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RESEARCH ARTICLE - EARTH SCIENCES

Building 3D Lithofacies and Depositional Models Using Sequential Indicator Simulation (SISIM) Method: A Case History in Western Niger Delta

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Abstract
Sequential indicator simulation algorithm is one of the popular stochastic simulation algorithms for reservoir geomodelling. It has been used to model delineated lithofacies and depofacies units within the OPO field, western Niger Delta. This simulation algorithm was chosen because of its ability to honour the well logs as local conditioning data using the global histogram, areal and vertical geological trends of the data, as well as the patterns of correlation. Three lithofacies were identified and modelled, namely sand, shaly sand and shale units. Vertical succession of the depositional facies within the field reveals five major facies which are basal shelf shale facies, heterolithic (sand–shale) facies, lower shoreface sand facies, upper shoreface sand facies and shoreface channel systems. The general environment of deposition is interpreted to be shoreline–shelf systems where the shoreface channel units, upper shoreface sand, lower shaly sand and heterolithic units constitute the parallic reservoir sequences, while the shale units within the shoreface and coastal environments act as potential source rocks and caprocks for hydrocarbon accumulation.

Keywords Geostatistical modelling · Facies modelling · EOD · Reservoir characterization · Niger Delta

1 Introduction

Spatial modelling of lithologic and environment of deposition (EOD) properties is quite essential in reservoir characterization since they show the stratigraphic architecture and structure [1]. They also reveal various compartments within the reservoir reflecting the flow unit zonation. Both lithofacies and depositional facies allow capturing of all the heterogeneity levels and scales that are important tools for a detail reservoir fluid flow model [2,3]. Adequate understanding of both architectural geometries and heterogeneities of the reservoirs will ease hydrocarbon exploitation, and expedite secondary and tertiary recovery plans. Both reservoir lithologic and depositional facies distributions are essential prerequisites for reservoir management and fluid flow simulation studies. Heterogeneities of reservoir are often times beyond expectation that geostatistical modelling techniques are being used to build the geological (lithofacies and depositional) models in order to unravel the inherent reservoir compartmentalization that drive the hydrocarbon migration.

The reservoir heterogeneities when accurately evaluated through improved lithofacies and depositional facies models will serve as guides for subsequent reservoir properties prediction and simulation, reservoir performance prediction, hydrocarbon field development and economic evaluation. Reservoir simulation programme with the sole aim of determining hydrocarbon field production performance requires detailed knowledge of the subsurface geology of the area which could include the understanding of the available rock types, environment of deposition (EOD), and distribution of continuous and discrete reservoir properties [4]. The existence of diversity in geological depositional environments is regarded as the sole justification for various stochastic approaches for facies models [5–10], and using their mode of construction, these methods are generally classified into pixel-based, object-based, process-based and multiple-point statistics models.

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The pixel-based modelling techniques are used to build image using pixel by pixel while assuming a nonparametric statistical distribution. This modelling technique is sometimes referred to as two-point statistics models since it uses variogram analysis to model the available data using its variation between two spatial points [9–11]. Pixel-based models rely generally on variogram analysis, and they include sequential indicator simulation (SISIM), sequential Gaussian simulation (SGSIM) or continuous Gaussian simulations (CGS) and truncated Gaussian simulation (TGS). Object-based models use the concept of spatial arrangement of objects and find lots applications in reservoir engineering where they can be employed to characterize channel systems, fracture networks and porous media at grain-sized scale. A typical example of object-based models is Boolean modelling, where objects are spatially distributed based on Poisson points with constant density, and objects' forms and sizes are function of their locations in space [5,6,9,12].

Process-based modelling technique, on the other hand, depends on sedimentary processes, and since the parameters of sedimentation models are usually largely uncertain, they can be represented using random variables or functions. This is why when this approach is being used to model geological formations, it is termed random genetic simulations. This random genetic approach to modelling was pioneered by Jacod and Joathon [13], later improved upon and used for modelling complex depositional systems by other researchers [14,15]. Process-based models can generate more realistic geometrical architectures that are not limited by assumptions of spatial structures. Multiple-point statistics modelling approach has been considered as a technique for conditioning process-based and/or object-based models [9]. The multiple-point statistics model enables the capturing of very complex geological targets than two-point statistics also known as pixel-based model [16,17]. The thrust of this research, therefore, is to build realistic reservoir geological models in terms of both the delineated lithologies and environments of deposition using sequential indicator simulation. The study will contribute significantly to improvement of hydrocarbon recovery rate within the study area, as the low rate of recovery is as a result of inefficient sweep due to inadequate understanding of the inter-well heterogeneity [18].

2 Geological Description

2.1 Structural Setting

The hydrocarbon field of study is located within the continental margin shallow offshore Niger Delta basin (Fig. 1). The basin is situated in the Gulf of Guinea, located within the failed arm of the rift system aulacogen which led to the opening of the south Atlantic during the Cretaceous. Damuth [19] divided the entire Niger Delta into three main gravity zones: (1) the upper extensional zone consisting of listric normal faults underlying the outer continental shelf, (2) the translational zone of diapirs and shale ridges underlying the upper slope and (3) the lower compressional zone consisting of imbricate thrust faults (toe thrust) underlying the lower slope and rise (Fig. 1). Bilotti and Shaw [20] later described the occurrence of thrust faults and fault-related folds within the deepwater toe of Niger Delta, where "giants" fields such as Agbami and Bonga fields were discovered. The predominant structural styles in this delta are the syn-sedimentary structures termed growth faults, deforming the delta under the Benin continental sandstone facies. These growth faults generally trending in NE–SW and NW–SE directions [21] are by-products of gravity sliding during the sedimentation of the deltaic deposits and are polygenic in nature with their complexity increasing in down-dip direction of the delta [22].

2.2 Stratigraphic Setting

The siliciclastic deposits within this basin are of Tertiary age with three stratigraphic formations namely, from youngest to oldest, Benin, Agbada and Akata formations (Figs. 2, 3). The topmost Benin Formation is composed of massive continental plain sands that are highly porous with relatively minor shale inter-beds connoting an alluvial environment of deposition. The underlying paralic sequence of Agbada Formation house the oil and gas bearing reservoir units in Niger Delta. It is composed of sandstone with inter-beds of shale units representing the delta front, distributary channels and deltaic plain [25]. Agbada Formation is characterized with decreasing shale content from the lower to the upper portion denoting the seaward advance of the Niger Delta basin in time. The basal marine shale Akata Formation extends down to the basement and is a pro-delta shale unit with characteristic dark grey and medium hard with floral fossils within its upper portion (Fig. 2). According to Orife and Avbovbo [26], the stratigraphic traps associated with unconformity surfaces for oil and gas accumulations are paleo-channel fills, crestal accumulations, sand pinch-outs, erosional truncations, canyons fills, incised valleys and lowstand fans. Shale intercalations or parasequence shale units as shown in Fig. 3 have been observed to act as reservoir seals within the Niger Delta basin.

3 Materials and Methods

3.1 Materials

The dataset used in this research consists of 3D seismic data comprising 496 in-lines and 780 cross-lines, covering an area of 83.85 square kilometres and digital suites of wireline logs