International Journal of Science Inventions Today
www.ijsit.com
ISSN 2319-5436
Research Article

RESERVOIR GEOLOGY AND SEQUENCE STRATIGRAPHY OF DEEP WATER SEDIMENTS, OFFSHORE DEPOBELT, NIGER DELTA, NIGERIA

Matthew O. Akpan[1], M.N.Oti[2] and Monday U. Udoh[3]

[1,2]*Department of Geology, University of Port Harcourt, Port Harcourt, Nigeria.*

[3]*Pioneer Alfa Petroleum Services Ltd, Benin City, Nigeria.*

ABSTRACT

Lithofacies, depositional sequences and reservoir stratigraphy of the Deep Offshore Field, otherwise tagged 'E-Field', located in the Southeastern Niger Delta; were studied by employing log-motif patterns defined for fluvial, deltaic, shelfal, slope and basinal facies. Gas-bearing sands and gas/oil contacts were identified from density logs in combination with neutron porosity logs. The resulting analyses and interpretation of wells in this field showed that there are nine (9) hydrocarbon-bearing reservoirs: E-R1, E-R2, E-R3, E-R4, E-R5, E-R6, E-R7, E-R8 and E-R9. These reservoirs were easily identified on the logs and they have different characteristics and quality which are controlled by the environments of deposition. A total of twenty-four (24) reservoir sand bodies with variable net thicknesses varying from 25–150m in places had been inferred. The average net thickness (h), porosity, effective porosity, clay volume and water saturation of 135m (approximately 473ft), 0.26, 0.22, 0.16 and 0.00252, respectively were estimated. These sands are Miocene to Early Pliocene in age and could be interpreted to relate to the periods of base level fall, if not Global Eustatic Lowstands. The E-field reservoir sands consist principally of one or more of the following genetic types: deltaic distributary mouth bars, channel and shoreface sands, barrier beach, shelf and offshore turbidite sands. The recognition of depositional surfaces on the stratigraphic cross-sections allows subdivision of the stratigraphy into systems tracts: HST, FSST, TST and LST. The pinch-out channel sands and lenticular reservoir sand-bodies are common stratigraphic traps duly observed.

INTRODUCTION

Detailed studies on Niger Delta tectonics, stratigraphy, depositional environments, petro-physics, sedimentology and hydrocarbon potential are well documented in the literature, but only a few full papers have been published (e.g; Weber,1971,Oomkens,1974; Weber and Daukoru,1975; Evamy et al; 1978; Peters, 1983; Knox and Omatsola, 1989; Beka and Oti,1995; Oti and Postma, 1995; Amajor, 1991, Hooper et al, 2002; Peters and Reijers, 1990, Nton and Adesina, 2009; Koledoye et al, 2003). Some studies such as Doust and Omatsola, 1990; Reijers et al, 1997 and Bruso et al; 2004 have related the depositional units of the delta to those of the surrounding basins in southern and southeastern Nigeria.

Sequence analyses of well-log suite, seismic and biostratigraphic data employed in this study were on the basis of identification of periods of basin margin progradation, aggradation and retrogradation and the recognition of variations of relative sea level.

Wireline logs measure the electrical, radioactive and acoustic properties of rocks, which were used to derive information on lithology, grain size, density, porosity and pore fluids. Using these data, log facies were defined and depositional sequences identified. Here, the nature of the parasequence geology depends on the facies associations and several end-members are described. The most common is the coarsening-up signature widely recognized in parasequence from non-marine to marine settings.

The study of E-Field Wells reveals that there are nine (9) hydrocarbon - bearing reservoirs: E-R_1, E-R_2, E-R_3, E-R_4, E-R_5, E-R_6, E-R_7, E-R_8 and E-R_9. Each reservoir in the E-Field was easily identified on the logs. The gamma ray log shows the E-field reservoir sandstone as a low gamma ray reading unit. Interrelated siltstone, mudstone and shaly partings show as minor deflections within the sandstone unit. The log is characterized by relatively higher resistivities opposite the sandstone than the subjacent and superjacent shales. On the neutron density curve, the gross 'E-Field' well sandstone shows increasing density porosity values, and decreasing neutron porosity values. This depicts gas-bearing effect superimposed on the lithology effect as evidenced by the divergence of the two (2) curves. In addition, minor influence on the separation of the two (2) curves indicates oil bearing reservoir.

The excellent reservoir characteristics in the E-field are probably a consequence of several factors: their quartz-dominated mineralogy; long residence in mildly over-pressured environments that probably built diagenetic effects; and their easily hydrocarbon charge in a multi-source, evaporative – fractionated petroleum system that has been generating and pooling hydrocarbons since, at least, the Neogene.

In addition, the hydrocarbon filled sandstones: E-R_1, E-R_2, E-R_3, E-R_4, E-R_5, E-R_6, E-R_7, E-R_8 and E-R_9 were seismically represented by a high amplitude reflection event. Lower E-R_2 sandstones are more lenticular and underlain by slope shales. E-R_7 sandstones are the main oil producing and averaged approximately 64.2m; which is equivalent of 210.53 feet in thickness. On the stratigraphic cross-section, the reservoirs consist of series of shallow-marine and marine parasequences arranged in progradational and retrogradational stacks. The maximum flooding surfaces and maximum progradation surfaces were used to guide the reservoir stratigraphy.

The maximum prograding surface in a type 1 sequence lies at the top of the lowstand prograding wedge and marks the time of turn-around between progradation and retreat.

METHODOLOGY

The methodology employed in this study is fully discussed in Vail and Wornardt,1990, 1991; Mitchum et al,1993; Van Wagoner et al, 1990; Armentrout et al; 1990; Vail and Jervey,1977;1988; amongst others. Conceptual models for depositional systems tracts are also presented in Posamentier and Vail, 1988; 1992; Emery and Myers, 1996; Catuneanu, 2006; Embry, 2009.

The boundaries of systems tracts identified on well logs were marked on two-way-time logs and then correlated with the corresponding systems tracts that had been independently identified on the seismic profiles using seismic-stratigraphic principles. Faunal abundance and diversity data plus paleo-bathymetric interpretation provided extremely valuable data to make reproducible chronostratigraphic correlations and to identify the rock types in relation to the depositional environments and systems tracts.

The well logs data provided for this study includes: Gamma ray (GR) logs; Porosity logs which are: Neutron log (NPHI); Bulk Density log (RHOB) and Sonic log (Acoustic velocity log) (DT). Others include: Resistivity logs:(Deep induction log (ILD); Deep Laterology (LLD); Shallow Laterology (LLS); Short Normal Induction Log (SN).The well logs and seismic section are scaled 1/10,000 and 50,000 or 10.0cm/second, respectively.

Neutron log (NPHI) was used in combination with the density log (RHOB) and sandstone porosity log scaled from + 1.55 to 2.75 g/cm^3 and +63 to – 9%, respectively. The Neutron log (NPHI) and Bulk density logs (RHOB) are recorded on a compatible sandstone porosity scale allowing immediate hydrocarbon identification as well as a quick estimate of true porosity.

In this study, neutron and density curves practically overlay over the whole porosity range in clean water-bearing sandstones. A departure between these two curves, according to Schlumberger, 1989, indicates that the lithology or fluid content does not correspond to that of clean water-bearing sandstone. The separation of the NPHI and RHOB curves indicates that there is obviously a considerable amount of residual hydrocarbons and/or shallow invasion.

The stratigraphic column covering the study area was used as a basic tool for interpreting facies, mapping description or correlation, and virtually any other approach to understanding strata and their origin. The biostratigraphic / paleobathymetric reports of reference wells: EW-E and EW-F were provided for mapping and interpreting the first appearance or inception (FAD) and the last appearance or extinction (LAD) of fossil species in the rock record and to establish useful markers for biostratigraphic correlation. Bio-facies data were used in conjunction with facies interpretation derived from seismic and well logs studies. Detailed study of the seismic data provided for this work shows that the 'E-Field' strata were deposited in the south eastern Niger Delta; a broad region from the shelf – slope break extending to the Ultra Deep Waters (> 1500m) (Figure 1).

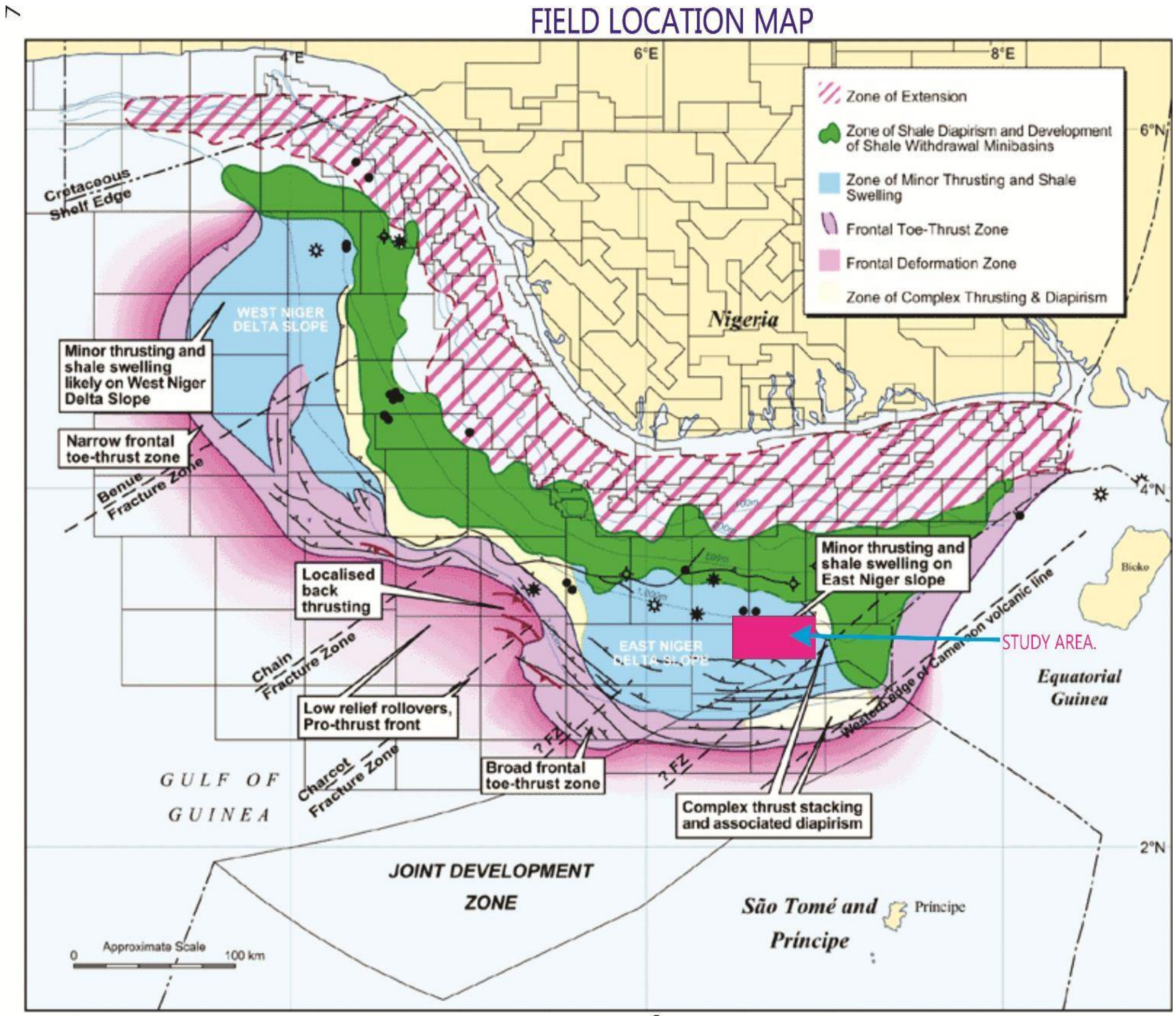

Figure 1: Field Location Map, with an area of about 990km^2, in the Deep Offshore Depobelt, Niger Delta.

The stratigraphic column covering the E-Field and Two-Way-Time/Biomarkers Recovery for wells C and F are shown in Table 1. Figure 2 illustrates the E-Field Mio-Pleistocene sequence stratigraphy. In the study area, the condensed section and its contained maximum flooding surface play a key role in the time correlation between the lowstand, transgressive and highstand systems tracts within a depositional sequence. The discrimination of biofacies helps place the associated strata into depositional settings.

TABLE 1: TWO-WAY-TIME IN SECONDS / BIO-MARKERS RECOVERY FOR WELLS C AND F.

DEPTH(m)	BIOSTRATIGRAPHY [WELL C] Bio-markers Recovery/Sequence surfaces and Age indicated.		TIME [Seconds]	DEPTH(m)	BIOSTRATIGRAPHY [WELL F] Bio-markers Recovery/Sequence surfaces and Age indicated.		TIME [Seconds]
875	*T mexicana [FB]*	SB 2.4Ma	0.950	700	*M.costata [FB]*	MFS 2.45Ma	0.700
1060	*M.costata [FB]*	MFS 2.45Ma	1.005	1060	*S abies [N]*	3.2Ma [Near SB 3.0Ma]	1.050
1720	*S abies [N]*	3.2Ma [Near SB 3.0Ma]	1.700	1125	*S. pseudoumbilica [N]*	3.3Ma [Near 3.4Ma]	1.120
1725	*S. pseudoumbilica [N]*	3.3Ma [Near 3.4Ma]	1.705	1760	*U.rustica [FB]*	SB 4.2Ma	1.650
1860	*U.rustica [FB]*	SB 4.2Ma	1.805	1775	*V. flexilis/T parvula [FB]*	MFS 5.0Ma	1.675
1875	*V. flexilis/T parvula [FB]*	MFS 5.0Ma	1.813	2230	*D. quinqueramus [N]*	5.6Ma [Near SB 5.5Ma]	2.005
2175	*D. quinqueramus [N]*	5.6Ma [Near SB 5.5Ma]	2.025				

Here, condensed sections were identified and located on well logs based on faunal abundance and diversity to recognize:

Warm water condensed sections associated with MFS's;

a. Cold water condensed sections associated with:

(i). Top slope fan surface (tsfs) and basin floor surface (tbfs) and;

(ii). Minor condensed sections between channel overbank lobes in slope fan complexes.

Secondary condensed sections were interpreted to have deposited above the tops of basin floor fan surface (tbfs) and slope fan surface (tsfs). The lowstand prograding wedge downlaps on the top slope fan surface (tsfs). The top slope fan surface (tsfs) downlaps onto the basin floor fan or sequence boundary seaward and onlaps onto the top of the underlying depositional sequence landward.

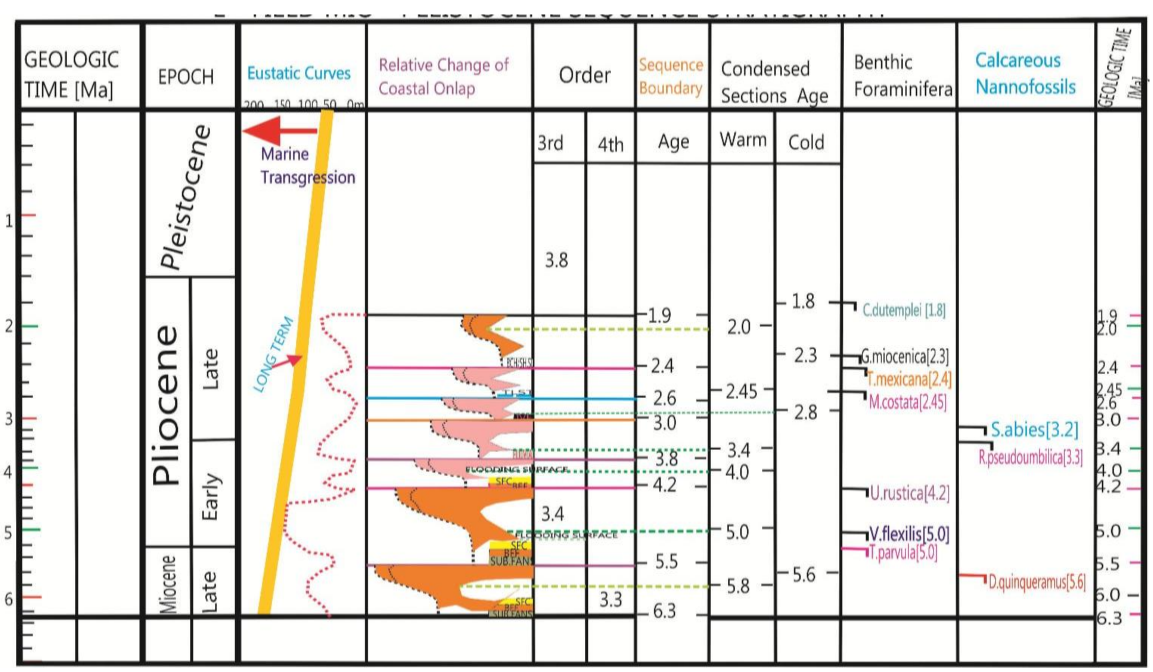

Figure 2: E-Field Mio-Pleistocene Sequence Stratigraphy

RESULTS AND INTERPRETATION

(a) Petrophysical Parameters of E-Field Reservoirs: The relevant wireline log signatures were adopted to identify hydrocarbon-bearing reservoirs and compute reservoir petro-physical parameters like porosity, water saturation, net reservoir thickness, gross reservoir thickness and the ratio of net-to-gross thickness. In addition, fluid contacts were delineated. These logs include: gamma ray log (for lithologic identification), volume of shale log (for porosity correlation), density and neutron log (for delineating fluid contacts), resistivity and water saturation logs (for identifying pore fluid types).

The minimum of gamma ray was used to compute shale volume as shown in equation I below:

$V_{cl} = (GR_{log} - GR_{min})/(GR_{max} - GR_{min})$ ……………………………………………………(I).

Where, V_{cl} = volume of clay, GR_{log} = Gamma ray log reading of formation;

GR_{min} = Gamma ray matrix (clay free zone), and GR_{max} = Gamma ray shale (100% clay zone).

Total porosity (Ø) was calculated from density - neutron log as shown in the following relationship:

$Ø = (6_{ma} - 6_b)/(6_{ma} - 6_n)$…………………………………………………………………………(2).

Where, Ø = porosity derived from density log,

6_{ma} = matrix (or grain) density;

6_b = bulk density (as measured by the tool and hence includes porosity and grain density), 6_n = fluid density.

Effective porosity ($Ø_e$) was estimated according to equation 3 below:

$Ø_e = \{(6_{ma} - 6_b)/(6_{ma} - 6_n)\} - \{V_{CL}*\{6_{ma} - 6sh)/(6_{ma} - 6_n)$…………………………(3).

Where, $Ø_{e}$ = Effective Porosity;

6sh = Density of shale; and

V_{CL} = {(6_{ma} – 6sh)/(6_{ma} – 6_{n}) = Clay Bound Water.

Average water saturation [(Sw(aveg)] of three wells: Wells C, E and F is 0.0252. Therefore, average So or (1 – Sw) = Oil Saturation = 1 – 0.0252 = 0.975. In addition, the calculations show that the resistivity index, R_t/R_o in this field is between 2 and 4. This is probably due to shallow invasion (e.g.; Schlumberger, 1984).In clean water–bearing formations, $R_{xo}/R_t = R_{mf}/R_w$, and $S_w = S_{xo} = 1$; and thus: $R_{xo}/R_t < R_{mf}/R_w$.

In the Niger Delta, of which the E-field is a part, hydrocarbons have occasionally been found in commercial quantities when the measured resistivities are usually low. These low resistivities, according to Schlumberger, 1984; have been found to be due to one or a combination of the following:

- High shale / clay content
- High silt content
- High irreducible water saturation; and
- Very deep invasion.

The study of E-Field Wells reveals that there are nine (9) hydrocarbon-bearing reservoirs. The sands encountered in these reservoirs are correlatable indicating a relatively longer period of depositional cycle.

A brief description of each reservoir is as follows:

(a) Reservoirs E-R_{1-3}: In a basinal position in the prograding complex, these are well-developed alluvial channel sands immediately above HFSB/TSF 4.1 Ma. These sands have a blocking log shape somewhat resembling a basin floor fan, but with a more thinly bedded character. This bedding is reflected in a ragged or "ratty" well log pattern (Armentrouct et al; 1993). High - resolution logs show better the interbedding of thin sands and shales. These sands may occur in levees adjacent to the channels. The retrogradational (backstepping) parasequence represents consecutive flooding events of the shelf. The gross thickness of the reservoir sand is 250m (820.25 ft), while the net thickness is 175m (574.18ft). Volume of clay, porosity and effective porosity were estimated at 0.13, 0.184 and 0.16, respectively.

(b) Reservoir E-R_4: These sands were interpreted as shingled turbidite reservoir sands deposited in the bottom-set area or near the toe of the lowstand prograding complex. These sands are of limited extent and have less reservoir potential than those in the basin – floor fan and slope fan systems because they tend to leak up-dip (Mitchum et al; 1993). Here, clinoform slope sediments are shales and are generally lean and gas-prone. These sands are commonly found in the expanded section down-dip of growth faults, with traps enhanced by roll-over anticline. The E-R_4 reservoir sands reflect delta lobes or near-shore to coastal plain transitions. The net thickness of the E-R_4 reservoir is within the depths of 1575m to 1625m.

Well A_1, tagged E-W_{A1}, has one or more parasequences within an overall coarsening-upward pattern. The pattern was interpreted as a gradual overall shallowing - upward pattern from upper bathyal or outer neritic to inner neritic or non-marine environments. The entire complex represents a pile of alluvial fan conglomerates coarsening-upward over 1025m (3363.03ft). Within this sequence, each of the seven (7) individual units (approximately 35m – 375m thick) passes from proximal alluvial fan conglomerates to beachface, shoreface, mouth bar sands and gravels, and finally to offshore fines.

E-R_3 and E-R_4 Reservoirs occur in an intermediate position in the prograding complex. These reservoirs are hydrocarbon bearing. The sands are interpreted as incised valley fills (IVFs). These sands are associated with a type 1 sequence boundary and represent a basinward shift in facies. They have a characteristic irregular, blocky pattern and are within depths of 1512.5m to 1725m or 1.4625s to 1.645s intervals, respectively.

Hydrocarbon entrapment in this prograding complex requires a structural closure to trap large reserves. Entrapment against tilted toe pinch-outs of the shingled turbidites is also a potential stratigraphic trap.

Well B, tagged E-$W_{B,}$ has progradational appearance sets with identical appearance. These sands are found in shelf environments of both a lowstand prograding wedge and a highstand systems tract. Sands forming this log pattern were interpreted as undifferentiated deltaic distributary mouth bar, crevasse splays and other related deltaic sands.

Well E-W_C, in an expanded intermediate position, has a 'classic' prograding complex character, with several upward-coarsening parasequences. The expanded sections of Well E-W_C are commonly found on the downthrown sides of faults that moved contemporaneously with sedimentation. The important morphological elements in well–W_C are offshore, shoreface and foreshore depozones. The offshore zone is characterized by sedimentation under low-energetic hydrodynamic conditions below the fair weather wave base (FWWB). The shale litho-facies is a representative of this depozone and effected by high-energetic conditions only during storms. Reservoir E-R_4 is located within the depths of 1512.m to 1712.5m in this well. The computed porosity and effective porosity values are 0.30 and 0.21, respectively. The reservoir contains oil and gas. Hydrocarbon entrapment involves unconformity enhanced, doubly plunging anticlines in growth fault expanded sandstone reservoirs.

Well W_D, in a sheltal position, typifies the formation of fourth-order incised valley fills in stratigraphically up-dip portion.

Reservoir in this well contains ER-$B_{1,}$ ER-S_1 and ER-S_2 sands classified on the basis of lithofacies type. The reservoir is hydrocarbon bearing and contains oil and gas.

Lowstand fans (basis floor fan, slope fans and a variety of ramp geometries) exist containing reservoir sands deposited by various gravity-flow (turbidite-related) processes.

Here, basis floor fan is the most obvious reservoir but stratigraphic trapping is more common in the smaller individual sand bodies observed within the more shale-prone slope fans.

The gross reservoir thickness of this reservoir is 612.5m (2009.6ft) and net thickness is 176m (572.5ft).

In Well W_E, the reservoir comprising S-IB, S-I and S-2 sands is hydrocarbon bearing and located within the depths of 1762.5m to 2125m.

It contains oil and gas. Porosity (Ø) and effective porosity ($Ø_e$) values are 0.22 and 0.21, respectively. Trap potential and reservoir quality are best in onlapping submarine fans and fault-controlled onlap facies (i.e. onlap facies contemporaneous with faulting) but poorest in off-lap fans (Mitchum et al; 1992). This is because stratigraphic trap and reservoir potential is higher in onlap slope facies and lower in off-lap slope facies.

Wells W_F, W_G and W_H reservoirs are located within the depths of 1625-2250m; 1775-2010m and 1800 – 2025m, respectively. These reservoirs require a four-way structural closure, but because of the abundance of sands, they will form good hydrocarbon migration pathways. The maximum flooding surface (MFS) forms a major stratigraphic surface associated with widespread shale deposits over the shelf, which forms good regional markers and hydrocarbon seals. The maximum flooding surface (MFS) represents the best potential for stratigraphic trapping because it contains isolated reservoirs and is overlain by a regional shale seal. Average porosity (Ø aveg.) of these reservoirs, which is 0.386 or 38.6%, was calculated from neutron; density and sonic logs.

The existence of a type I or a type 2 sequence can be a function of local factors such as the rate of tectonic subsidence(Posamentier and Allen, 1993); and major drops in relative sea level (Oboh-Ikuenobe et al; 2004). In this E-field, a type I sequence was interpreted as one in which there is a relative fall in sea level below the position of present shoreline and a type 2 sequence refers to a sequence in which the relative fall in sea level does not force a shift in the position of the shoreline. The sequence boundary in the interfluve wells in this field is stratigraphically equivalent to the erosional surface at the base of the incised valley. The best basis for correlating the wells in this field was to pick a prominent maximum regressive surface (MRS) at the top of the LST (PGC). BY flattening the section on this datum, it was possible to determine the amount of erosion by the fluid incision and to local where the underlying HST markers are truncated by the unconformity.

The depozones of the "foreshore – shoreface – offshore" model of Walker and and Plint, 1992) can be filled with various depositional elements that were identified by the lithofacies and ichnofacies analyses. The differing facies types represent a continuum of laterally adjacent, high-to-low energetic depozones with characteristic hydrodynamic conditions. These diagnostic, compositional and textural sedimentological aspects of foreshore, shoreface and offshore environments in the E-field are are documented in the analyzed Isopach/Isochron maps on tops of ERS-2 Sands and Horizon H_1(Base of Miocene)

CONCLUSION

Working within well-log sequence stratigraphic framework, seismic and biostratigraphy, eight (8) sequences have been delineated on the basis of tying log-motif patterns to biostratigraphy. The major sequences were related to a sea level fall during which the shelf was exposed. The presence of type 1 and type 2 sequence boundaries is indicative of stratigraphic signature of major drops in relative sea level during the Paleocene and Eocene.

Depositional environments in this field have been delineated to characterize the distribution of reservoir facies. Reservoir sand bodies consist principally of one or more of the following genetic types: deltaic distributary mouth bars, channel and shoreface sands, barrier beach, shelf and offshore turbidite sands. From this study, the basin floor fans have customary porosity values (average of 0.22). Slope fans exhibit several depositional styles depending on the vertical gradient of the slope.

This can be the reason for the range of porosity values observed in them (e.g. 0.22, 0.31 and 0.35). Within the E-field, the differing facies types represent a continuum of laterally adjacent high – to low-energetic depozones with characteristic hydrodynamic conditions. The variation in lithofacies thickness observed could be attributed to variations in sediment supply, rate of sea level rise and fall (eustacy), syn – sedimentary tectonics or error in data processing. In spite of these variations, there exists a good correlation between the wells.

The most prolific sandstone reservoirs in this field are from deltaic distributary mouth bars, channel sands and shallow marine sediments. Petroleum in subaqueous (submarine) fans is mainly from upper and middle channel and proximal turbidite sands. In this study area, submarine fans are relatively under-explored reservoir types that hold great promise because of the amount of sand that is present, the potential for stacking fan lobes, and the likely proximity to deep basinal rocks.

The oldest sequence in this field onlapped onto a major upper Neogene unconformity surface otherwise called Basal Qua Iboe unconformity – SB 6.3Ma. This late Miocene disconformity surface was formed when southern margin of the Niger Delta underwent catastrophic failure and slid ocean ward around 6.3 million years. The Mio-Pliocene channels gradually evolved in slope canyon systems that were backfilled with sandstone units and eventually covered with fine grained clastics during Qua Iboe time. Most of the E-field reservoirs are lenticular deposits and traps are not always coincident with the structural closure. .

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