Sedimentological and stratigraphic analyses as a guide for reservoir quality prediction and distribution: a case study of X1 and X2 reservoirs in Koca field, Niger delta

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Abstract

The basic architecture of reservoir models is heavily impacted by the stratigraphic interpretation. The estimation of in-place hydrocarbon volumes and recoverable hydrocarbon volumes will rely on the accuracy of predicting and distributing reservoir quality away from well control. In this paper the interpretation of sedimentological and stratigraphic analyses is used to define reservoir geometry, lateral continuity and determine technique needed for 3D static modelling. The objective of this study is to use a sequence stratigraphic framework and depositional model to predict the characteristic fabric of X1 and X2 reservoirs in unknown portions of the field. Log motifs from four wells (Koca-01, Koca-02, Koca-03 and Koca-04) and core report from a nearby well Z07 were used to classify facies types. Biostratigraphy data from Koca-01 were used to identify key stratigraphic markers. A sequence stratigraphic framework of the facies was built and correlated across the field. This interpretation was further used to build a conceptual depositional model that best represented the environment of deposition for these reservoirs. Results show the major facies associations as distributary channels and shoreface sands. X1 and X2 reservoirs are interpreted to be progradational sands within a highstand system tract. Correlation shows good sand connectivity and distribution of gross reservoir thickness in 2D. The depositional model in this paper was used in 3D static models to improve geometric characterization in 3D static modelling.

Keywords Sequence stratigraphy · Conceptual depositional model · 3D static modelling · Reservoir quality

Introduction

The stratigraphic techniques (lithostratigraphy and sequence stratigraphy) used in correlation of stratigraphic subunits in Niger delta fields have a significant impact on the gross reservoir thickness. The interpreted stratigraphic framework defines a surface-based compartmentalization that is important to guide strategies for creating conceptual depositional models (Jose et al. 2011). In the quest to build a 3D static model, a suitable conceptual depositional model is required as a basis for the type of analogue data/modelling technique needed to constrain gross rock volumes and in-place hydrocarbon estimates. However, the idea of building a conceptual depositional model is to try and represent the ideal of what

the subsurface looks like in the modelled area which will enable appropriate prediction and distribution of properties in the static model. La Pointe (2011) observed that there is a huge significance in selecting the best geological conceptual scenarios from among multiple alternative conceptual models.

Geology of the Niger delta basin

The Niger delta basin lies within the Gulf of Guinea continental margin in equatorial West Africa between latitude 3° and 6° N and longitude 8° E (Fig. 1). The Niger delta basin is a wave-dominated delta with tidal and fluvial influences with its sediments typically sourced from the Benue and Niger River. Its subaerial exposure is about 300 km from apex to coast, spreading over about 75,000 km², with two lobes protruding 250 km into the deep waters (Doust 1990). From the Eocene to the present, the delta has prograded south-westward, forming depobelts (Fig. 1) that represent the most active portion of the delta at each stage of its

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Fig. 1 Group of maps: Africa, Nigeria (modified from Obaje 2009) and Niger delta

development (Doust and Omatsola 1990). The basin is pervaded with faults, some of which are large syn-sedimentary faults, which divide the basin into five (5) depobelts (Fig. 2). These syn-sedimentary faults are mainly formed due to the mobility of the underlying overpressured marine shale (Akata Formation) which is overlain by deltaic sediments (Agbada Formation), and finally, the continental deposits (Benin Formation) typically migrate southwards outbuilding the delta (Knox and Omatsola 1989). The structural deformation of the Niger delta shows extensional features at the northern onshore part, compression features offshore and transtension features in the middle. This characteristic deformation forms the primary controls for hydrocarbon traps and accumulation in the basin. The Onshore Niger delta hydrocarbons are trapped mainly by growth faults, rollover anticlines and collapsed crest structures which are characteristic

of extensional deformation. Offshore Niger delta on the other hand is characterized by collapsed crests, back-to-back features and k-faults (Doust and Omatsola 1989).

Well sections through the Niger delta generally display three vertical lithostratigraphic subdivisions: an upper delta top facies; a middle delta front lithofacies; and a lower pro-delta lithofacies. These lithostratigraphic units correspond, respectively, with the Akata Formation (Palaeocene-Recent), Agbada Formation (Eocene-Recent) and Benin Formation (Oligocene-Recent) of Short and Stauble (1967) (Fig. 3). The Akata Formation is composed mainly of marine shales, with sandy and silty beds which are thought to have been laid down as turbidites and continental slope channel fills. It is estimated that the formation is up to 7000 metres thick (Doust and Omatsola 1990). The Agbada Formation is the major petroleum-bearing unit in the Niger delta. The

Fig. 2 The Niger delta depobelts (modified from Ejedawe 2012)

formation consists mostly of shoreface and channel sands with minor shales in the upper part and alternation of sands and shales in equal proportion in the lower part. The thickness of the formation is over 3700 metres. The Benin Formation is about 280 metres thick, but may be up to 2100 metres in the region of maximum subsidence (Whiteman 1982), and consists of continental sands and gravels.

Statement of problem

The tertiary Niger delta basin has been studied by several workers of sedimentology, sequence stratigraphy and geomodelling. Notwithstanding these previous publications, few fail to recognize the relationship between the stratigraphic framework and conceptual depositional model with 3D static modelling techniques. Hence, this study will provide a 2D stratigraphic model that can establish the link between the lithofacies interpretation, sequence stratigraphy, conceptual depositional model and 3D static model.

Aim and objectives

The aim of this study is to use stratigraphic framework and depositional model to predict reservoir quality and build static models that represent the reservoirs geometry and connectivity in unknown portions of Koca field.

Location of study

The Koca field is situated in OML 28, Bayelsa State, about 110 km west of Porthacourt (Fig. 4). It is located within the Central Swamp depobelt, onshore land, Niger delta. The field was discovered in 1977 by an exploration well named the Koca-01. Subsequently, three other appraisal/development wells have been drilled, Koca-02, Koca-03 and Koca-04. However, no production has taken place in the field till date. The Koca field is situated within a structure comprising a series of interlocking WNW_ESE trending rollover anticlines. It is separated from adjoining fields by structural building boundary faults. The Koca field sand depositional environment is channel and shoreface dominated with average to very good reservoir properties which includes permeability, porosity, net to gross, among others.

Reservoir description

Reservoirs X1, X2W and X2E are one of the 13 hydrocarbon-bearing reservoirs within the Koca field. X1 is a gas reservoir and has four well penetrations (Fig. 5): Koca-01, Koca-02, Koca-03 and Koca-04. It contains 203ft of gas with clear GWC at 7261ft. Reservoir X2W is also a gas reservoir penetrated by the Koca-03 well (Fig. 5). It has 103ft of gas with clear GWC of 9333ft. X2E is a gas and

Fig. 3 Stratigraphic data sheet west of the Niger delta (Reijers 2011)

Fig. 4 Location of study area Koca field

Fig. 5 Top structure map for X1 and X2 reservoirs with cross section along strike direction

oil reservoir penetrated by Koca-02 (Fig. 5). It has 9ft of gas with GOC at 9311ft and an oil rim of 13ft with OWC at 9324ft. The X reservoirs are all within a channelized shore-face environment with average to very good petrophysical properties. The reservoirs all have closed structures with major boundary faults that form the structural framework. The X2 is a segmented reservoir separated by a saddle. For this reason the western and eastern regions of this reservoir are not in communication in terms of structure, sand quality, pressure regimes, fluid type and contacts. Because of this existing saddle, the western and the eastern regions of X2 are named X1W and X1E, respectively. This saddle is being captured by the Koca-01 well where the X2 reservoir is water wet as compared to the Koca-02 and Koca-03 wells that saw hydrocarbon on the western and eastern regions of X2, respectively. Finally, this saddle concept is validated by structural interpretation where the surface maps show structural highs at the western and eastern regions of the reservoirs with a saddle in between (Fig. 5).

Data and methodology

The sedimentological and stratigraphic method of interpretation in this study combines the strata architecture (geometric relationship) of the sedimentary facies and the chronological order of their accumulation to enhance the interpretation of depositional setting and prediction of strata continuity (Catuneanu et al. 2011). Building a sequence stratigraphic framework involved interpreting log motifs, biostratigraphy and sedimentological data and tying them together into a coherent stratigraphic model. This stratigraphic model is further used to create a conceptual depositional model. A

suitable conceptual depositional model is needed as a basis for the type of analogue data/modelling technique needed to constrain gross rock volumes and in-place hydrocarbon estimates. The ideal of building a conceptual depositional model is to try and represent the ideal of what the subsurface looks like in the modelled area which will enable appropriate prediction and distribution of properties in the static model. La Pointe (2011) emphasized the significance of selecting the best geological conceptual scenarios from among multiple alternative conceptual models.

The study approach involves carrying out stratigraphic interpretation using Schlumberger Petrel software. The data set used includes: wireline logs from Koca-01, Koca-02, Koca-03 and Koca-04, biostratigraphy data for Koca-01 and seismic data for the Koca field.

Facies interpretation

Facies type was identified on the four Koca wells from log motifs analysis, patterns and trends (Fig. 6). Fining-upward sand sequences were taken to be channel systems, while coarsening upward sand sequences were taken to be shore-face systems. Further subdivision into channel and channel heterolith, lower and upper shoreface was based on the how clean the sand packages were. A total of five facies types were identified (as shown in Fig. 7). Due to the absence of core data in Koca field, a core analogue report for a nearby field was used to confirm identified facies. Facies types include:

Heteroliths

The channel heterolithic units are characterized by fining-upward, bell-shaped gamma ray log signature (Fig. 7). They

Fig. 6 Idealized gamma ray trends (modified by Reijers et al. 1997)

Fig. 7 Facies types identified from log motifs analysis, patterns and trends within the Koca field

generally cap the channel sands in the Koca field. They have higher density value than the upper shoreface and channel sands. This genetic unit consists of interbedded sandstone and silt which can be inferred from the log signature and knowledge of the regional geology. The overall fining upward is the result of an upward increase in clay content interpreted to be the product of the deposition by lateral accreting fine-grained point bars in the upper part of the fluvial channels. These units have similar gamma ray and neutron/density response with the lower shoreface deposits; however, the development above channels is distinct.

Channel sands

These channel sand units are characterized by fining upward to blocky, bell-shaped gamma ray log signature but lower gamma ray and density values due to the presence of cleaner sands in comparison with the channel heteroliths. The channel sands are the most prominent type of reservoirs in Koca field. They consist of amalgamated channels all stacked up, and this can be inferred from the log signatures. The typical blocky logs with weak coarsening and fining-upward trends represent channel stacking patterns (Fig. 7).

Upper shoreface

The upper shoreface units are characterized by coarsening upwards, funnel-shaped gamma ray log signature (Fig. 7).

They have low gamma ray value which indicates the occurrence of clean sands with little or no shale at base. Although some of these characteristics are like the fluvial channel deposits, upper shoreface sands can be distinguished from channels by their coarsening upward log profile, gradational contact with underlying lower shoreface and their gradational lateral change in thickness and continuity. The units are inferred to have been deposited in the upper part of a prograding wave-dominated shoreface.

Lower shoreface

This unit is characterized by coarsening upwards, funnel-shaped gamma ray signature on log (Fig. 7). They have relatively higher density values which can be attributed to the silty to shale predominance with limited sand. The lower shoreface deposits as seen in reservoirs are overlain by upper shoreface deposits and channels. They are inferred to have been deposited in a wave-dominated shoreface system. The alternation of silt, shale and sand is due to the rhythmic change from storm wave to quiet water condition between storm and fair weather base.

Shale

They represent condensed zones formed during marine flooding events. The shales are formed above and below reservoirs, thus forming the base and capping the reservoir.

They are distinguished by their large degree of positive separation on the neutron/density logs.

Sequence stratigraphic interpretation

The predictions about reservoir potential based on sequence stratigraphy depend on the changes in global sea level, tectonic movements and how they affect lithologic facies and boundaries (Ijomah et al. 2015). An existing basin scale sequence stratigraphic framework for Niger delta was used to put the reservoir scale interpretation into a framework. Flooding surfaces (FS) were identified in deepening gamma ray log trends within shales where the density and neutron readings show up as a wide separation (when neutron/density log is displayed on the same track, neutron log is displayed in reverse) and the resistivity log shows the lowest resistivity reading (Fig. 8). These identified flooding surfaces were correlated across the field and used to create a sequence stratigraphic framework for Koca field. The key regional markers which are chronostratigraphy time lines were picked from available biostratigraphic data for Koca-01. The identified regional markers (MFS and SB) were constrained to the regional Niger delta Chronostratigraphic Chart (Table 1) and correlated with other wells across the fields using similar log Motifs (Fig. 9).

Correlation

On a field scale, sand packages were correlated in both strike and dip directions. In the strike direction correlation was done to infer the lateral reservoir character and predict lateral continuity, while in the dip direction correlation was done to tell the depositional story. Sequence stratigraphic principles studied above (Fig. 9) are the basis for facies distribution and correlation. The wells were flattened on the base

Fig. 8 Identification of flooding surfaces used to build sequence stratigraphic framework

of the Continental Benin Formation. The top and base of the reservoirs in each well across the field were then identified (Fig. 10).

Reservoir and intra-reservoir correlation

Once the markers were used to constrain the packages, a shale-to-shale correlation was attempted across the reservoirs. This was because sands typically exhibit a significant variation in thickness and character from well to well and are often not laterally discontinuous, especially on a regional scale. Intra-reservoir lithostratigraphic correlation involves identification of genetic flow units within the reservoirs and correlating to other wells within the field (Fig. 11). A reservoir flow unit represents flow zones bounded above and below by intra-reservoir shales. For modelling purposes, the flow unit concept was applied for the zonation of the reservoir complex. An intra-reservoir correlation was done to identify these flow zones and barriers/baffles that could impede flow and affect production performance (based on facies with similar reservoir properties).

Conceptual modelling and environment of deposition

The conceptual depositional model is an integration of data and information from well log, seismic, sequence stratigraphy principles, outcrop analogue studies and paleobathymetry studies. The model (Fig. 12) mimics the subjective interpretation of the environment of deposition and attempts to illustrate the nature and geological processes by which the reservoir was deposited in time and space. The conceptual model was based on the correlation framework (field and reservoir scale), biostratigraphy, seismic facies analysis (Fig. 13) and analogue information. The vertical facies profile was determined reasonably from the well information, but because lateral facies determination can be a bit challenging, it was inferred from analogues. The outcrop studies and aerial photographs were used to determine suitable analogues for facies conceptualization.

Stratigraphic modelling

Zones and layering

The importance of this is mostly seen in the results of property modelling. Since the zones represent intervals of similar flow zone character in communication in each well, they act as a vertical limitation to the extent of population of properties.

The model of the layers is dependent on the zone model and is modelled to fit the zone heterogeneity. The modelling fully captures property variations clearly illustrated by the model of the reservoir facies replicating the reservoir facies log closely and capturing changes in reservoir properties.

Table 1 Nature of third-order composite sequences and their parasequence sets in the Niger delta (Reijers 2011)

Sequence <i>Main shale</i> <i>(Secondary shale)</i>	(<i>named shales</i>)	Time span (Ma)	Cycle (Ma)	Cycles (nbr)	Higher-order duration (Ma)	Depobelt
Sequence 11 <i>BOLIVINA-46</i> (6 unnamed)	1	5.00–0.00	5.00 (~)	6	0.83 (–)	Offshore
Sequence 10 <i>UVIGERINA-8</i> (1 unnamed) (<i>Haplophragmoides-24</i>)	2	9.50–5.00	4.50 (~)	3	1.50 (~)	Offshore/Coastal Swamp
Sequence 09 <i>DODO SHALE</i> (<i>Nonion-4</i>)	2	11.50–9.50	2.00 (–)	2	1.00 (–)	Coastal/Central Swamp
Sequence 08 <i>CASSIDULINA-7</i>	1	12.80–11.50	1.30 (–)	1	1.30 (~)	Central/Coastal Swamp
Sequence 07 <i>CHILOGEMBELINA-3</i> (<i>Bolivina-25</i>)	2	15.90–12.80	3.10 (–)	2	1.55 (+)	Central/Coastal Swamp
Sequence 06 <i>OGARA SHALE</i> (1 unnamed)	1	19.40–15.90	3.50 (–)	2	1.75 (+)	Central Swamp/Ughelli
Sequence 05 <i>ALABAMINA-1</i> (2 unnamed) (<i>ALABAMINA-2</i>) (<i>Bolivina-26</i>)	3	26.20–19.40	6.80 (+)	5	1.36 (~)	Ughelli
Sequence 04 <i>UVIGERINELLA-5</i> (<i>Bolivina-27</i>)	2	31.30–26.20	5.10 (~)	2	2.55 (+)	Ughelli/Northern Delta
Sequence 03 <i>OROGHO</i> (<i>Textularia</i>) (1 unnamed)	2	35.90–31.30	4.60 (~)	3	1.53 (+)	Northern Delta
Sequence 02 <i>UVIGERINELLA-8</i> (1 unnamed)	1	38.00–35.90	2.10 (–)	2	1.05 (–)	Northern Delta
Sequence 01 <i>EPONIDES-11</i> (<i>Umutu</i>) (8 unnamed)	2	54.60–38.00	16.60 (+)	11	1.51 (+)	Northern Delta
Total	19 named					
Average			4.96 (~)		1.37 (~)	
Third-order composite sequences or genetic (mega)sequences				Third-order genetic (para)sequences sets		

(~) within 10% of average total duration

(+) more than average duration

(–) less than average duration

Gamma ray, density and porosity logs are used to check the quality of layering (as shown in Fig. 14).

Static modelling

As with every model, the facies model serves as a reference for prediction, interpretation and observations as well as a

guide towards understanding the heterogeneity and physical process that operate within a depositional environment (Walker and James 1992). Key elements used as guide to building static models include the conceptual depositional model and sequence stratigraphy surfaces which help to define the framework (Fig. 15) and essential for reservoir property prediction and distribution (Figs. 16 and 17).

Fig. 9 Sequence stratigraphic framework for the Koca field

Fig. 10 Field-wide facies distribution and correlation in strike direction

Fig. 11 Reservoir and intra-reservoir correlation

Fig. 12 Conceptual depositional model showing a channelized shoreface environment

Results

Sequence stratigraphic interpretation

Within the Koca field maximum flooding surfaces 15.9 and 19.4 ma and one candidate sequence boundaries were

interpreted (Fig. 9). The X1 reservoir exists within highstand systems tract (HST), and X2 and X2E fall into transgressive systems tract (TST). The HST identified here was deposited as part of regressive shoreline at a time when sediment supply and accommodation space occurred at a faster rate than relative rise in sea level. With the aid of biostratigraphic

Fig. 13 Seismic facies analysis for Koca field in strike direction

Fig. 14 Upscaled logs used to QC the zoning and layering of reservoir model

Fig. 15 3D grid from reservoir structural model after using corner point gridding

Fig. 16 Facies model showing distribution of facies in X1 and X2

data and identified maximum flooding surfaces, it was determined that the HST was deposited during the Miocene period. Also, the TST identified by the top bounding surface (MFS) was deposited as part of a transgression movement of the shoreline which could be interpreted as a time when the relative rise in sea level occurred at a faster rate than creation of accommodation space and sediment supply. The top shale regionally forms the top seal for the reservoir, and the intra-reservoir shales act as baffles. The stacking patterns

are generally progradational/aggradational. The correlation of these identified MSFs' and SB together with the picked flooding surfaces formed the sequence stratigraphic framework (Fig. 9).

Correlation

The field-wide correlation along the strike shows a lateral continuity in facies moving from Koca-04 in the most

Fig. 17 Petrophysical models showing porosity, permeability and net-to-gross distribution in X1 and X2 reservoirs

proximal location progressively down to Koca-02 in the most distal location (Fig. 10). Within the targeted reservoirs three different flow units were observed and correlated across wells as shown in Fig. 11. Each flow unit is separated by shale baffles which can cause vertical permeability barrier in that part of the reservoir.

Environment of deposition

The environment of deposition for X1 and X2 reservoirs was interpreted to be a channelized shoreface environment (Fig. 12). This is indicative of a transitional marine setting. Integrating this result with seismic data for Koca field, the identified channels were not resolvable at reservoir scale. However, after carrying out field scale seismic facies analysis (Fig. 13) channel reflection patterns were seen. For the facies model, Object modelling technique was chosen as the preferred method because its best captures the stratigraphic interpretations and geological ideas in the conceptual model.

Discussion of results

The integration of sedimentology and stratigraphy, combined with geostatistical tools, provided a better understanding of geometrical relationships and connectivity potential of the reservoirs within each stratigraphic unit of X1 and X2. Additionally, it was established from this study that reservoir quality (in terms of porosity, permeability and net to gross)

of the X1 and X2 reservoirs is significantly affected by stratigraphy at that depth and location. Conclusively from this study, it shows that sequence stratigraphic interpretation provides a 2D stratigraphic framework that will better predict and distribute gross reservoir volumes. The 2D stratigraphic framework and depositional model built was the key input into static modelling workflow.

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