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DEPOSITIONAL FACIES ANALYSIS OF COASTAL TO SHALLOW MARINE DEPOSITS IN THE ONSHORE NIGER DELTA BASIN: ACCESSING THE INFLUENCE OF SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENTS ON RESERVOIR QUALITY

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ABSTRACT

Sedimentology and depositional environment of E2000-Sand in the southern part of the Central Swamp depobelt have been studied using core and wireline log data. Nine wells were used for the study, one of which has some 200ft of core in the southern part of the field. Key wells were correlated based on normalized gamma-ray and other logs. Using two main panels, one along the depositional dip across syn-sedimentary intra-field faults and another along strike, lateral continuity, reservoir development, and shoreline proximity were evaluated. The cores were described to identify lithology, sedimentary structures, depositional processes, and genetic units. The results from the electro-facies analysis, wireline log correlation, core description, and core permeameter measurements were integrated to interpret depositional environments. The E2000-Sand normalized gamma-ray log profile showed three broad sections made up of (from bottom to top) a coarsening upward funnel-shaped basal section overlain by an overall cylindrical-shaped gamma-ray log signature capped by a short coarsening upward funnel-shaped interval. The overall gamma-ray log profile is consistent with a deltaic progradational setting typical of a shoreface sequence inundated by channel activities. Seven genetic units were identified in the cored interval comprising Marine Shale, Offshore Transition Heteroliths, Lower Shoreface, Upper Shoreface, Lagoonal Shale/ Heterolithics, Tidally Influenced Channel/Crevasse Splay, and Distributary Channel. Petrophysical analysis of these units showed a direct correlation between lithofacies type and grain size with flow properties deteriorating with decreasing grain size. Using such attributes as permeability, porosity, and grain size, four genetic units in the sand namely Lower Shoreface, Upper Shoreface, Tidal Channel, and Distributary Channel were interpreted as reservoir units. The best reservoir flow properties were preserved in the Distributary Channels with a porosity range of 20-29%, permeability in the range of 3,300-9,900mD and average grain size ranging from 177-500µ, while the Lower Shoreface corresponded to the worst quality reservoir units with porosity ranging from 17-26%, permeability varying from 0.01-180mD, and average grain size varying from 62-125µ. Three of the genetic units including Offshore Transition Heteroliths, Lagoonal Shales/Heterolithics, and Marine Shale were interpreted as non-reservoir units with porosity and permeability ranging from 4-17%, and 0.03-36mD respectively, while average grain size was below resolution. The E2000-Sand is interpreted as deposited in a coastal shoreface/delta mouth shallow marine setting. Reservoir quality in the sand is strongly facies-dependent with sedimentology and depositional environments controlling the reservoir properties of the sand bodies.

Keywords: Lithofacies, Electrofacies, Facies Association, Genetic Units, Porosity, Permeability, Shallow Marine, Reservoir Quality, Niger Delta.

INTRODUCTION

Deltas including the Niger Delta basin form major habitats for petroleum resources globally (Ahlbrandt *et al.*, 2005). The drive to deepen the understanding of deltaic environments and maximize hydrocarbon recovery has made these coastal basins the focus of sustained research. This motivation becomes more compelling in aging basins such as the Niger Delta where declining reservoir pressure due to prolonged hydrocarbon production combined with increasing water and sand cut make maximizing rewards from these old hydrocarbon assets more intricate. In this scenario, deeper reservoir understanding is imperative to facilitate improved field management and optimize infill development to enhance value-addition from these matured fields.

Deltas, by reason of being the intermediary area between land and sea, are inundated by both continental and marine activities forming mixed-process environments with multiple sub-environments. Attempts towards understanding deltaic depositional environments have a long history (Barrell, 1912; Boyd *et al.,* 1992). Contemporary evidence continues to show that depositional environments play dominant roles in reservoir performance and determine such reservoir attributes as internal architecture, heterogeneity, quality, and ultimately hydrocarbon recovery efficiency (Flint and Bryant, 1993; Reynolds, 1999). Understanding depositional environments is therefore fundamental in optimizing field development and effective field management. A historical challenge, which remains in studying deltas is the difficulty of adequately fitting them into simplified classification models (Galloway 1975; Boyd *et al.,* 2006) given the temporal and spatial complexities inherent in mixed-process environments. Until recently, adopted clastic depositional models for the deltaic environments, while still recognizing the mixed processes at the coastline, tended to be focused mainly on the dominant process at the time of deposition making them limited in their predictive capability. In a bit to improve this limitation, Ainsworth *et al.*, (2011) offered an update, which incorporates the fluctuations in deltaic depositional processes. The new scheme uses a one-to-three letter code that described the processes that impact a depositional system from dominant to least important to define a fifteen category of classification systems.

In this framework, it is possible to describe all the processes impacting a system. When there are two or more processes in a system, the classification is designated in the order of the importance of the prevailing processes as dominating, influencing, and affecting. The dominant process is depicted by a capital letter followed by the influencing process as the letters in small letters and the affecting process as the last small letter (Ainsworth *et al.*, 2011). Applying Ainsworth *et al.,* (2011) classification scheme offers the flexibility to define each reservoir uniquely and properly to adequately highlight its depositional variability and to keep in focus the corresponding facies architectural complexities, highlighting their impact on reservoir properties distribution and hydrocarbon recovery dynamics (Ichaso *et al.*, 2016). For example, in the Niger Delta traditionally described as a wave-dominated delta, various parts of the basin may now be more correctly and specifically classified as applicable using any combination of the interpreted importance of the operating processes at the time of deposition to designate the dominating, influencing, and affecting

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process to specifically define the environment. This ability facilitates the construction of a more granular reservoir understanding and representative 3D models with the ability to enhance uncertainty quantification and improve hydrocarbon recovery.

The current study focuses on one of such matured fields in the Onshore Niger Delta basin. The E2000-Sand is the main oil reservoir in the field. It is currently at its mature stage with increasing pressure decline including rising water and sand production. A major concern is that cumulative oil production to date compared to quoted initial resource volumes and ultimate recovery in the field indicate substantial reserves. To address this main problem and close the gap to ultimate recovery, it is crucial to building a geologically consistent, front-end loaded integration platform based on updated sedimentological understanding to improve the E2000 reservoir characterization and provide a tool for optimized infill field development targeting by-passed oil in the field. The study used an integrated sedimentological core, petrophysical and wireline logs data to reconstruct the environments of deposition of the E2000-Sand consistent with the mixed-process depositional setting of the study area with a view to understanding the influence of depositional facies on the reservoir quality. It provided an optimum framework for describing depositional environments and offered a tool for reservoir uncertainty management.

Generalized Geology of the Niger Delta Basin

The Niger Delta basin is situated between longitudes 4.0ºE and 8.8ºE and latitudes 3.0ºN and 6.5°N. The geology and origin of the basin as a failed arm of a triple junction rift system is well documented (Short and Stauble, 1965; Burke *et al*., 1971). The development of the proto-Niger Delta began with the formation of the Benue-Abakaliki Trough in the early Cretaceous associated with the opening of the South Atlantic. The province covers some 300,000 km^2 and includes the geologic extent of the Tertiary Niger Delta (Akata-Agbada) Petroleum System (Tuttle *et al*., 1999).

Several tectonic activities between the Aptian and the Miocene within the basin and its adjoining areas resulted in episodes of forward and backward movements of the coastal shoreline forming major regressive-transgressive sequences (Short and Stauble, 1965; Murat, 1972) with five main siliciclastic depositional cycles (Fig. 1) commonly called depobelts (Stacher, 1995). The basic Tertiary stratigraphy of the Niger Delta was defined by Short and Stauble (1965) who recognized three distinct facies in ascending order in the basin as the prodelta facies (AKATA FORMATION); the paralic delta front facies (AGBADA FORMATION; and the continental delta top facies (BENIN FORMATION).

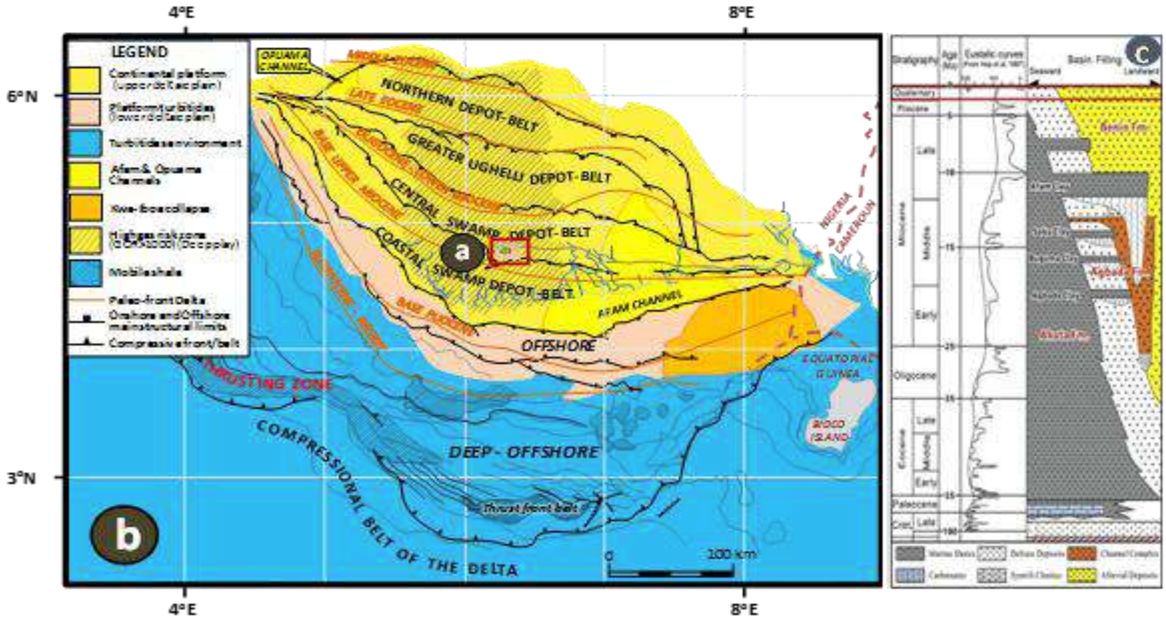

Fig. 1: Overview of the Niger Delta Basin: (a): Outline of the Study Area, (b) Niger Delta Basin Area with the outlines of the main depo-belts of the basin (modified after Stacher 1995) (c): Stratigraphy of the Niger Delta Basin, (modified after Corredor et al., 2005)

The Akata Formation is generally open marine and prodelta dark gray shale. It ranges in age from Eocene to Recent. The Paralic delta front facies (Agbada Formation) consists of cyclic coarsening upward regressive sequences, and poorly sorted deposits indicative of fluviatile influence. The coarsening-upward sequences are composed of shales, siltstones, and sandstones, which include delta front and lower delta plain deposits (Weber, 1971). The thickness of the Agbada sequences is highly variable, but most are about 150m (Fig. 2).

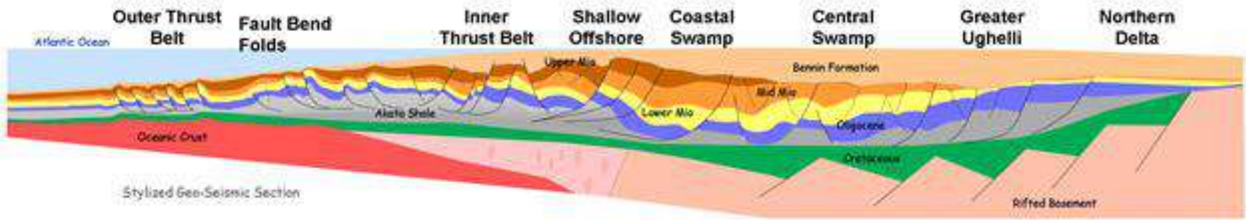

Fig. 2: SSW-NNE Schematic dip section of the Niger Delta, showing the main structural styles and thickness characteristics in depo-belts of the basin, (Modified from Merki, 1971).

Location of the Study Area

The study area (see Fig. 1) is located in the seasonal fresh-water swamp area of the Niger Delta, some110Km west of Port Harcourt within the southern part of the Central Swamp Depo-belt in the onshore Niger Delta. It has an aerial extent of approximately 50Km^2 and was discovered in 1971 with production starting two years later. The resolution of the data used, the number and spread of the nine wells applied in the study including their proximity, ranging from inter-well distances of some 600 to 2000m (Fig. 3) in both depositional strike and dip directions across the field, formed critical data selection attributes which provided sufficient coverage that enabled reliable geological conclusions to be drawn.

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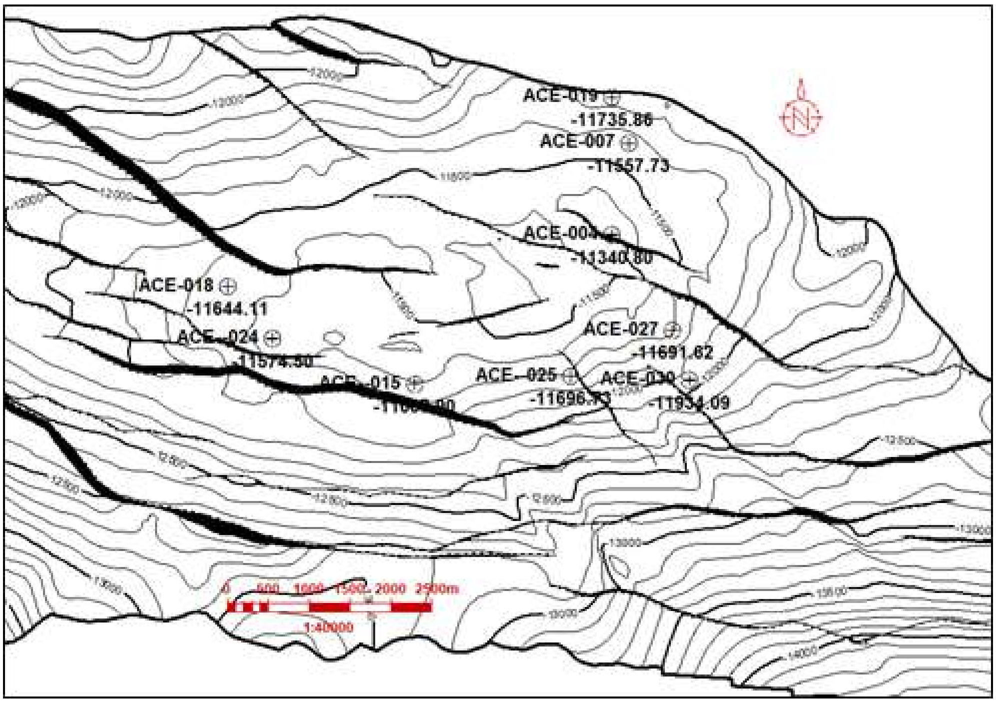

Fig. 3: Structural Depth Map of E2000 Sand, showing Well locations

MATERIAL AND METHODS

The dataset for the study was obtained from the Shell Petroleum Development Company of Nigeria Limited under a confidentiality agreement. The datasets include suites of wireline logs from 9 wells (ACE-019, ACE-007, ACE-004, ACE-027, ACE-030, ACE-025, ACE-015, ACE-024, and ACE-018) including normalized Gamma Ray (GR), Spontaneous Potential (SP), Resistivity, Sonic, Neutron, and Density logs. In addition, some 200ft of cores covering most of the E2000-Sand from 11,780.0ft to 11,981.25ft (drillers depth), and 30 core plugs were obtained from well ACE-027. These datasets were imported into Petrel 2020 running on a high-end personal computer with a full Microsoft Office suite as the interpretation platform.

Methods adopted in the interpretation of the datasets included sedimentological core description to understand the lithology, lithofacies, their associations, lateral extent, development trend, and flow performance including variations in grain size, porosity, and permeability in a bid to delineate the sedimentology and environments of deposition of the E2000 interval (Campbell, 1967; Slatt, 2006; Ugwueze *et al.*, 2019). Lithofacies analysis provided a comprehensive technique for unravelling the depositional setting of the sedimentary deposits. It involved the interpretation of strata in terms of the depositional processes that generated them by defining lithofacies with specific lithological, textural, sedimentary, structural, and diagenetic characteristics impacted by a set of energy conditions within an environment of deposition. Some 200ft of cores were taken from the E2000 sequence (11,780.0-11,981ft). The cores were sedimentologically described using a simplified lithofacies scheme, (Fig. 4) based on lithology, texture, and physical structures observed on the core. Similar schemes have been deployed by other authors such as Ugwueze *et al.*, 2014 and 2019.

Lithology / Dominant Grain Size	Dominant Sedimentary Structure	Lithofacies Codes (identified in E2000 Sand)
S (sandstone) c – coarse m – medium f – fine > 90% sand H (heterolithic) >50% sand >50% mud > 90% mud M (mudstone) C (coal)	**M** (massive) **X** (cross-bedded) **P** (planar, parallel laminated) **H** (hummocky – swaley cross-bedded) **W** (wave rippled) **C** (current rippled) **B** (bioturbated) **R** (rooted) **F** (fossiliferous) **O** (organic – carbonaceous)	ScX SmX SC SW SH SP HmC HmB HsB HmW MR MP

Fig. 4: Facies Determination Process – Lithofacies Identification Scheme

The lithofacies identification scheme uses a three-letter format where the first letter referred to the lithology, the second to the dominant grain size, and the third to the dominant sedimentary structure. In a situation where the grain size was of no practical essence like in mudstones or not visually discernable, a two-letter format was adopted, which focused only on the lithology and the dominant sedimentary structure. Textual evaluation including roundness and grain size was mainly by virtual estimation. The cores were cut lengthwise into two portions at one-third of the diameter. The-two thirds portion was Sedimentologically described and subsequently sampled at 30 carefully selected points by plugs of 3cm length by 2.5cm diameter for petrophysical evaluation. In a bid to qualify the grain size estimates made visually and calibrate the relationship between grain size and genetic units in the sand, the 30 plug samples were analyzed using the Sedimentation Balance.

The samples were selected based on variation in observed facies types corresponding to different facies associations, such that each genetic unit defined by the sedimentological core description, except the marine shale was sampled. The plug sampling covered some 90% of the cored interval, from 11,783.0 to 11,961.4ft (drillers depth). The stacking patterns and facies development trends of the wells were reviewed using wireline log correlation anchored on sequence stratigraphic principles (VanWagoner et al. 1990; Kendall, 2003; Ugwueze *et al*., 2019). This was applied to understand the sand continuity, depositional trends, lateral facies variation, and sand-body connectivity. The wells were correlated both in the strike and dip directions to map the extent, and depositional trends of the sand across the field (Slatt, 2006).

Finally, the sand was subjected to petrophysical evaluation using the full-length core, the core plugs, and wireline logs. Parameters investigated include bulk density, grain density, grain size, porosity, permeability, and their distribution in a bid to estimate flow potential and its relationship to the depositional environment. -Core-Gamma-Ray measurement was done on the full-length core while permeameter measurements were carried out on cores plugs. The results were transformed into a simulated density profile

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and correlated with the wireline Compensated Formation Density log (FDC) to determine the corresponding logging depths of the core sections. The correlation between the computer-derived density log and the wireline FDC log was good except for where borehole wash-out impacted the FDC below 11950ft making the FDC readings too low. The core depths according to this correlation were between 4 and 7ft greater than the drillers' depths. The digital output was corrected for core diameter fluctuations and the core bulk densities were calculated using the Archie and Timur equations (Archie, 1942; Timur, 1968).

a. Porosity from Bulk Density

$$\text{Porosity } (\Phi_D) = \frac{\rho_{ma} - \rho_{mb}}{\rho_{ma} - \rho_f} \qquad (1)$$

Where:

ρma = matrix (or grain) density, 2.65 g/cm^3 for quartz

ρf = fluid density, ρf (fresh H_2O) = 1.0 g/cm^3, salt water = 1.146 g/cm^3,

ρb = formation bulk density (as obtained from wireline Density Log)

b. Saturation from Total Resistivity

Water Saturation (S_w)

$$= [(a/\Phi^m) * (R_w / R_t]^{(1/n)} \qquad (2)$$

Where:

Φ = porosity

R_w = formation water resistivity

R_t = observed bulk resistivity

A = a constant (often taken as 1)

M = cementation factor (varies around 2)

N = saturation exponent (generally 2)

c. Permeability from porosity and water saturation

$$\text{Permeability (K)} = \frac{0.136\Phi^{4.4}}{S_{wirr^2}} = \qquad (3)$$

Where:

Φ = porosity

S_{wirr} = irreducible water saturation, being the water saturation at which all the contained water in the rock will be trapped by capillary pressure and/or surface tension such that all the water within the reservoir is immovable and hydrocarbon production is water-free.

RESULTS AND DISCUSSION

a) Electrofacies Analysis: Depositional Environments from Logs

Log patterns (GR and Res) in the E2000 revealed a sequence of coarsening upward, blocky, finning upward, flat, and structureless profiles. These profiles were combined with FDC/CNL (Compensated Formation Density and Compensated Neutron Density Logs) to define the Electro Facies Association Scheme for the field (Fig. 5), which is related to the genetic units and depositional environments (Salley, 1998; Kendall, 2003).

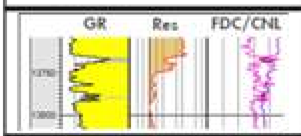
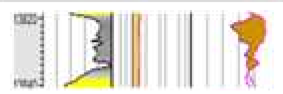
Log Signature	Facies Association Description
	**Distributary Channel**: Blocky to fining upward low count gamma ray log motif, negative separation of neutron-density log pair - with minor positive cross-overs indicating stacking of individual channels.
	**Upper & Lower shorefaces**: Cleaning upward gamma ray log motif with negative separation of neutron-density log pair; shalier section above shale is lower shoreface. Neutron-density separation may be larger if sand package contains gas.
	**Non-marine shale**: High count gamma ray log motif with low resistivity and positive neutron-density log separation. Distinguishing it from marine shale is based mainly on occurrence between channels, and less importantly paucity of foram occurrence.
	**Heterolith**: High count gamma ray log motif with streaks of lower counts, positive separation of neutron-density log pair with negative cross-overs and higher resistivity where streaks of lower readings are present.
	**Marine shale**: High count gamma ray log motif with large positive separation of neutron-density log pair, low resistivity. Not drawn to scale.

Fig. 5: Electro-Facies Association Scheme for the Studied Field, (Modified from Salley, 1985).

From the interpreted log patterns, the sands were subdivided into intervals to represent by three depositional episodes interpreted from the base as shoreface sands overlain by channel-dominated sands followed by another shoreface sand on top.

b) Shoreface Sand (SFS)

The basal depositional unit is composed of multiple cycles of coarsening upward profiles on top of a marine shale forming a funnel-shaped gamma-ray log succession typical of a prograding delta (Salley, 1998). The interval was characterized by relatively high values of gamma-ray and neutron log responses as well as low values of density, resistivity, and sonic log responses from the base, which gradually changed to low gamma-ray log response with neutron-density porosities that showed little or no separation to the top defining a typical coarsening upward profile. It is interpreted as shoreface sand.

In a wave-dominated depositional setting, sediments that were brought into the basin by fluvial systems are quickly reworked and dispersed along the coastline by storm/wave action forming a linear shoreline. This generates a well-defined sediment profile, which passes to the offshore environment from a foreshore through sand dominated shoreface. The offshore represents the area, which lies below the storm wave base and is dominated by hemi pelagic mud and silts sedimentations. As such, systems essentially develop in an area of high wave energy, that is, an open basin with the depositional environments being typically micro-tidal. Shoreface deposits typically extend from mean fair-weather wave base (MFWB) to mean water level (MLW) (Reading,1986).

The shoreface sands are generally cleaner upwards, and thickly bedded towards the top as typified by reducing gamma-ray log count *(see Fig. 5*). Based on the sand-shale ratio, these Shoreface units were divided into lower shoreface, middle shoreface, and upper shoreface intervals. Upper shoreface deposits formed good reservoirs because of relatively coarser grains, high porosity, and permeability that probably arose from winnowed grains by wave actions. The lower shoreface had an alternation of sand and shale sequence forming a serrated log shape. They were of poorer quality compared to the upper shoreface because of their intercalated nature, and

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volume of shale content. They were usually deposited in the outer neritic sub-environment at a depth range of 20-50m. The shoreface sands generally showed reduced sand quality towards the basin as a function of being distal from the shoreline with the effect that more on down-dip wells, which were more marine-influenced were less developed than up-dip sections (Fig. 6).

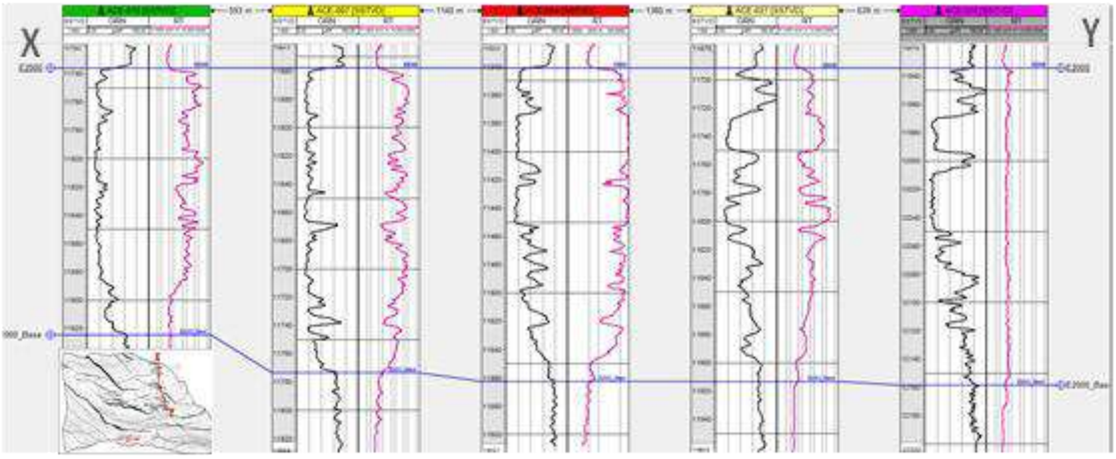


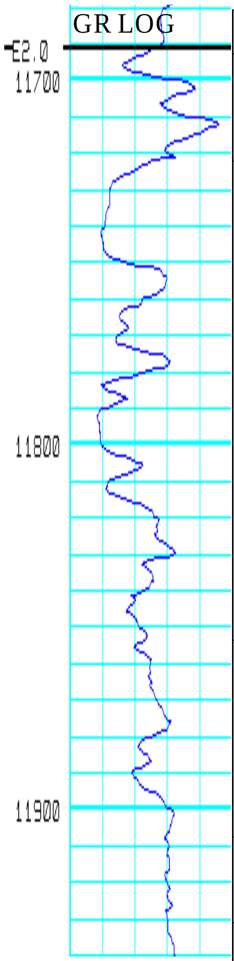
Fig. 6: Dip Correlation Panel highlighting North - South Sand Development Trend across the field, (Increasing Marine Influence and Decreasing Sand Quality Southwards, towards the basin-more channels in the proximal parts (X: Northern part) and more shoreface preserved in the distal parts, (Y: Southern part) of the field

c) Fluvial Channel Sand (FCS)

The second depositional episode was made up of a series of fining-upward sequences of sandstones that were characterized by blocky (boxcar) to bell-shaped gamma-ray log responses with little or no separation between the neutron and density porosities. The units were locally separated by thin shale/mud bands with high gamma-ray log counts. The interval was interpreted as a succession of channel deposits. The interval showed an overall aggradational gamma-ray log signature with minor serrated retrogradational units. The blocky gamma-ray motif was interpreted as evidence of fluvial channel fills, while the serrated units were interpreted as being tidally influenced intervals with the tiny high gamma-ray units interpreted as indicating channel abandonment heterolytic that separated individual channel intervals (Selley, 1998). On the strength of the observed electro-facies association, the interval was interpreted as a fluvially dominated, and tidally influenced estuarine environment. Fluvial channel sands are relatively better reservoirs than tidal channel sands because they represent relatively higher energy deposits, and are more porous, permeable, and cleaner with low shale content. The clay drapes and the more serrated nature of tidally influenced units hamper reservoir flow performance. Thus, tidal channel sands usually possess lower reservoir flow potential due to their higher degree of heterogeneity as compared to fluvial channels.

The blockier nature of the up-dip wells in the study area suggested more fluvial dominance at the proximal location compared to the distal wells, which had more serrated and punctuated profiles (*see the dip correlation panel – check the log profile of ACE-030 compared to ACE-019 in Fig. 6*). The upper depositional sequence was a radioactive interval whose resistivity log suggested an upward increase in sand content indicative of a coarsening upward log profile. The interval was interpreted to represent the early phase of a shoreface build-out episode. All the depositional cycles (except the top episode, which was not covered by the core) were distinctly picked out in the cored interval as validated by the core-log calibration (Fig. 7). These major cycles showed the vertical repetition and lateral variation typical of a prograding delta system (Reading,1996).

Core-Log Calibration



Depth (ft) Log depth	Description	Lithology	Depositional Environment
11745.0	Not cored but Resistivity log suggest another upward increase in sand content overlain by shale	**Predominantly sandy unit**	Upper shoreface with thin beach deposit
11778.0	Intruduction of coarse-grained sands showing typically erosive bases and large-scale x-bedding structures. Seven in number and range in thickness from 1ft to 20ft, each separated by thin shales with barren fauna.	**Predominantly sand with thin shales separating individual units.**	Distributary channel system comprising channel fills, channel abandonment and fresh to brackish lagoonal deposits. Intermittent sands represent crevasse-splays from the main channels. Increasing tidal influence occur towards top of system (11803.0 - 11822.0 ft). The topmost channel-fill (11783.63 ft 0- 11803.0 ft) does not show the tidal influence.
11868.02	Dominant wavy x-lamination. Progradation indicated by upward decrease in bioturbation, increase in sand content and general increase in higher wave-energy structures e.g. x-beddings.	**Predominantly sandy unit**	Upper shoreface with thin beach deposit at top (11896.02 ft - 11891. ft). Occasional thin shaly horizon indicates fluctuations in energy regime.
11947.72	Increased sand input, wave-induced ripples, bioturbated with brackish water fauna	**Heterolithics**	Transition zone from inner-neritic to coastal plain (Lower Shoreface)
11971.0 Base	Fauna indicates very shallow marine conditions becoming increasingly brackish upwards	**Inner-neritic Shales**	Marginal Marine with restricted fauna

Fig. 7: Well ACE-027 Core-Log Calibration, showing the key Depositional Cycles and Environments in the E2000 Sand

d) **Facies Analysis: Lithofacies Association and Depositional Environments from Cores**.

The cores used for the study came from the late 1970s and are currently in a dilapidated state with the coarsest intervals generally disintegrated into loose sands, despite the best efforts at preserving them. The current interpretation was aided by earlier core photos taken when the cores were more integral. Twelve lithofacies were identified namely Cross-bedded Coarse Sandstone (ScX), Cross-bedded Medium-Fine Sandstone (SmX), Planar/Parallel Laminated Sandstone (SP), Current-Rippled Sandstone (SC), Wave-Rippled Sandstone (SW), Current-Rippled

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Muddy Heterolith (HmC), Wave-Rippled Muddy Heteroliths (HwC), Rooted Mottled Mudstone (MR), Massive-Laminated Mudstone (MP), Hummocky/Swaley Cross-Stratified Sandstone (SH), Bioturbated Sandy Heteroliths (HsB) and Bioturbated Muddy Heteroliths (HmB). Of these, the most perversive lithofacies are SmX, SP, ScX, SW, SH, and HsB with key example intervals shown in Figure 8.

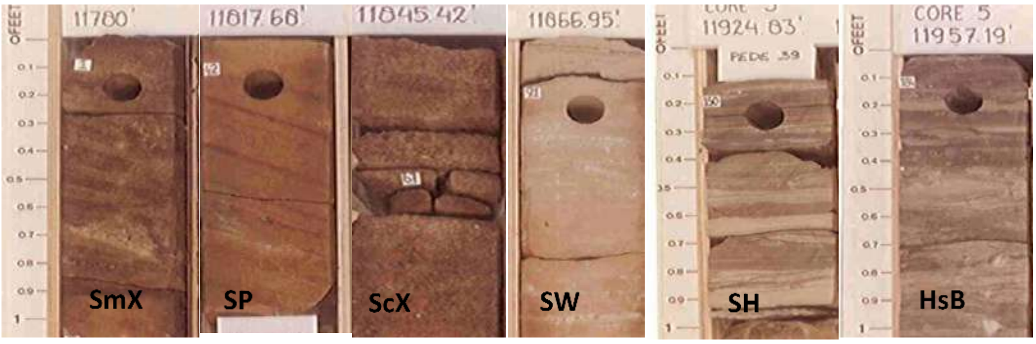

Fig. 8: Example intervals of the pervasive lithofacies in ACE-027 Core viz: 11780-11781 (Cross-bedded Medium-Fine Sandstone, 11817.68-11818.68 (Planar/Parallel Laminated Sandstone), 11845.42-11846.42 (Cross-bedded Coarse Sandstone), 11866.95-11867.95 (Wave-Rippled Sandstone), 11924.83-11925.83 (Hummocky/Swaley Cross-Stratified Sandstone, 11957.19-11958.19 (Bioturbated Sandy Heteroliths)

The Twelve lithofacies as observed in the cored interval were organized into seven lithofacies associations using Walter's law of facies succession (Middleton, 1973), based largely on the stacking patterns, and observed sediment profile having a deepening (finning) or shallowing (coarsening) upwards attributes. Results of the lithofacies analysis were integrated with the genetic units evaluated, depositional process assessed, and depositional environments interpreted to form the core description summary chart.

e) ***Lithofacies Association-I***

Lithofacies in this association consists of amalgamated and/or isolated sharp-based, fining- and thinning-upwards, medium-coarse-grained, cross-bedded, and planar to parallel laminated sandstones. The units were locally separated by thin shale/mud bands and may be up to 50ft in gross thickness with individual units being up to 20ft. Facies in this association are moderate to poorly sorted, subangular to subrounded sandstones which commonly formed lags at the bases and contained a suite of sedimentary structures including trough-planar-, and herringbone cross-stratifications, flaser bedding, reactivation surfaces and bivalve shell fragments with *Ophiomorpha*, *Skolithos*, and *Arenicolites* as the common trace fossil suites, suggesting high-energy deposition. Visual estimation showed good porosity in the unit.

The facies association is interpreted as fluvial deposits of distributary channel origin with no tidal influence inter-spaced with minor units of channel heterolytic. The overall coarse-grained texture, moderate to poor sorting, and aggraded bedding sedimentary structures were indicative of channel deposition in a high-energy environment (Reading, 1996). Thickly bedded channelized conglomerates with basal erosional surface recorded lateral erosion of channel thalweg (Olariu and Bhattacharya, 2006). The interbedded heterolithic layers were interpreted as intra-channel abandonment facies separating individual channel units. The presence of *Ophiomorpha*, *Skolithos*, and *Arenicolites* buttressed a sandy high-energy setting consistent with a distributary channel environment. The distributary channels of the E2000-Sand are interpreted as excellent quality reservoir units based on grain size and visual estimate of the reservoir properties.

f) ***Lithofacies Association-II***

The association comprised an alternation of fine to medium-grained sandstone (with low-angle trough- and planar-tabular cross-bedding, herringbone structures, flaser bedding, and climbing ripples) with instances of sparsely bioturbated sandy siltstones, and *Skolithos ichnofacies*. Localized minor intervals with a shallowing (coarsening) upward attribute were preserved within the association (11,810-11,808ft). Identified trace fossils include *Skolithos* and *Glossifungites ichnofacies* suggesting brackish conditions. The visual inspection highlighted the dominance of upper fine sand grains (fsU) with good porosity.

*The f*acies association is interpreted as tidally influenced channel deposits associated with crevasse splay deposits. The tidal influence was reflected in the presence of erosional lower-bounding surfaces, herringbone cross-stratification, flaser bedding, mud drapes, and reactivation surfaces, which were probably related to ebb-flood tidal cycles (Shanley *et al.,* 1992). The encountered coarsening upward facies within the unit suggested levee overspill deposition from the main channel, which was interpreted as crevasses splay unit. Brackish water conditions were reflected by the presence of *Skolithos ichnofacies*. The unit is interpreted as a high-quality reservoir unit based on its visually estimated reservoir properties.

g) ***Lithofacies Association-III***

The association is made up of current rippled muddy heterolytic (shales interbedded with thin lenses of very fine-grained, wavy, or lenticular-bedded siltstones), which often contained fragile shells of bivalves and disseminated plant matter. The silty laminae often showed evidence of tidal influence including current ripples suggestive of flood flows.

The facies association was interpreted as lagoonal shales in a fresh to brackish water low energy swamp to lagoon setting. The silty lenticular mudstones were interpreted as tidal flat sediments. Brackish water conditions were reflected by the presence of plant remains and fragile shells (Reading, 1996). The unit is interpreted as a non-reservoir unit based on its poor petrophysical properties.

h) ***Lithofacies Association-IV***

The association is composed of fine to medium-grained planar, parallel laminated and swaley cross-bedded, and wave-rippled lithofacies. Intervals of heterolithic sandstone containing gently inclined lamination swaley bedding / lenticular bedding, and a mixed suite of *Cruziana* and *Skolithos ichnofacies* were common including fossil shells of *Bivalves* and *Gastropods*. The unit generally showed an upward increase in grain profile with improved sorting of grains dominated by upper fine sand (Ufs) and good visual porosity. The association is interpreted as wave-dominated proximal shoreface deposits composed of upper shoreface sands with good flow properties. The coarsening upward grain size profile, sorting, and presence of *Skolithos ichnofacies* support the interpretation of the unit as a subtidal upper shoreface (Reading, 1996).

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i) ***Lithofacies Association-V***

Lithofacies association V is made up of fine to medium-grained, hummocky to swaley cross-bedded, and wave-rippled facies. The association presents as a series of sharp-based heterolithic sandstone/ mudstone consisting of hummocky cross-stratification, gently inclined lamination, swaley bedding, and a mixed suite of *Cruziana* and *Skolithos ichnofacies*. Instances of bivalve and gastropods fossil shaves were commonly observed. The unit showed a subtle upward increase in grain profile from lower fine sand to upper-sized sediments (Lfs-Ufs). The basal parts were dominated by wave-rippled muddy heterolytic. The unit showed an overall poor visual porosity. The facies association is interpreted as a wave-dominated proximal lower shoreface of low flow potential. Hummocky cross-stratification was commonly attributed to storm-generated waves above fair-weather wave bases (Walker and Plint,1992). The thin-bedded wave-ripple laminated sandstone and sharp-based graded heteroliths probably reflected deposition from waning storms generated by flows and reflected lower shoreface sedimentation.

j) ***Lithofacies Association-VI***

This association consists of a series of laminated interstratified thin bands of sharp-based hummocky cross-bedded and wave–ripple laminated siltstones and shales forming intercalations of bioturbated sandy heterolytic and bioturbated muddy heterolytic. These intervals exhibited high frequency and diversity of *Zoophycos* trace fossils particularly those of inner neritic water affinity including *Chrondrites*, *Thalassinoides*, and *Cylindrichnus*, which was often interpreted to represent the normal low-energy environment below the storm-wave base (Bromley 1990). The grain size in the unit was not quite visually discernible but showed very poor visual porosity.

The facies association is interpreted as distal shoreface deposits dominated by offshore transition facies based on the observed intense bioturbation, presence of brackish marine pelagic fauna, and marine organic matter. Evidence for the anoxic condition was provided by the abundance of planktonic fossils. Interbedded shale and thin bands of hummocky cross-stratified sandstone reflected sedimentation in shallow shelves along storm-dominated coastlines (Walker and Plint, 1992). The argillaceous heterolithic nature of the interval, the pervasive bioturbation, and the preservation of tiny bands of sand laminae were suggestive of sudden short-term change from low to high-energy conditions usually associated with spasmodic storm events and indicated deposition in a low-energy marine setting fed episodically with sands from storm currents. The unit is interpreted as a non-reservoir unit.

k) Lithofacies Association-VII

The association comprises medium to dark gray shales with localized strands of lighter-colored silty laminae. It was massive in appearance and weakly laminated. Physical sedimentary structures were limited to the occasional strands of ripple cross-laminated silty sandstone laminae towards the top of the unit. Textural characteristics of the facies association, and its gradational relationship with the overlying offshore transition facies indicated very shallow marine conditions becoming increasingly brackish upwards. The argillaceous nature of the facies suggested deposition under low hydraulic energy conditions primarily by suspension fallouts. Thus, the association is interpreted as inner-neritic shales below the effective wave base (Reading, 1996). The unit is interpreted as a non-reservoir bottom seal rock of the E2000-Sand.

An overview of the results of the E2000 facies analysis including identified genetic units and interpreted depositional environment is shown in the core description summary chart (Fig.9).

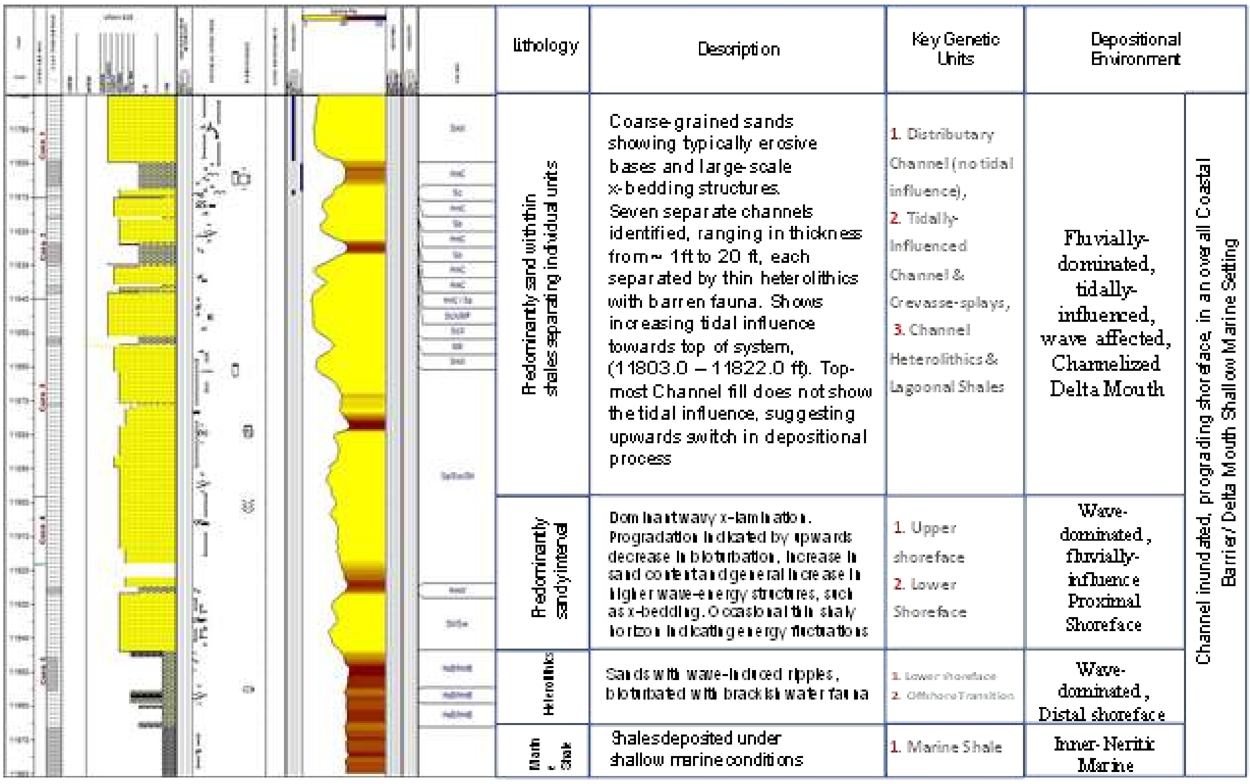

Fig. 9: Well ACE-027 Core Description Summary Highlighting Key Lithofacies, Genetic Units, and Depositional Environments of the E2000 Sand

Depositional Setting and Impact on Reservoir Quality

The E2000 sequence as identified from wireline logs and cores is made up of two lithologies namely sand and shale. Depositional style is deduced from sedimentological evidence for different depositional processes. In mixed-process coastal depositional systems, there is sedimentological evidence to support different depositional processes (wave, fluvial and tidal) being active at approximately the same time and in the same geographic location. Assuming that the sedimentary structures generated by the principal or most dominant depositional process have the highest preservation potential, then the facies associations can be classified based on the abundance of features observed from the cores resulting in an interpretation of prevailing depositional processes at the time of deposition. The most common sedimentary structures define the dominant depositional process. Secondary processes, which lead to the generation of subordinate proportions of sedimentary structures are said to have influenced deposition while the least impacting process with the smallest preserved evidence is interpreted as having affected the deposition (Ainsworth *et al*, 2011).

Using the scheme developed by Ainsworth *et al* (2011), the E2000-Sand is classified as being generated in a mixed-process setting typified by three sub-environments ranging

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from an inner-neritic marine environment through a wave-dominated, fluvially-influence (Wf) shoreface setting to fluvially-dominated, tidally influenced, wave affected (Ftw) channel environment in an overall prograding shoreface/delta mouth shallow marine setting. Based on the sedimentological description, from the base of the cored interval at 11,966. 0ft is interpreted as inner-neritic shales deposited below the effective wave base. Faunal evidence indicated very shallow marine conditions becoming increasingly brackish upwards. These shales are expected to be laterally extensive and are interpreted as deposited in a marginal marine environment without the possibility of any flow potential.

Integrating core description with petrophysical analysis (Table 1) showed from 11,966.0 to 11,944.0ft as typified by increased sand input and the presence of wave-induced ripple structures and strong bioturbation, a transition zone from the inner-neritic to a distal shoreface regime.

Table 1: Core Depth, Log Depth, Facies Association, and Petrophysical Properties of E2000-Sand in Well ACE-027

S/N	**Core Depth** (ft)	**Log Depth** (ft)	**Facies Association** (*Genetic Unit*)	**Porosity** *(%)*	**Permeability** *(mD*	**Average Grain Size** *(µ)*
1	11,783.0	11,787.0	Distributary Channel	24.0	4300	177 – 500
2	11,786.4	11,790.0	Distributary Channel	25.4	6200	177 – 500
3	11,791.0	11,795.0	Distributary Channel	28.6	>9900	177 – 500
4	11,796.9	11,800.0	Distributary Channel	26.0	>9900	177 – 500
5	11,799.7	11,804.0	Lagoonal Shale	8.8	-	-
6	11,801.9	11,805.0	Lagoonal Shale	10.8	-	-
7	11,808.0	11,813.0	Crevasse Splay	24.0	820	125 - 177
8	11,812.3	11,817.0	Tidal Channel	27.6	1100	125 - 177
9	11,815.5	11,819.0	Tidal Channel	28.1	1400	125 - 177
10	11,821.4	11,826.0	Distributary Channel	27.0	3300	177 - 500
11	11,827.8	11,832.0	Crevasse Splay	18	1600	125 - 177
12	11,832.4	11,837.0	Distributary Channel	26.4	>9900	177 - 500
13	11,837.1	11,842.0	Distributary Channel	26.9	7500	177 - 500
14	11,840.3	11,845.0	Distributary Channel	24.4	>9900	177 - 500
15	11,842.5	11,847.0	Distributary Channel	25.0	>9900	177 - 500
16	11,849.8	11,854.0	Distributary Channel	25.6	>9900	177 - 500
17	11,853.4	11,858.0	Channel Heterolithics	9.5	13.2	-
18	11,858.1	11,865.0	Distributary Channel	27.8	>9900	177 - 500
19	11,863.8	11,770.0	Upper Shoreface	27.8	860	88 - 125
20	11,870.7	11,877.0	Upper Shoreface	27.0	530	88 - 125
21	11,878.4	11,885.0	Upper Shoreface	28.7	1100	88 - 125
22	11,887.2	11,894.0	Upper Shoreface	25.7	390	88 - 125
23	11,892.1	11,899.0	Upper Shoreface	29.1	2200	88 - 125
24	11,901.2	11,908.0	Upper Shoreface	26.1	560	88 - 125
25	11,913.4	11,920.0	Upper Shoreface	27.6	410	88 - 125
26	11,923.3	11,930.0	Lower Shoreface	21.9	140	62 - 125
27	11,933.2	11,940.0	Lower Shoreface	24.4	170	62 - 125
28	11,940.3	11,944.0	Upper Shoreface	26.6	540	88 - 125
29	11,948.5	11,952.0	Offshore Transition	9.7	36	62-125
30	11,961.4	11,965.0	Offshore Transition	15.3	0.12	62-125

Petrophysical analysis of the unit showed porosity ranging from 7-17% and permeability from 0.004-36mD. This interval is interpreted as a laterally extensive non-reservoir unit. The whole sequence is from 11,944. 0ft to 11,861. 0ft is interpreted as a proximal shoreface system composed of lower and upper shoreface sands. Wavy cross-lamination is the dominant sedimentary structure in this interval. Progradation of the shoreface system is indicated by the upward decrease in bioturbation, increase of sand content, and general upward increase in wave-energy structures including crossbedding being prominent at 11,891. 8ft depth interval.

Fluctuation of energy regime and sand input is indicated by thin, shaly horizons (11,924.8ft to 11. 925.6ft) and locally towards the upper part of the shoreface deposits, which displayed large burrows, overlain by facies of thin, coarse sand influxes that indicated some early fluvial influence. The proximal shoreface systems showed a wide range in reservoir properties with poorer properties in the lower shoreface units, where the dominant grain size ranges from 62-125µ, porosity between 17-26%, and permeability between 0.01-180mD highlighting its low reservoir flow potential. On the other hand, in the upper shoreface units, core plug analysis showed modal grain size as 88-25µ, porosity as varying from 20-30%, and permeability as varying between 35-2200mD. At approximately 11,861. 0ft, the onset of the distributary channel system was marked by the introduction of coarse-grained channel fill with typical erosive bases and large-scale cross-bedding structures. There are seven main channel-fill sands from 11,861.0 to 11,780.0ft cored intervals. The individual channels ranged from approximately 1ft to 20ft in thickness and were separated by thin shales, barren of fauna often containing thin, fine-grained sand laminae. The shales are interpreted generally as fresh to brackish lagoonal deposits, while the intermittent sands are thought to be crevasse-splays (levee overspill deposits) from the main channels. Both the lagoonal shales and the channel fills showed increasing tidal influence towards the top of the cored intervals evidenced by current ripples, which possibly reworked the sands separated by thin clay layers. The interval showing the most intensive tidal reworking was preserved between 11,800.0 and 11,817. 0ft cored intervals, comprising the upper part of a channel fill overlain by non-marine shale (lagoonal shales) containing crevasses splay sands (11,807.8 - 11,809.6ft). The topmost channel-fill at about 11,780.0ft to 11,799.8ft cored intervals showed negligible tidal influence.

On the scale of the field and inter-well distance, the units of E2000 appeared to coalesce forming a laterally extensive reservoir (Fig. 10) with a pattern of increasing marine influence and decreasing sand quality from the proximal to the distal parts of the field, in an overall north-south direction (*see Fig.6*). The distributary channels within the interval possess the best reservoir properties with porosity ranging from 20-29%, permeability varying from 3,300 to greater than10,000mD and the dominant grain size between 177 to 500µ. They are interpreted as units of excellent flow performance. The fluvial channels were followed in quality by the tidally influenced channels and crevasse-splay which have an average grain size of 125-177µ, porosity ranging from 20-29%, and, permeability varying from 800-4,800mD. The lagoonal shales and heterolithics within the channel system are interpreted as non-reservoir units based on their poor reservoir properties with 30mD and 14% as maximum permeability and porosity respectively.

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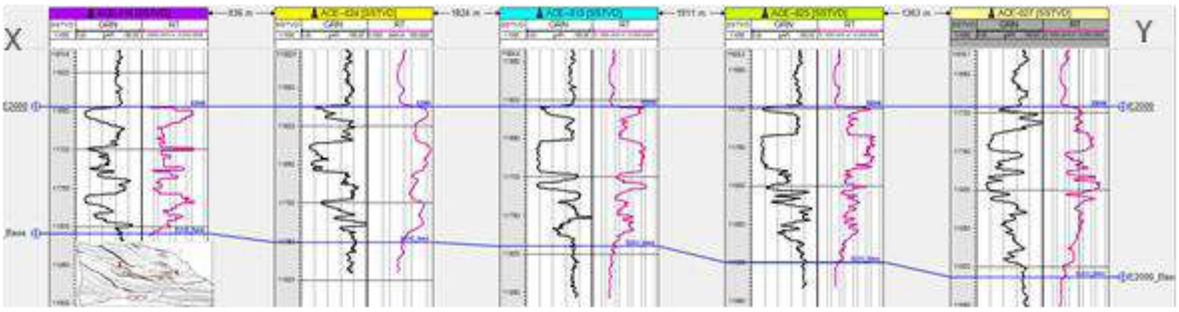

Fig. 10: Strike Correlation Panel highlighting Lateral Gross Sand Continuity over a kilometer-scale across the field, subtle thickness, and facies variation with distance suggesting dynamics in depositional processes

CONCLUSION

This study concludes that the E2000-Sand was deposited in a mixed-process environment inundated by wave, fluvial, and tidal activities, which produced reservoir units of varying qualities in an overall prograding coastal, shoreface/delta mouth shallow marine setting. Within this system, the depositional environment was the main control of reservoir quality with two factors most visibly dominating flow performance such as grain size and roundness. These two factors in turn have a direct relationship with lithofacies types and their relative values, which provided a good indication of reservoir quality. Seven genetic units were interpreted in the E2000-Sand, four of which are interpreted as reservoir units while three are non-reservoir units. The reservoir units included distributary channels, tidally influenced channels, and crevasse splays, upper shoreface and lower shoreface sands ranked in declining order of reservoir quality. The three non-reservoir units of the E2000 sequence included the offshore transition unit, lagoonal shales/heterolitic, and marine shales at the base of the sequence. All the interpreted genetic units were correlatable across the field. Sand development in the field showed a clear North-South trend with the sand units deteriorating towards the south with increasing marine influence as the delta prograded from the shoreline. The study buttressed the application of sedimentological, petrophysical, and stratigraphic techniques in the evaluation of the depositional environments while reservoir quality assessment offered an integrated methodology, which enabled a better understanding of the reservoir complexity and lateral variation within the field under study.

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