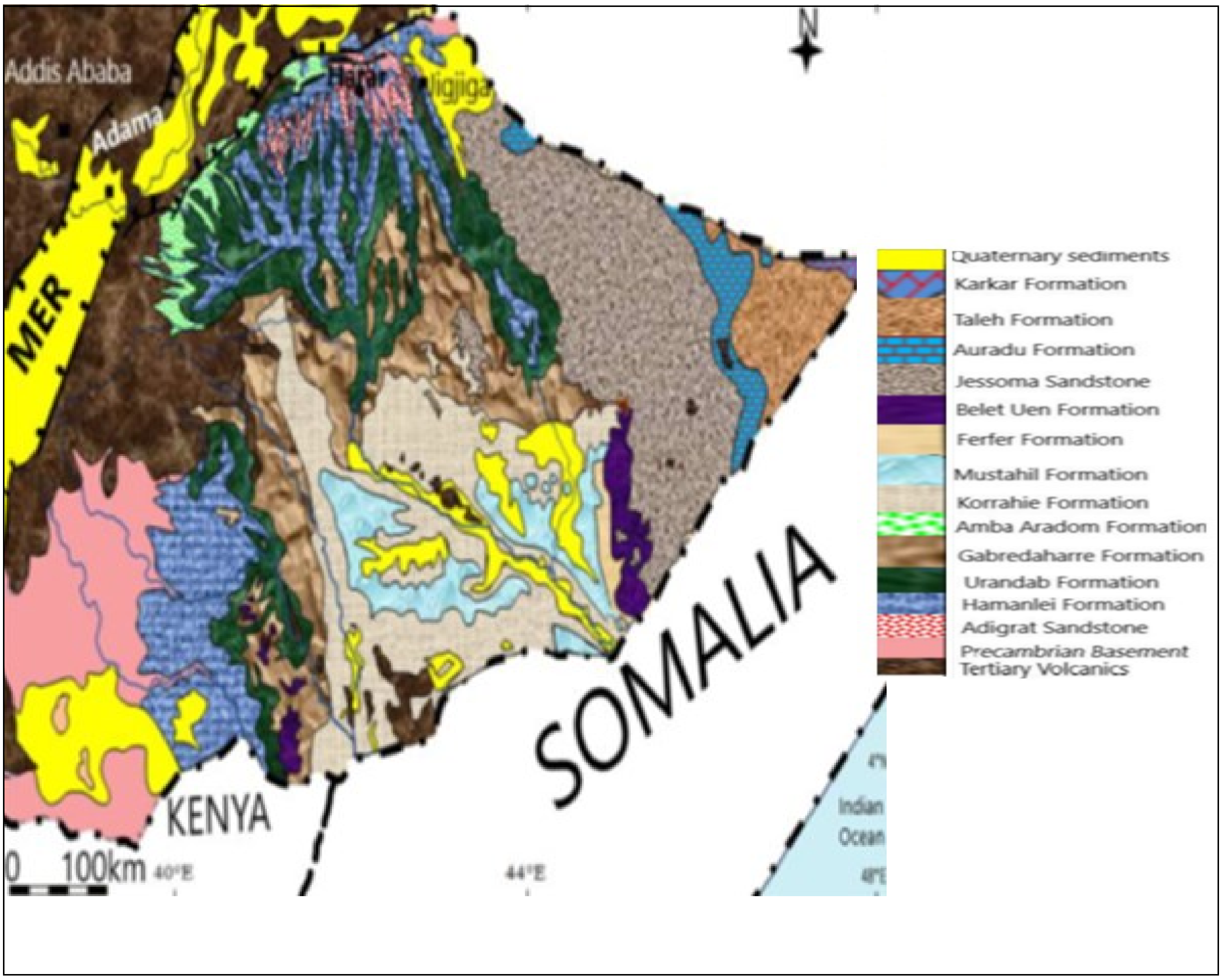

Figure 2
Geological map of Ogaden Basin (Modified After Menge et al., 2015).

According to the Ministry of Mines of Ethiopia (2011), Bokh formation is characterized by an intercalating shale, and sandstone beds were deposited in equal proportion (50%). However, the overlaying Gumburo formation was mostly sand (75%) with minor shale intercalations. Its oldest units of sediments are Permo–Triassic to Early Jurassic in age. The overlaying formations from the transitional formation upwards were interpreted to be shallow to the deep marine origin and are composed of thick carbonate with minor amounts of clay and silt. In contrast, the Karro formations underlies the entire basin and are typically over pressured. The overlying Lower, Middle, and Upper Hamanlei formations represent an Early Jurassic to Callovian syn-rift marine sequence and consist of the following lithologies: limestone with intercalated shales (in the lowermost section); anhydrite, dolomite, and limestones with local oolitic and stromatolitic beds (in the middle section); and Bioclastic Oolitic limestones (in the uppermost section). Restricted lagoonal deposits during upper cretaceous likely deposited sands within the basin include Mustahil and Ferfer formations during sea regression (Purcell, 1992).

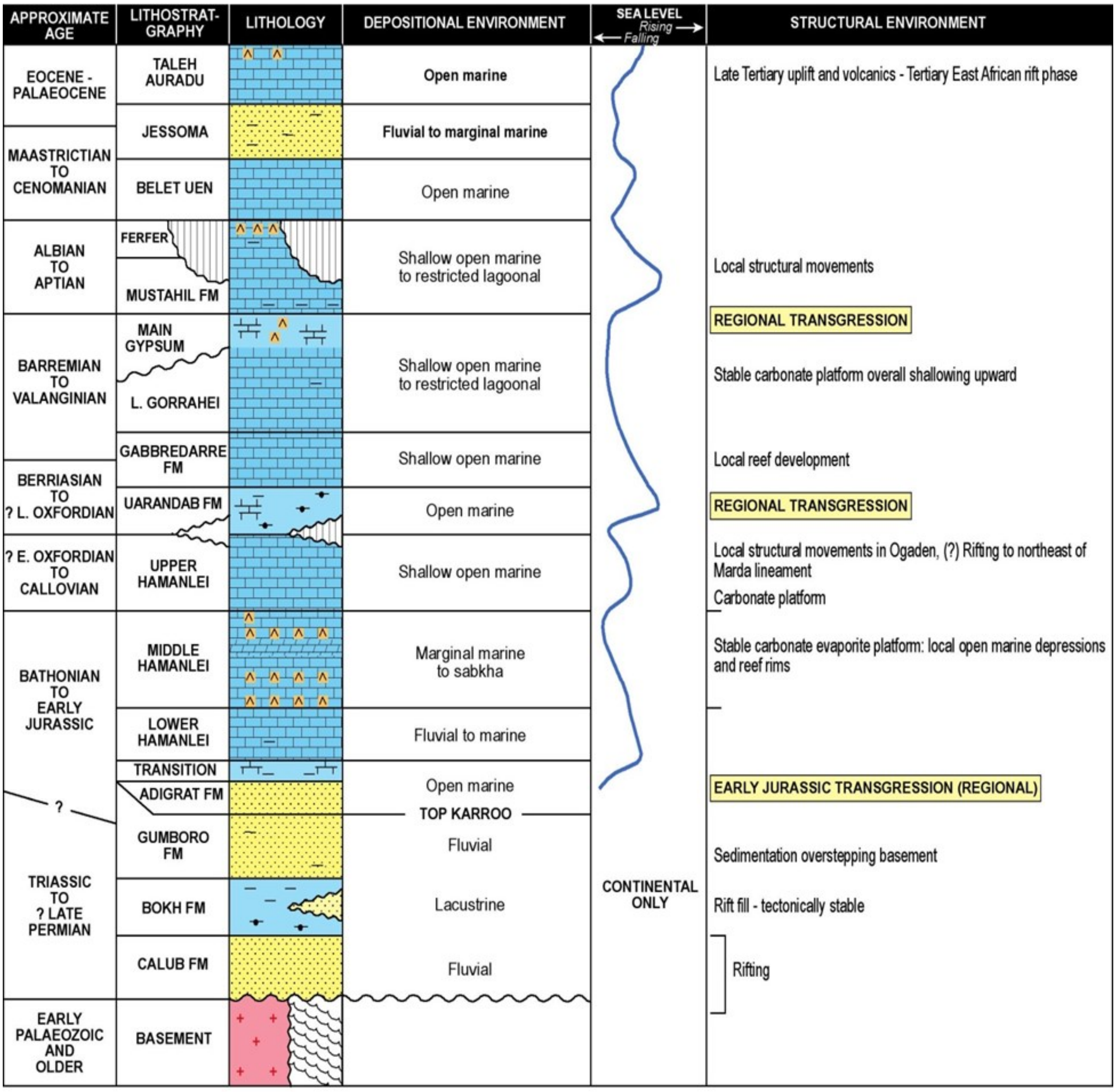

Figure 3
Generalized sedimentary column, Ogaden Basin (Modified after MoMP and NG, 2011).

3. Data set and methods

3.1. Materials

The data set for the study is made up of well-logs and core samples collected from the Ministry of Mines, Petroleum and Natural Gas, Addis Ababa, Ethiopia. Data from wells used in this study included gamma ray, effective porosity, and resistivity logs from three wells: Bodle-1, Calub-1, and Hilala-2. In addition, the core samples from the three wells were used (Figure 4 and Table 2). Schlumberger's Petrel software, version 2009, interpreted well-logs and well-log correlations. The gamma-ray logs of the three wells were first placed at an equal depth to facilitate correlation.

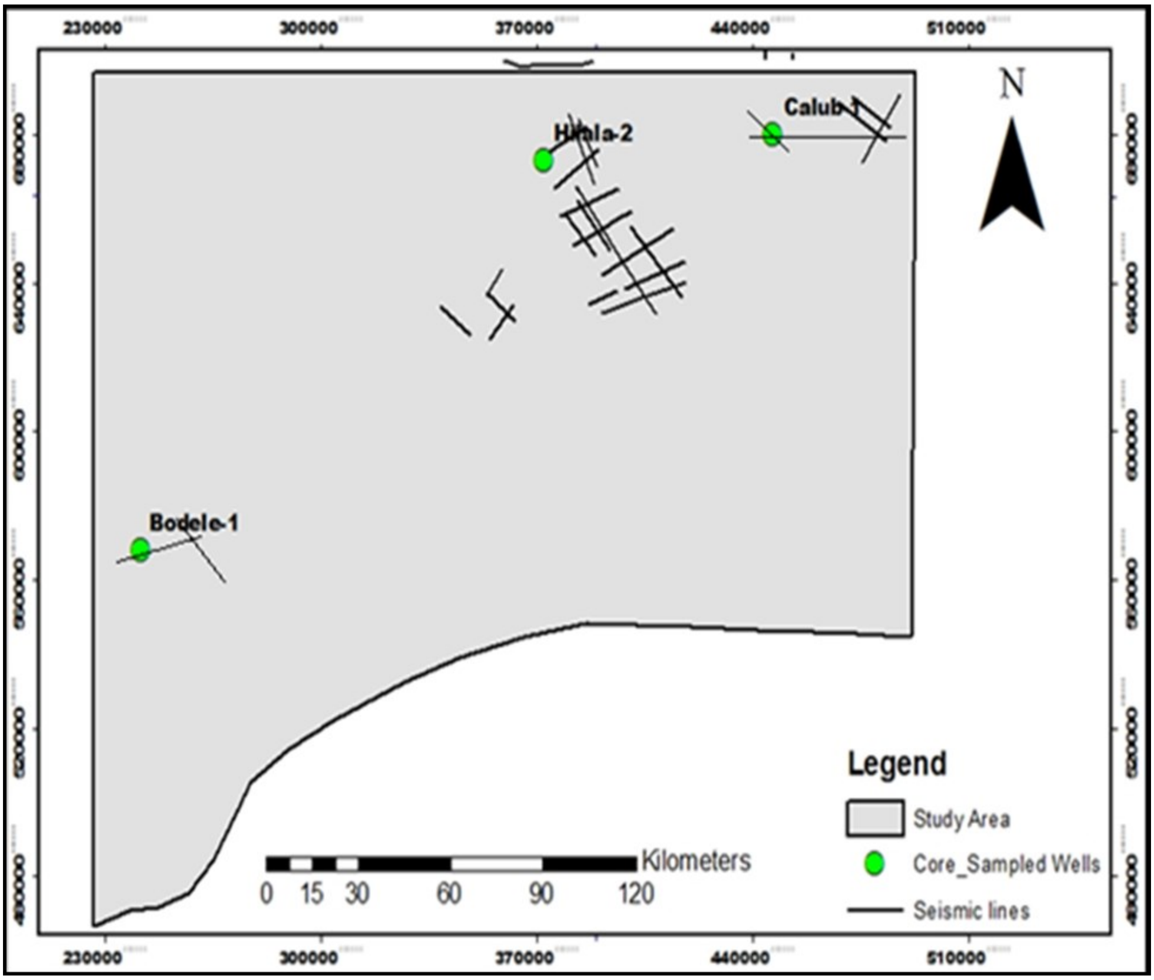

Figure 4
Map showing spatial distribution wells from which the core and cutting samples are retrieved.

Table 1
A general summary of wells used for the study and associated wireline log suites.

Well	Coordinate		The last formation penetrated	Dominant lithology	Elevation datum KB (m)	Total depth reached (m)	Log signature readings					
	X	Y					SP	GR	DT	RHOB	SNP	ILD
Bodle-1	**241476.67**	**568027.37**	**Bokh**	**Shale**	**532**	**3100**	✓	✓	✓	✓	✓	✓
Calub-1	**446800.61**	**679871.29**	**Calub**	**Sandstone**	**469**	**3999**	✓	✓	✓	✓	✓	✓
Hilala-2	**372434.3**	**672798.16**	**Lower Hamanlei**	**Limestone**	**616**	**2072**	✓	✓	✓	✓	✗	✗

SP is the spontaneous potential, GR indicates the gamma ray, DT denotes the sonic log, RHOB is the density log, SNP represents the sidewall neutron porosity log, ILD is the deep resistivity log, ✓ indicates “available”, and ✗ represents “missing”.

3.2. Methods

The lithofacies and stratigraphic secessions of Ogaden Basin were identified based on LAS log signature patterns. While picking the formation tops, the Kelly Bush (KB) depths (Table 1) were used as the reference datum with values of 532, 469, and 619 m for Bodle-1, Calub-1, and Hilala-2 wells, respectively. Matching similar lithologies was then carried out from well to well using the top and bottom horizons as controls. Similar features in terms of gamma-ray signatures and resistivity were marked. The resistivity log was used in conjunction with the gamma ray to determine whether the sand bodies were productive or not. Deflection of the resistivity log to the left indicates low resistivity-highly conductive shale or water-bearing formations. Sandstones with high resistivities or low conductivities were inferred as reservoirs with the prospect of bearing hydrocarbon. Prediction of depositional environment can be made based on sandstone composition, grain size characteristics, spontaneous potential, and gamma-ray log shapes (Morris et al*.,* 1990).

Stratigraphic modeling involving creating logs showing facies and depositional environments was carried out in Petrel software and interactive Petrophysics software. In the case of log curve shapes, well-log curves have long been interpreted in terms of depositional facies because of their resemblance to grain size successions (e.g., Selley, 1978); an example is the classification of bell-shaped gamma-ray profiles as fining-upward, meandering-stream facies successions. In those specific studies where log patterns have been calibrated to understand the depositional facies successions in cores and outcrops, the log-pattern method can be applied successfully to interpret correlative uncored facies successions.

Attempts were also made to relate the Calub–Hilala field successions with broad and adjacent areas within the basin. The emphases were on aspects relevant to the petroleum systems within Ogaden Basin. Efforts were also made to deduce depositional environment, which was paramount in predicting hydrocarbon potentiality in the basin. For the basin-wide correlation of stratigraphic units between wells, the three primary correlation methods, namely the marker beds, pattern matching, and slice techniques (electrofacies) based on a model developed by Cant (1992), were considered (Figures 5 and 6).

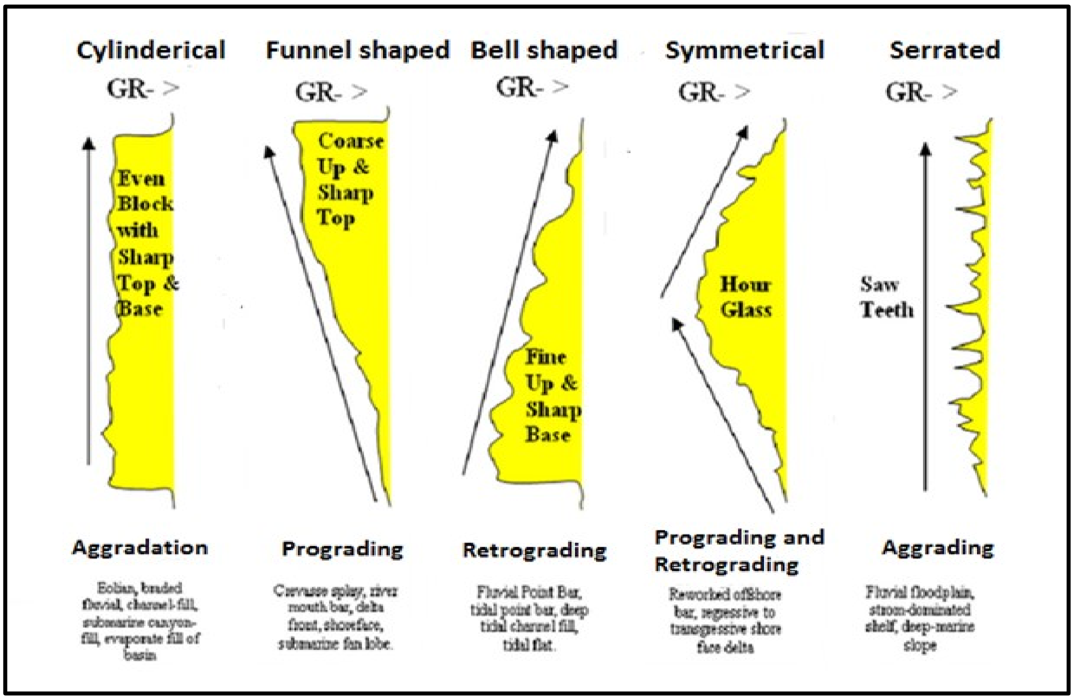

Figure 5
The correlation between facies and log shapes relative to the sedimentological relationship (After Cant, 1992).

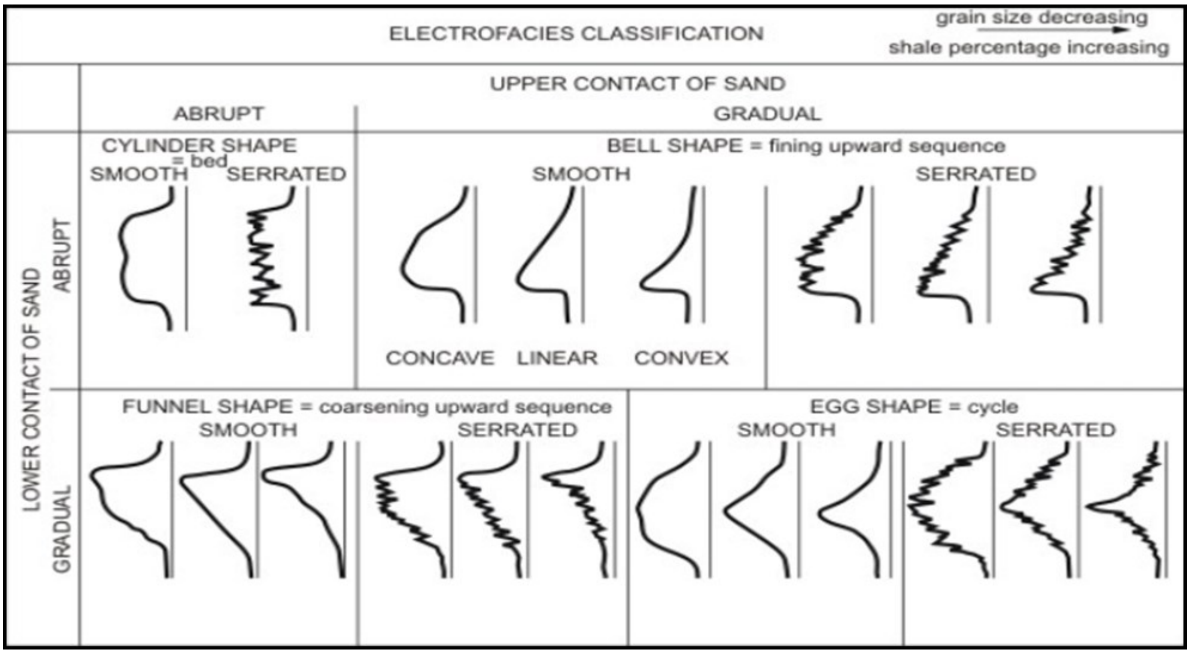

Figure 6
Gamma-ray facies association from the well log pattern used in defining lithology and depositional environment (After Cant, 1992).

4. Results

The depositional environment prediction was made using gamma-ray log shapes, porosity logging tools, and resistivity logging tool trends, and the results are presented in Figures 7–13. The gamma ray log, porosity logging tools, and resistivity logging tool were used to identify lithology encountered in the wells. The log motifs of prograding, retrograding, and aggrading features were identified in the study area and used to characterize the depositional environment. The depositional environments were recognized by vertical grain size, log shapes, and morphology.

5. Discussion

5.1. Well log facies interpretation

Well-log facies representing Calub, Bokh, Gumburo, Adigrat, Transition, Hamanlei, Urandab, Gebredare, Gorrahei, and Mustahil formations were identified from the combined well log analysis of the four different log curve characters with depth in the three wells (Figure 7). Delineation of corresponding boundary intervals across the different types of well logs for each well allows for the stratigraphic subdivision of the well log facies into different genetic groups with lateral relationships. The lithofacies displayed consistent pattern behavior in the GR and resistivity log pairs and correlated with the bulk-density and sonic logs corresponding to individual sedimentary cycles. Each lithofacies is separated by a sudden observable change in log pattern with associated changes in the multi-log physical properties and log values due to the specific change in lithology. Lithofacies identified were designated into strata and characterized into stratigraphic intervals to interpret the various depositional and stratigraphic frameworks for the study area from the basal to the upper units. Individual facies characteristics were classified based on differences in their lithological composition, thickness, clay content, and stratigraphic position. Interpretation of the facies based on the well-log data was consistent with the previous study of generic lithostratigraphic descriptions of the formations in Ogaden by Purcell (1979), BEICIP (1985), and Abate et al. (2015) while the variations in the thickness of the delineated formations are observed. The thickness of the delineated formations is presented in Table 2. The well-log facies are described as follows.

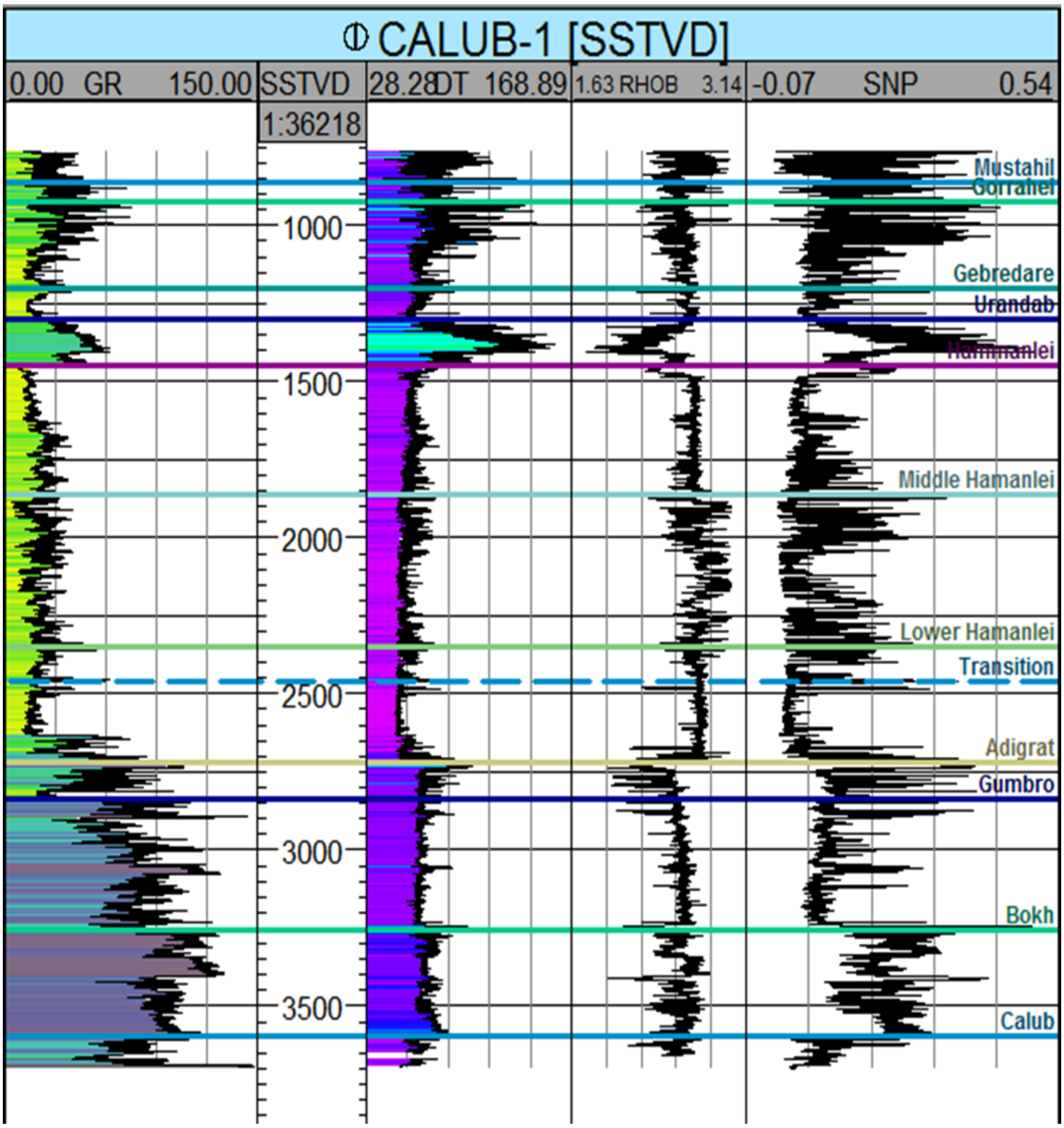

Figure 7
Stratigraphy identification plot using wireline log data of Calub-1 well; GR is gamma-ray log, SSTVD indicates subsurface true vertical depth, DT denotes the sonic log, RHOB is the density log, and SNP stands for the sidewall neutron porosity log.

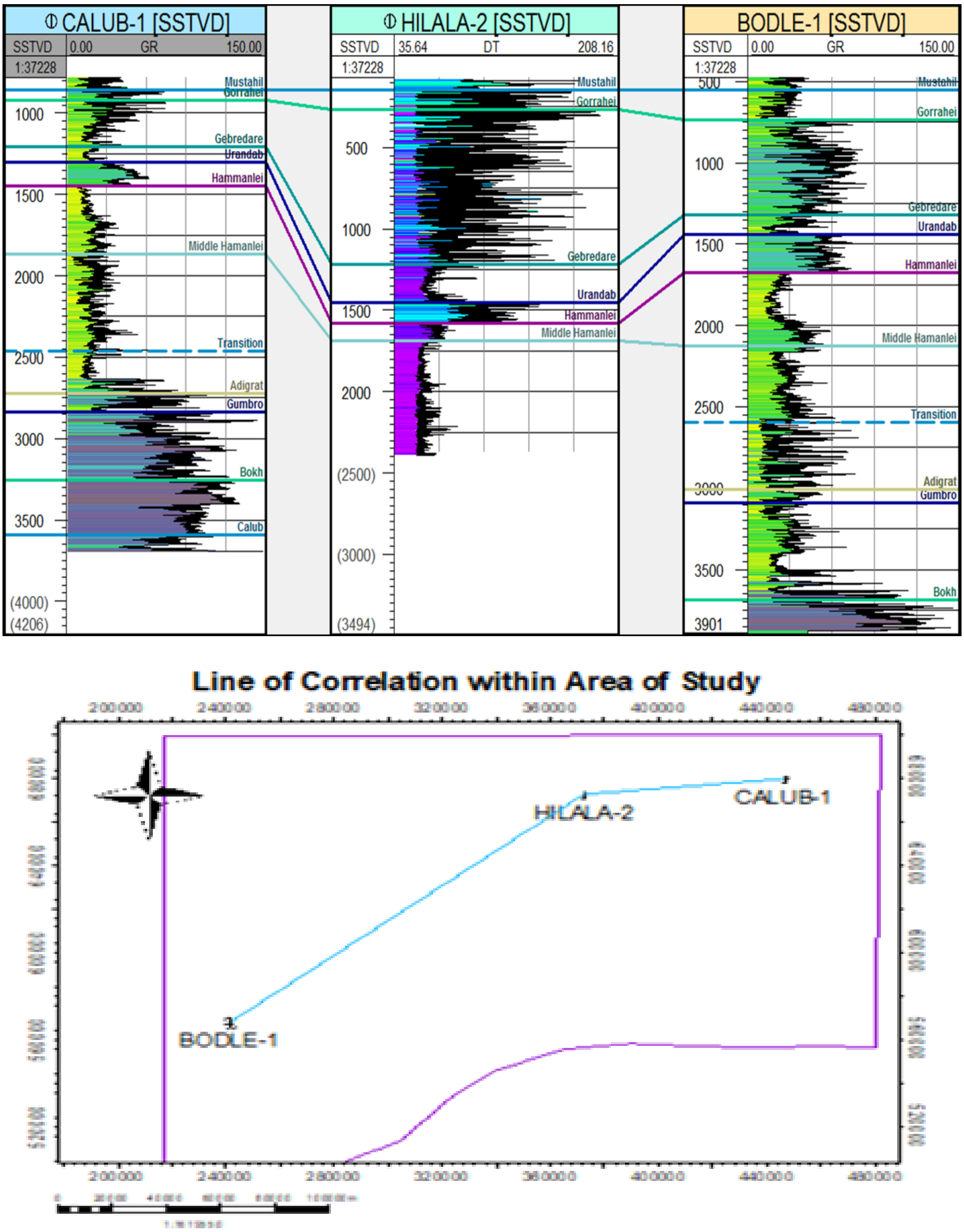

Figure 8
(a) The location map of the correlation line and (b) the correlation diagram along an East–Southwest transect; SSTVD represents the subsurface true vertical depth, GR is the gamma ray, and DT denotes the sonic log.

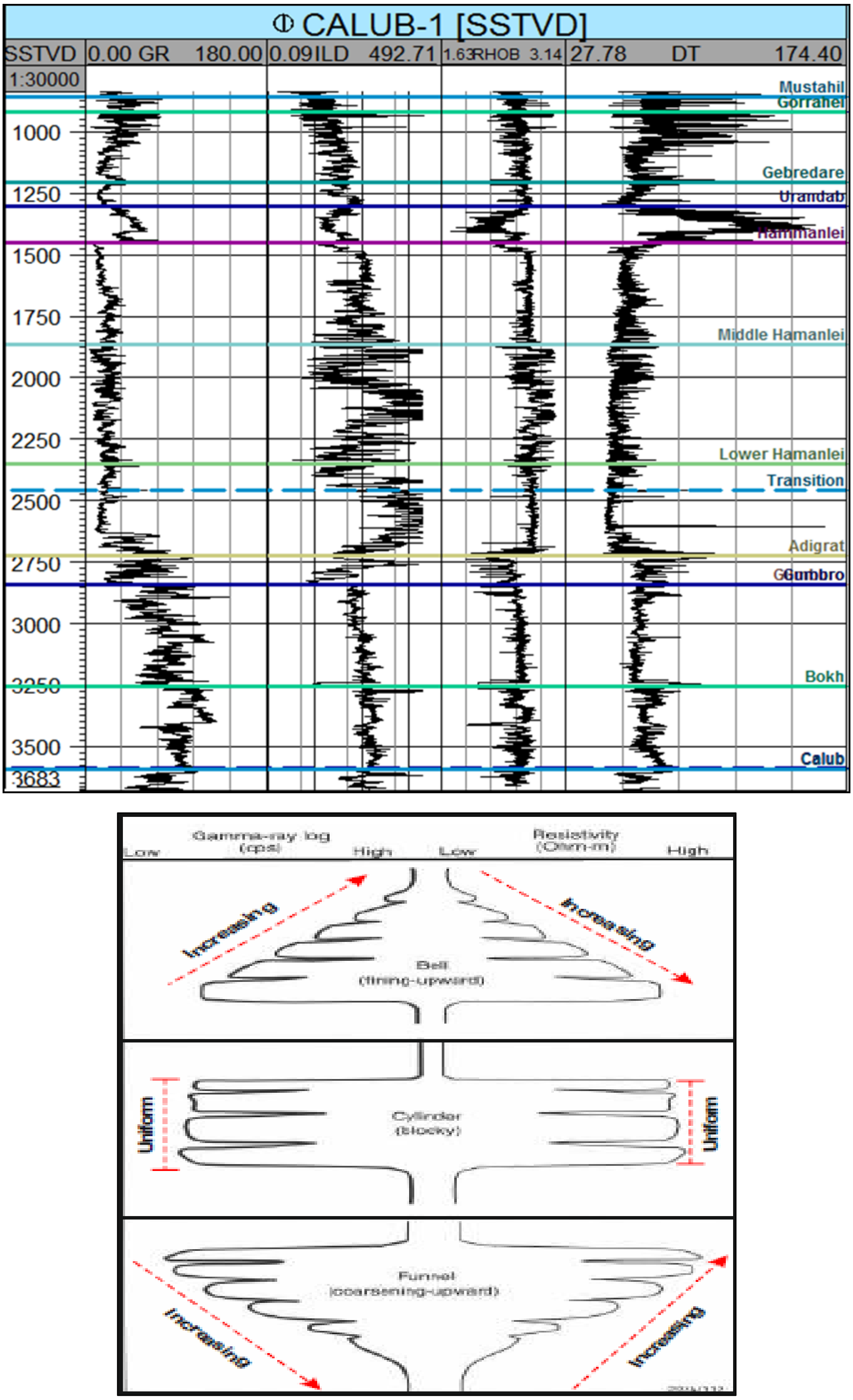

Figure 9

a) Interpreted wireline log responses from Calub-1 well to reveal stratigraphic facies; b) the illustration of the mirrored well log curves.

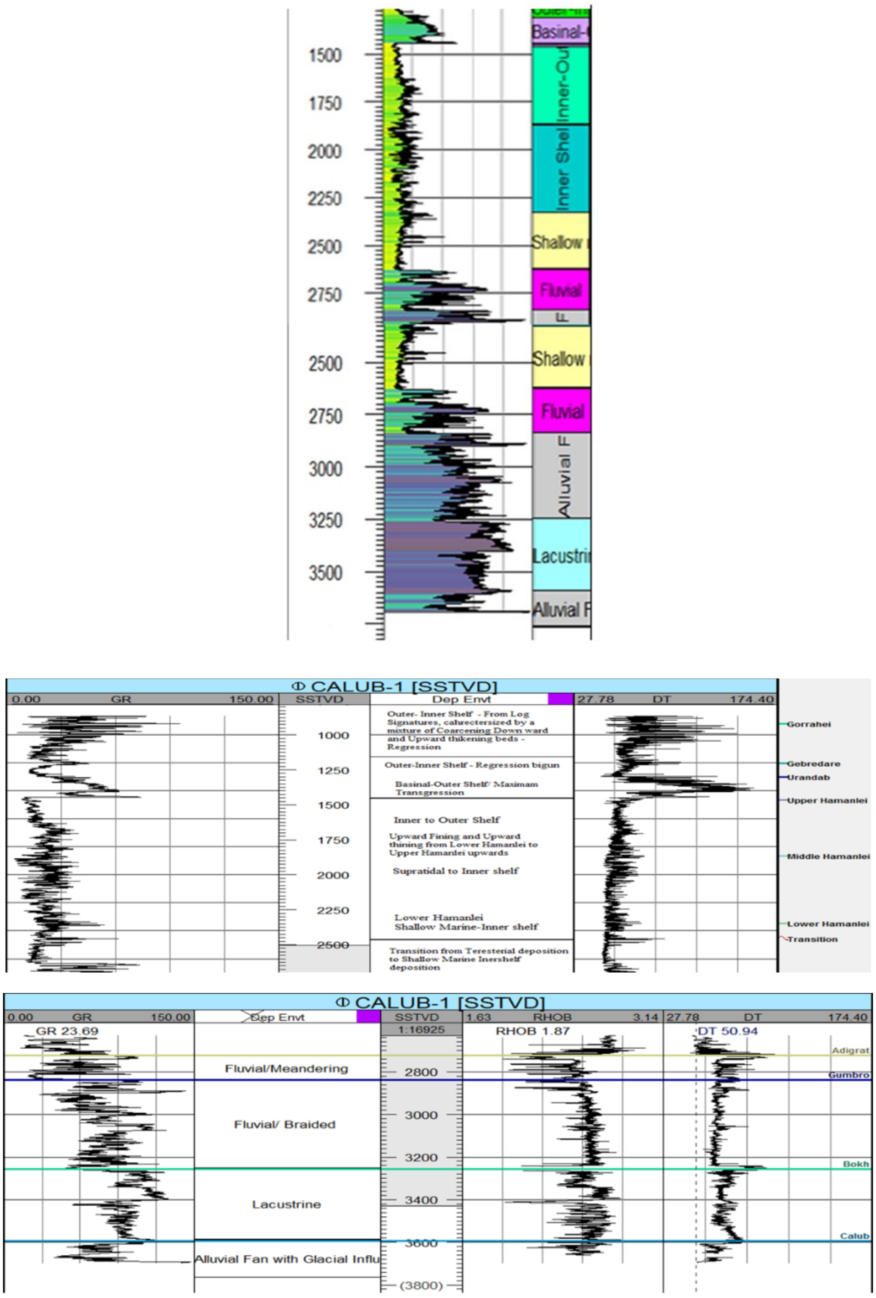

Figure 10

A depositional environment interpretation based on Calub-1 Well.

Figure 10 demonstrates that within a depth interval of 2600–3900 m, a funnel-shaped coarsening upward sequence was interpreted. According to a model developed by Krassay (1998), a classic terrestrial (Calub sandstone, Bokh shale, Gumburo sandstone, and Adigrat sandstone were intercepted) depositional environment within the stated depth range was interpreted. Within the depth interval of 1400–2600 m, a cylindrical shape log response was observed, and based on Cant (1992) and Krassay (1998), a carbonate reef as a result of shallow-to-deep marine paleo-environment was interpreted.

Table 2

Formation tops, the corresponding thickness of the formations and associated facies sequence; NB indicates “not defined” and NR denotes “not reached”.

Formation \ Wells		BODLE-1			CALUB-1			HILALA-2			Well Log facies lithology	Sediment stacking pattern	Environment of deposition
		Formation tops (m)		Thickness (m)	Formation tops (m)		Thickness (m)	Formation tops (m)		Thickness (m)			
		Top (m)	Bottom (m)		Top (m)	Bottom (m)		Top (m)	Bottom (m)				
Mustahil		550	735	185	859	921	62	138	261	120	Mixed sandy and shally	Retrogradational (fining upward) bell shape	Shallow marine
Gorrahei		735	1325	590	921	1203	283	261	778	907	Limestone/Dolomite		Shallow marine
Gebredare		1325	1439	114	1204	1302	98	778	1450	277	Limestone		Shallow marine
Urandab		1439	1673	234	1302	1463	161	1450	1675	127	Shally	Progradational	Deep Marine
Hamanlei	Upper	1673	2123	451	1463	1864	401	1675	1688	109	Limestone	Progradational (cylinder)	Sallow marine to deep marine
	Middle	2125	2352	228	1864	2349	485	1675	2221	533	Dolomite		
	Lower	2352	2594	241	2349	2460	110	2221	2386	165	Limestone		
Transition zone		2594	3000	406	2460	2722	261	NR	NR	NR	Mixed sandy and carbonate sequence		Shallow marine
Adigrat		3000	3095	94	2721	2840	118	NR	NR	NR	Sandy	Aggradational (coarsening upward) serrated shape	Fluvial
Gumburo		3095	3687	592	2840	3245	405	NR	NR	NR	Sandy		Alluvial
Bokh	Upper Unit	3687	3789	188	3245	3429	343	NR	NR	NR	Shally		Lacustrine
	Lower Unit	3789	3876		3429	3588		NR	NR	NR			
Calub		NR	NR	NR	3588	3691	103	NR	NR	NR	Sandy		Alluvial

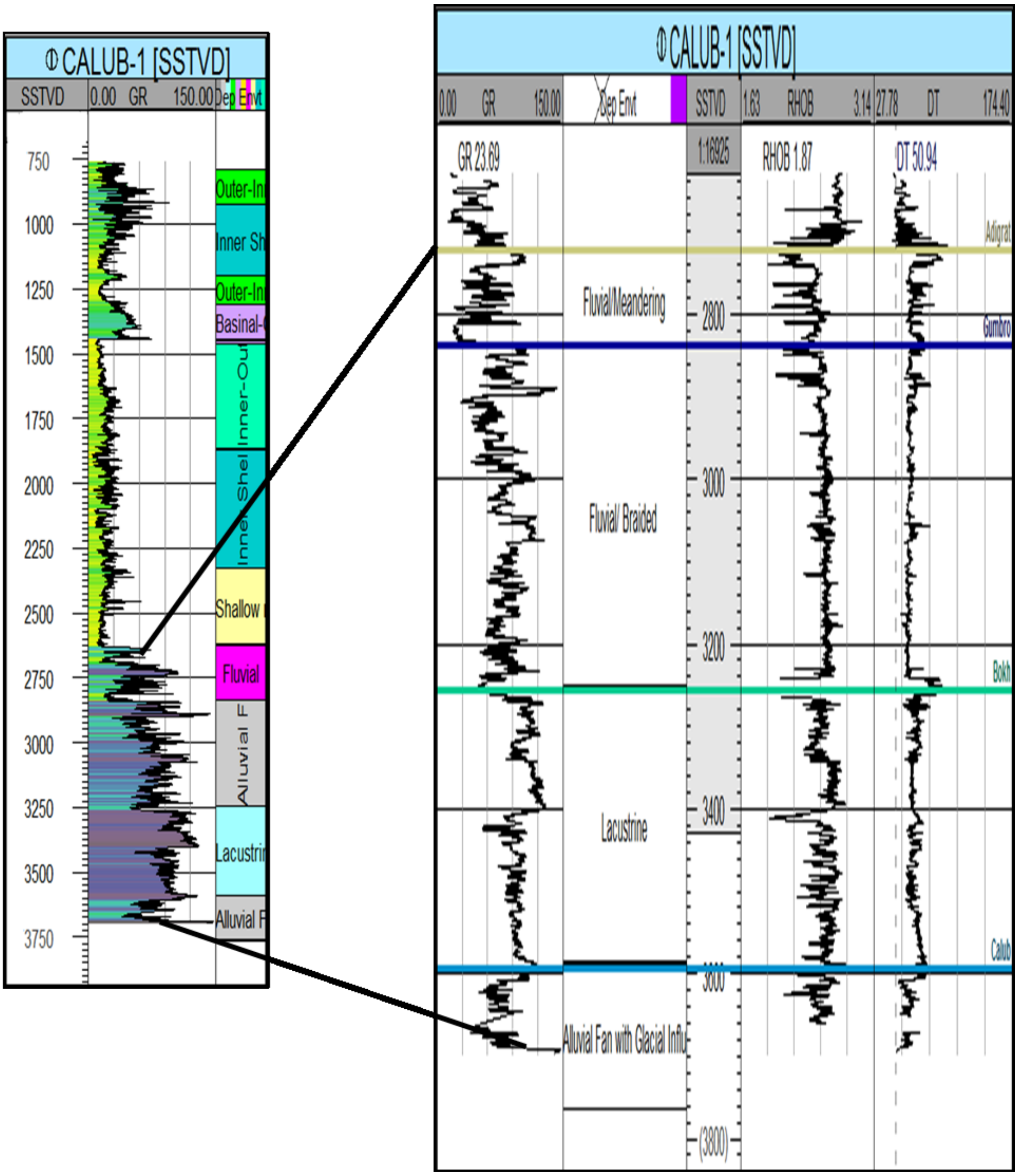

Figure 11
Depositional environment interpretation based on Calub-1 well within a depth interval of 2600–3900 m.

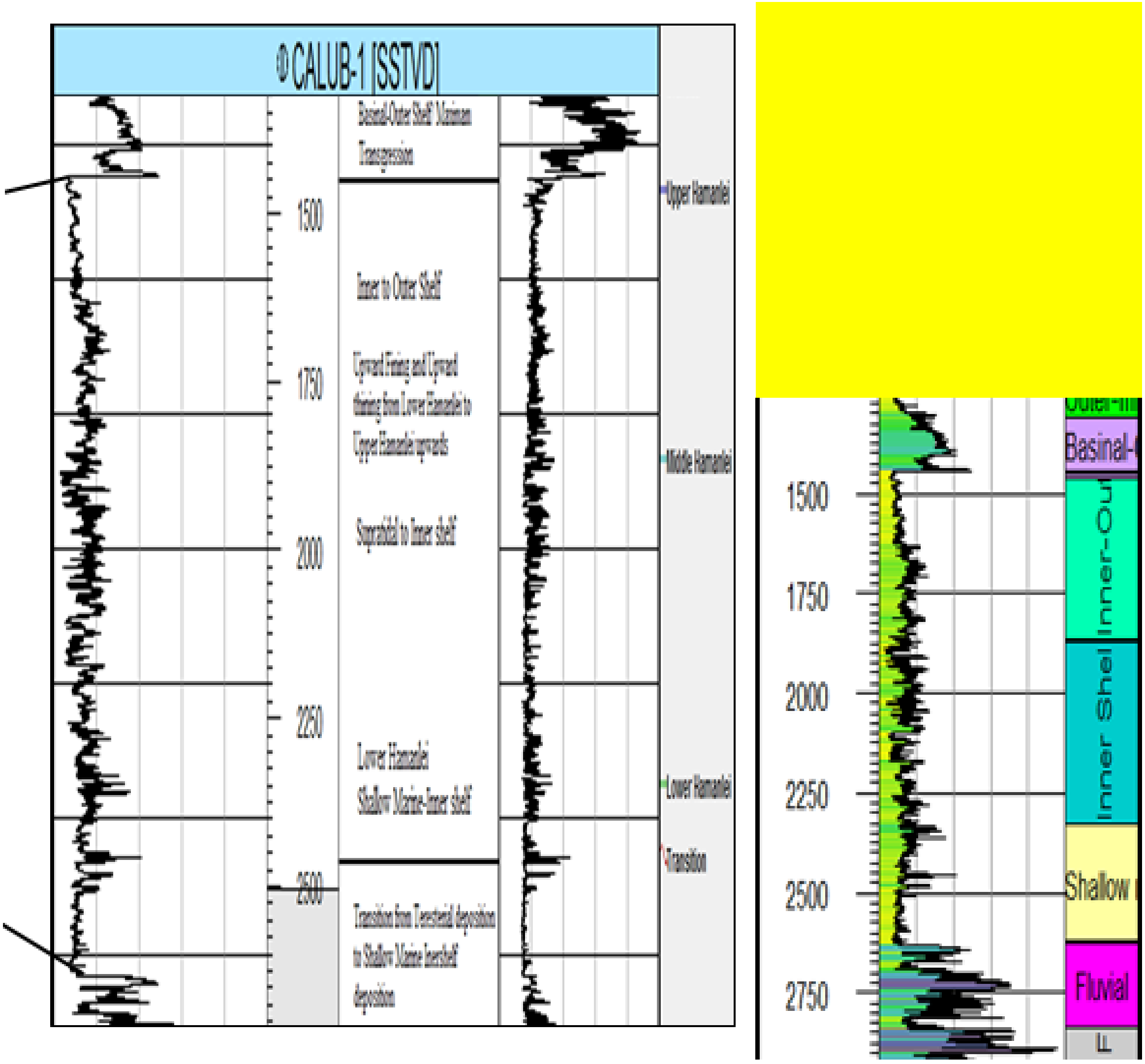

Figure 12
Depositional environment interpretation based on Calub-1 well within a depth interval of 1400–2600 m (Upper, Middle, and Lower Hamanlei formations were intercepted).

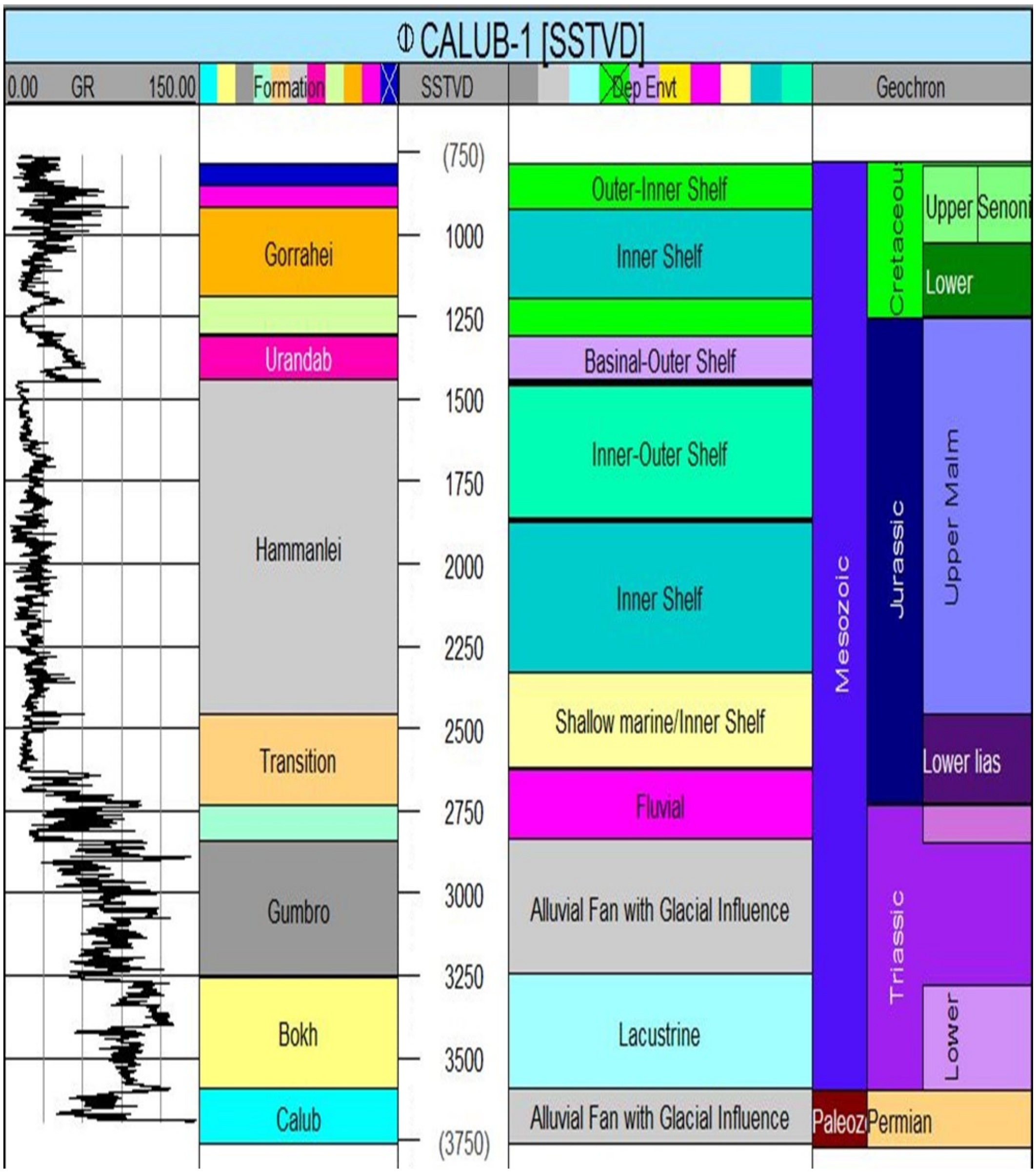

Figure 13
Depositional environments of delineated formations of the study based on Calub-1 well; GR is the gamma ray, SSTVD denotes the subsurface true vertical depth, Dep Envt indicates depositional environment, and Geochron stands for geochronology.

a. Calub formation

Calub formation is the basal facies that displayed characteristic blocky-shaped gamma ray and resistivity curves pair primarily having both gamma ray and resistivity values vertically unchanging, indicating uniform lithology and lack of overall facies change. This general trend is also observed in the corresponding bulk density and sonic logs. Gamma-ray API values are relatively lower than the overlaying shally Bokh formation. Resistivity values are generally high, bulk density values are high, and p-sonic velocity values are low, indicating sandy unit as the basal rock formation (Figure 4–7 and Table 2). The Calub formation is the oldest sedimentary unit in the studied area, with an overall thickness of 103 m in well Calub-1 ranging in depth from 3588 to 3691 m (Figure 7, Table 2). The maximum depth of the Calub formation was recorded in Ogaden Basin after being intercepted by Calub-1 well. The basal Calub formation, the oldest formation in Ogaden Basin, was deposited over the basement complex. Calub formation consists of sandstone with even grain size and sediment sorting indicative of a continental depositional environment. Due to the continental (alluvial) depositional environment, the uniform lithology and overall facies character indicate an aggradational sedimentary stacking pattern.

b. Bokh formation

Bokh formation directly overlies the Calub formation, and it displayed characteristic overall funnel shape in combined GR and resistivity curves pair often with repeated alternating block intervals of GR and resistivity spike readings. A similar distinguishing trend was observed in the bulk density and sonic logs, indicating alternating shale–sandstone facies sequence with the dominance of shaly formation. Cross section analysis of the NE–SW axes in the area indicated thickness ranging from 188 m in Bodle-1 well to 343 m in Calub-1 well (Figure 7 and Table 2). Gamma-ray and resistivity log patterns within the interval of Bokh formation indicated progressive coarsening upward succession, representing progradational regressive sedimentation in transitional lacustrine to shallow marine depositional environment.

c. Gumburo formation

Gumburo formation directly overlies Bokh formation and displayed characteristic curve pattern similar to Adigrat formation except for relatively higher GR values with corresponding lower resistivity values, lower density values, and higher p-sonic velocity values indicative of uniform sandstone with shale intercalations (Figure 7 and Table 2). Cross section analysis based on Bodle-1 and Calub-1 wells indicated that the layer ranged in thickness from 592 m in Bodle-1 well to 405 m in Calub-1 well (Figures 7 and 8 and Table 2). The characteristics of Gumburo are consistent with the literature description of the overlying formation representing the mud-rock facies unit interpreted as the Gumburo sandstone, which consists of predominantly sandstone. The characteristic blocky shape indicated an aggradational sedimentary stacking pattern, probably in a transitional fluvial (meandering) depositional environment.

d. Adigrat formation

The Adigrat unit is the uppermost facies of the Karro formation overlying the Gumburo formation, displaying characteristic overall serrated to bell-shaped gamma ray and resistivity curves pair having gamma ray values increasing upward and resistivity values decreasing upward. Similar patterns were repeated in the corresponding bulk density log and sonic log, indicating a sequence of sand and clay interbeds (Figure 7 and Table 2). Cross section analysis of the NE–SW axes indicated that the Adigrat formation attained a thickness of 94 m in Bodle-1 well and 118 m in Calub-1 well (Figure 7 and Table 2). The combined well-log curve pattern indicated a retrogradational and landward movement of shorelines and an overall fining upward succession typical of fluvial depositional environments.

e. Transitional formation

The transition zone marks the change from a continental to a marine environment of deposition and may represent a rise of sea level at the Triassic–Jurassic boundary lithologically is clastic–carbonate mixture and is overlain by the Hamanlei group and attained a thickness of 406 and 261 m in Bodle-1 and Calub-1 wells, respectively (Table 2).

f. Hamanlei formations

The lithological character of the Hamanlei ground is predominantly composed of shallow marine carbonates with shallow marine to tidal flat to sabkha evaporites and associated facies in the Middle Hamanlei. The formation consists of three distinct units from the log signature readings and cores sample analyses results. The lower part of the formation is dominated by limestone and overlain by dolomite-dominated unit, and on top, the limestone-dominated unit comprises the formation. Cross section analysis of the NE–SW axes (Figure 7 and Table 2) indicates that the transition unit attained a penetrated thickness of 406 and 261 m at Bodle-1 and Calub-1 wells, respectively, whereas the Hamanlei formation attained a thickness of 920, 996, and 808 m in Bodle-1, Calub-1 and Hilala-2 wells, respectively.

g. Urandab formation

The lithological characteristics of the Urandab formation range from a succession consisting of Black shale, Marly, Gypsiferous limestone, and intercalated grey argillaceous limestone. The Urandab formation is a relatively deep marine low energy sequence. Cross section analysis of the NE–SW axes indicates a thickness of 234, 161, and 127 m in Bodle-1, Calub-1, and Hilala-2 wells, respectively (Figure 7 and Table 2).

h. Gebredare formation

Gebredare formation consists of thinly-bedded alternation oolitic and marly limestone with gypsum-bearing shale in its lower part. The formation attains a maximum thickness of 114, 98, and 277 m in Bodle-1, Calub-1, and Hilala-2 wells, respectively (Figure 7 and Table 2). The overall trend in the Gebredare formation is gradual shallowing. Minor subsidence rates and sea-level changes caused the observed variation and development of upward coarsening cycles.

i. Gorrahei formation

The Gorrahei formation represents the lower part of Cretaceous succession in the Ogaden Basin. Thickness variations in the three wells are 589, 282, and 907 m in Bodle-1, Calub-1, and Hilala-2 wells, respectively (Figure 7 and Table 2). It has gradational contact with the underlying Gebredare formation and is overlain by the Mustahil formation. Based on GR log readings, the lithological characteristics of the lower unit are characterized by varying lithology units made up of interbeds of carbonate shales with minor anhydrite.

j. Mustahil formation

The lithological characteristic of the Mustahil formation consists of a thinly-bedded alternation of sandstone and shale. The formation attains a maximum thickness of 184, 62, and 120 m in Bodle-1, Calub-1, and Hilala-2 wells, respectively. The overall trend in the Mustahil formation is gradual shallowing upward and similar log signature response patterns with the underlying Gorrahei formation, defined by the retrogradational sediment stacking pattern (Figure 7 and Table 2).

5.2. Depositional environments based on log facies

Gamma-ray log shapes and results from the core analysis were used to define the log facies and depositional environments. The analysis of the gamma-ray logs indicated that the log trend falls primarily into five categories: cylindrical/box car-shaped trends, funnel-shaped, bell-shaped successions, symmetrical trends, and irregular trends.

a. Cylinder-shaped successions

The cylinder-shaped gamma-ray logs in the study area have a serrated pattern. This trend is dominant in the reservoir units of the Hamanlei formation, mainly in Calub-1 well (Figures 10 and 12). The log signature observed characterizes the gamma-ray logs of the Hamanlei formations (Lower, Middle, and Upper) of carbonate bodies of the Jurassic succession. The upper and lower boundaries of the Hamanlei formations are sharp and bounded by marine shale and the transitional unit, respectively. According to Cant (1992) (Figures 5 and 6), gamma-ray facies association from well log pattern used in defining lithology and depositional environment indicated carbonate reef due to shallow-to-deep marine paleo-environment. A similar interpretation was made by Shell's (1982) log shape classification scheme as cylindrical-shaped gamma-ray logs could indicate a slope channel and inner fan channel environments. This log shape classification scheme is based on a measuring system. The Hamanlei formations were deposited in a slope channel environment overlain by Urandab shale, which exhibited an irregular and a higher gamma-ray reading (Figures 10 and 12). According to Emery et al. (1997), cylindrical trends with a broader range of thickness, like those of the Hamanlei formation from Calub-1, Hilala-2, and Bodle-1 wells, were interpreted to result from shallow marine transitional to transgressive depositional environments.

b. Funnel-shaped successions

According to a study by Selley (1998), the environments of shallowing-upward and coarsening successions were divided into three categories: regressive barrier bars, prograding marine shelf fans, and prograding delta or crevasse splays. The first two environments are commonly deposited with glauconite, shell debris, carbonaceous detritus, and mica (Selley, 1998). The absence of shell debris, carbonaceous detritus, and glauconite in the core report excludes the possibility of the environment being a regressive barrier bar or prograding marine shelf. However, funnel-shaped log patterns were observed at units of Gebredare and Gorrahei formations of Calub-1 well, showing a shallowing, upward-to-regressive depositional paleo-environment (Figure 10). Based on a model developed by Krassay (1998), within the stated depth range, funnel-shaped coarsening upward sequences were inferred where formations within the depth interval are Calub, Bokh, Gumburo, and Adigrat. Coleman et al. (1980) reported that parallel laminae are the most common primary structure since deposition is entirely from suspension. In Calub-1 well, a more evident funnel-shaped trend was observed within a depth range of 2600–3900 m. Based on a model developed by Krassay (1998), within the mentioned depth range, funnel-shaped coarsening upward sequences were interpreted.

c. Bell-shaped successions

The bell-shaped gamma-ray logs in the wells were found to have a thickness of around 161 m. They occur in the upper portion of the Upper Hamanlei unit, the Urandab shale, as were observed in Calub-1 well. The gamma-ray log trends in Urandab shale of Bodle-1 and Hilala-2 wells showed a bell motif overlaying a thin funnel motif. The bell-shaped successions were interpreted to indicate a transgressive shale/sand and calm deep marine depositional environment. Nelson and James (2000) showed that tidal channels commonly contain glauconite and shell debris. Shell debris and glauconite were not included in the sample descriptions available, eliminating the possibility of the environment being a tidal channel. Bell-shaped successions with carbonaceous detritus are deposited in environments of fluvial or deltaic channels (Selly, 1998). The absence of carbonaceous detritus in the samples excludes the possibility of the environment being a fluvial or tidal channel. Most cycles of sedimentation begin with the erosion of underlying sand units and the deposition of thin fossiliferous transgressive marine sand, Weber (1971). The bell-shaped successions are thin, which indicates that the sands were deposited in the environment of the transgressive marine shelf. The formations resulting from a transgressive marine shelf deposition were the Upper Hamanlei and the Urandab formations, which attained a thickness of 400 and 161 m, as observed in Calub-1 well (Figure 9 and Table 2), showing a bell-shaped log pattern. In contrast, the gamma-ray log trend of Hilala-2 well (Figure 9 and Table 2), which occurs between depths of 1515 to 1631 m, was rugged and funnel-shaped and attained a thickness of about 126 m. The trend is usually interpreted to indicate the deposition of cleaning upward sediments or an increase in the shale content with the minor sand effect of the turbidite bodies, as applied to a deep marine setting where Urandab shale was deposited.

d. Symmetrical Log Patterns

The symmetrical log trends observed were within intervals of Gebredare, Gorrahei, and Mustahil formations. According to Coleman et al. (1980), symmetrical log patterns indicate a transgressive–regressive environment, alternating fining upward and coarsening upward sequence (Figure 7).

e. Irregular log trends

The irregular shape of the gamma-ray log in the analysis classifies the log facies as belonging to a plain basin environment. The environment is characteristically a blanket of clays and fine silts deposited from suspension, with high lateral continuity and low lithologic variation. The periodic log trends have no character but can represent aggradations of shales or silts, according to Emery et al. (1996). In Calub-1 well, where there is a cored interval, periodic log trends were observed, indicating the presence of shale and silts. The trend observed is also more prominent in Bodle-1 well within a depth interval of 3687–3875 m and 1438–1573 m of the Bokh shale and the Urandab shale intervals, respectively. The irregular-shaped facies representing fluvial floodplain interpretation were also consistent across the three wells as the angular to sub-rounded fluvial channels fill sandstones for the deposition of Adigrat formations within the range (Figure 11).

6. Conclusions

Based on the facies study using the well-log data and interpretations, the present study supported the existence of 10 stratigraphic units. Calub-1 well intercepted Calub sandstone, Bokh shale, Gumburo and Adigrat sandstones, Transition, Hamanlei carbonate, Urandab shale, Gebredare, Gorrahei, and Mustahil. Formations Bokh shale, Gumburo and Adigrat sandstones, Transition, Hamanlei carbonate, Urandab shale, Gebredare, Gorrahei, and Mustahil laterally continue toward Bodle-1, while formations intercepted by Hilala-2 wells are Lower Hamanlei, Middle Hamanlei, Upper Hamanlei carbonate, Urandab shale, Gebredare, Gorrahei, and Mustahil.

In addition, a consistent upward increase in the sand content within the basin was observed. Based on Calub-1 well, in the lower portion of the stratigraphic column of the Basin Bokh shale, Gumburo, and Adigrat sandstone, beds are deposited in equal proportion (50%). However, the upper section was observed to be more sand (70%) with minor shale intercalation. A Jurassic carbonate platform deposition was observed within a depth range of 1400–2600 m (Figure 7). The oldest units of sediments are the Permo–Triassic Karro formations in age and deposition continues to recent. Based on the models developed by Cant (1992) and Krassay (1998), well log patterns were interpreted; terrigenous depositional environments included the Calub, Bokh, Gumburo, and Adigrat formations, while shallow-to-deep marine depositional environments included deposits of Hamanlei carbonate group and Urandab shale (Figures 10 and 12). A regressive and transgressive deposit included the Gebredare, Gorrahei, Mustahil, and Ferfer formations (Figure 7). The stacking patterns of individual sedimentary formations were also deduced from the combined well-log analysis, and the Karro formations (Calub, Bokh, Gumburo, and Adigrat) were characterized by aggradational stacking pattern. Progradational stacking patterns characterized the overlaying transition unit, Hamanlei carbonate group, and Urandab formations. A transgressional–regression retrogradational stacking pattern characterized the overlaying Gebredare, Gorrahei, and Mustahil formations.

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Nomenclature

Dep Envt	Depositional environment
API	American Petroleum Institute
DT	Sonic log
PAULESI	Pan African University Life and Earth Sciences Institute
Geochron	Geochronology
GR	Gamma ray
ILD	Deep resistivity log
RHOB	Density log
SNP	Sidewall neutron porosity log
SP	Spontaneous potential
SSTVD	Subsurface true vertical depth

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