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Effects of Shale Diapirism on Sedimentation and Hydrocarbon Entrapment in 'Odeiga Block' Offshore, Niger Delta, Nigeria

Kawekwune N, MN Oti

Geology Department, Faculty of Science, University of Port Harcourt, Nigeria

Abstract This paper examines the effects of Mud diapirism in 'Odeiga block' and its impact on sedimentation, reservoir development and hydrocarbon entrapment. The data available for this work include a 3D PSDM seismic volume, two wells Odeiga-1 and Odeiga-2 with high resolution biostratigraphic summary. Seismic mapping revealed presence of mass transport, turbidity and amalgamated channel complexes with some structural features folds, faults and mud-diapirs. The present and paleo-fairway maps of sands were generated with the aid of co-blended seismic attributes premised on well results. It was observed that the shale intrusion impacted on channel switching. Faulting and re-activation is believed to have been caused by gravity tectonics in the Deep Offshore Niger Delta. Furthermore, the interplay between hydrocarbon migration and entrapment within the vicinity of these major faults and mud-diapirs has also been investigated and no trap breach was detected within the studied interval. These combined structures comprising impervious shale plug(s) empierced with faults have good shale gouge ratio within their interface hence constitutes an efficient seal. This is validated through the final 3D framework model built around these combination traps. The findings from this research would boost prospectivity around similar structures which are abundant in most of the offshore acreages of the Niger Delta and would significantly increase reserves.

Keywords Mud diapirism, Controls on Sedimentation, Hydrocarbon Entrapment.

Introduction

The French word 'Diapir' has its origin from the Greek word '*diapeirein*' which means to pierce through. Hence, Diapirism is simply defined as the existence of diapirs or the process that leads to the formation of diapirs. A diapir is therefore defined in the context of geology as a type of intrusion in which a more mobile and ductile deformable material is forced into brittle overlying rock units. In recent times rigorous deep-water exploration has led to the understanding that many continental margins are shaped by deformation processes connected with a mobile substratum [1]. This has resulted in overpressure generation which is either caused by external or internal factors. External factors cause a reduction of the pore volume due to an increase in compressive stress, connected with disequilibrium compaction or tectonic compression. Also, Osborne and Swarbrick (1997) suggested that internal factors such as temperature increase, diagenetic processes, hydrocarbon generation causes overpressure due to change in fluid volume [2]. Mud expulsion thus depends on pore fluid pressure and tends to be momentary because overpressure conditions can change through time. Researchers like Judd & Hovland (2007) cited Vendeville (2005),Were episodic loss of fluids from the deforming mass has been said to reduce the overpressure, strengthen the fluid-sediment mixture and temporarily halt mud movement. There are two major types of diapirism namely Salt diapirism and Shale diapirism [3-4].

The purpose of this paper is to analyse diapirism, its architecture and how it impacts sedimentation and reservoir development and hydrocarbon entrapment. The concept adopted for the realization of the set objectives include to carry-out analyses on the structural interplay of these diapirs side by side its evolution and how it relates to the shale diapir geometry, rapid sedimentation around it, sand fairway switching, reservoir development and Hydrocarbon entrapment. However, the similarity in the structures (domes and up-dipping of strata) that clusters around both salt and shale diapirs spurred the interest for this research.

Geological Setting of Odeiga Block

The 'Odeiga Block' is located in the offshore depobelt of the Niger delta; it straddles the extensional (proximal parts) to the transitional (distal portion) zones of the Niger Delta Basin(figure 1). According to Doust and Omatsola (1990), the Niger Delta started building out into the Gulf of Guinea in the Eocene and has continued to do so till Present [5]. The Eocene to Quaternary stratigraphic succession comprises a wedge of clastic sediments, which is 12km thick at maximum. This essentially regressive clastic wedge is subdivided lithostratigraphically into three units - a basal section of marine shales (the Akata Formation), a middle paralic sand/sandstone succession interbedded with subordinate shales (the Agbada Formation), and a continental sand/sandstone uppermost unit (the Benin Formation) [6-7]. These sediments are debouching into the Atlantic Ocean in a deltaic setting [8]. The early origins of the site of the Niger Delta and the closely related Benue Trough can be traced to rifting at the Rift-Rift-Rift (RRR) triple junction in the area defined by the present position of the Gulf of Guinea. This rifting is believed to have led to the separation of the South American and African plates during the late Jurassic [8]. Rifting in the region diminished altogether in the Late Cretaceous, and the failed arm of the triple junction (now the Benue Trough) began developing Cretaceous deltas, and by Campanian times these deltas began prograding down the trough, interrupted by short-lived Maastrichtian and Paleocene marine transgressions. The Niger Delta began to develop in the Early Tertiary, eventually prograding over the subsiding continental-oceanic lithospheric transition zone; and by the Oligocene had spread onto oceanic crust of the Gulf of Guinea.

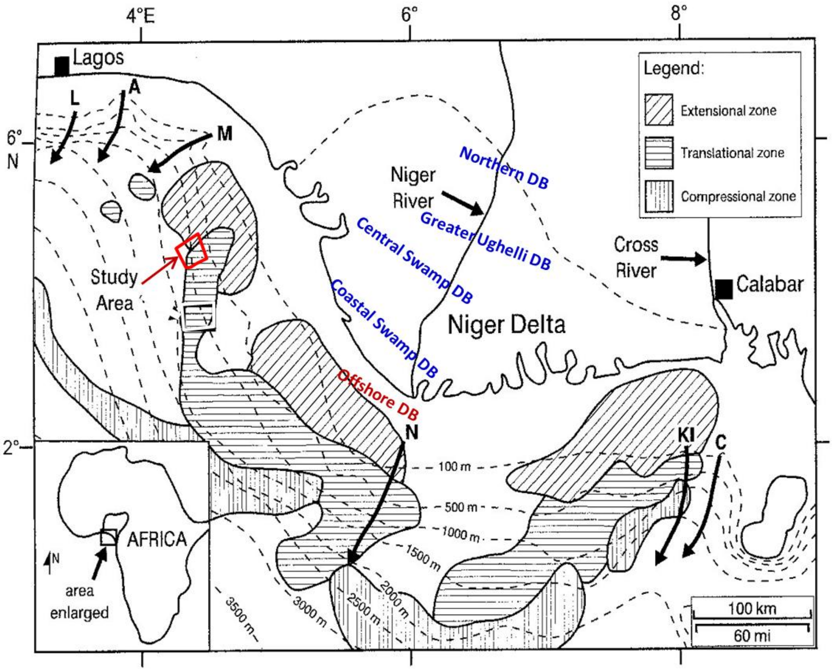


Figure 1: Niger delta basin showing bathymetry, zones of gravity tectonic structural style, depocenter sand modern submarine canyons (modified after Knox and Omatsola, 1989;Damuth, 1994) [9-10]. Thick arrows show submarine canyons. L–Lagos; A –Avon; M – Mahin; N – Niger; KI–Kwa Ibo; and C– Calabar. See study area in red box

The growth faults in the Niger Delta region can be seen on seismic (figure 2) they either act as migration pathways or structural traps depending on the prevailing conditions, and the associated rollover anticlines act as traps for hydrocarbon accumulations. The translational zone has a combination of extensional growth faults, and compressional mud diapirs and shale ridges. Connors *et al.* (1998) and Corredor *et al.* (2005) further subdivided the delta into five structural provinces based on seismically imaged structural styles: (1) an extensional province beneath the continental shelf, defined by listric basin-ward dipping (roho type) as well as counter-regional normal growth faults and associated rollover anticlinal structures; (2) a zone of mud diapirs beneath the upper continental slope (where the study area belongs); (3) the inner fold and thrust belt characterized by basin ward-verging thrust faults and associated folds; (4) a transitional detachment fold zone beneath the lower continental slope; and (5) the outer fold and thrust belt characterized by both basin ward-and hinterland-verging thrust faults and associated folds see figure 3 A and B below [11-12]. However, Beka and Oti (1995) showed that stratigraphic traps are most likely in the flanks on the Delta. The primary seal rock in the Niger Delta is the inter bedded shale within the Agbada Formation. They provide seals for the reservoir rocks in three (3) ways namely - as clay smears, as inter bedded sealing units against which reservoir sands are juxtaposed due to faulting, and as vertical seals produced by laterally continuous shale-rich strata [5].

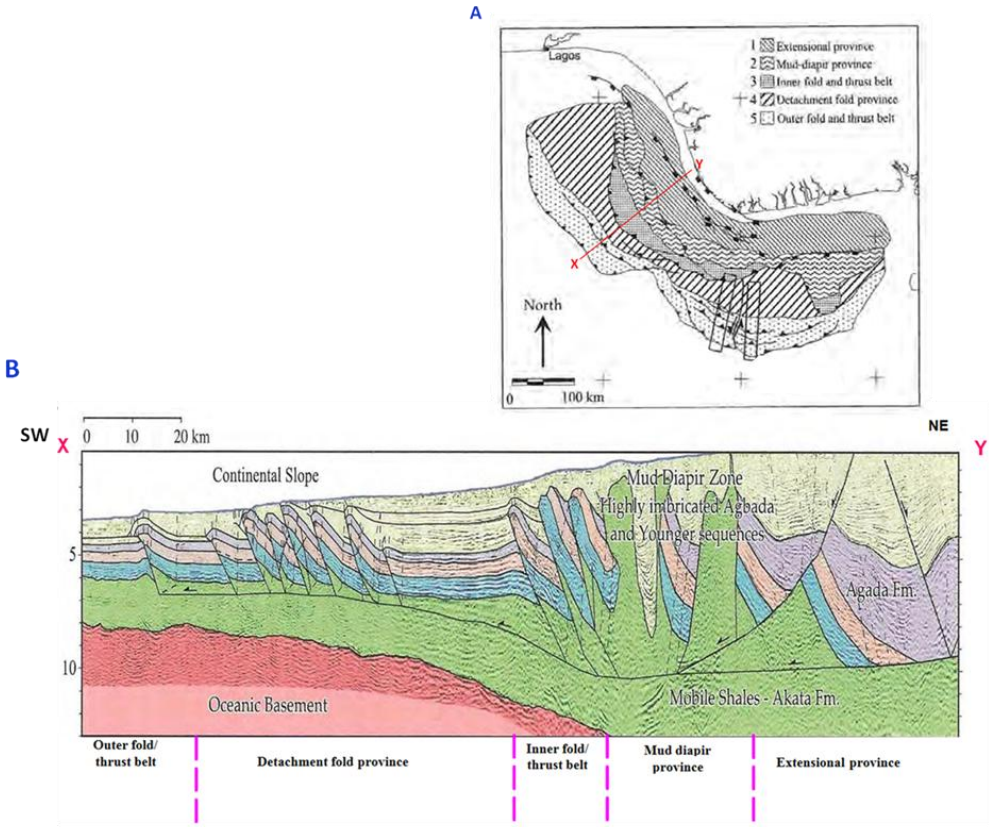


Figure 2: (A) Cross sectional Map of southern Nigeria showing regional tectonic classification (B) 2D seismic dip line showing associated structures in the five tectonic provinces in the Niger delta (modified after Corredoret al. 2005) [12]

Also other researchers both in the academia and petroleum industry have made efforts in studying deep-water stratigraphy, depositional elements, turbidite deposition, reservoir types and architecture, and channel patterns. Efforts include those of Beaubouef *et al.* (1998, 2000), Badalini *et al.* (2000), Posamentier *et al.* (2000), Weimer *et al.* (1995, 2004), Myall (2000), Pirmez *et al.* (2000), Booth *et al.* (2000), Demyttenaere (2000), Brami (2000), Gardner *et al.* (2003),Posamentier and Kolla, (2003), Edith *et al.* (2005),and Adeogba*et al.* (2005) [13-25]. These and other relevant studies have led to the development of the fill and spill model for diapir withdrawal intra-slope basins in the Gulf of Mexico and Guinea, facies associations and stacking patterns in the deep-water system, deep-water depositional elements and their associations, and submarine fan types and architecture. Adeogba *et al.* (2005), in their work on the Niger delta slope, identified seismic facies around the study area to include mass transport complexes, distributary channel and lobe complexes, and drape complexes. They interpreted distributary channel and lobe complexes as the sandy reservoir facies in the system. They also attributed the lack of leveed channel complexes in this area to the lack of fine-grained sediment to build levees. Also, they interpreted nick-points development and migration for the shallow near-surface interval [25]. The most recent purpose related research in the western lobe of the offshore depobelt close to Odeiga block were by Mathew *et al.* (2010) on 'Resolving the structural complexities in the deep-water Niger Delta fold and thrust belt: a case study from the western lobe, Nigerian offshore depobelt. They carried out an integrated seismic and subsurface characterization of Bonga Field [26].

Materials and Methods

The data set used for this research includes Well logs, Pre-stack depth migration (PSDM) 3D seismic volume, high resolution biostratigraphic data, T-Z profile, temperature and pressure data. The data provided for time (T) to depth (Z) conversion was used to generate a polynomial curve, which was derived from check shot of the Odeiga-2 well. The Chart below (figure 3) is a summary of the workflow adopted for this research, which highlights all the work done in a concise sequence.

Seismic Data and QC: The most important factor in seismic data QC is to know the polarity of the seismic data as processed. In this case it is SEG Polarity where the red is sand and the blue reflection coincides mostly to shales. From the geophysical wavelet tool box in *Petrel*^{TM} the other Seismic parameters were also determined. From the analyses the seismic is a Zero Phase data, with modal frequency around 20Hz and the Ricker type wavelet (figure 4).

Fault interpretation and QC: The faults in the structural smoothened (noise filtered) 3D Seismic volume were mapped in every ten (10) in-lines and also cross lines depending on the dipping and orientation of the fault to ensure that none of the faults were left out. The variance cube (an amplitude contrast seismic volume for structural discontinuity) aided the mapping of some oblique-slip faults. A high degree of confidence in fault interpretation is necessary for accurate definition of geometry, orientation, magnitude and dip of a fault. This also has impact on the amount of control it exerts on sedimentation and weak zones that help the evolution of diapirs and also the geometry and truncation of these reservoirs against them. Figure 5 below shows the final QC of faults with variance cube in 3D.

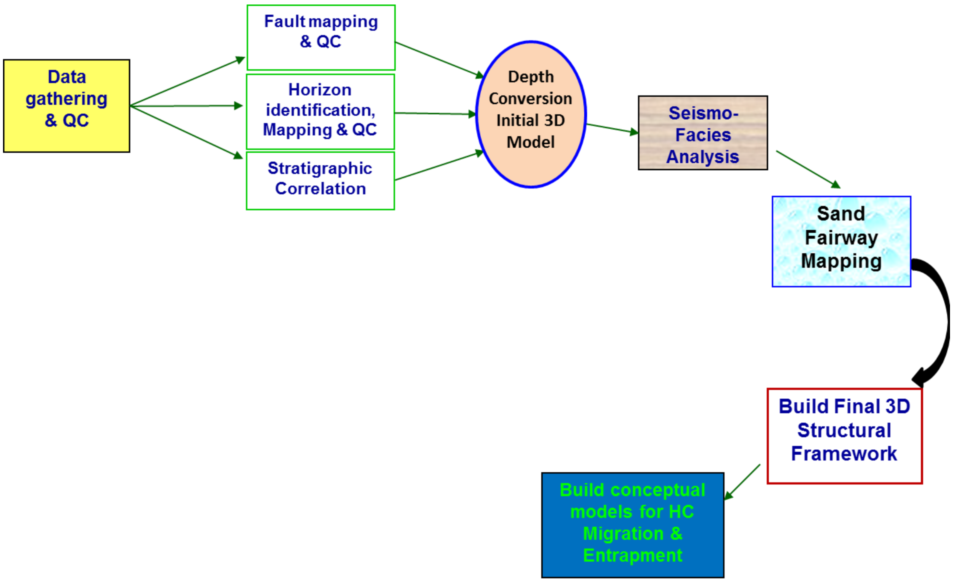
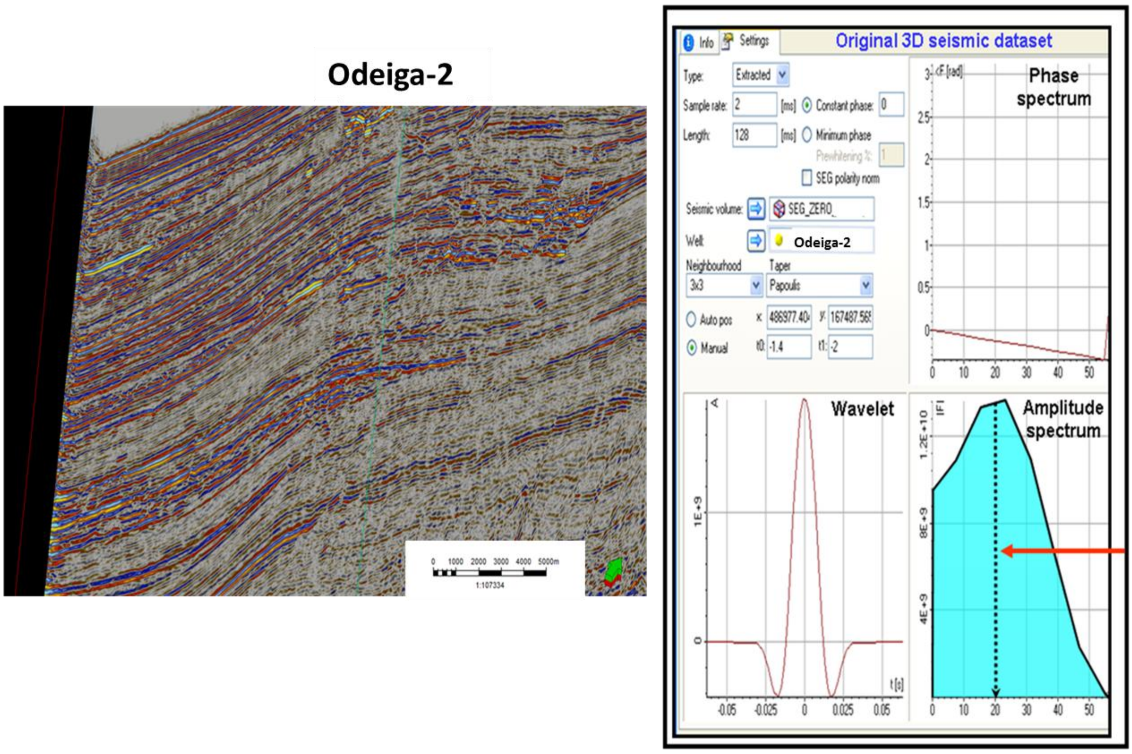


Figure 3: Methodology / Workflow Chart



Type: Extracted
Sample rate: 2 [ms] ● Constant phase: 0
Length: 128 [ms] ○ Minimum phase
Prewhitening %: 1
☐ SEG polarity norm
Seismic volume: SEG_ZERO_
Well: Odeiga-2
Neighbourhood: 3x3
Taper: Papoulis
○ Auto pos x: 486977.40 y: 167487.56
● Manual t0: -1.4 t1: -2

Figure 4: A Zero Phased Seismic data with maximum amplitude coinciding with Lithologic interface (top)

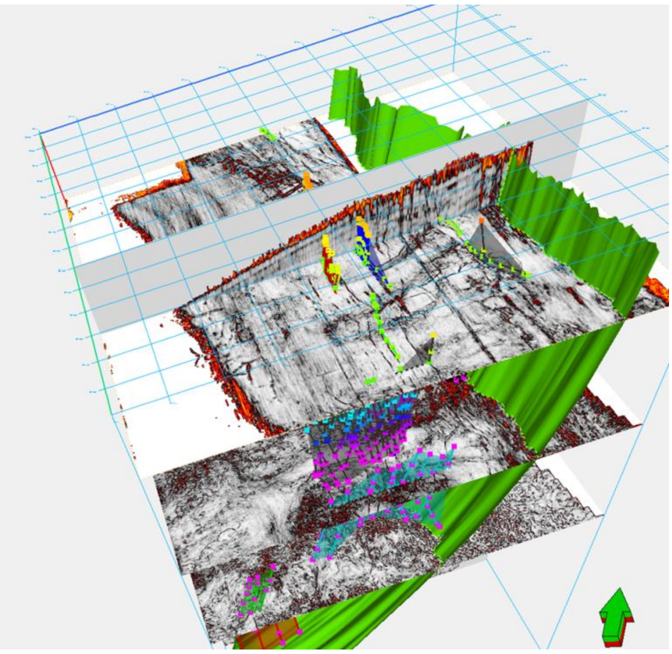


Figure 5: Final QC of interpreted faults with variance cube in 3D window

Biostratigraphic analyses: The summary of high resolution biostratigraphic analysis carried out on Odeiga-2 well was integrated into the Seismic/Stratigraphic correlation. This includes; Nano-fossil analysis, Palynology and Foraminifera analysis. The different zonation schemes were incorporated for determination of the Absolute age of the studied interval. The Neogene Nano-fossils *(NN) Zones* of Martini (1971) was the scheme adopted for the calcareous Nano-fossil classification [27]. The Palynological analysis done included the classification of the flora into Sub-series (Late Miocene), Germeraad *et al.* (1968) Zone *(Echitricolporites Spinosus)*, Evamy *et al* (1978) [28-29] broke it down to the lowest units of P-Zones:(P830, P840, P850, P860, and P870). The

Bioevents markers, sequence stratigraphic surfaces were correlated with seismic events (figure 8). There are only two wells in the study area which are relatively close; these are Odeiga-1 and 2. The Odeiga-2 is the deepest well in the area and tested deeper stratigraphy (as seen on the seismic volume). The result of the high resolution biostratigraphic analysis was incorporated and helped define the stratigraphic marker shales. These helped standardize the well correlation. The integration of these geology and geophysical data helped enhance output of Seismic to well calibration (Figure 8). The major sequence stratigraphic surfaces were used to calibrate the well results and the maximum flooding surfaces as picked are shown in the integrated well correlation panel well (figure 9).

Seismo facies analysis: The successful mapping and QC of faults in the block was pertinent in understanding structural disposition of the several fault blocks which directly impacts on stratigraphic correlation. The data from high resolution biostratigraphic analyses carried out in the field were used to identify stratigraphic markers from well lithology tops. These tops were tied to seismic horizons and the identified ones were mapped regionally in the block. The major flooding events from the well-seismic tie done have been delineated and the MFSs mapped. The figure 10 below shows a seismic section through Well Odeiga-2 with details of the data (logs, deviation survey, well tops and key stratigraphic markers) that aided the well - seismic calibration. A close look into the well to seismic calibration is as shown in figure 10 below highlights MFSs (1.3ma, 2.7ma, 5.0ma...up to 10.4ma) are on display along the well path. The identified seismo-facies include: mass transport complexes (MTCs), drape complexes (DCs), accretionary channel complexes (ACCs), distributary channels and lobe complexes (DCLCs) and fan-sheet complexes(FShCs) modified after earlier workers such as Beaubouef and Friedman (2000), Badalini *et al.* (2000) and Posamentier and Kolla (2003) [14, 15, 23].

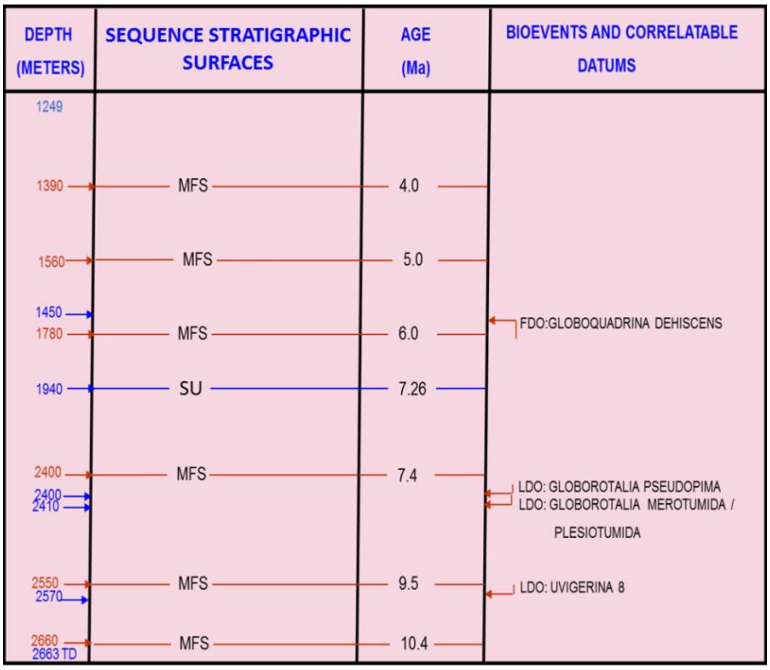


Figure 8: Mapable sequence stratigraphic surfaces in Odeiga block, stratigraphic markers and associated age

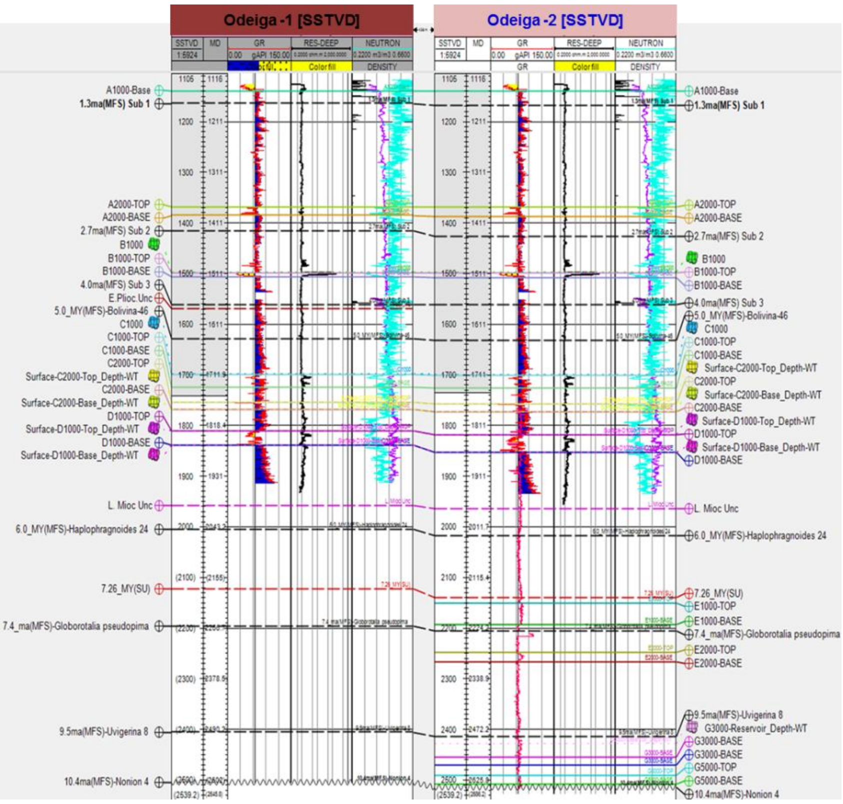


Figure 9: Odeiga Well correlation panel with integration of biostratigraphic and seismic data

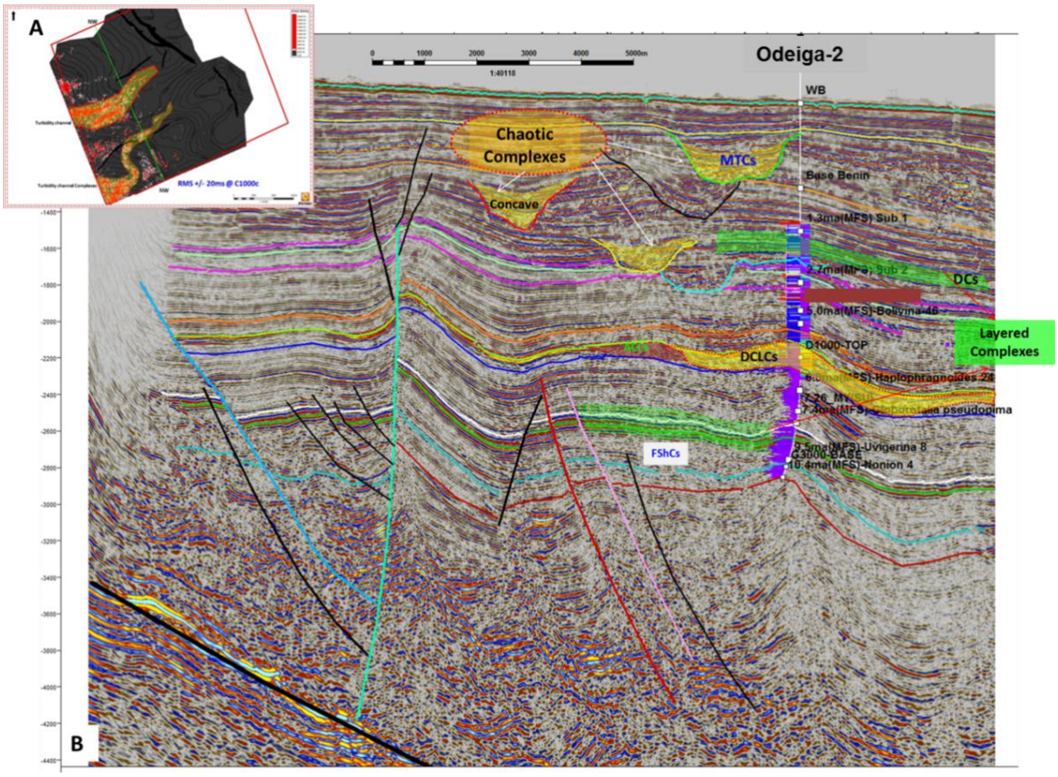


Figure 10: Seismic line through well Kofima-2 used for well-seismic calibration showing several mapped horizons and well tops

Present and Paleo-Fairway analysis: Sand Prediction at prospect scale from 3D seismic data falls under the 3rd order cycles [30]. The above mentioned small-scale sequences and their respective log motifs were correlated to specific seismic reflection patterns. The spatial variations in seismic attributes such as amplitude and frequency and other specialized geophysical attributes were used to determine the sand provenance and supply. This transportation goes through specific routes (fairways) and adopts unique morphology as they are mobilized into the offshore depobelt of the Niger Delta.

A good understanding of the type of sand bodies in the study area is premised on one of the basic principles/laws of geology which states that the present is the key to the past and vice versa. The present day ocean floor analysis fairway analysis result is a pointer to what had happened in the past (older stratigraphic sequences).

A 2D view of the ocean floor morphology (Bathymetry column) and sand architecture (Facies distribution) is as shown in figure 11. It has been mentioned earlier the seismo-facies associated with them were validated by well to seismic match of the drilled interval.

However, it is important to note that we must not be in a forced regression with its characteristic erosion and valley incision for sands to get into the deep offshore. Reservoir sands mainly travel through turbidity current into the slope and ocean basin floor [30].

The Paleo sand fairway map of C1000 reservoir was done with the aid of RMS amplitude map and it reveals the switch of turbidity channel axis around the north west corner of the study area further south and the central Fan/Sheet complex having a change in its geometry indicating evolution through time of the fan/sheet complex (Figure 12).

The time grids interpreted from seismic horizons were used to generate time structure maps using some algorithms (e.g. the minimum curvature gridding). The surface calculator in the software was used to generate time structure maps honouring all digitized fault cut-offs (figure 13). The time-depth (TZ) survey (figure 14) from Odeiga-2 was used to generate a polynomial function for depth conversion of all the mapped faults and horizons of interest. These depth maps generated (figure 15) were later calibrated with lithology tops encountered by the wells to enhance the accuracy of the depth structure maps, which is used afterwards for building 3D structural framework model.

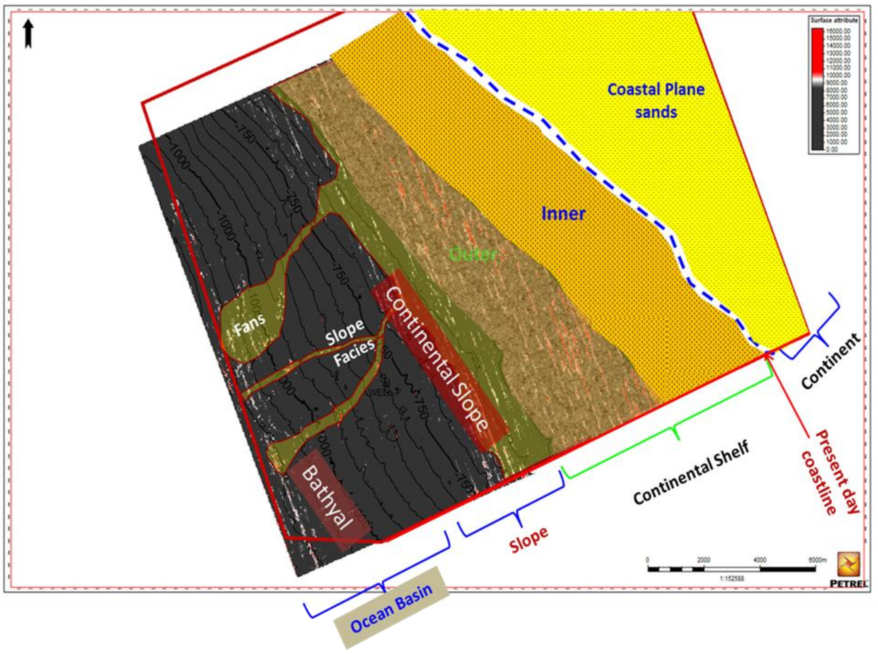


Figure 11: Present day Ocean Bottom architecture and sand fairway map using RMS amplitude technique.

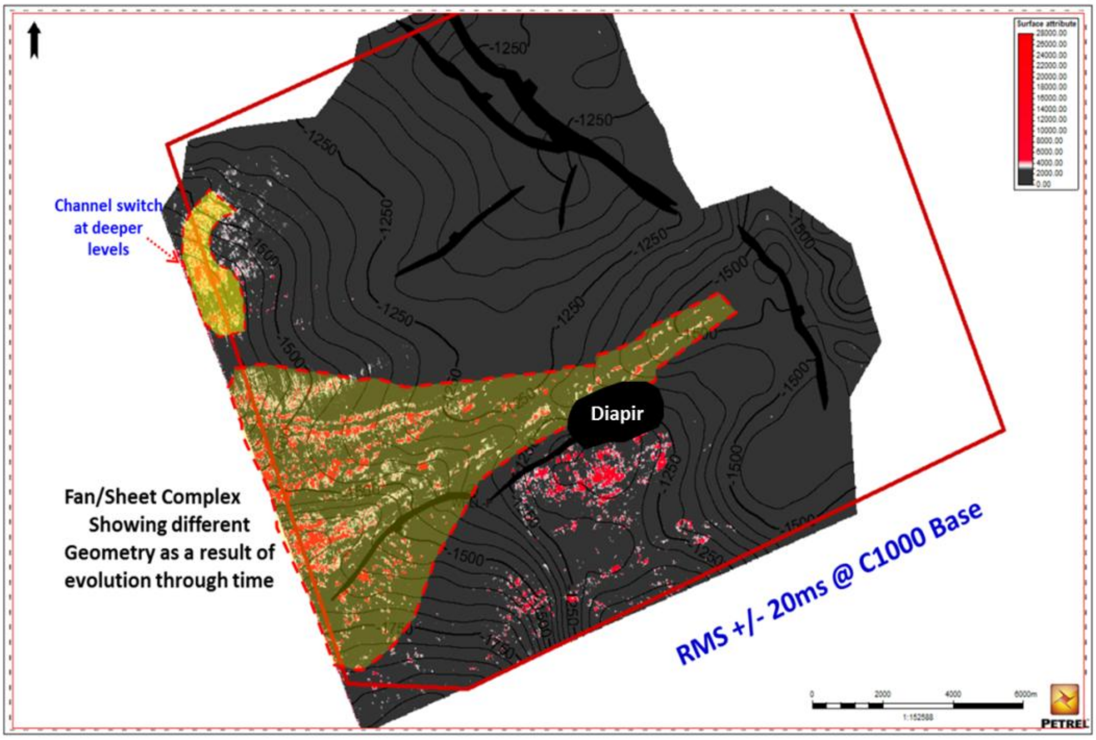


Figure 12: Paleo-fairway map of C1000 reservoir using RMS amplitude technique showing a channel with its axis switching.

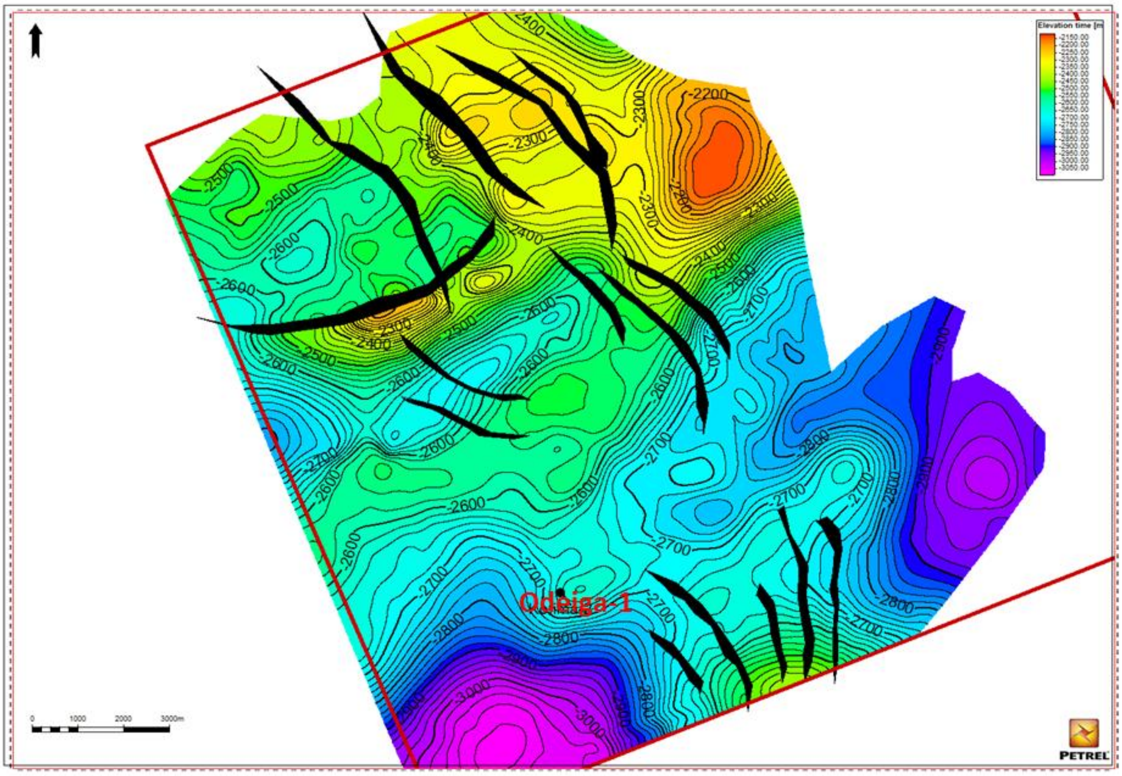


Figure 13: Time Map Top H3000 Reservoir

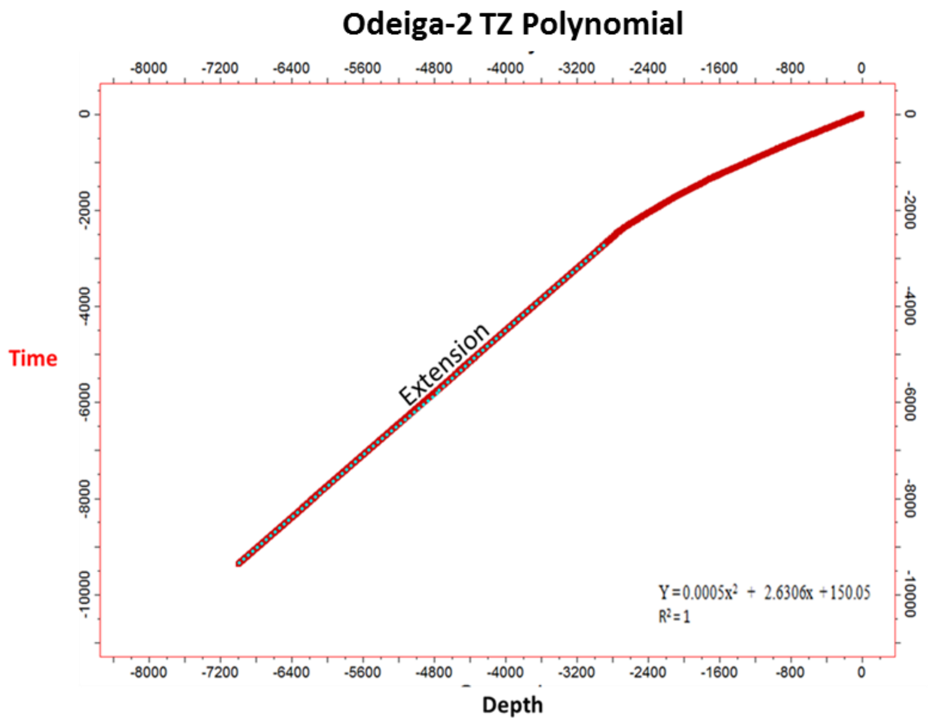


Figure 14: Time-Depth curve generated from checkshot and extended with the Polynomial function represented by Y.

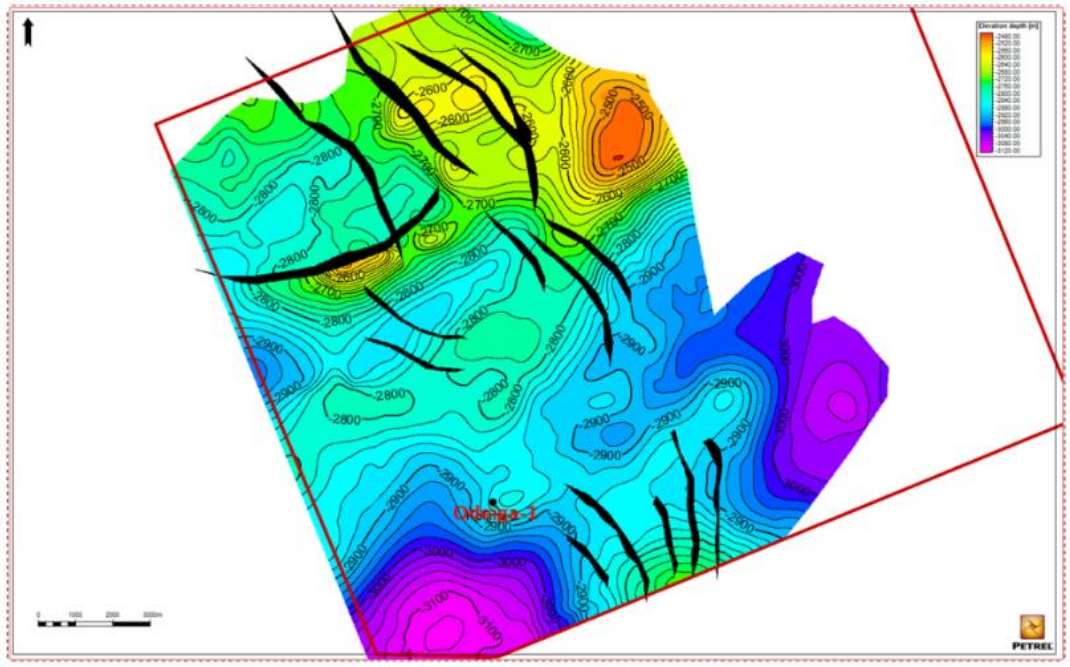


Figure 15: Depth Map Top H3000 Reservoir

Results and Discussion

Structural: This section presents various results from different aspects of this research. A 3D model was built with quality controlled faults, horizon and depth maps. It was observed that the growth fault (F_1) had a strong influence in the evolution of the shale diapir as shown in figure 16. This mud diapir was found to have associated radial fault (F_2) propagated from the epicentre if the diapir. It was also modelled in the structural framework as it had interface with the reservoir trap configuration. The shale gouge ratio (SGR) which has a threshold value of 0.25 for fault to seal in the Niger delta [31] it also matches with the range needed for the fault

(F_2) interface with the mud diapir and reservoir to retain hydrocarbon. Figure 17 shows the 3D SGR model of fault (F_2) with the footwall hanging wall cut-off (known as Allan diagram).Walsh *et. al.*, (1998) simply defined SGR as fault zone composition. It is a reliable fault seal attribute also used for predicting hydrocarbon column heights. It has been tested and proven in a wide range of siliciclastic basins like the Gulf of Mexico, North Sea and Niger Delta. Filbrandt *et. al.*, (2007) [31] defined effective SGR (weak point SGR) as the lowest SGR value capable of supporting the shortest column around the shallowest depth of a closure. Yielding *et. al.*, (1999) established SGR threshold value of 0.25 – 0.35 for Niger Delta and Gulf of Mexico faults (figure 17) [32].

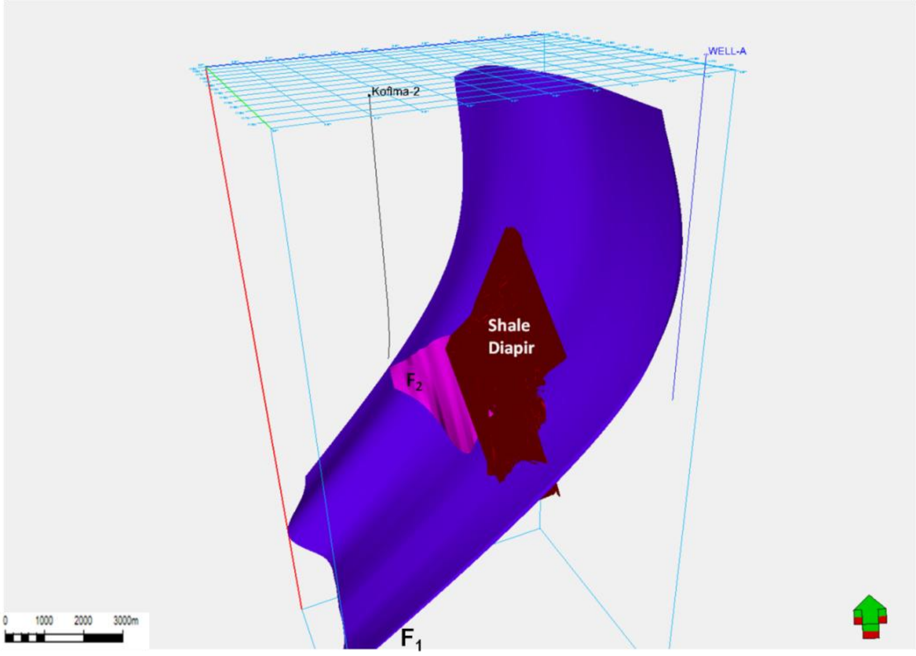


Figure 16: A 3D model of Shale Diapir with the major regional growth fault (F_1) and splay fault (F_2)

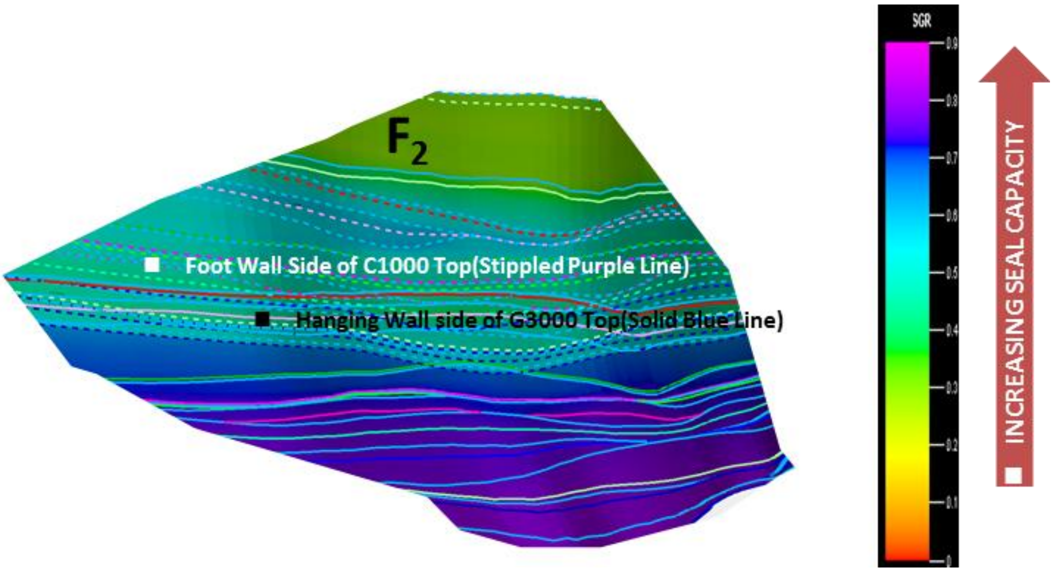


Figure 17: A 3D model of SGR on splay fault (F_2) within the combination trap vicinity with footwall-hanging wall cut-offs (Allan, 1989)

Stratigraphic: The results of the high resolution biostratigraphic analyses done classify the studied interval as NN11 to Recent (Calcareous Nanno-fossil). This is also equivalent to F9600 to F9900 (Foraminifera) in the Niger Delta Chronostratigraphic chart which puts the absolute age of the study interval at 10.4ma (million years) to Recent. This falls within the Late Miocene to Recent (the. present day ocean bottom sediments).In Odeiga block eight (8) maximum flooding surfaces (MFSs) subdivide the sediments into seven Genetic Stratigraphic Sequences (MFS to MFS). These were picked in the marine shales sequences overlying some sand tops as tested by Odeiga-2 well and are dated (Absolute age) as follows:

- 1.3ma (MFS) Un-named
- 2.7ma (MFS) Un-named
- 4.0ma (MFS) Un-named
- 5.0ma (MFS) *Bolivina 46*
- 6.0ma (MFS) *Globoquadrinadehiscens*
- 7.4ma (MFS) *Globorotaliapseudopima*
- 9.5ma (MFS) *Uvigerina 8*
- 10.4ma (MFS) *Nonion 4*

Hydrocarbon Migration and Entrapment Model

The Hydrocarbon distribution pattern in this block could be deduced from the proven resources as tested by drilled wells in the block (Odeiga 1 & 2) which are hydrocarbon bearing. They are located on structural highs (Anticlines) favoured by sand fairways presence (figure 12). Also, the source rock abundance and presence of migration pathways through the small faults increases the geological chance of success. A model modified after [33] is presented below that relates faults to migration and entrapment of Hydrocarbon. The basic assumption of the model is that a fault is neither a seal nor a conduit. Therefore, the effect of faulting on both migration and entrapment depends on the rock properties of strata juxtaposed by the fault and on the structural attitude of the juxtaposed fault blocks. Fault-plane sections used with structure maps (figure 18) give a two-dimensional view of migration and trapping, and they illustrate the interplay of some critical elements (figure 19).

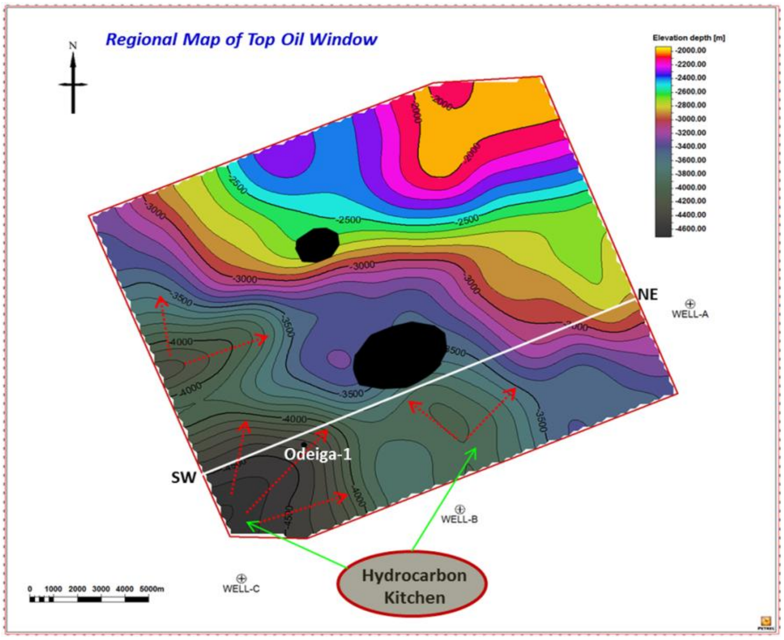


Figure 18: Regional Map of Top Oil generation window

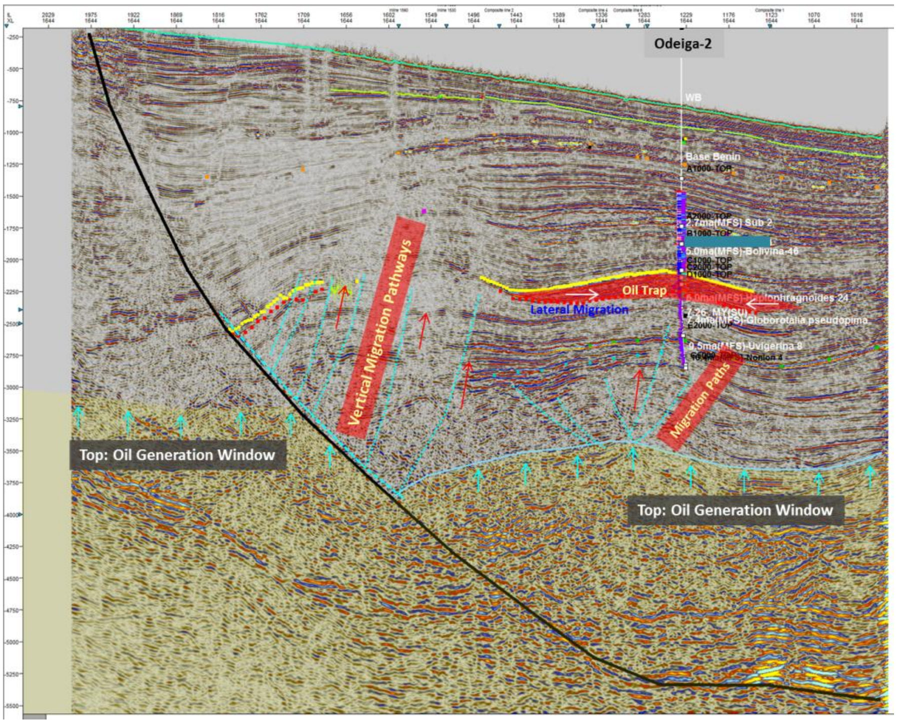


Figure 19: A 2D model of hydrocarbon migration and entrapment

Hydrocarbon Entrapment (3D) Model

The area surrounding the shale diapir is uplifted because of the forceful piercing of the shallower layers by the intrusion. It is also noteworthy that these shale diapirs are highly impervious which supports lateral seal of hydrocarbon [34]. The main concern is the attendant risk of high pressures that may be associated with them. A target specific processed seismic volume like the PSDM mitigates the stratal inclination uncertainty towards the diapir and hence reduces the risk of drilling amiss.

Therefore, a 3D structural model of the entire trapping elements was built to determining the interfaces between them. This is aimed at building a high integrity hydrocarbon entrapment model. These models were built independently for each of the three reservoir levels, for firm control on each in relation to the sealing efficiency of the diapir. Figure 20 below is a 3D entrapment model for C1000 and C2000, which is an example of one of the three reservoir zones modelled. This conforms structurally to the high confidence model of a petroleum trap. The figure also shows the Structural Spill point in a 3D view running parallel to the contours. The crest of the structure hinging (terminates) on the mud diapir-1. The reservoirs are stacked (C1000 and C2000) but they coalesce towards the hinder part of the shale diapir. This brings the two reservoirs into communication which would make them have same pressure regime. The resultant common hydrocarbon spill point is also clearly seen Figure 20.

Summary and Conclusion

Detailed seismic interpretation had been instrumental to definition of the geometry of subsurface structures (faults, folds and diapir) that exist in the Odeiga block. Sediment heterogeneity and structural Controls under disequilibrium compaction led to subsidence and mini-depocenter evolution in Odeiga block. Mud diapirism mostly triggers dipping of beds away from its orifice thereby creating accommodation space for sediments to settle around its flanks this resultantly leads to submarine channel switching its axis as the uplifted zones obstructs the sand fairway. Hydrocarbon entrapment in Odeiga block was favoured by the impervious nature of the shale diapir and high SGR of the adjoining fault planes

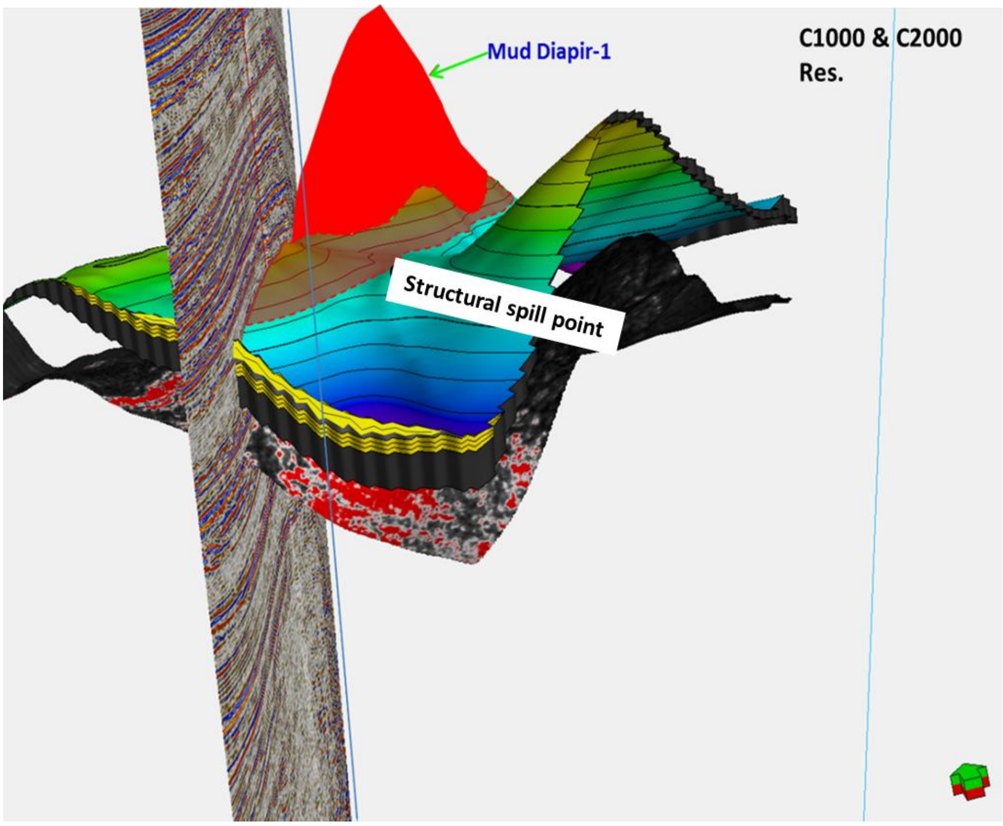


Figure 20: A Three dimensional (3D) Hydrocarbon Entrapment Model of reservoir against shale diapir with structural spill point

The mapping, interpretation and calibration of seismic data with wells data helped define key stratigraphic surfaces and in turn showed the origin and evolution of these diapirs. Faults and horizon mapping and conceptual model building in Odeiga block helped define the subsurface structures and shale diapirism was seen to be pre-depositional at shallower intervals where it was found to have significant control on sedimentation and sand fairway switching. The geological impact of these diapirs on structure formation, hydrocarbon migration and entrapment was also be ascertained.

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