

Application of Sequence Stratigraphy Principles: A Case Study of the Emi Field, Offshore Depobelt, Eastern Niger Delta Basin, Nigeria.

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Abstract

*Principles of sequence stratigraphy have been applied in the study of the Emi Field, Offshore Depobelt, Eastern Niger Delta. Using 3D seismic data, wireline logs of six wells, check shots, and biostratigraphic data sets, two sequence boundaries and three maximum flooding surfaces were identified as the key surfaces of three depositional sequences. Marker shales, characterized by index fossils *Haplophramoides*-24 and *Bolivina*-48 were used to date the maximum flooding surfaces, separated by the 5.6 Ma and 4.1Ma sequence boundaries. Based on log motifs and biostratigraphic data, the stratigraphic interval penetrated by the six wells was inferred to be deposited in a neritic paleoenvironment. Two major faults named F1 and F3 run across the study area and closures considered as good hydrocarbon prospects were identified and delineated. Analysis of horizons within the sequences and individual systems tracts reveals that hydrocarbon is hosted both in reservoirs within the transgressive systems tracts and highstand systems tracts. The existence of reservoirs, and the presence of well-developed fault systems in the sands associated with the systems tracts, indicates that the Emi field has great potential for hydrocarbon productivity.*

Keywords: Hydrocarbon, Sequence boundaries, System tracts, Marker shales.

INTRODUCTION

Sequence stratigraphic concepts in defining sediment accumulation and preservation trends within basin fills have become a highly successful exploration tool in the search for hydrocarbon resources¹. Thus, the subdivision of a basin's sedimentary fill into time stratigraphically constrained depositional packages is imperative in unraveling its development and inherent hydrocarbon potentials. Sequence stratigraphic principles are increasingly finding new and unique applications in the regressive siliciclastic sediments of the Niger Delta Basin.

The petroliferous Niger Delta Basin is rich in hydrocarbons with more promising reserves yet to be discovered as exploration proceeds to the deeper waters. The lithostratigraphic subdivision of the Niger Delta sediments cuts across time lines and their lateral associations suggest that the sedimentary deposits were strongly influenced by eustacy and tectonics. Sequence stratigraphy facilitates the subdivision of the Niger Delta into packages of sediments that are essentially bounded by chronostratigraphically significant surfaces. The aim of this study is to assist the continued search for hydrocarbons in the shallow offshore Niger Delta by subdividing the stratigraphic section within the Emi field into packages of sediments bounded by chronostratigraphically significant surfaces.

The Emi field is located in the offshore depobelt of the Niger Delta-(Fig. 1)² and covers an area of 58.24 km². The Niger Delta basin is located on the continental margin of the Gulf of Guinea in the equatorial West Africa and lies between latitudes 4⁰ and 7⁰N and longitudes 3⁰ and 9⁰E ³.

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¹ Oresajo, B.S., Adekeye, A.O. and Haruna, K.A., 2015. Sequence Stratigraphy and Structural Analysis of the Emi Field, Offshore Depobelt, Eastern Niger Delta Basin, Nigeria. *Ife Journal of Science*, v. 17(2), p. 395-408.

² Nton, M.E and Esan, T.B., 2010. Sequence Stratigraphy of EMI Field, Offshore Eastern Niger Delta, Nigeria, *European Journal of Scientific Research*, v.44 (1), p. 115-132.

³ Whiteman, A., 1982. Nigeria: Its Petroleum Geology, Resources and Potential, *London Graham and Trotman*, v. 1 and 2, p. 1 – 182.

Studies of parts of the Niger Delta have applied sequence stratigraphy. These include the work by Bowen⁴ who established an integrated geologic framework of the Niger Delta, using sequence stratigraphic concepts to analyse a seismic data set of the Niger Delta along with a biostratigraphic data from twenty-six (26) key wells. Stacher⁵ produced a delta wide framework of Cretaceous chronostratigraphic surfaces, and a sequence stratigraphic chart for the Niger Delta using digital biostratigraphic data, for eight hundred and fifty (850) wells. Krusi and Idiagbor⁶ linked some types of stratigraphic traps to incised valley fills and lowstand fans, and were thus able to improve the identification of stratigraphic plays in the eastern Niger Delta. Ozumba⁷ developed a sequence stratigraphic framework of the western Niger Delta using foraminiferal and wireline log data sets obtained from four wells drilled in the coastal and central swamp depobelts. He concluded that the late Miocene sequences were thicker than the Middle Miocene sequences. Nton and Esan² applied sequence stratigraphy in the analysis of data from four wells in the Emi field and identified two sequence boundaries and three maximum flooding surfaces. The present study is based on wire line log data of six wells, 3D seismic data and biostratigraphic data, in addition to an evaluation of fault system within the field.

STRATIGRAPHY AND GEOLOGICAL SETTINGS

The Niger Delta (Fig. 2)⁸ is a large arcuate Tertiary prograding sedimentary complex deposited under transitional marine, deltaic, and continental environments since Paleocene in the north to Recent in the south. It covers an area of about 75,000 km². It is characterized by coarsening upward regressive successions which reach a maximum thickness of 30,000 to 40,000 feet⁹. The overall regressive motif of clastic sediments was formed in a series of offlap cycles that were interrupted by periods of relative sea level rise. The structural configuration and the stratigraphy of the Niger Delta have been controlled by the interplay between rates of sediment supply and subsidence^{9,10}.

This clastic wedge has been divided into three large-scale lithostratigraphic units (Fig. 3)¹⁰; the basal Paleocene to Recent pro-delta facies of the Akata Formation, Eocene to Recent paralic facies Haq *et al.*,¹¹ of the Agbada Formation and the Oligocene to Recent fluvial facies of the Benin Formation^{3,9,12}.

MATERIALS AND METHODS

Six (6) exploratory wells and 3D seismic data acquired within the Emi field were collected. The wells are as follows: Emi 01, Emi 02, Emi 03, Emi 04, Emi 05, and Emi 06. Well logs including gamma ray, resistivity, sonic, density, and neutron were also used. A summary of suite of open-hole wireline log data used for the study is shown in Table 1. Niger Delta chronostratigraphic

⁴ Bowen, B.E.; Hall, D.J.; Rosen, R.N and Shaffor, B.L. 1994, Sequence stratigraphic and structural framework of southeast Niger Delta shelf. *NAPE Bulletin*, v. 9(1), p. 51-58.

⁵ Stacher, P., 1995. Present understanding of the Niger Delta hydrocarbon habitat. In: Oti, M.N., and Postma, G., (Eds.), *Geology of Deltas*: Rotterdam, A.A. Balkema, p. 257-267.

⁶ Krusi, H.R. and Idiagbor, C. 1994. Stratigraphic traps in Eastern Niger Delta – inventory and concepts, *NAPE Bulletin*, v. 9(1), p. 76-85.

⁷ Ozumba, B.M. 1999. Middle to Late Miocene sequence stratigraphy of the Western Niger Delta. *NAPE Bulletin*, 13 & 14(2), p. 176-192.

⁸ Tuttle, L.W., Charpentier, R.R. and Brownfield, E. M. 1999. The Niger Delta Petroleum System: Niger Delta Province, Nigeria Cameroon, and Equatorial Guinea, Africa. U.S. Geological Survey Open-File Report 99-50-H, Denver, Colorado, p.70.

⁹ Evamy, B.D.; Haremboure, J.; Kamerling, P.W.; Knaap, W.A.; Molloy, F.A. and Rowland, P.H. 1978. Hydrocarbon Habitat of Tertiary Niger Delta. *American Association of Petroleum Geologists Bulletin*, v. 62, p. 277-298

¹⁰ Doust, H. and Omatsola, E. 1990. Niger Delta, In: Edwards, J. D., and Santogrossi, P.A. (eds.) *Divergent/passive Margin Basins. American Association of Petroleum Geologists, Memoir 48*, Tulsa, p. 239-248.

¹¹ Haq, B.U.; Hardenbol, J. and Vail, P. R. 1988. *Mesozoic and Cenozoic Chronostratigraphy and cycles of sea level changes*. In: Wilgus, C. K., Hasting, B. S., Kendall, C. G., Posamentier, H. C., Ross, C.A., and Van Wagoner, J. C., (eds), *Sealevel changes: An Integrated approach: Soc. Econ. Paleontologists and Mineralogists Spec. Pub.*, Vol. 42, pp. 71 – 108.

¹² Short, K.C. and Stauble, A.J. 1967. Outline of the geology of the Niger delta. *Am. Assoc. Petroleum Geologists Bull.*, Vol. 51, p. 761-779

chart, an adaptation of the global chronostratigraphic chart of was used along with the biostratigraphic data to assign ages to the key bounding surfaces identified within the Emi field. This data set created broad constraints on the interpretation of age and depositional environments within the study area. The interactive Schlumberger petrel software package 2009 was used for the analysis of the seismic and well log data. A simplified work flow chart of the method adopted in this study is shown in Figure 4.

RESULTS AND DISCUSSION

Lithostratigraphy

The gamma ray logs of the six wells studied were interpreted based on lithology. Detailed observation of the logs shows progressive alternation of sand and shale. The upper parts of the sequences across wells display thicker sand intervals than the shales and also coarsen upwards. In the lower parts, shale intervals are generally thicker than the sands. Within the logged intervals, the lithology is dominated by alternating sand and shale in a ratio of 65:35 (Fig. 5). There are rare silt intervals.

Well Correlation

Well correlation for the Emi field was done after lithological interpretation based on well logs. The focus was on mapping sequence boundaries and maximum flooding surfaces. These surfaces were identified based on the abrupt change in well log properties – gamma-ray, resistivity and density, among others. The following steps were taken in order to correlate maximum flooding surfaces across the field on well logs:

1. Identification of flooding surfaces using highest gamma ray value and lowest shale resistivity values;
2. Marking the maximum flooding surfaces as those flooding surfaces with highest relative neutron porosity values and the corresponding lowest resistivity values relative to surrounding flooding surfaces;
3. Identification of trends in flooding surfaces;
4. Correlation of maximum flooding surfaces in all wells within a background of parasequence and parasequence sets stacking patterns.¹³

Two sequence boundaries were identified across the wells except in Emi 03 well where only one sequence boundary was identified. Three maximum flooding surfaces were identified across the wells with exception of Emi 02 and Emi 03 where only two maximum flooding surfaces were identified (Fig. 6).

Dating of Key Bounding Surfaces

The biostratigraphic interpretation was focused on the identification of major faunal abundance and diversity peaks, which coincide with MFS within condensed sections, while faunal abundance and diversity minima correspond to SB. The Niger Delta chronostratigraphic chart aided in this identification and was also used in dating the key bounding surfaces. The maximum flooding surfaces identified in the study area correspond to the transgressive marker shales using the Niger Delta chronostratigraphic chart are marked by *Haplophragmoides*-24 (6.0Ma) and *Bolivina*-48 (5.5Ma). Both marker shales were identified in the Emi 6 well. Two sequence boundaries (SB) were identified and dated 5.6Ma and 4.1Ma. The sequence boundaries are represented in all the wells. Table 3 shows the age and depths of the key bounding surfaces as present in all the wells after correlation.

Depositional Sequences and System Tracts

¹³ Van Wagoner 1990, Neal *et al.*, 1993, Posamentier and George, 1994.

The study interval was divided into three depositional sequences (1 – 3) spanning 5.6 to 4.1 my (Fig. 7). Transgressive systems tracts (TSTs) and highstand systems tracts (HSTs) were recognised using their stacking patterns and bounding surfaces (maximum flooding surfaces and sequence boundaries). Lowstand systems tract (LST) is absent in the field.

Correlation across the wells indicates that sequences are not all represented in the wells. Sequence 1 is not represented in Emi 03 well; this well is in the north- western flank of the field. Sequence thickness increases in sequence 1 and displays reverse thickness trend in sequence 2, implying changes in accommodation space relative to sediment supply, beginning with high rates of accommodation and evolving into low accommodation rates.

Systems tracts display varying degrees of representation across the three identified depositional sequences in the Emi field. The transgressive system tract (TST) is thickest in Emi 01 well in sequence 1 and relatively less thick across the same sequence of other wells. High stand system tract (HST) is relatively thick in sequence 1 of Emi 01, 04, 03 and 05 (Fig. 7).

Seismic Sequences and Maximum Flooding Surfaces

Analyses of strata termination patterns present on the seismic profile of Emi field have assisted in the identification of seismic sequences bounded above and below by seismic sequence boundaries (Fig. 8). These sequence boundaries were identified by stacking patterns in well logs and were then transferred onto the seismic. Generally, sequence boundaries are identified by characteristic onlap and erosional truncation patterns. These features are not present on the seismic. Unconformity surfaces characterized by a down lap at the top and an apparent truncation at the bottom, represents the condensed sections of the depositional sequence.

The maximum flooding surface is characterized by dipping strata geometries on seismic section. The highstand system (HST) was identified on the seismic profile by clinoforms down lapping onto the maximum flooding surface (MFS). It occurs when sediment supply rate exceeds the accommodation space causing the parasequence stacking pattern to either aggrade upwards or prograde basin wards. Deltaic progradation observed from this systems tract is characterised by oblique clinoforms on the seismic profile. The oblique clinoforms are typically associated with delta progradation; high energy depositional environment with prevalent sands¹⁴.

¹⁴ Brown, L.F. and Fisher, W.L. 1980. Principles of seismic stratigraphic interpretation, A.A.P.G. continuing education course note series, No. 16.

Structural Analysis of Seismic Section

There are two major growth faults F1 and F3 that run across the study area (Fig. 9). They are sub-parallel to one another and trend east-west. The faults are sealing on the up-thrown block, where most of the hydrocarbons could be trapped.

In this study, the seismic section of Emi Field as shown in Fig. 9, shows the effect of growth fault in an expanded fault system. All the seismic sections were migrated allowing for the tying of seismic sections at the intersection points between the cross-lines and in-lines. Most of the major faults picked on the seismic records of the field are counter-regional growth faults which are characteristics of the self-edge, offshore Niger Delta¹⁵. Prospects regarded as good hydrocarbon areas have been delineated in the structure contour map (Figs. 10 and 11).

Interpretation of Stratigraphic Trends

The Emi field stratigraphic intervals fall within the paralic succession of alternating sand and shale bodies of variable thicknesses. The sand/shale ratios generally decrease with depth. The entire sequence constitutes an overall prograding delta with periods of transgression. Three stacking patterns; progradational, aggradational and retrogradational patterns were identified. Log trends generally change from thicker, sandier, blocky and upward fining successions to thinner upward-coarsening successions, suggesting a progression from channel deposits to dominantly offshore prograding lobes. This reflects a progression from fluvial depositional settings to prodelta and deltaic shorelines. The Agbada Formation is generally interpreted to contain fluvial deltaic deposits¹⁶. The maximum flooding surfaces (MFS) delineated in the study area are interpreted to have developed during the highest point of sea level rise and maximum landward incursion of the shoreline. They exhibit pelagic deposition and sediment starvation on the shelf and slope, and separates phases of retrogradation (transgression) from those of progradation (regression). Maximum flooding surfaces delineated across the field correspond to the transgressive marker shales: *Haplophragmoides*-24 (6.0Ma) and *Bolivina*-48 (5.5Ma). Two sequence boundaries (major erosion surface) divides the Emi field into three sequences, each formed during a low relative sea level. Two system tracts were delineated; these are the highstand systems tract and transgressive systems tract.

The highstand systems tract (HST) overlies the preceding transgressive systems tract (TST) phase in the study area across the six wells studied. This occurs when the sediment supply rate exceeds the accommodation space, causing parasequence deposition to either aggrade upwards or prograde basinwards. The highstand systems tracts (HST) in the wells are thick with mainly sandy units occurring within its lithological sequence. The reservoir quality of the sands within the highstand systems tracts HST could serve as good reservoir while growth faults, active in this area, could serve as conduits for upward migration of hydrocarbon. The pelagic shales of the transgressive systems tract could form good cap rocks for the underlying and overlying HST given the right conditions. Stratigraphic correlation across the wells in the Emi field has shown the sequence 3 to be the thickest across the field.

Hydrocarbon Potential

Analysis of horizons within sequences and individual systems tracts reveals that hydrocarbon is hosted both in the highstand systems tracts and transgressive systems tract (Table 4). This is corroborated by the findings of Nton and Esan². Table 4 shows hydrocarbon occurrences with their associated systems tract based on well log data interpretation of the Emi field.

¹⁵ Ojo, A. O. 1996. Pre-drill prospect evaluation in deep water Nigeria. *Nig. Assoc. Petrol. Explo. Bull.*, v.11, p. 11-22.

¹⁶ Weber, K. J. and Daukoru, E. M. 1975. Petroleum geology of the Niger Delta: Proceedings of the 9th World Petroleum Congress, v. 2, Geology: London, Applied Science Publishers, Ltd., p. 210-221.

SUMMARY AND CONCLUSION

Two sequence boundaries (major erosion surfaces) sub-divide the Emi field into three sequences, each formed during a low relative sea level. Ages assigned to the sequence boundaries are 5.6 Ma and 4.1Ma. The three (3) major depositional sequences were identified in all the wells studied. Maximum flooding surfaces were delineated across the field and correspond to the transgressive marker shales of the Niger Delta chronostratigraphic chart: and they are marked by *Haplophragmoides*-24 (6.0Ma) and *Bolivina*-48 (5.5Ma).

Progradational, aggradational and retrogradational stacking patterns were identified in the Emi field. Lateral continuity of facies depended on parasequence associations. Most reservoir units occur between the 4.1Ma maximum flooding surface (MFS) and 5.6Ma sequence boundary (SB). The morphology and importance of reservoirs and seals vary between system tracts. The transgressive sands and the highstand sands constitute good (potential) reservoirs. The highstand shales and transgressive shales form seals for the (potential) stratigraphic traps in the Emi field. Possible migration pathways include carrier beds and faults.

Integrated results of well log and biofacies interpretation revealed that these strata originated through the interaction of subsidence, eustatic changes in sea level and varying sediment supply rates during the late Miocene to Pliocene. The integration of the data sets has facilitated the understanding of the process that generated the vertical stratigraphic succession of sediments and lateral facies changes, which are the characteristic features of the systems tracts across the Emi field. It is recommended that appraisal wells should be drilled targeting prospects delineated on the southwestern flank of the field.



Fig. 1: Map of the south-south Nigeria showing hydrocarbon fields and the location of the Emi field in the offshore eastern Niger Delta (after Nton and Esan 2010).

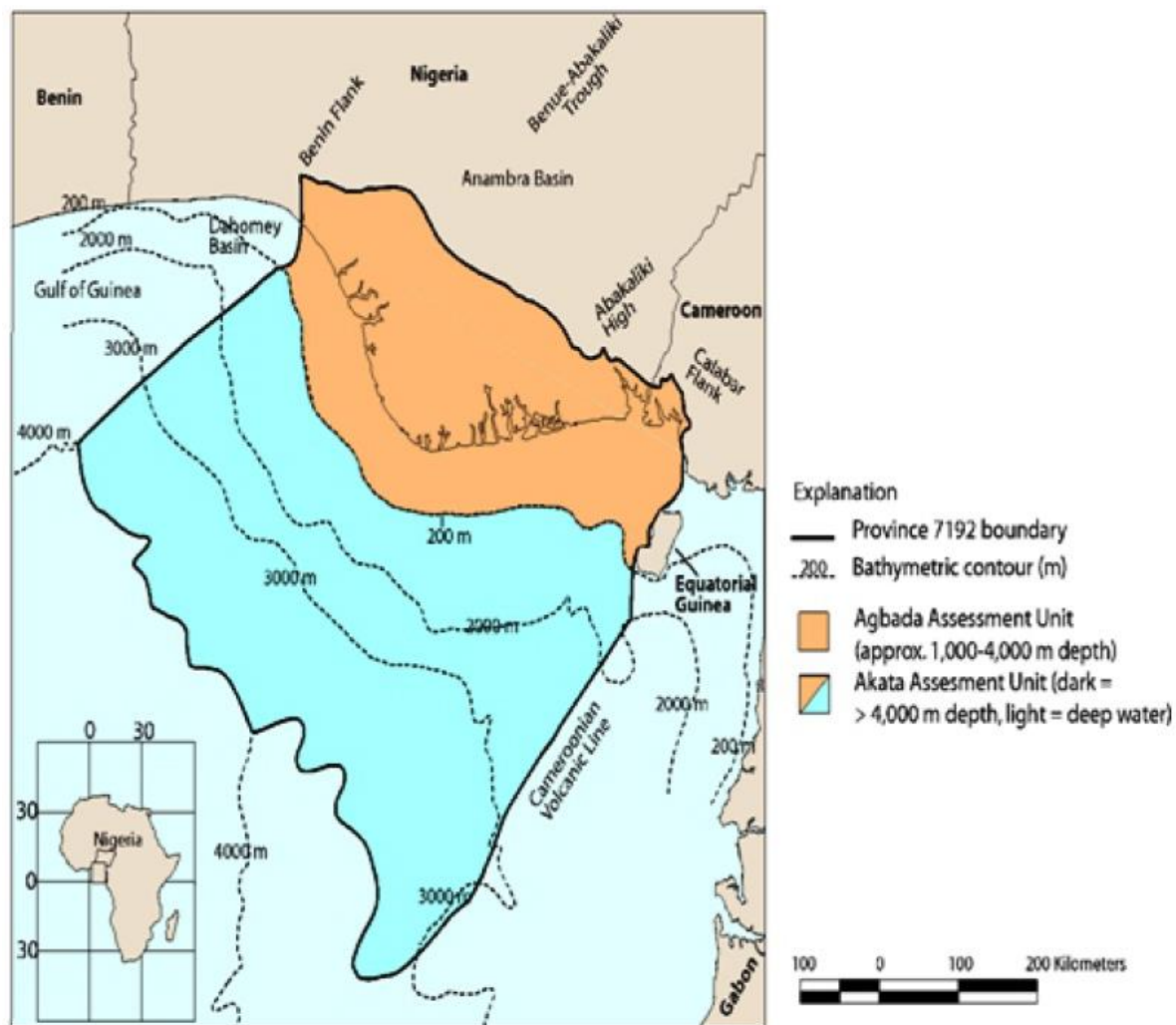


Fig. 2: Map showing province outlines and bounding structural features in the Niger delta Basin (adapted from Tuttle *et al* 1999).

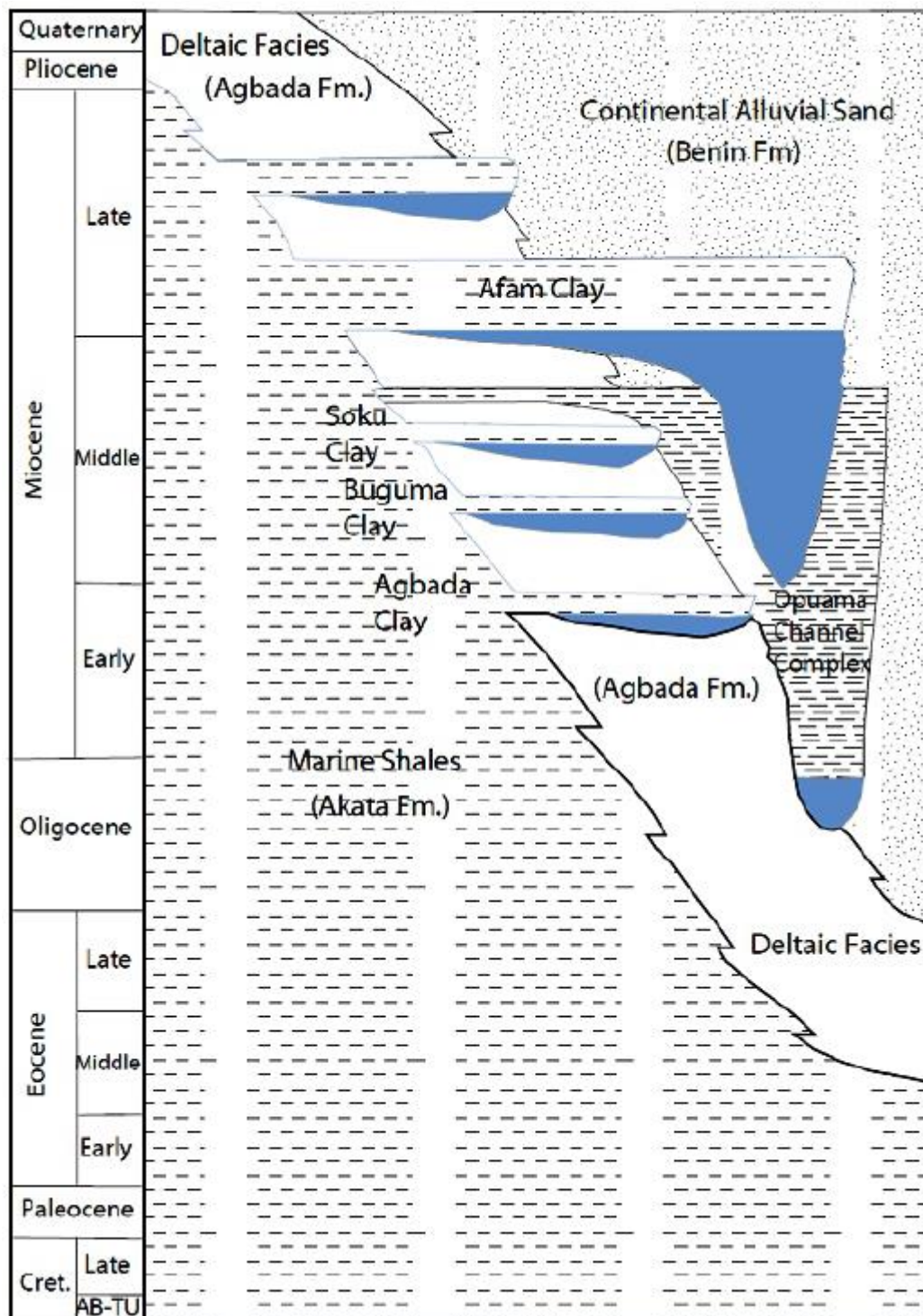


Fig. 3: Stratigraphy of the Niger Delta (adapted from Doust and Omatsola, 1990).

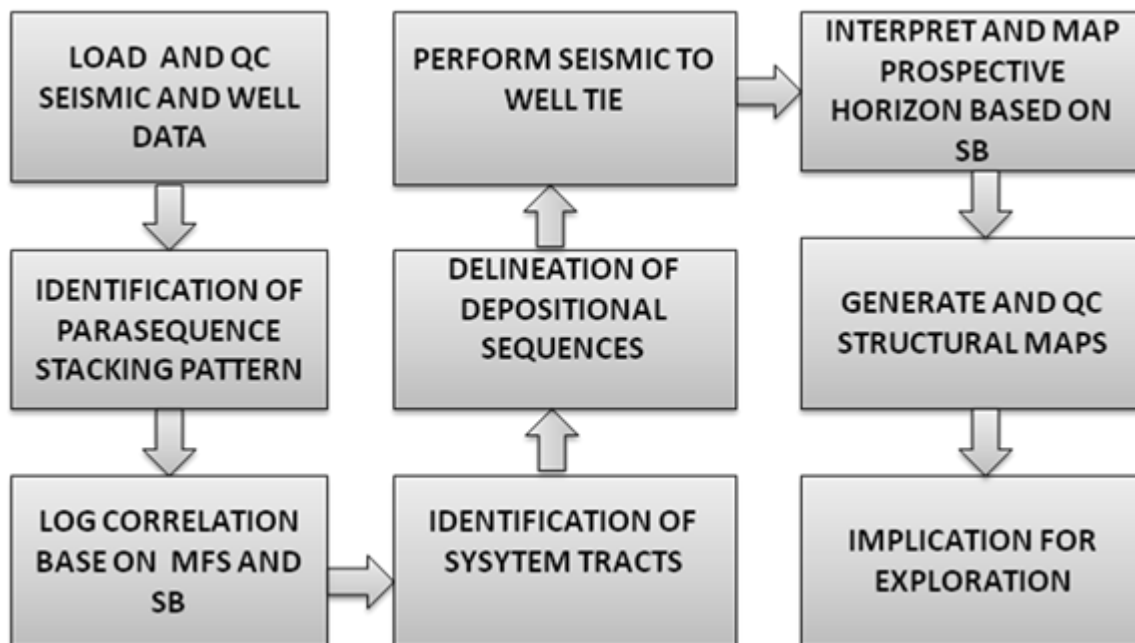


Fig. 4: Workflow Chart.

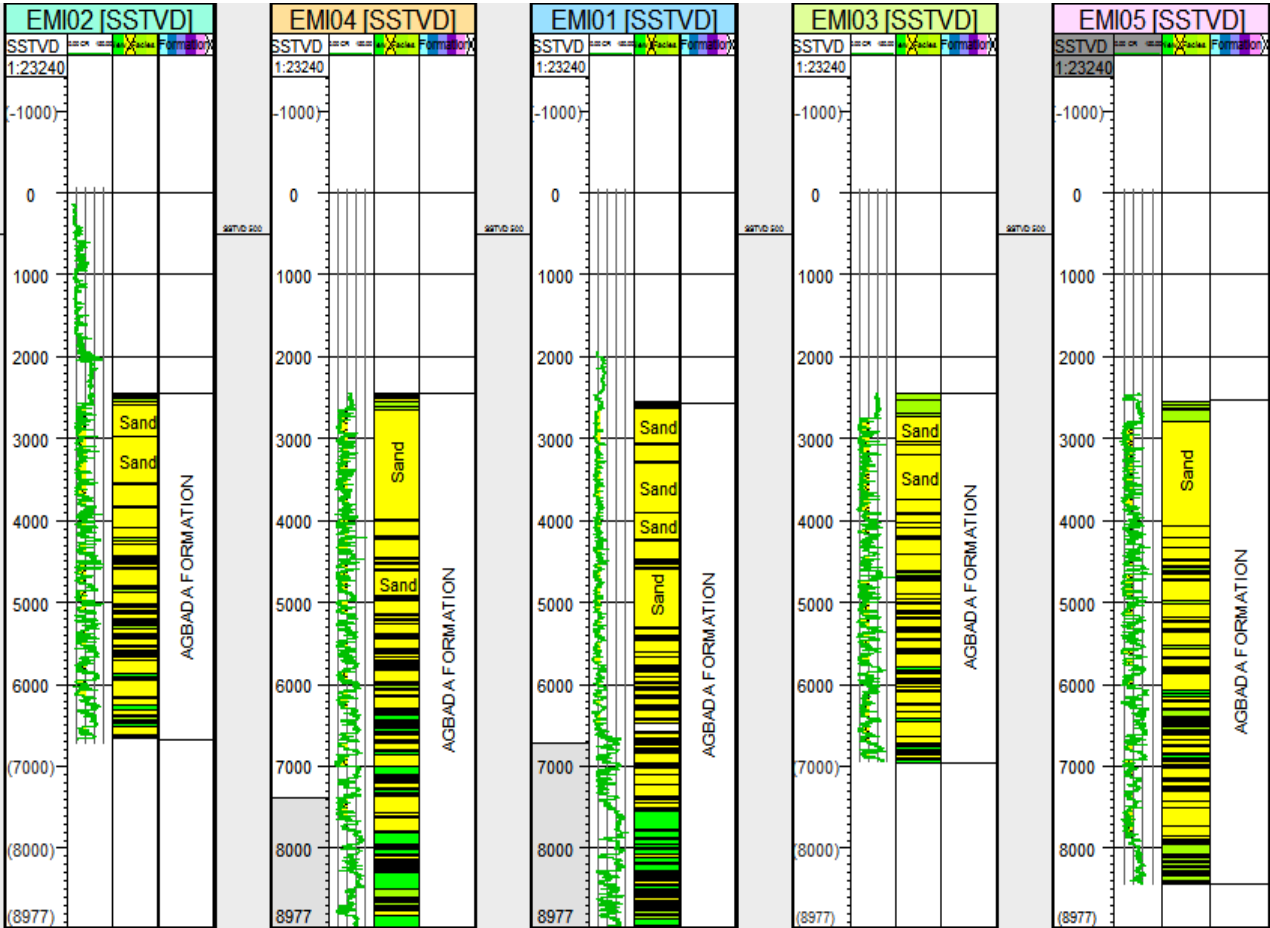


Fig. 5: Sand/shale lithologies within the Emi field.

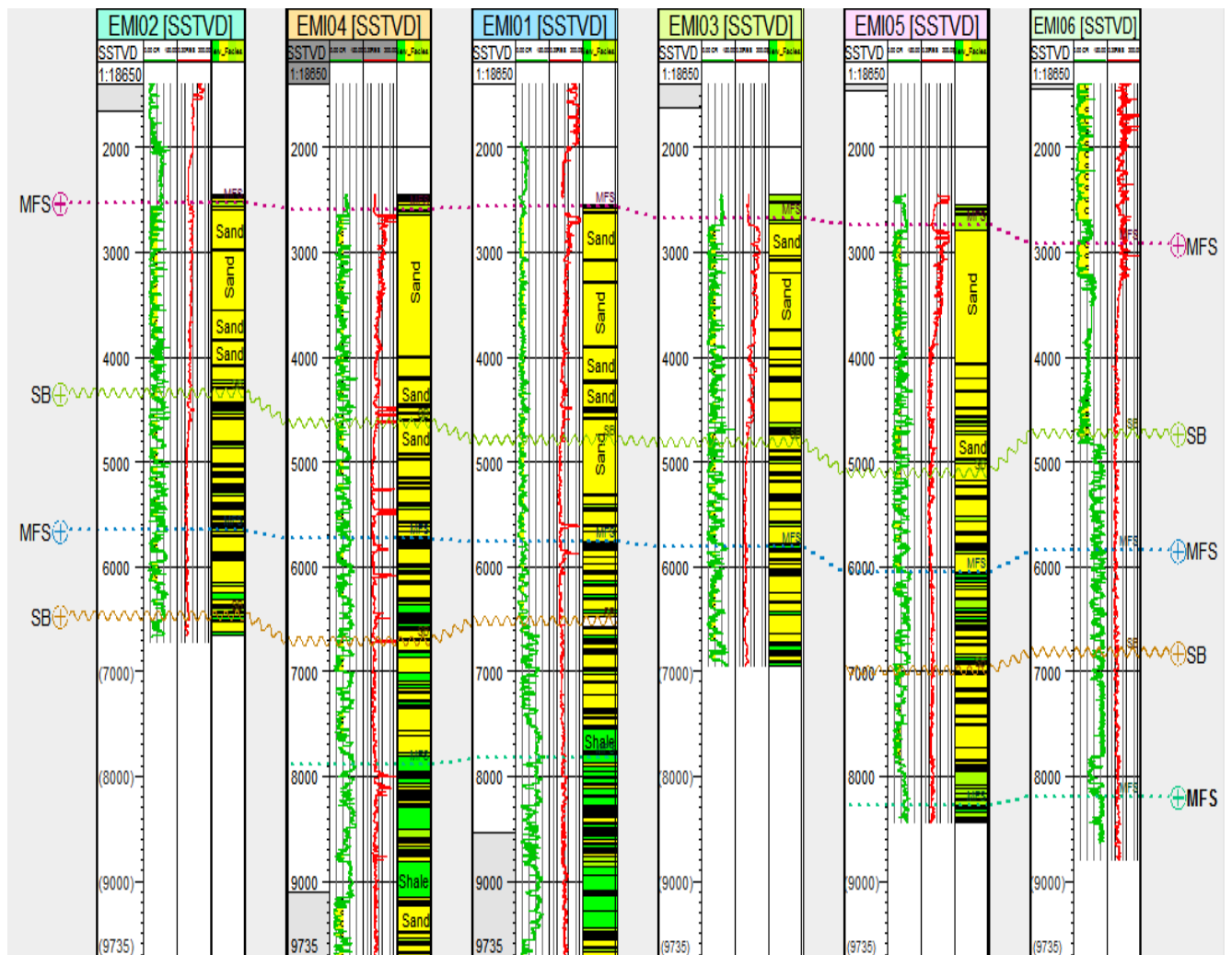


Fig. 6: Maximum Flooding Surface and Sequence Boundaries Interpreted on Well Section.

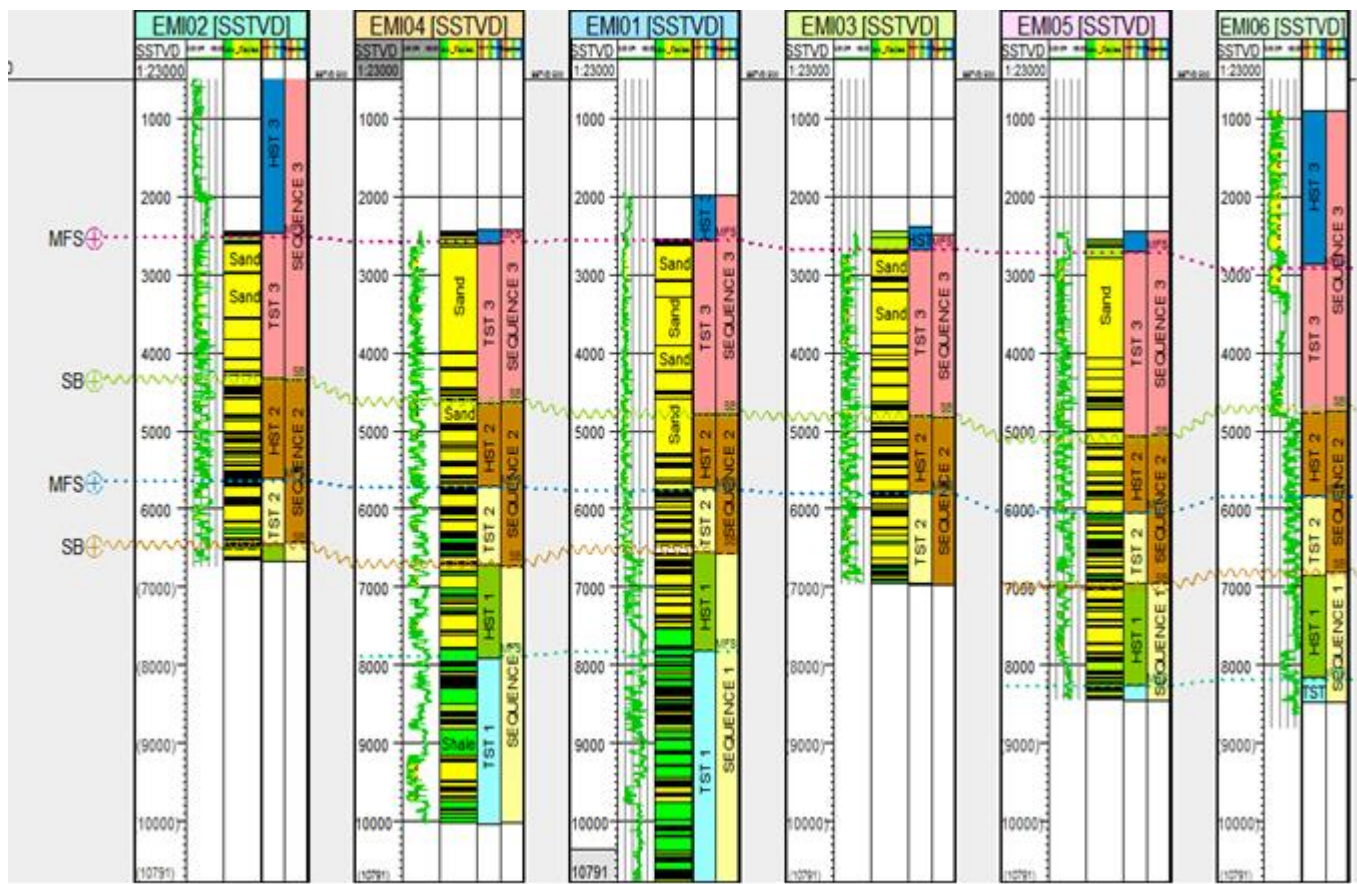


Fig. 7: Stratigraphic correlation showing all 6 wells in the field of study.

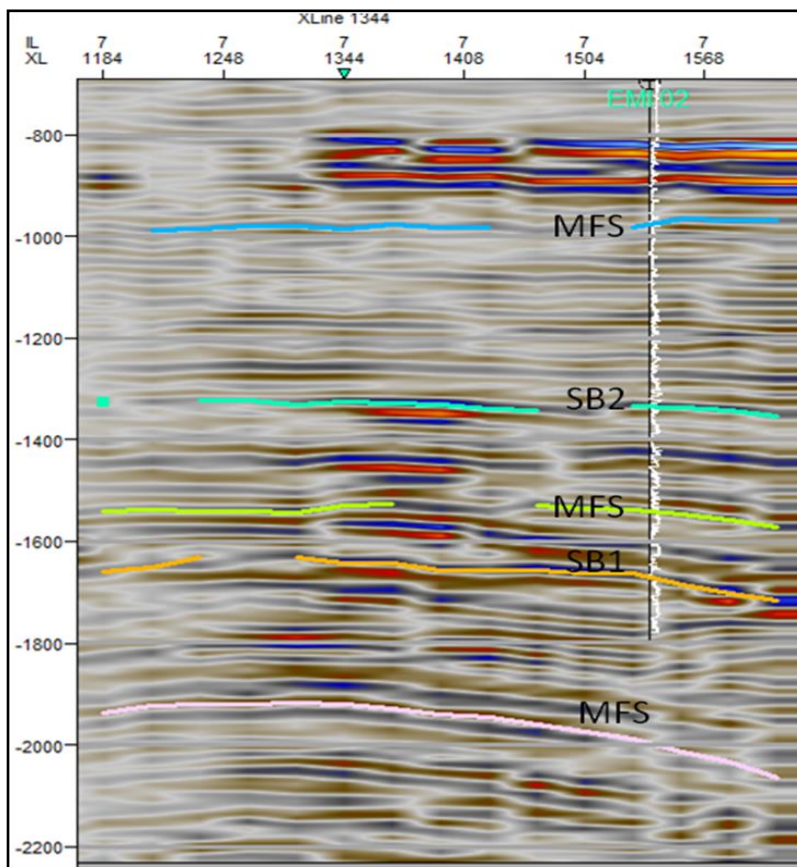


Fig. 8: Reflection pattern, sequence boundary and maximum flooding surface identified on seismic cross sections in Emi field.

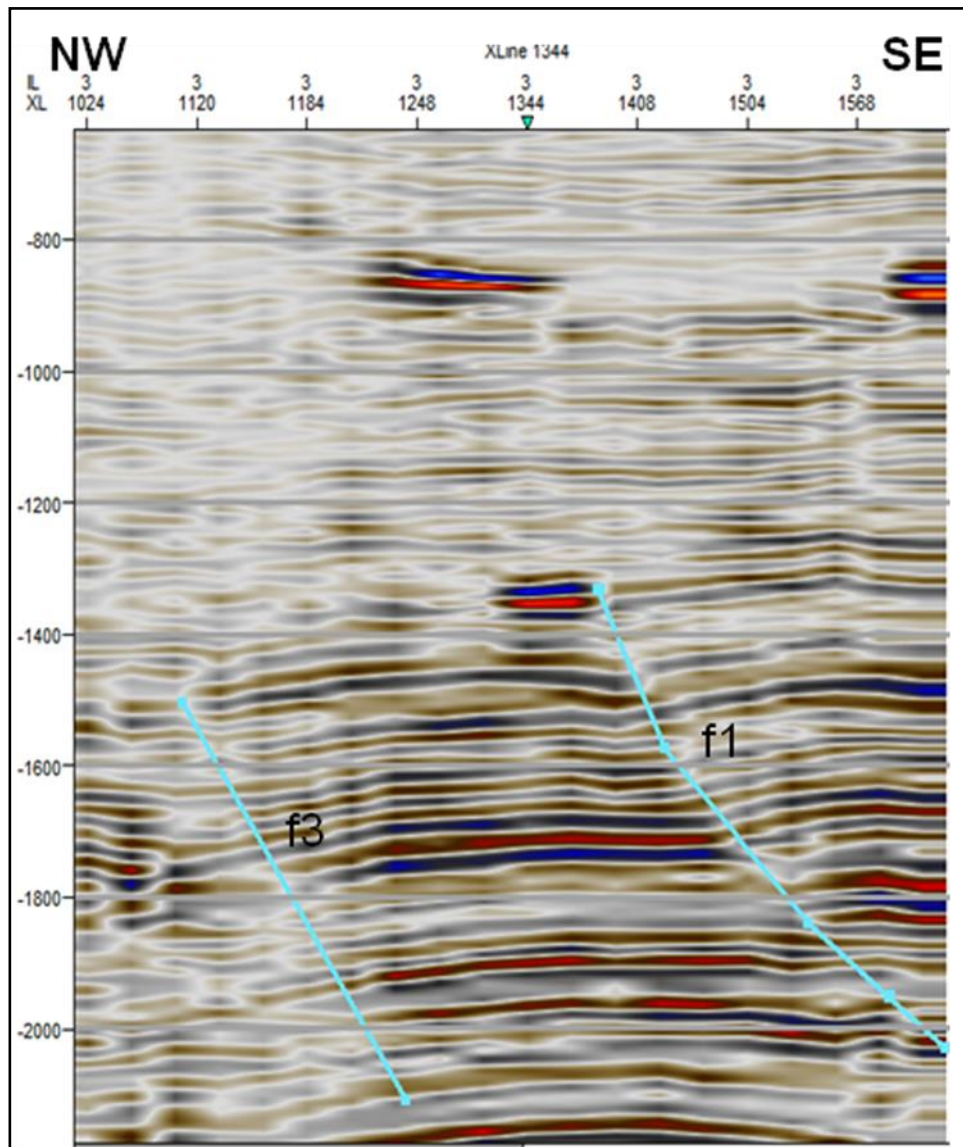


Fig. 9: Seismic cross section along inline 3 showing cross cutting fault f1 and f3

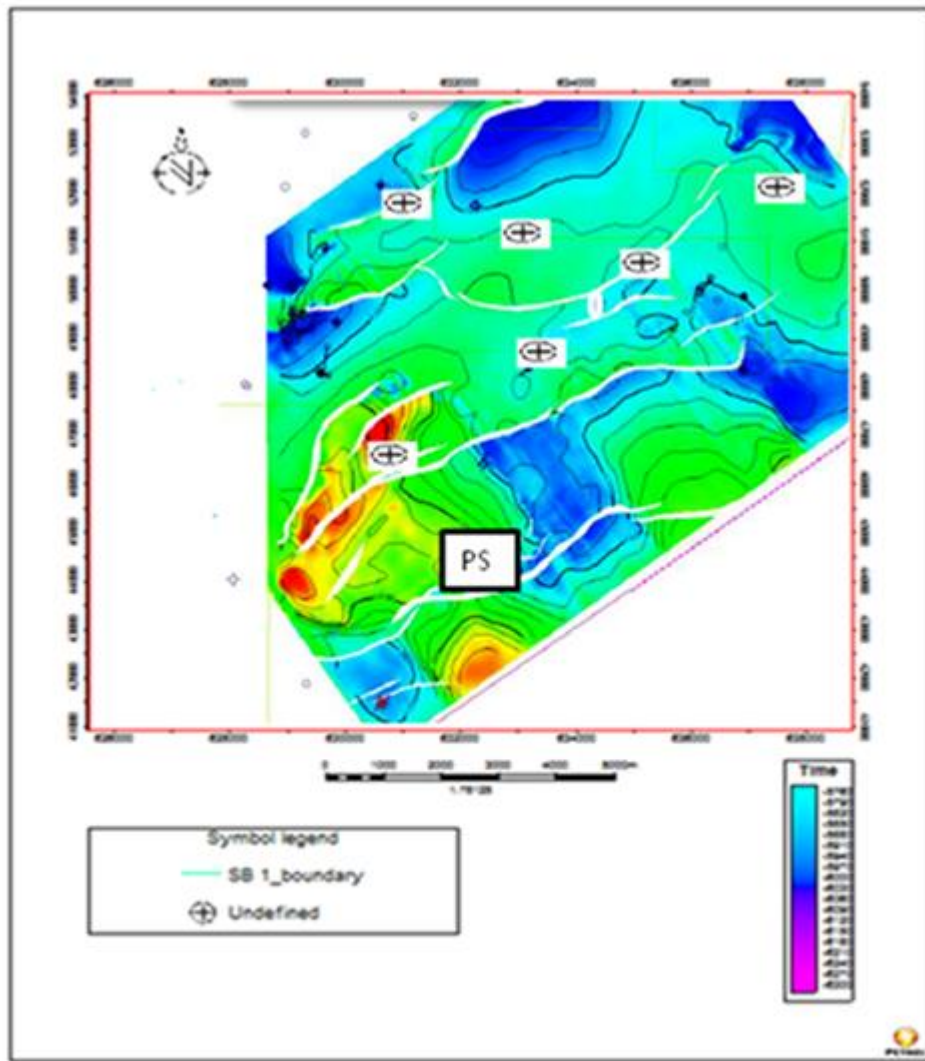


Fig. 10: Structural contour map of sequence boundary 1 showing prospect (PS) characterized by well- developed fault system in south-western flank of the field

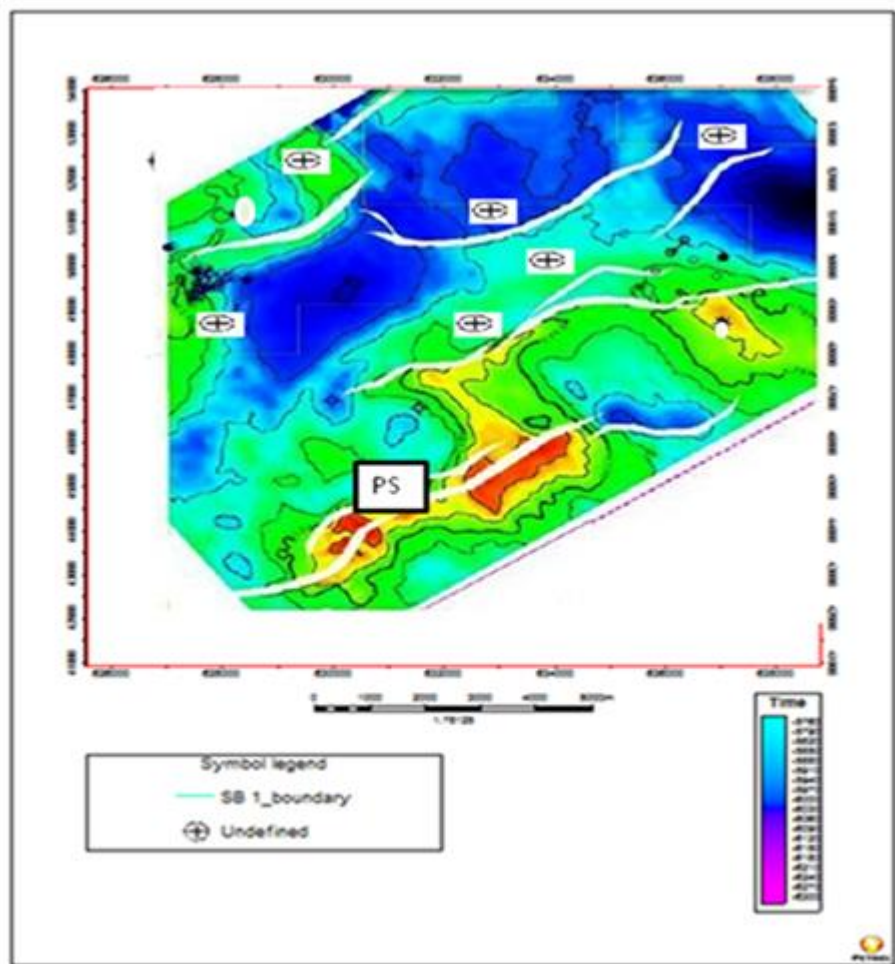


Fig 11: Structural contour map of sequence boundary 2 showing prospect (PS) characterized by well- developed fault system and anticlinal closure in the south-western flank of the field.

TABLES

Table 1: Summary of suite of open-hole wireline logs data used for the study

S/No	Well logs	Emi 01	Emi 02	Emi 03	Emi 04	Emi 05	Emi 06
1	Bulk Volume	✓	✓				
2	Depth	✓	✓	✓	✓	✓	✓
3	Gamma Ray	✓	✓	✓	✓	✓	✓
4	Sonic	✓	✓	✓	✓	✓	✓
6	Shale volume	✓	✓	✓	✓	✓	
7	Neutron Porosity	✓	✓				✓
8	Total Porosity	✓	✓		✓	✓	✓
9	Conductivity	✓	✓	✓			✓
10	Deep Resistivity	✓	✓	✓			✓
11	Caliper	✓	✓	✓	✓	✓	✓
12	Bulk Density						

Table 2: Benthic foraminiferal zones established for Emi 6 well

Depth (FT)	Benthic zones	Age
2000 - 6810	ZONE I (VALVULOINA FLEXILIS)	PLIOCENE
6810 - 10796	ZONEII	LATE MIOCENE



Table 3: Age and depths of key bounding surfaces

Key Bounding Surfaces	Emi 01 (ft)	Emi 02 (ft)	Emi 03 (ft)	Emi 04 (ft)	Emi 5 (ft)	Emi 6(ft)
SB (4.1 Ma)	4795	4331	4811	4628	5093	4712
MFS (<i>Bolivina</i>- 48)	5711	5655	5804	5721	6053	5820
SB (5.6 Ma)	6532	6450		6715	6980	6831
MFS (<i>Haplophragmiodes</i> 24)	7824			7890	8255	8189

Table 4: Hydrocarbon occurrence and associated systems tracts from Emi 04

Zone	Top MD(ft)	Base MD(ft)	Gross Int (ft)	Sw pay	Sh Pay	System tract
Zone A	4522.67	4938.28	415.61	0.454	0.546	HST
Zone A1	4586.09	4637.55	51.46	0.351	0.649	HST
Zone A2	4658.13	4714.74	56.61	0.401	0.599	HST
Zone B	5303.08	5332.5	29.42	0.152	0.848	HST
Zone C	5494.46	5606.77	112.31	0.467	0.533	HST
Zone D	5845.9	5902.43	56.53	0.335	0.665	HST
Zone E	6114.82	6177.47	62.65	0.242	0.758	HST
Zone E1	6485.8	6551.41	65.61	0.374	0.626	TST
Zone F	6751.6	6846.72	95.12	0.212	0.788	TST
Zone G	8001.18	8068.18	67	0.212	0.788	HST
Zone H	8112.07	8340.76	228.69	0.212	0.788	TST