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FACIES ANALYSIS OF AFENMAI FIELD IN EASTERN NIGER DELTA OF NIGERIA, USING COMBINED GEOPHYSICAL LOGS, LITHOLOGIC AND PALEONTOLOGICAL DATA

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Abstract

Facies analysis of Afenmai field was carried out to generate some of the information required for upgrading the status of this old discovery into the development stage. This is conventionally performed either by singly correlating lithologic tops, or biozones, or geophysical log motifs. This often results in false reservoir continuity and attendant disappointing drilling results. In this study, sequence stratigraphic principles were employed in an integrated approach to relate the combination of geophysical log data, lithologic and paleontologic information to time-significant lithostratigraphic surfaces. The top of Agbada Formation and base of E8000 sand were found to be sequence boundaries. The top of the E8000 sand is a transgressive surface, while the base of E4000 sand constitutes a maximum flooding surface. The E8000 sand belongs to lowstand systems tract, while the lithofacies sandwiched between the top of E8000 sand and base of E4000 sand constitute transgressive systems tract. The D-sands together with E1000 to E4000 sands form highstand systems tract. The lithofacies below the base of E8000 sand also belong to the highstand systems tract. Potential stratigraphic traps exist along the regional unconformity surface which constitutes the sequence boundary that defines the top of Agbada Formation. Opportunities for infill well drilling were established between wells 6 and 7, as well as between wells 1 and 2.

Keywords: Facies analysis, sequence stratigraphic principles, potential stratigraphic traps

Introduction

Afenmai Field is located within the Central Depobelt of the eastern portion of the Niger Delta Basin, along the continental margin of West Africa and the Gulf of Guinea (Figure 1).

The field covers an areal extent of approximately 242Km^2 with eight drilled wells, giving an average well density of one well per 30Km^2. Undersaturated oil, as well as oil with associated gas have been discovered in some reservoirs in six of the wells. Though an old discovery, it is waiting to be advanced into the development status.

Part of the requirements for the exercise is generating a field-wide facies correlation within a chronostratigraphic framework. This would ascertain reservoir continuity between wells and enable identification of opportunities for infill drilling. This work was embarked upon to achieve these objectives.

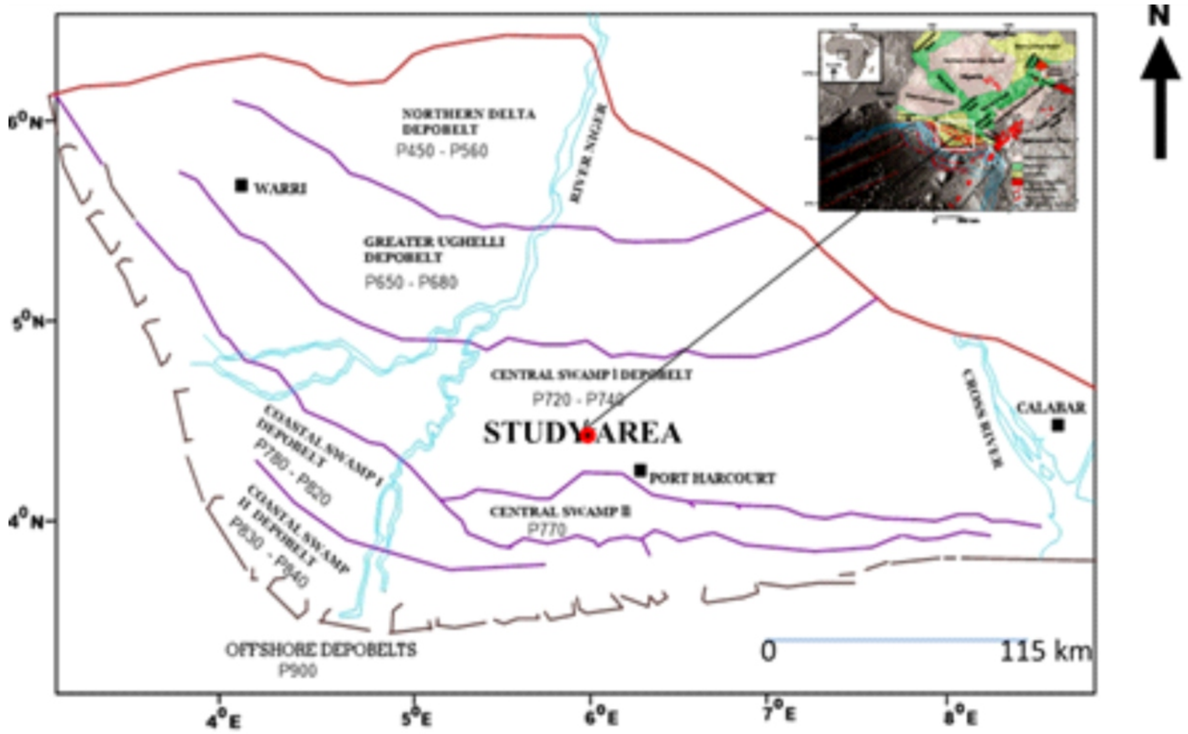


Figure 1: Location of Afenmai Field in the eastern part of Niger Delta's Central Swamp Depobelt (Source: Whiteman, 1982; Doust and Omatsola, 1990; Okosun and Libau,1999)

Facies correlation is conventionally performed on geophysical logs, using lithologic similarities and paleontological events. Examples of such correlation are in Weber (1971), Hubbard *et al.* (1985), Neal *et al.*(1993), Aizebeokhai and Olayinka (2011), Obaje and Okosun (2013), Okosun and Chukwuma- Orji (2016), Okosun and Chukwuma- Orji (2017), Nazeer *et al.*(2016), and Ukpong *et al.*(2018). The correlation is a fusion of genetically unrelated stratigraphic units that are time-transgressive or diachronous (Hubbard *et al.,* 1985; Van Wagoner *et al.*, 1990; Nichols, 2009; Unuevho, 2014; Parvin and Woobaidullah, 2019). Step-out drilling carried out on the basis of structural maps produced from time-transgressive correlations will result in numerous dry holes (Hubbard *et al.*, 1985; Unuevho, 2014; Hasan *et al.*, 2018). Petroleum geoscientists now overcome this shortcoming by conducting sequence stratigraphic correlations along genetically constrained surfaces such as Maximum Flooding surfaces (MFS), Transgressive Surfaces (TS) and Sequence Boundaries (SB). Emujokporue and Eyo (2016), Nwaezeapu *et al.*(2018), and Hasan *et al.*(2018) identified MFS as horizons where highest GR values coincide with maximum foraminiferal abundance and diversity. They also identified SB as horizons that combine minimum GR value on well logs with lowest foraminiferal abundance and diversity. Parvin and Woobaidullah (2019) placed SB at the base of blocky or coarsening upward log motif. They also placed TS at the base of fining upward motif. Emujokporue and Eyo (2016) identified TS as the first major flooding surface that follows SB, and is recognized on the motif.GR log as base of fining upward.

Methodology and Data Employed

The data employed in this study comprised conventional geophysical logs, subsea-vertical depth (SSVD) to top and base of sand units, biostratigraphic and hydrocarbon fluid contact information. In the study, sequence stratigraphic principles were employed in an integrated approach to infer depositional environments, paleobathymetric changes, sequence boundaries and systems tracts from foraminiferal fauna, lithologic data and geophysical logs. Paleoenvironments and paleobathymetry were inferred as follows:

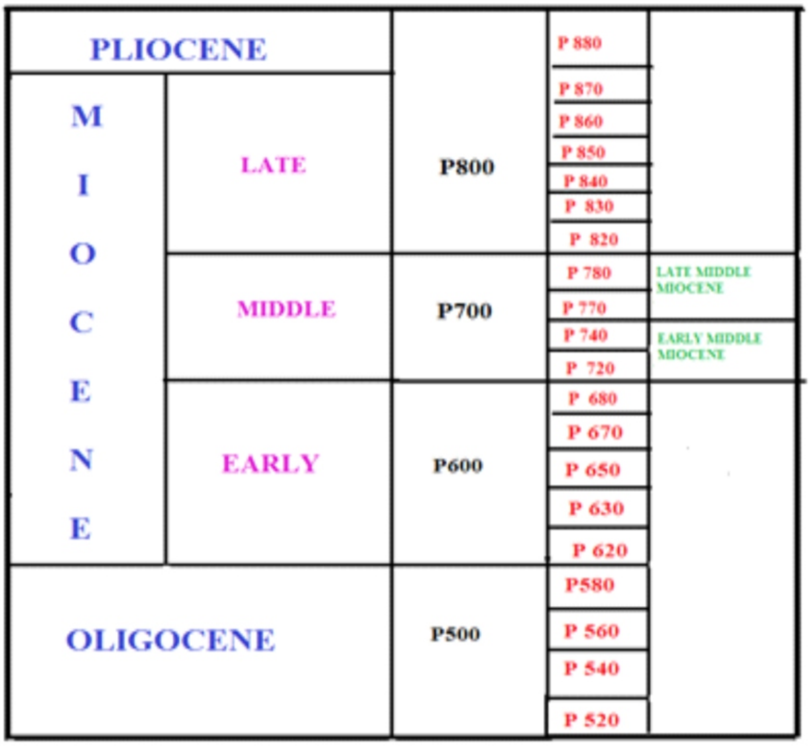
I. From information on foraminiferal genera using the templates given by Braiser (1980), Boersma (1980), Petters(1982), Ozumba (1988), Okosun and Libeau (1999), Okosun and Chukwuma- Orji (2016), Okosun and Chukwuma- Orji (2017);

II. From continuity of lithologic units following Allen and Roberts (1982), Dunbar and Rodgers (1957), Serra (1989), Van Wagoner *et al.* (1990), Boggs Jr.(2006); and

III. From gamma ray(GR) log motif following Weber (1971), Selley (1978), Edeki (1991), Neal *et al.*(1993), Adegoke (2002), Larue and Legarre (2004), Shell (2011) and Nazeer *et al.* (2016).

Sequence boundaries (SB), Transgressive Surfaces (TS), Maximum Flooding Surfaces (MFS) and systems tracts were identified following Van Wagoner *et al.* (1990), Neal *et al.* (1993), Adegoke (2002), Coe and Church (2003), Larue and Legarre (2004), Shell (2011), Nton and Ogunbemi (2011), Obaje and Okosun (2013), Moosavizadeh *et al.* (2015), Emujokporue and Eyo (2016), Nwaezeapu *et al.*(2018), Hasan *et al.*(2018), and Parvin and Woobaidullah (2019). The correlation was performed on a workstation operating on *Geographix 5000* software.

The geologic ages of penetrated lithofacies were inferred using Niger Delta's Neogene Stratigraphic data sheet (Figure 2).



PLIOCENE		P800	P 880	
MIOCENE	LATE		P 870	
			P 860	
			P 850	
			P 840	
			P 830	
			P 820	
	MIDDLE	P700	P 780	LATE MIDDLE MIOCENE
			P 770	
			P 740	EARLY MIDDLE MIOCENE
			P 720	
	EARLY	P600	P 680	
			P 670	
			P 650	
			P 630	
			P 620	
OLIGOCENE		P500	P580	
			P 560	
			P 540	
			P 520	

Figure 2: Niger Delta's Neogene Stratigraphic data sheet (Source: Whiteman.1982; Doust and Omatsola,1990; Reijers,2011)

Each penetrated sand unit and its associated shale unit were identified with an alphanumeric name. Thus a D1000 sand unit is underlain with D1000 shale unit. The thickness of each sand and shale unit was obtained by subtracting given SSVD to top of unit from the SSVD to its base.

Data Analysis and Discussion

The given biostratigraphic information reveals that then wells penetrated Early Miocene to Late Miocene lithofacies (tables 1,2,3,4,5,6,7). The interpretation of the Foraminiferal fauna in terms of depositional environments is given in Figure 3. The intervals that are barren of foraminifera are interpreted to constitute continental to marginal marine lithofacies. Selley (1978), Boggs (2006), Nichols (2009), Hasan *et al.*(2018), and Parvin and Woobaidullah (2019)interpreted such clastics to be fluvial lithofacies. The presence of *Nonion-6* reflects inner-shelf depositional environments, in line with Petters (1982) and Nwaezeapu *et al.* (2018). Outer shelf to upper bathyal depositional environments were inferred from the presence of *Uvigerina, Chiloguembelina* and *Cassigerinella* genera in accordance with Boersma (1980), Braiser (1980), Petters (1982), Ozumba (1995), and Okosun and Liebau (1999). Occurrence of *Bolivina* genera reflects outer shelf to middle bathyal depositional environments (Boersma,1980; Ozumba ,1995).

Table 1: Biostratigraphic data for well 001

SUB-SEA DEPTH TO TOP (IN ft)	SUB-SEA DEPTH TO BASE (IN ft)	ZONE CODE	FORAMINIFERA	GEOLOGICAL AGE
30	**3980**		**Barren**	
2520	**5400**	**P840**		**Late Miocene**
3996	**5260**	**F9600/F9700**		**Middle Miocene**
5280	**6170**		**Undiagnostic**	
6180	**7870**	**F9500**		**Middle Miocene**
7880	**8640**	**F9300/F9500**		**Early-Middle Miocene**
8660	**10190**	**F9300**	**Rich *Bolivina 25***	**Early Miocene**

Table 2: Biostratigraphic data for well 002

SUB-SEA DEPTH TO TOP (IN ft)	SUB-SEA DEPTH TO BASE (IN ft)	ZONE CODE	FORAMINIFERA	GEOLOGICAL AGE
40	**4040**		**Barren**	
4060	**5360**	**F9600/F9700**		**Middle Miocene**
5380	**6160**		**Barren**	
6170	**6200**		**Undiagnostic**	
6220	**7980**	**F9500**	**Top *Uvigerina 5***	**Middle Miocene**
6270	**6270**	**F9540**	***Bolivina 25/ Uvigerina 5***	**Middle Miocene**
8000	**10066**	**F9300**		**Early Miocene**

Table 3: Biostratigraphic data for Well 003

SUB-SEA DEPTH TO TOP (IN ft)	SUB-SEA DEPTH TO BASE (IN ft)	ZONE CODE	FORAMINIFERA	GEOLOGICAL AGE
0	1490		No data	
121	3659		Barren	
1500	2812	P850/P880		Late Miocene
2960	4489	P830/P840		Late Miocene
3689	4940	F9600/F9700		Middle Miocene
4490	4800	P770		Middle Miocene
4970	6240	P740		Middle Miocene
4970	6390		Barren	
6300	7460	P720		Middle Miocene
6400	8020	F9500	Top *Uvigerina5*	Middle Miocene
7540	9850	P680		Early Miocene
8040	8980	F9300/F9500		Early Miocene
9000	10010	F9300	Rich *Bolivina*	Early Miocene

Table 4: Biostratigraphic data for Well 005

SUB-SEA DEPTH TO TOP (IN ft)	SUB-SEA DEPTH TO BASE (IN ft)	ZONE CODE	FORAMINIFERA	GEOLOGICAL AGE
0	550		No data	
530	3670		Undiagnostic	
3710	5650	F9600/F9700		Middle Miocene
5680	6070		Undiagnostic	
6080	8880	F9500	Top *Nonion6*	Middle Miocene
8890	10160	F9300	*Bolivina25*	Early Miocene

Table 5: Biostratigraphic data for Well 006

SUB-SEA DEPTH TO TOP (IN ft)	SUB-SEA DEPTH TO BASE (IN ft)	ZONE CODE	FORAMINIFERA	GEOLOGICAL AGE
0	**7750**		**No data**	
7770	**7775**	**F9500**		**Middle Miocene**
7772	**7772**	**F9520**	***Chiloguembelina3***	**Middle Miocene**

Table 6: Biostratigraphic data for Well 007

SUB-SEA DEPTH TO TOP (IN ft)	SUB-SEA DEPTH TO BASE (IN ft)	ZONE CODE	FORAMINIFERA	GEOLOGICAL AGE
0	**7700**		**No Data**	
7701	**7781**		**Top *Cassigerinella***	**Middle Miocene**
7703	**7703**	**F9520**	***Chiliguembelina3***	**Middle Miocene**

Table 7: Biostratigraphic data for Well 008

SUB-SEA DEPTH TO TOP (IN ft	SUB-SEA DEPTH TO BASE (IN ft)	ZONE CODE	FORAMINIFERA	GEOLOGICAL AGE
0	**4140**		**No data**	
1920	**4680**	**P780/P810**		**Middle-Late Miocene**
4150	**5170**	**F9600/F9700**		**Middle Miocene**
4750	**5860**	**P720/P770**		**Middle Miocene**
5260	**5746**		**Undiagnostic**	
5797	**7640**	**F9560**	**Top *Uvigerina***	**Middle Miocene**
5946	**8248**	**P680**		**Early Miocene**

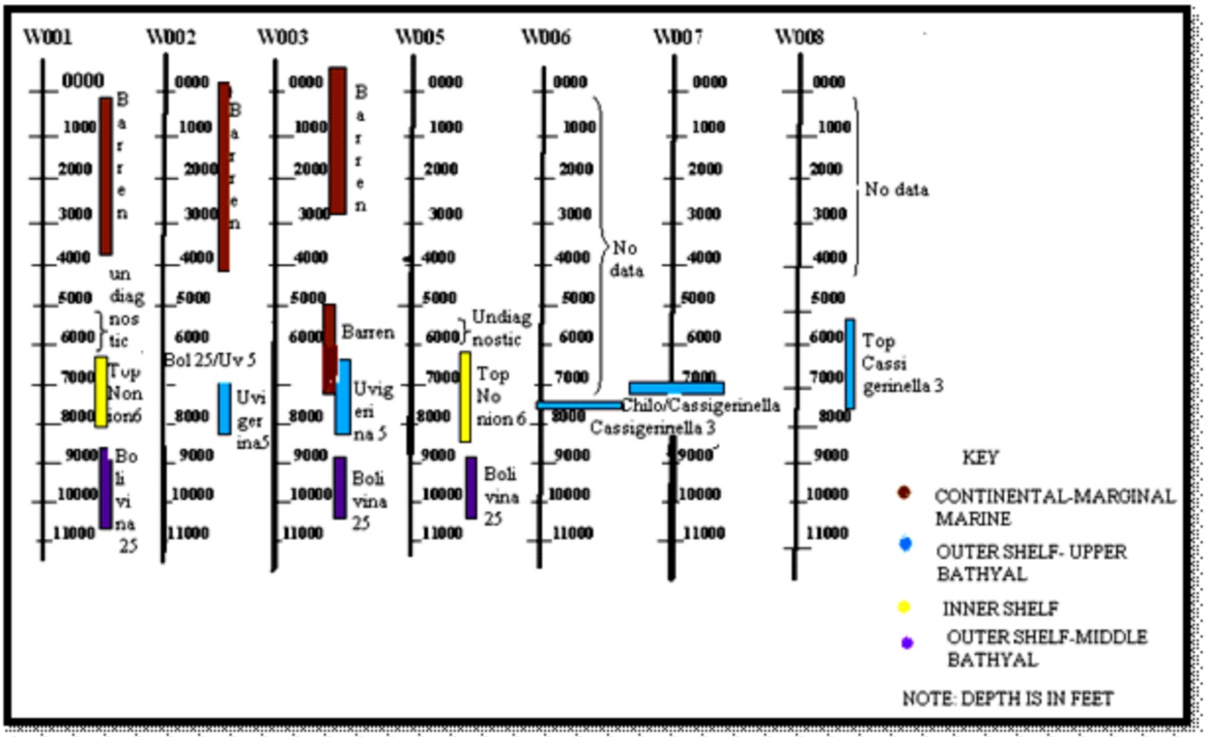


Figure 3: Depositional environments inferred from biostratigraphic data

The D1000 to D5000 sand units appear generally considerably thicker than the associated shale units (table 8). These constitute the upper portion of the Agbada Formation, in conformity with subdivisions of Agbada Formation given by Short and Stauble (1967) and Agagu (1978). The top of the Agbada Formation is defined along the base of the shallowest regional marginal marine shale in the study area, in agreement with the occurrence of marine shales at the lower portion of Benin Formation in eastern Niger Delta. This regional marginal marine shale is thick and overlies the top of the Agbada Formation. Marine shales have been reported in literature to be associated with the lower portion of Benin Formation in eastern part of the Niger Delta (Okosun and Liebau, 1999), and to constitute major sediment fill of the shallowest canyons and valleys cut by erosional processes associated with relative sea level fall (Adejobi and Olayinka, 1997). The well-section correlation of the top of Agbada Formation as well as the D-sands in wells 1,2, and 3 are shown in Figure 4. The same stratigraphic correlations for wells 3, 4, 5 and for wells 5, 6, 7 are shown in Figures 5 and 6 respectively. The extension of the correlations to well 8 is shown in Figure 7. The recognition of the shale capping the Agbada Formation in all the geophysical logs reflects its subsurface continuity, as characteristic of marine shales. Its low resistivity in comparison with resistivity values of shales above it reflects increased salinity of its pore water. The GR values of the shale are comparatively higher and more homogeneous, as expected of GR values of shales deposited during slow sedimentation in quiet waters. The shales at shallower depths above this marginal marine shale are characterised by lower GR reading with higher variation in values. This is typical of continental shales. The higher variation in values is due to lithologic heterogeneity resulting from miscellaneous materials (lignite fragments, silts and sand) deposited with shales turbulently in delta plains at higher flow. Above the top of the regional marginal marine shales on top of the Agbada Formation, sands associated with continental lithofacies are characterized by GR logs that display a sharp base and finning upwards gradational top of bell log motif. This log shape is typical of delta plain fluvial distributary channel fills and tidal flat sands. The larger bell motifs are possibly the fluvial channels lithofacies while the numerous smaller motifs probably reflect oscillatory tidal variations in tidal flats. *Chiloguembelina, Cassigerinella* and *Uvigerina* foraminifera genera together with cylindrical and crescent log motifs just beneath the marginal marine shale at wells 8,3 and 2 implies that shelf to upper bathyal lithofacies underlie the Agbada Formation's top. This vertical juxtaposition of delta plain fluvial distributary channel and marginal marine lithofacies directly above outer shelf to bathyal lithofacies, in all the wells, reflects that the top of Agbada Formation is a widespread unconformity surface and therefore a sequence boundary. Thus the top of the Agbada Formation constitutes a regional unconformity that separates overlying regional marginal marine shale from underlying outer marine to upper bathyal lithofacies.

Table 8: Thickness of individual D-sand and D-shale units in the wells

LITHOLOGIC UNIT	THICKNESS IN ft WELL 1	THICKNESS IN ft WELL 2	THICKNESS IN ft WELL 2	THICKNESS IN ft WELL 4	THICKNESS IN ft WELL 5	THICKNESS IN ft WELL 6	THICKNESS IN ft WELL 7	THICKNESS IN ft WELL 8
D1000 SAND	**40**	**15**	**72**	**10**	**-**	**56**	**14**	**-**
D1000 SHALE	**13**	**12**	**-**	**18**	**-**	**33**	**15**	**-**
D1100 SAND	**84**	**80**	**-**	**51**	**-**	**57**	**62**	**-**
D1100 SHALE	**55**	**42**	**-**	**79**	**-**	**68**	**73**	**-**
D2000 SAND	**114**	**135**	**-**	**67**	**-**	**113**	**98**	**-**
D2000 SHALE	**21**	**29**	**-**	**23**	**-**	**25**	**24**	**-**
D3000 SAND	**285**	**73**	**97**	**185**	**-**	**278**	**285**	**94**
D3000 SHALE	**12**	**-**	**284**	**15**	**--**	**16**	**21**	**30**
D4000 SAND	**26**	**-**	**16**	**12**	**-**	**30**	**19**	**252**
D4000 SHALE	**6**	**-**	**14**	**42**	**-**	**6**	**5**	**70**
D5000 SAND	**336**	**353**	**320**	**281**	**-**	**304**	**223**	**62**
D5000 SHALE	**62**	**57**	**74**	**88**	**-**	**90**	**46**	**-**

NOTE: - means no available information for its determination

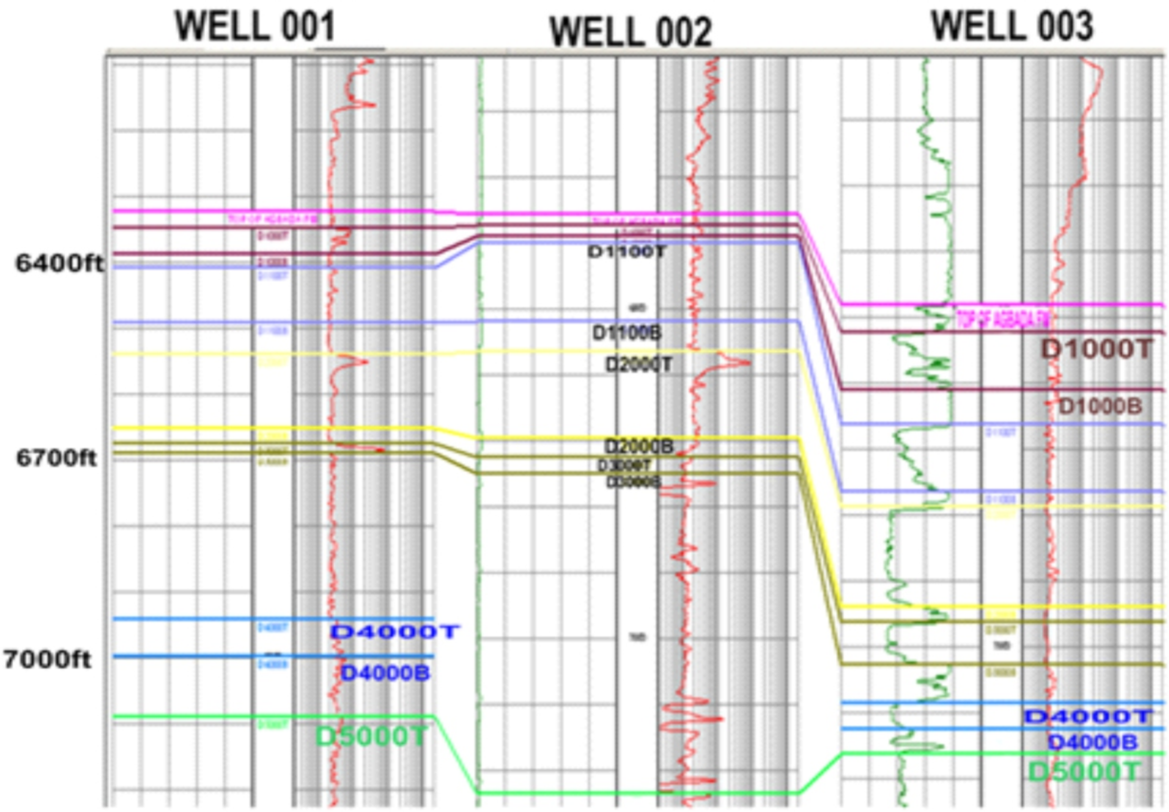


Figure 4: Correlation of top of Agbada Fm and D-sands in Wells 001, 002 and 003

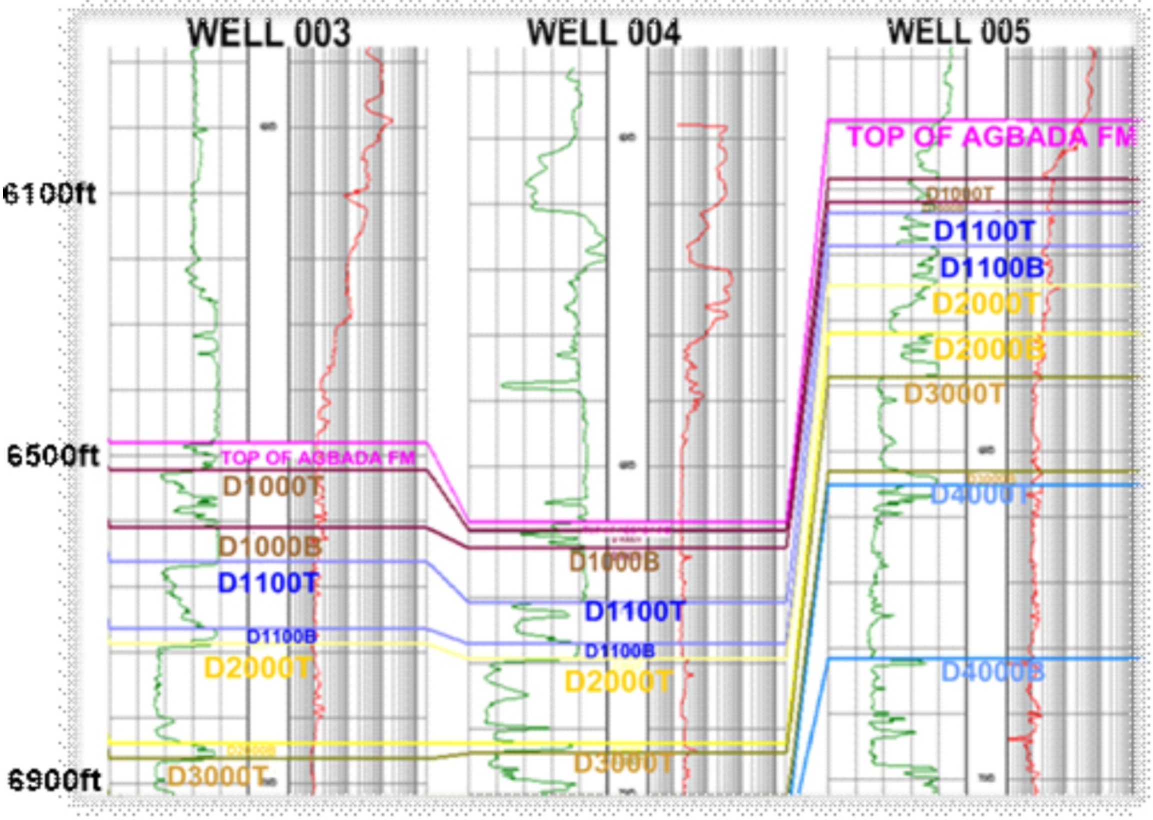


Figure 5: Correlation of top of Agbada Fm and D-sands in Wells 003, 004 and 005

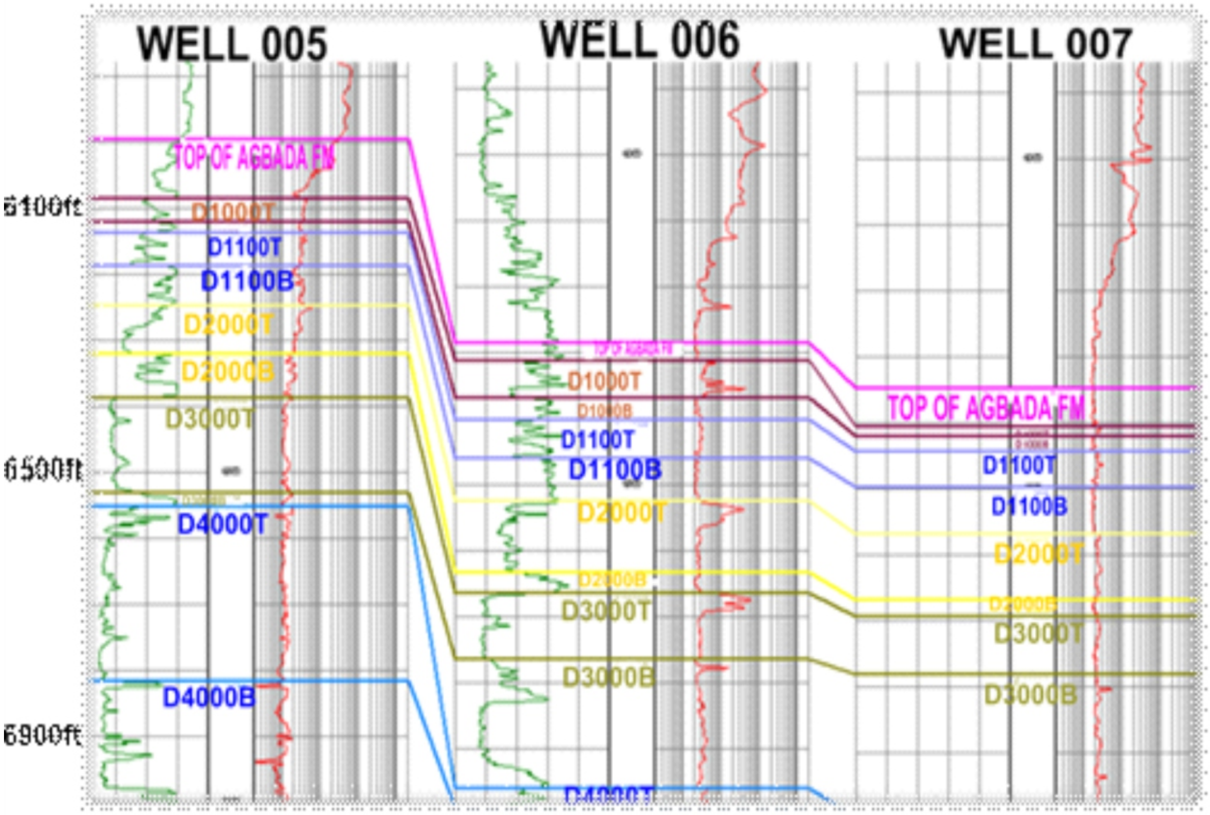


Figure 6: Correlation of top of Agbada Fm and D-sands

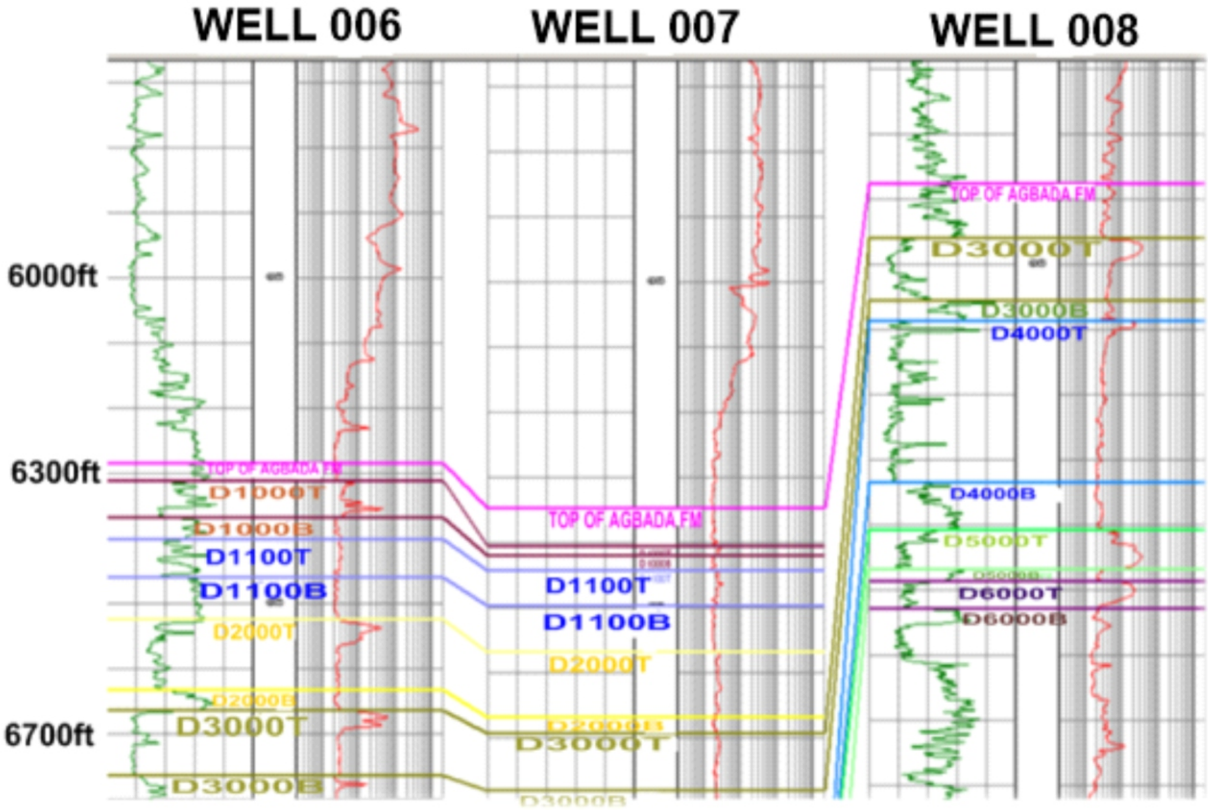


Figure 7: Correlation of top of Agbada Fm and D-sands in Wells 006, 007 and 008

The correlation of the deeper sands (E and F sands) is shown in Figure 8 for wells 1, 3 and in Figure 9 for wells 3, 4, 5. The correlation of the same sands in wells 5, 6, 7 and wells 6, 7, 8 are shown in Figures 10 and 11 respectively. E8000 sand has a cylindrical GR log motif in all the wells. The *Bolivina 25* horizon (reported in four of the wells) approximately lays within E8000 shale in wells 1 and 3. The E8000 sand is fossil barren and displays a cylindrical GR log motif. This attribute characterizes distributary mouth bar and channel sands of marginal marine environment. The presence of marginal marine facies directly above outer to bathyal facies (reflected by the presence of *Bolivina 25*) in the wells indicates a regional unconformity. The E8000 sand is thus a lowstand systems tract (LST) while its base (E8000B) constitutes a sequence boundary in the wells. The lithofacies units directly vertically below E8000B display an upward-coarsening (funnel pattern) GR motif and belong to highstand systems tract (Figure 9). The lithofacies between E8000T and E4000B display upward finning (bell shape) GR log motif and increased thickness of the shale vertically separating the sand units (Figures 10 and 11). The E8000T is thus a transgressive (or marine flooding) surface. The E4000B approximately coincides with a surface that is dotted with different marine (both benthic and planktonic) foraminifera, ranging from bathyal to inner neritic. Thus the E4000B approximates a maximum marine flooding surface. The lithofacies sandwiched between E8000T and E4000B thus constitute transgressive systems tract. The lithofacies between E4000T and the top of the Agbada Formation form highstand systems tract.

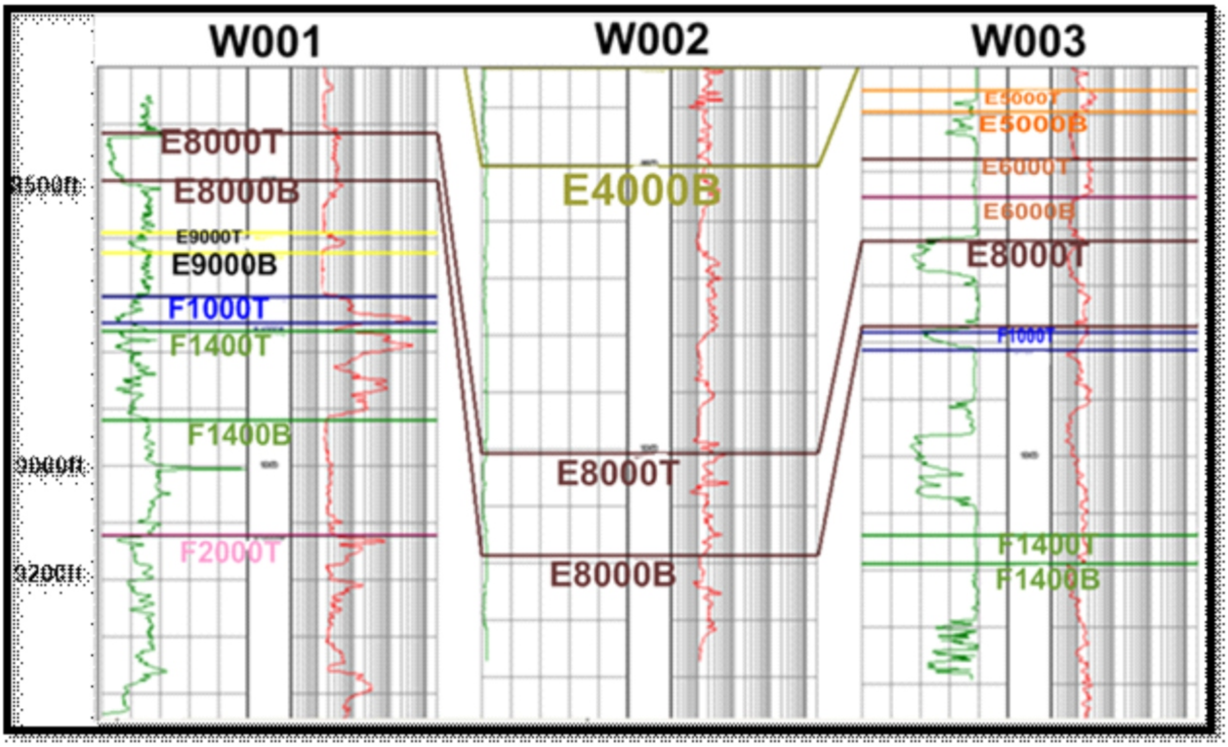


Figure 8: Correlation of deeper sands(E and F sands) for Wells 001, 002, 003

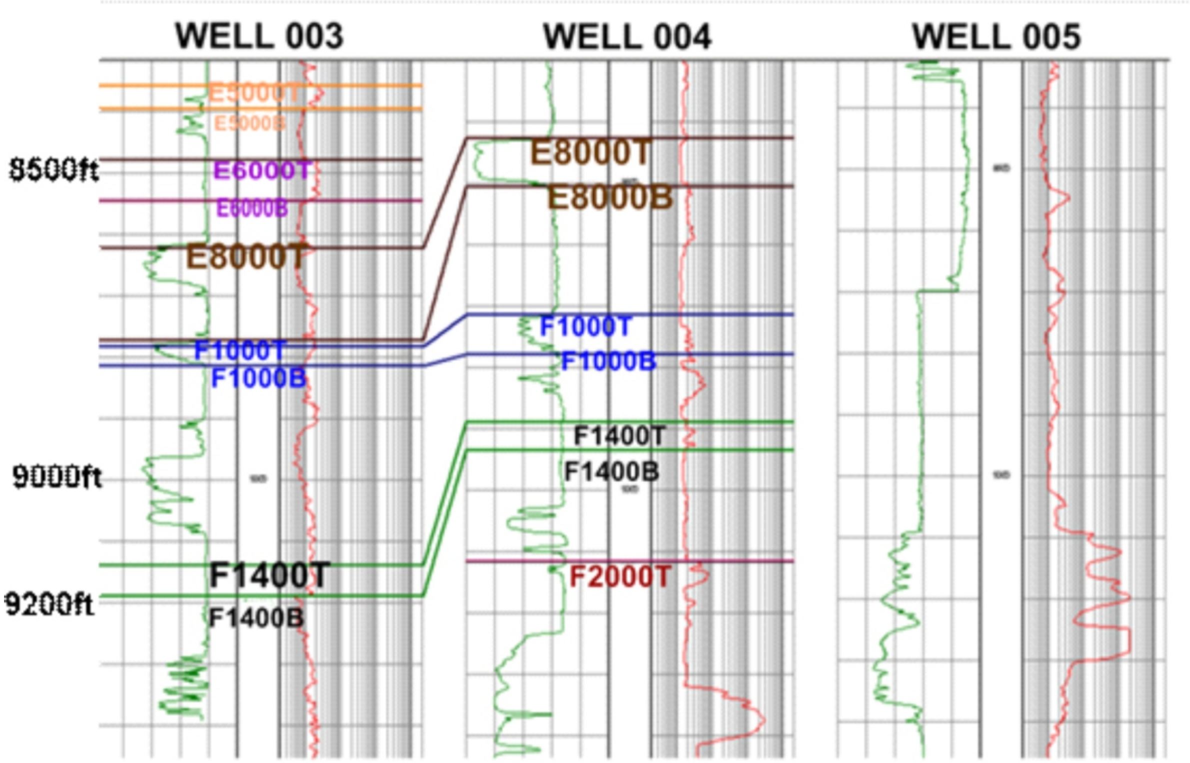


Figure 9: Correlation of deeper sands(E and F sands) for Wells 003, 004, 005

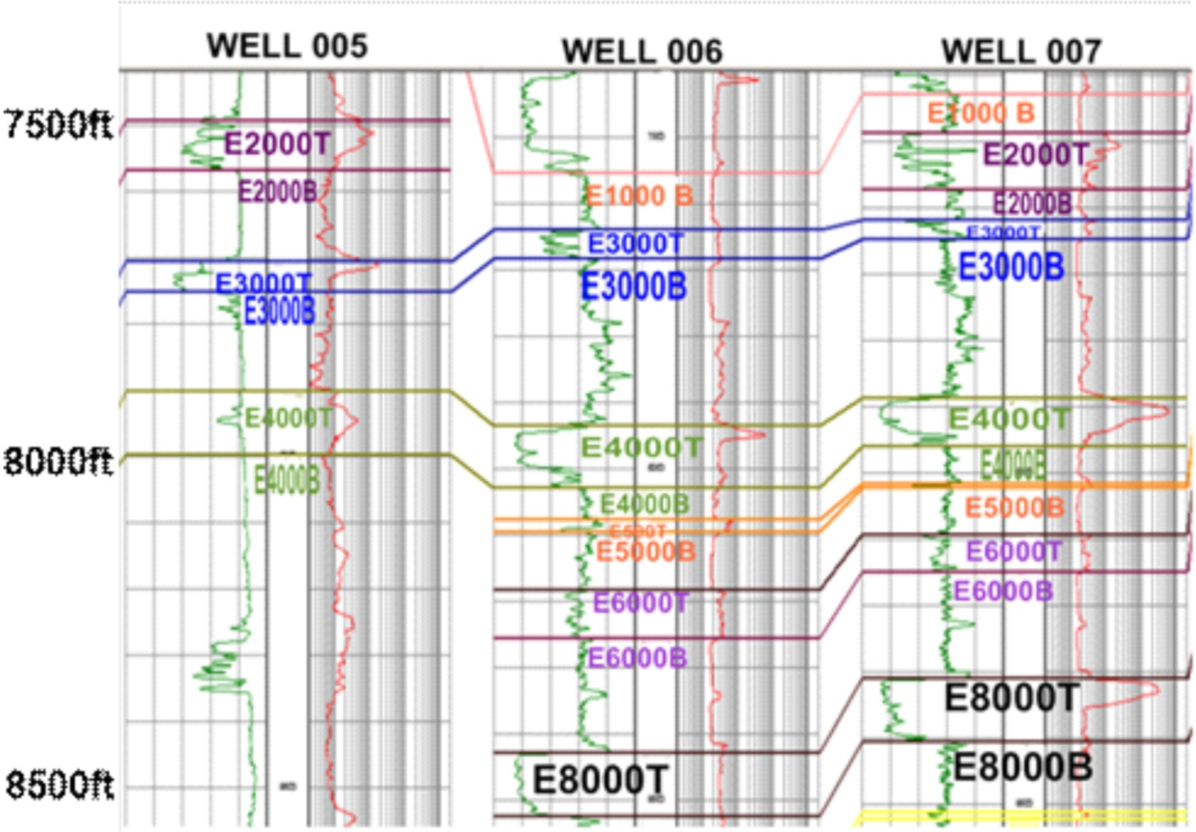


Figure 10: Correlation of deeper sands(E and F sands) for Wells 005, 006, 007

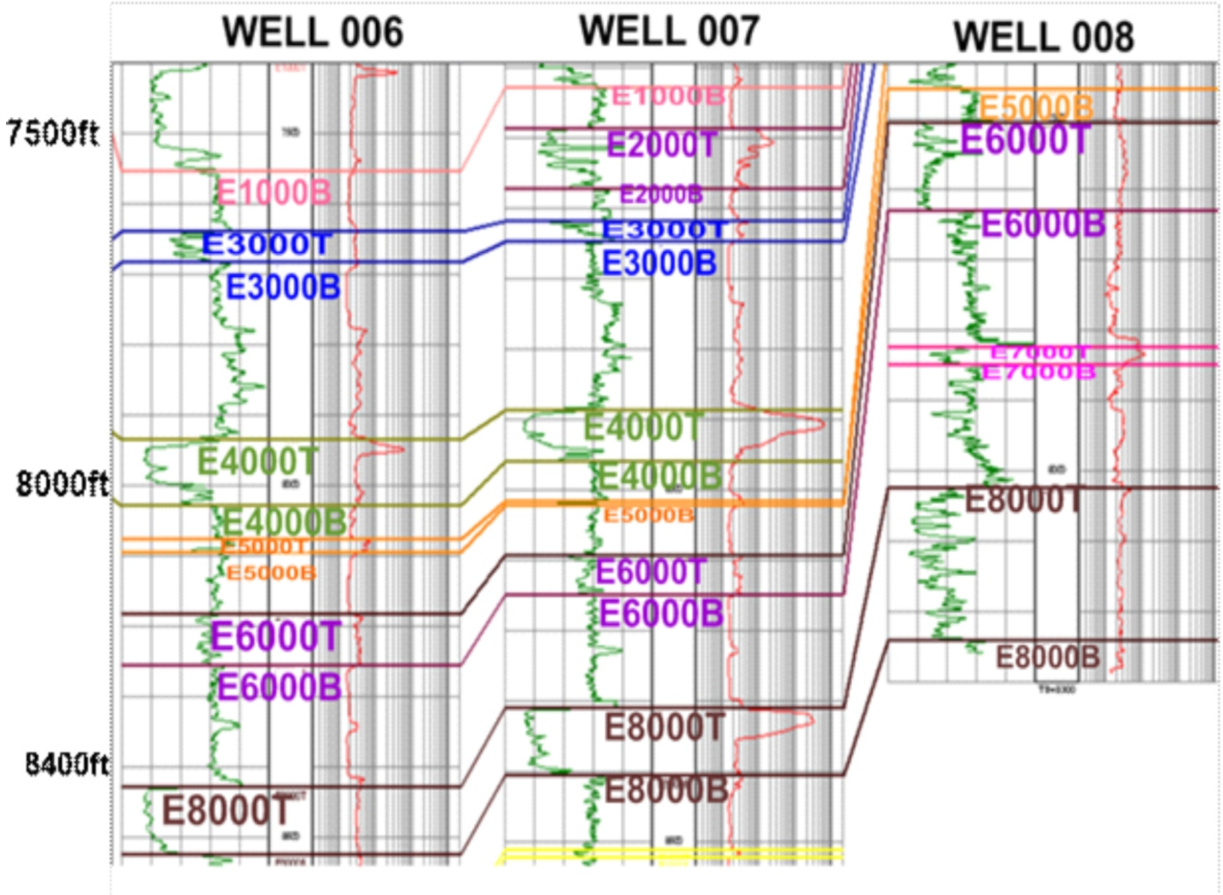


Figure 11: Correlation of deeper sands (E and F sands) for wells 006, 007, 008

Potential Hydrocarbon Leads

The sands vertically juxtaposed with the marginal marine shale at the top of Agbada Formation (or base of Benin Formation) are potential hydrocarbon reservoirs with low resistivity values. The D1000 sand immediately underlying the shale is a potential unconformity trap possibly truncating against the overlying shale. The sands within the shale are intra channel sands and potential stratigraphic traps. The sands were not tested probably because of their low resistivity values. Adejobi and Olayinka reported hydrocarbon accumulations in such sands in Opuekeba and Gwato fields in western Niger Delta, and in Tapa and Ubit fields in southeastern offshore of the Niger Delta.

Opportunities For Infill Well Drilling

Wells 1 and 6 are very closely located (Figure 12). SSVD to top of D2000 sand in the two wells is also very close (6542ft in well 1 and 6528ft in well 6). This suggests that D2000 sand is not significantly faulted between the two wells. Hydrocarbon accumulation was reported in D2000 sand in only well 6. It is inferable that the hydrocarbon accumulation in well 6 continues into well 1 because SSVD to top of D2000 sand in well 1 is shallower than the hydrocarbon - water contact depth (6562ft) in well 6. Similar magnitude of D2000 sand's resistivity kick in wells 1 and 2 (Figure 13) validates the presence of hydrocarbon within the sand in the two wells. Well 2 is 2km NW of well 1 (Figure 12) and this creates opportunity for drilling four infill wells at 400m equidistant spacing. Well 6 is located 2km NW of well 7 and similarly creates opportunity for drilling four infill wells at 400m equidistant spacing to increase hydrocarbon recovery from E4000 reservoir.

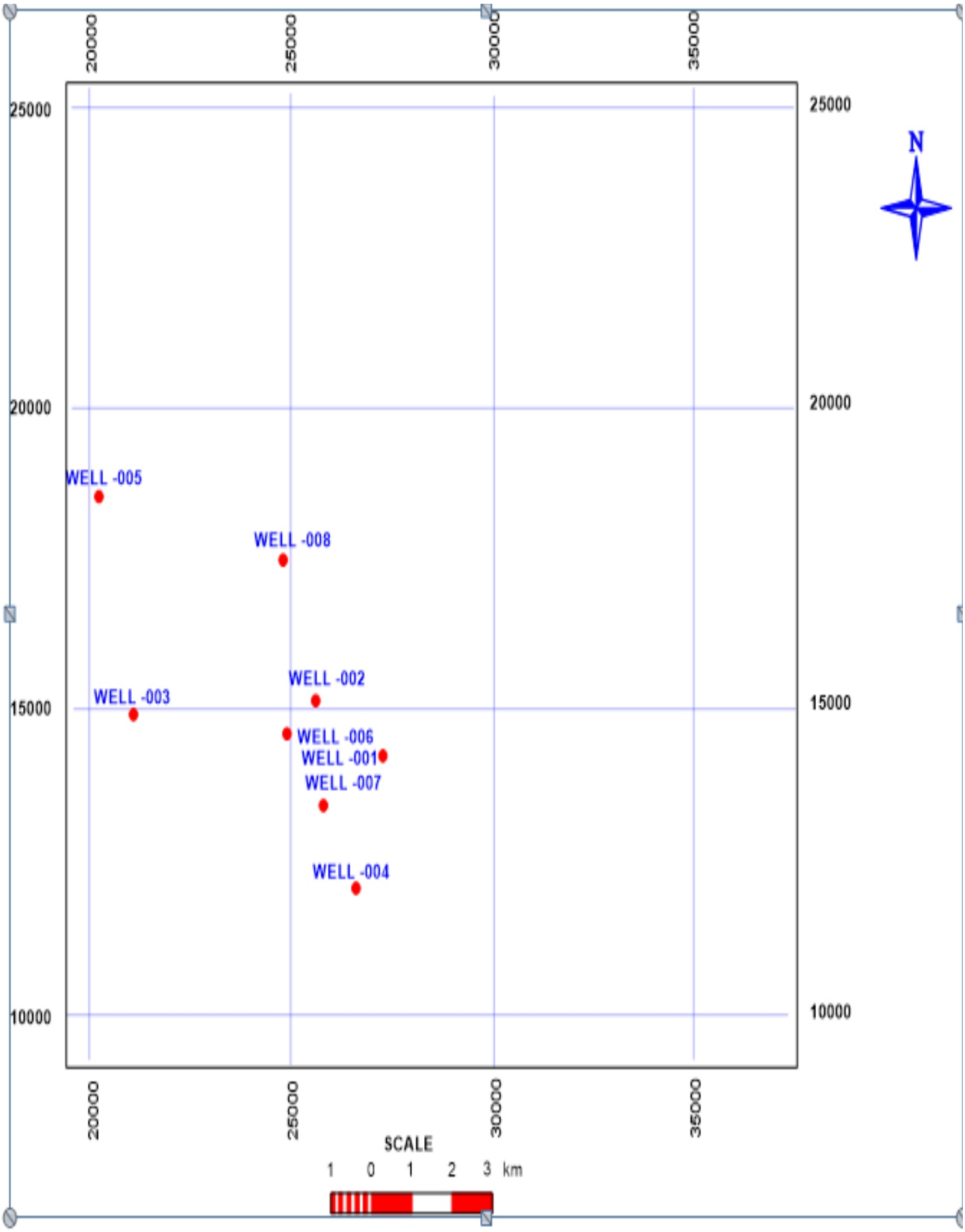


Figure 12: Well locations within world geographic coordinate systems

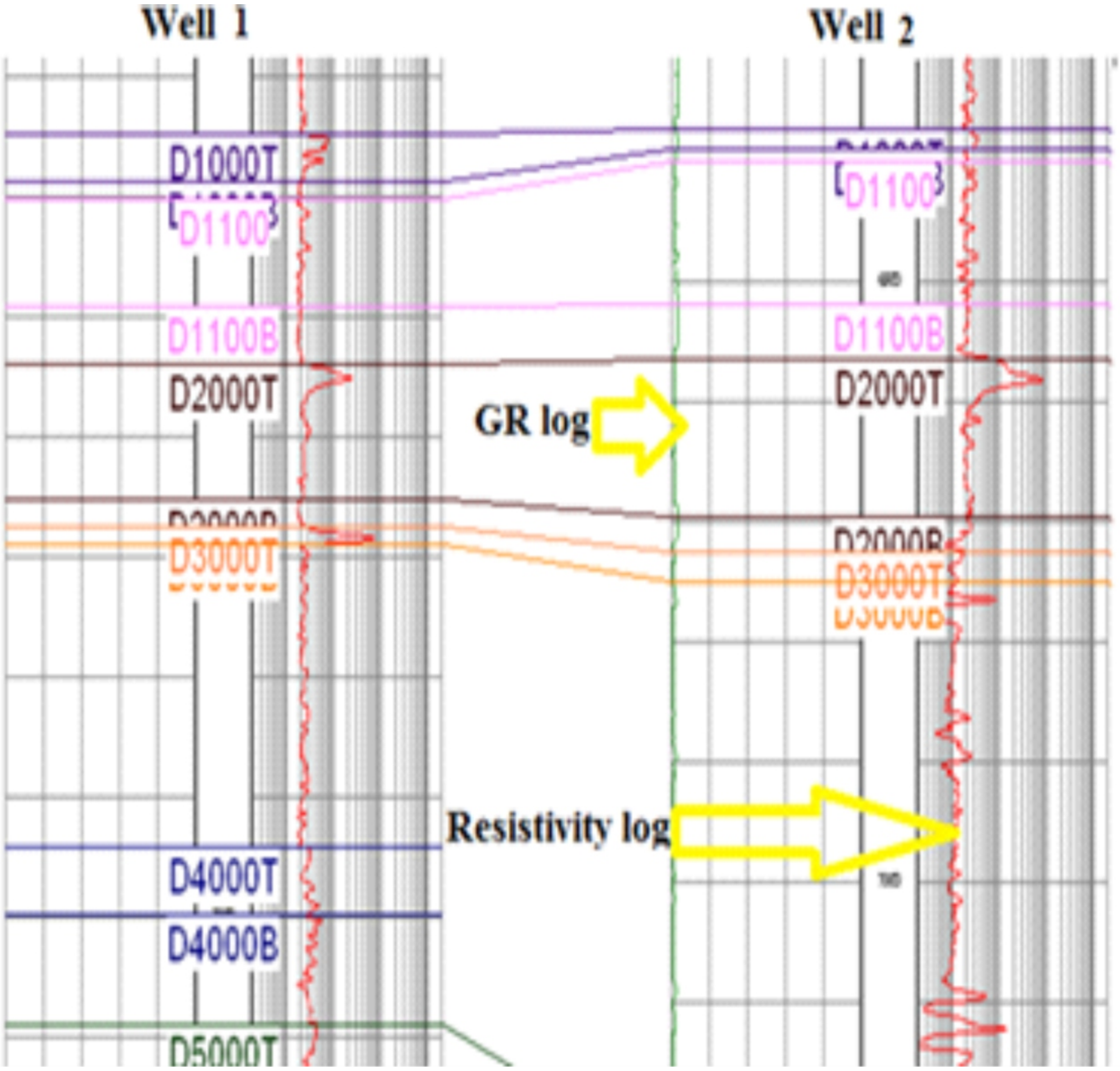


Figure 13: Resistivity los showing D2000 sand to be hydrocarbon bearing in wells 1 and 2

Conclusion

Integrated lithologic, foraminiferal and geophysical well data enabled sequence stratigraphic correlation of sedimentary successions penetrated in eight wells within Afenmai Field. Maximum flooding surface and transgressive surface were established at the base of E4000 Sand and top of E8000 Sand respectively. The interface between marine shale directly overlying Agbada Formation top is a field-wide unconformity surface, and constitutes a sequence boundary. The base of E4000 Sand is also a sequence boundary. Lithofacies directly below base of E8000 Sand constitute highstand systems tract. All the lithofacies directly above the base of E4000 Sand are also highstand systems tract. The E8000 Sand is a lowstand systems tract. All lithofacies between E8000 Sand top and E4000 Sand base constitute transgressive systems tract. Potential opportunities for infill well drilling exist between wells 1 and 2, and between wells 6 and 7. Sand bodies vertically juxtaposed with the marine shale uncorformably overlying the Agbada Formation top are potential stratigraphic traps.

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