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Research Article

Evidence of Episodicity of Shale diapirism in 'Kofima Block' Gulf of Guinea offshore Nigeria

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Abstract This paper investigated episodicity of shale diapirism in 'Kofima Field' as it relates to evolution of the mini-basins and reservoir development around it. The data used include a 3D Pre-stack depth migration (PSDM) seismic volume, two wells Kofima-1 and Kofim-2 with a biostratigraphic summary. Seismic mapping revealed: mass transport, turbidity channel and amalgamated channel and facies. Structural features: folding, faulting and mud-diapirism was also been mapped in detail. Paleo-fairway map of sands were generated with the aid of co-blended seismic attributes premised on well results and it was observed that the shale intrusion impacted on channel switching. The evolutionary trend of these mud-diapirs through time were also interpreted and dated and found to occur between 12.8 to 7.4ma MFS. Faulting and re-activation of diapirs was discovered to be as a result of gravity tectonics and abundance of undercompacted shales. Three episodes of shale diapirism occur in the block as interpreted and a simplistic model has been built for better understanding of its configuration.

Keywords Episodicity, Shale diapirism, Paleo-fairway map, Faulting and Re-activation of diapirs.

Introduction

The word diapirism is simply defined as the existence of diapirs or the process that generates diapirs. The word diapir is a French word from Greek called '*diapeirein*' which means to pierce through. Diapir is therefore a type of geologic intrusion in which a more mobile and ductile deformable material is forced into brittle overlying rocks. Recently, some developments and new techniques for deep-water exploration led to the understanding that many continental margins are shaped by deformation processes connected with a mobile substratum [1]. Overpressure can be generated either 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. Furthermore, Osborne and Swarbrick (1997) also 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 episodic because overpressure conditions can change through time. Vendeville (2005) [3] as cited by Judd and Hovland (2007) [4] gave an example that episodic loss of fluids from the deforming mass can reduce the overpressure, strengthening the fluid-sediment mixture and temporarily halting mud movement. There are two major types of diapirism namely Salt diapirism and Shale diapirism (figure 1). The purpose of this paper is to analyse diapirism and its architectural characterization by studying the relationships between structural features (growth faulting and diapir evolution) and how it impacts sedimentation and reservoir development. The concept adopted for the realization of the set objectives include: (a) review of global occurrence of diapirism (salt and shale). (b) carry-out analyses on the structural interplay of these diapirs side by side its evolution and how it relates to the shale diapir geometry. Also, it is important to note that salt diapirs mostly originate from restricted marine basin which encourages salt precipitation as against shale that occurs more in unrestricted high detrital, rapid sedimentation basins that disallows significant salt precipitation. 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.

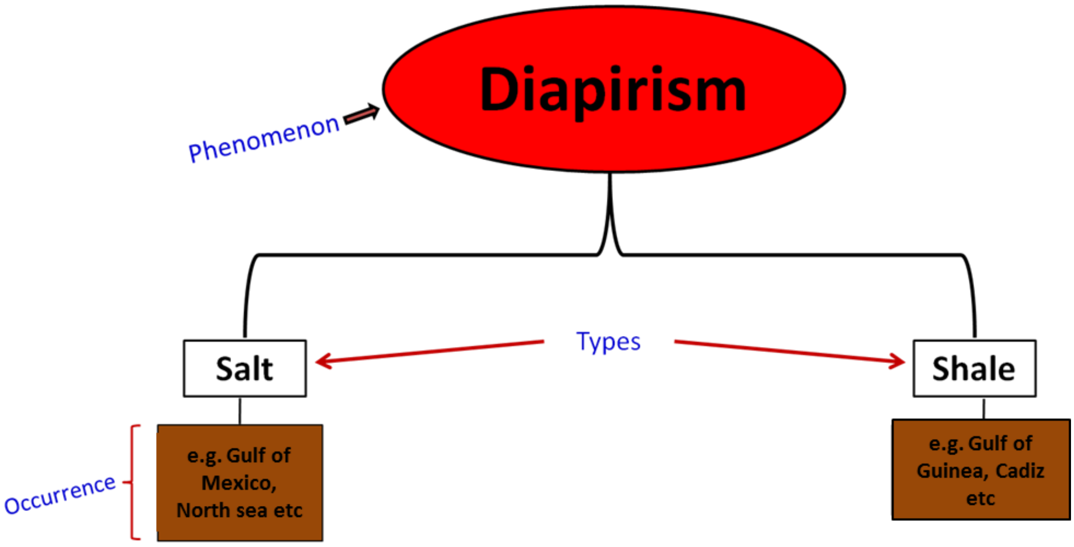


Figure 1: Diapirism, two major types and regions of dominance

Furthermore, Salt and Shale diapirs are impervious so any case of truncation of the steeply dipping reservoir sands by these intrusions, will add-up to the trapping elements. The episodic nature of shale diapirism as seen in a seismic section in gulf of Cadiz, Europe and illustrated by Somoza and Pinheiro (2002) [5] is insightful. The figure shows reservoir development at its flanks as the upwelling encourages channel switching and sand deposition around the mini-basins that forms close to the orifice of the mud plugs (figure 2).

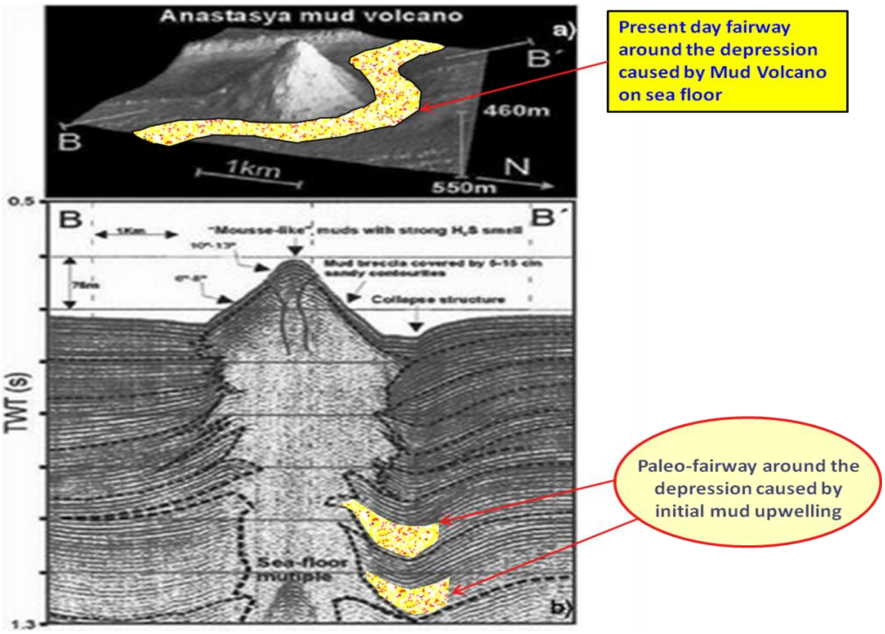


Figure 2: (a) & (b) Anastasya mud volcano. (a) Topography from multibeam bathymetry, showing the surrounding collapse moat around the mud vulcano. (b) High-resolution seismic profiles of several mud volcano in the Tasyo field with typical chrismas tree, indicative of multiple episode in mud volcanicity.[5]

The study area is located in the Niger Delta basin, within the Gulf of Guinea, in the western part of the African continent. It straddles the extensional and transitional zones in the offshore Depobelt (Figure 3). This study corroborates efforts of earlier workers in this area by evaluating the influence of structural features (growth faulting and shale diapirism) on depositional processes, sedimentation, stratigraphy, reservoir-facies distribution and architecture. A better understanding of their configuration is key to successful exploration of structures around these diapirs in the study area and other deep-water regions with related features.

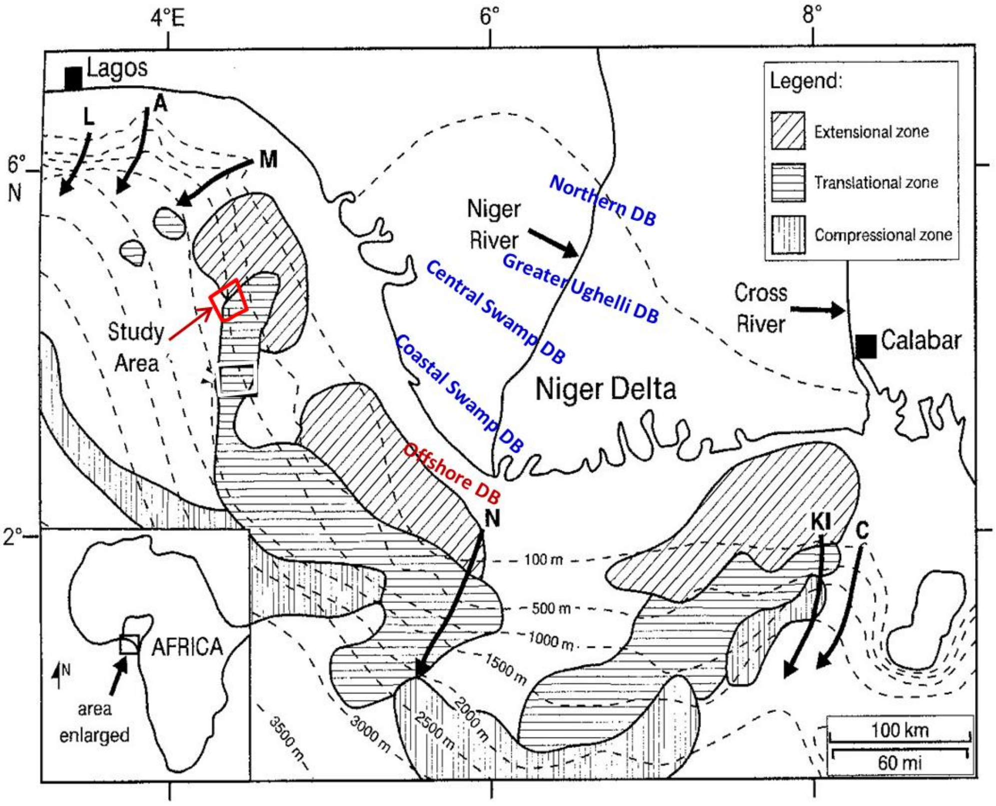


Figure 3: Niger delta basin showing bathymetry, zones of gravity tectonic structural style, depocenter sand modern submarine canyons (modified after Knox and Omatsola, 1989; Damuth, 1994) [6-7].Thick arrows show submarine canyons. L–Lagos; A –Avon; M – Mahin; N – Niger; KI–Kwa Ibo; and C– Calabar. The red box is the study area.

Geological Setting

The 'Kofima Block' is located within the offshore depobelt, of the Niger Delta Basin. It straddles the extensional and the transitional zones (figure 3). The Niger delta started building out into the Gulf of Guinea in the Eocene and has continued to do so till Present [8]. The Eocene to Quaternary stratigraphic succession comprises a wedge of clastic sediments, which is some 12km-thick at the thickest portion. This essentially regressive clastic wedge is subdivided lithostratigraphically into three units viz: 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) [9-10]. These sediments are debouching into the Atlantic Ocean in a deltaic setting [11]. The early origins of the position of the Niger Delta and the closely related Benue Trough can be traced back to rifting at a Rift-Rift-Rift (RRR) triple junction in the area defined by the present position of the Gulf of Guinea, which eventually led to the separation of the South American and African plates during the late Jurassic[12]. 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 Palaeocene 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 [12]. The growth faults in the Niger Delta region can be seen on seismic (figure 4) 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 or beyond 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 4 A and B below [13-14]. 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 interbedded shale within the Agbada Formation [15].

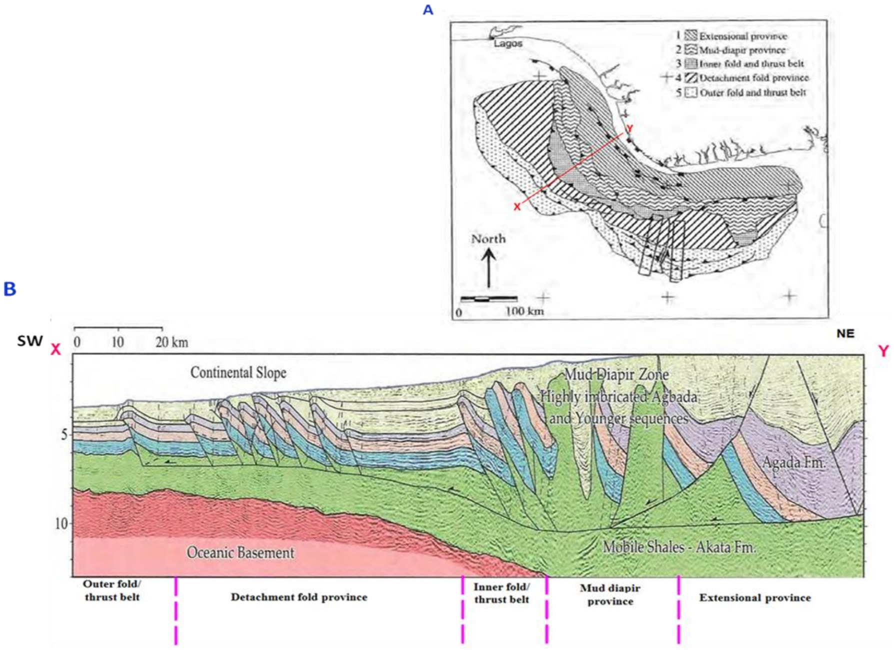


Figure 4: (A) Cross sectional Map of southern Nigeria showing regional tectonic groups (B) 2D seismic dip line with structures associated with the five tectonic provinces in the Niger delta (modified after Corredor et al. 2005) [14]

Materials and Methods

The data set used for this research includes 3-D seismic volume, wire-line logs, high resolution biostratigraphic data, T-Z profile, pressure and temperature data. The Chart below (figure 5) is a summary of the workflow adopted for this research, which highlights all the work done in a concise sequence.

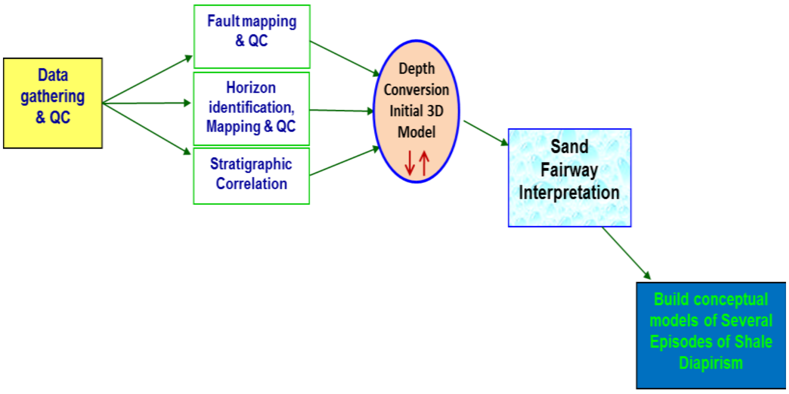
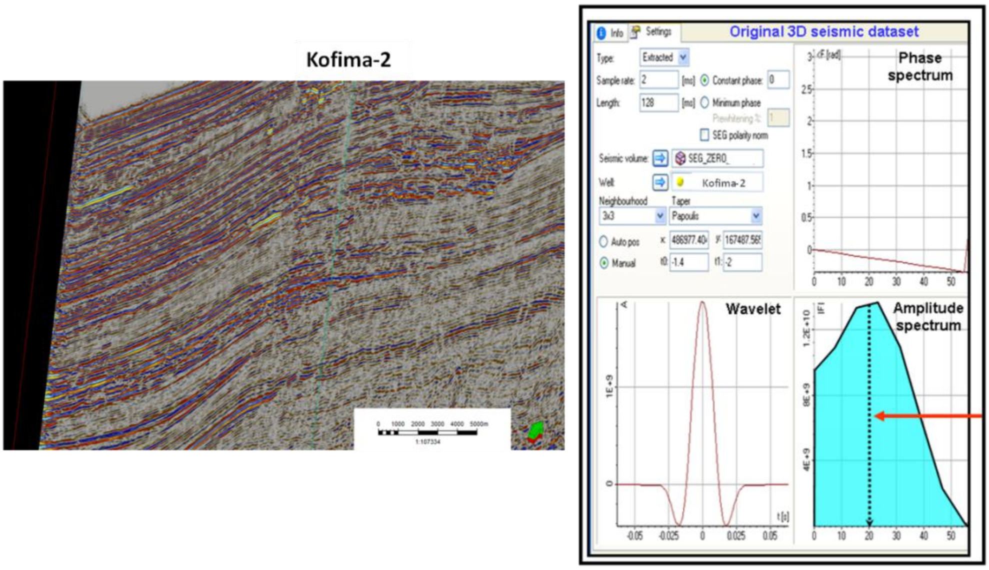


Figure 5: Methodology / Workflow Chart

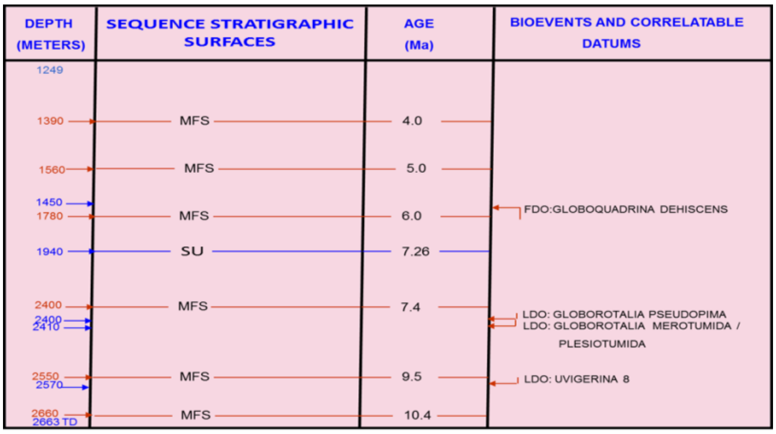
A 3D seismic data with reflectivity –zero phased (RZP), Pre-stack depth migration (PSDM) was used as it had better resolution and improves the spatial positioning (dipping) of seismic reflections. The entire area is about 400 square kilometres with 2,100 in-lines and 1,900 crosslines acquired with 25m by 25m bin size (see other details in figure 6).



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

Figure 6: A Zero Phased Seismic data with maximum amplitude coinciding with Lithologic interface (top)

The summary of high resolution biostratigraphic analysis carried out on Kofima -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) [17] was the scheme adopted for the calcareous Nano-fossil classification. The Palynological analysis done included the classification of the flora into Sub-series (Late Miocene), Germeraad *et al.* (1968) [17], Zone *(Echitricolporites Spinosus)*, Evamy *et al* (1978) [18] broke it down to the smallest units known as the 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 Kofima-1 and 2. The Kofima-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 this geology with geophysical data helped enhance output of Seismic to well calibration (Figure 8).



DEPTH (METERS)	SEQUENCE STRATIGRAPHIC SURFACES	AGE (Ma)	BIOEVENTS AND CORRELATABLE DATUMS
1249			
1390	MFS	4.0	
1560	MFS	5.0	
1450 1780	MFS	6.0	FDO:GLOBOQUADRINA DEHISCENS
1940	SU	7.26	
2400	MFS	7.4	
2400 2410			LDO: GLOBOROTALIA PSEUDOPIMA LDO: GLOBOROTALIA MEROTUMIDA / PLESIOTUMIDA
2550 2570	MFS	9.5	LDO: UVIGERINA 8
2660 2663 TD	MFS	10.4	

Figure 7: Mapable sequence stratigraphic surfaces in Kofima block, stratigraphic markers and associated age

The faults were mapped in detail every ten (10) in-lines and also crosslines depending on the dipping and orientation of the fault to ensure that none of the faults were left out. The semblance slice (an amplitude contrast seismic volume) aided the final QC of mapped faults. After which the key marker horizons identified from well to seismic-tie were mapped see Figure 7.

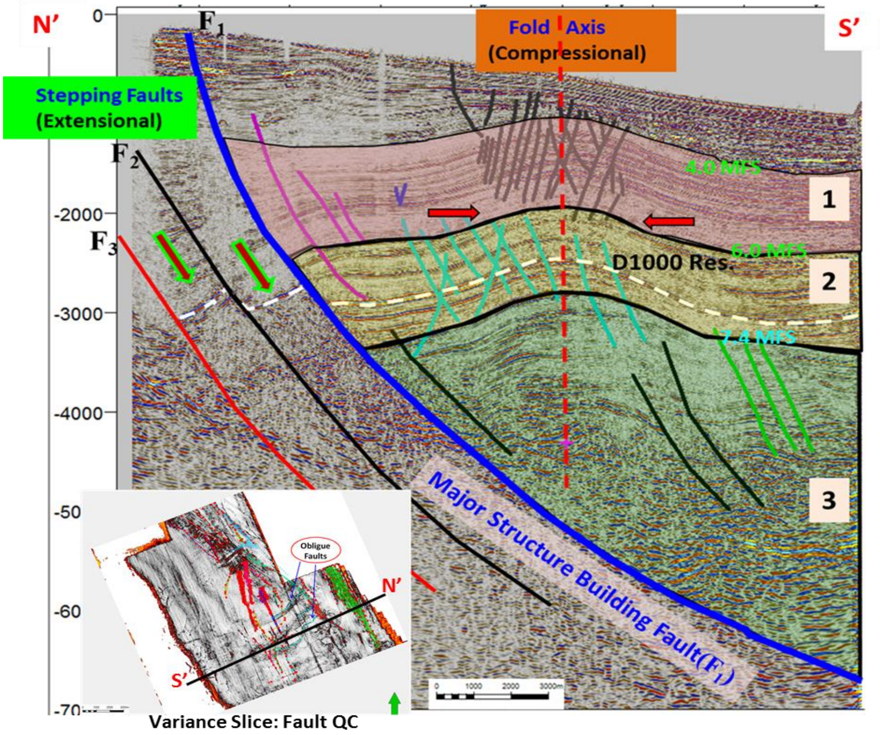


Figure 8: Seismic Dipline N'- S' showing the three major faults F_1, F_2, and F_3 Insert variance slice for fault QC and Interpreted horizons indicating Folding

The major seismic reflections transparent packs that coincided with the major flooding events from the well-seismic tie done have been delineated and the MFSs mapped. The figure 9 below shows a seismic section through Well Kofima-2 with details of the data (logs, deviation survey, well tops and key stratigraphic markers) faults mapped and Horizons for well - seismic calibration.

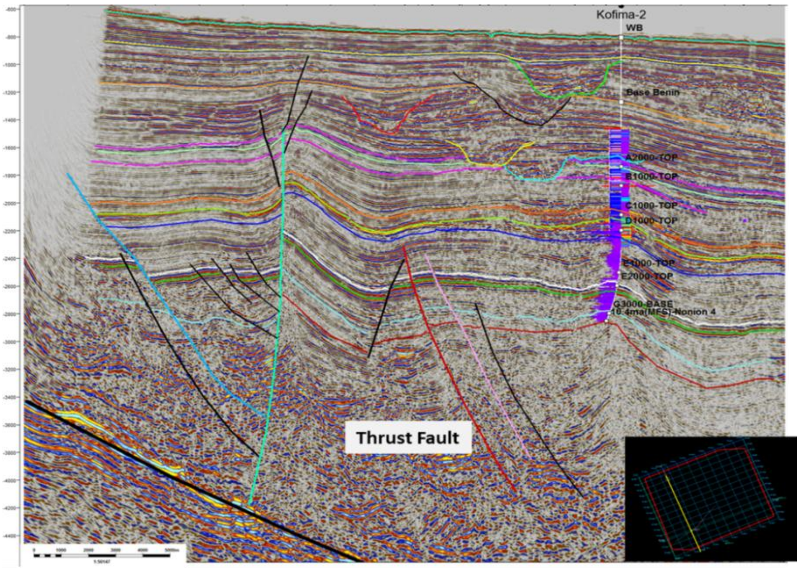


Figure 9: Seismic line through well Kofima-2 used for well-seismic calibration showing several mapped (14) horizons and well tops

The time grids interpreted from seismic horizons were used to generate time structure maps by using some mapping algorithms (e.g. minimum curvature gridding). The surface calculator in the software was used to generate time structure maps which were in turn converted to depth using the extended T-Z curve (figures 10, 11 and 12 respectively).

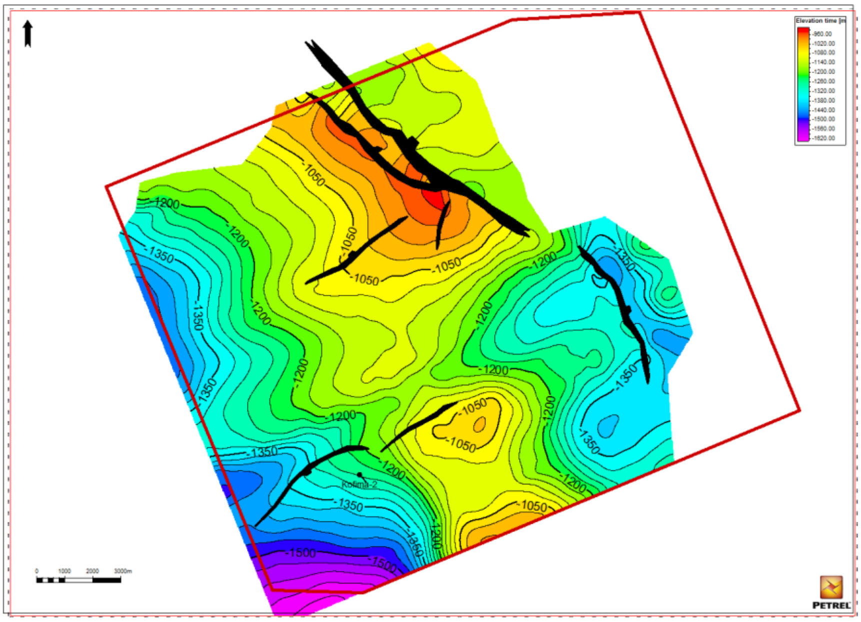


Figure 10: Time structure map of WB from auto-track of the very strong reflection with gradational time low in the NE-SW direction

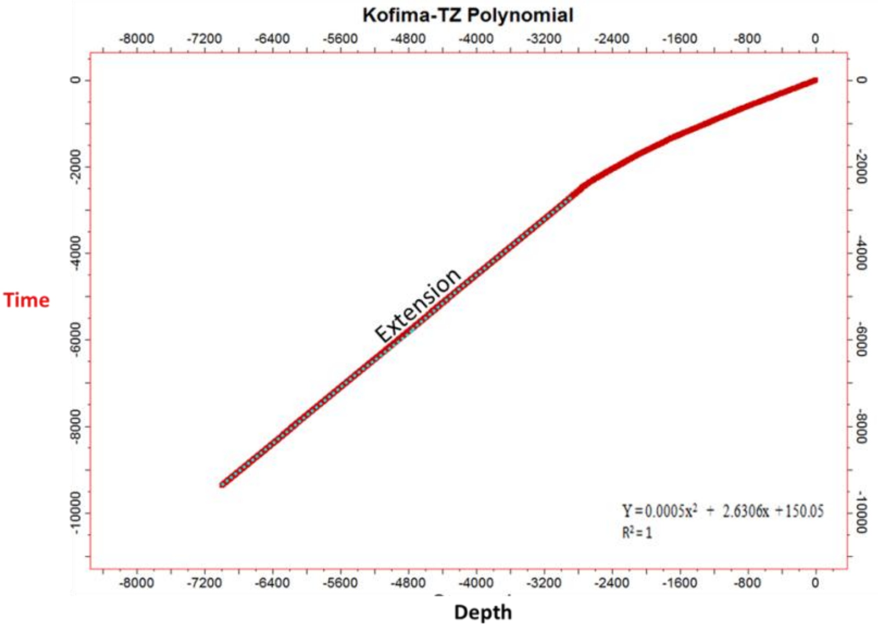


Figure 11: Extended Time-Depth (TZ) Curve of Kofima-2 well check shot

The time (T) - depth survey of well Kofima 2 (Checkshot) was used for depth (Z) conversion of faults and horizons interpreted before modelling. A polynomial curve was generated and used to extend the T-Z curve to cover the deepest seismic events mapped. Pressure and Temperature Data from the well was also incorporated to understand the pressure regime of the block.

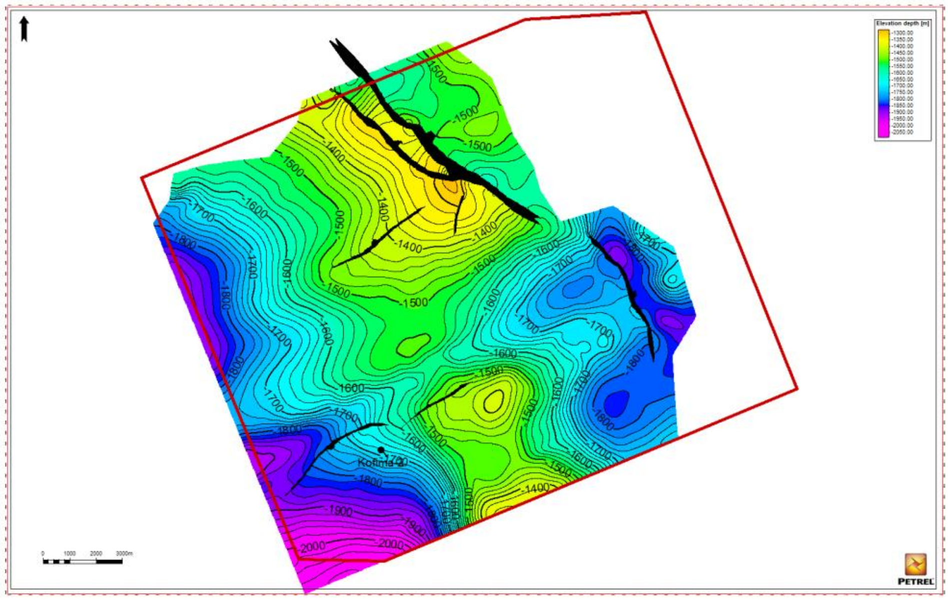


Figure 12: Depth Structure Map Top C1000 Reservoir

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 13. This mud diapir resultantly had influence on sand fairway switching as seen in figure 14.

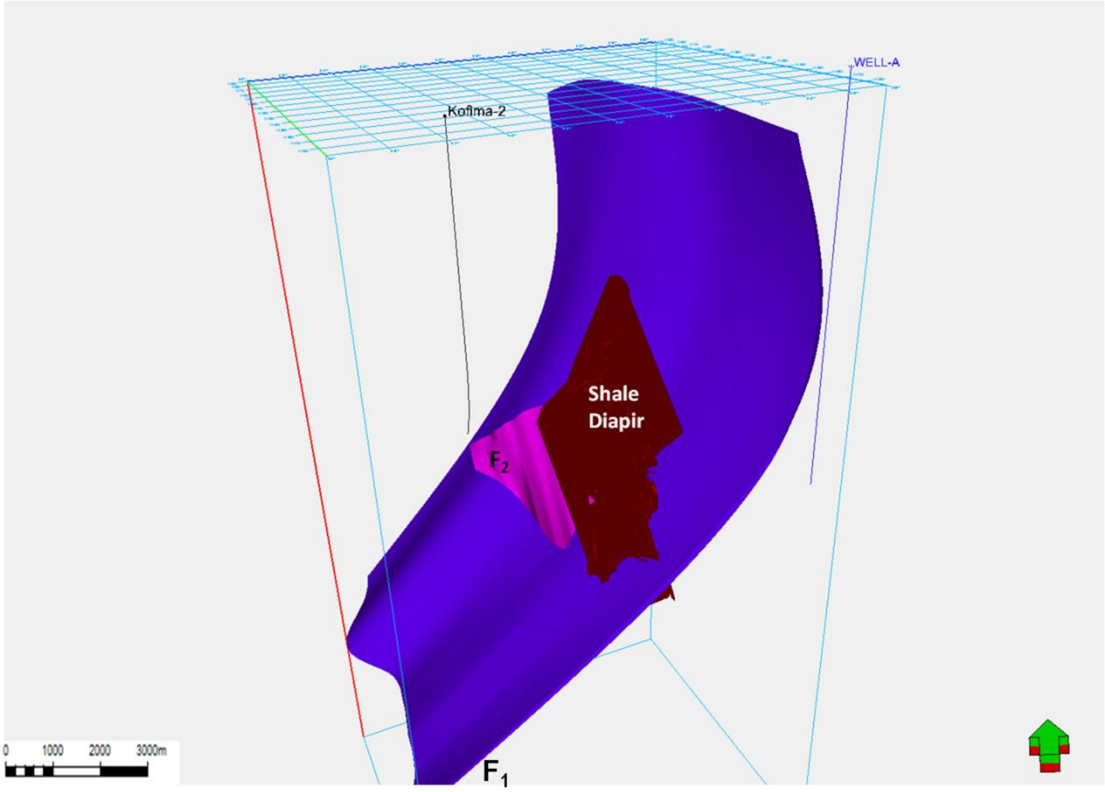


***Figure 13**: 3D modelling of Shale Diapir with the major regional growth fault (F_1) and splay fault (F_2)*

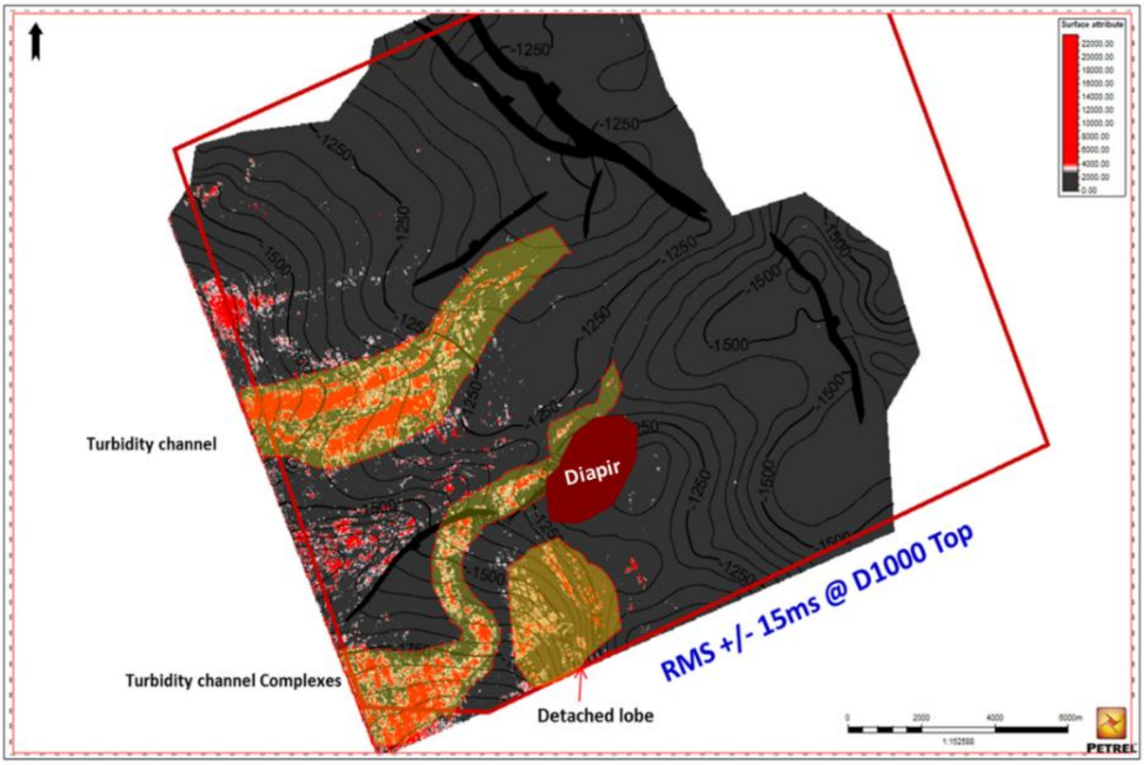


Figure 14: A 2D model of Shale Diapir with Sand fairway of the D1000 Reservoir showing channel switching

Stratigraphic: The results of the Foraminifera zonation were from the abundance and diversity chart of the various fauna analysed. These classify the studied interval as N17 to Recent. This is equivalent to F9600 to F9900 in the Niger Delta Chronostratigraphic chart. This also puts the absolute age of the study interval at 10.4ma (million years) to Recent. This falls within the Late Miocene to Recent (i.e. present day ocean bottom sediments).

Shale Diapir Evolutionary Episodes

Detailed seismic interpretation and calibration with well results showed that the transparent packs are equivalent to major marine flooding events which is subsequently followed by rapid sedimentation and layering of denser facies on the fluidized, overpressured shales. The enhanced 3D seismic co-blended volume interpreted also brought out the geometries and the point sources of the injection of these pressured muds. The major sources of these shales are deep seated, confirming their Akata (deep marine shale) Origin. The associated down to basin growth faults is indicative of the extensional zone been the primary source of shale diapir evolution [19]. The enhanced seismic attribute volume also affirms this position as shown in figure 15. However, the interplay between base level rise and fall which resultantly created several sequence cycles [20], marine flooding typical of the Agbada (lower) formation created some pressured shales injected into the initial diapir column which lead to its growth through time. This is the situation in this block in the Niger Delta basin and corroborates the episodic (Christmas tree) diapir of Tasyo field in gulf of Cadiz, Europe. In this field Somoza and Pinheiro (2002), reached a conclusion after interpretation of high resolution seismic profile [5]. This typical christmas tree is indicative of multiple pulse in mud volcanic activity (figure 4). The seismic section below is a dipline in NE-SW direction. It shows the Episode-1 of the diapir evolution. From results of the high resolution biostratigraphic analysis it is adjudged to evolve from the oldest known shale of the area (the Akata marine Shales). This shale at some time was a detatchment surface. The shale is older than the deepest drilled stratigraphy (The *Nonion 4* Stratigraphic marker dated as 10.4ma MFS) as evidenced on seismic. The 2D seismic profile showing point source, evolution and geometry of the shale diapir is as shown in figure 15 below.

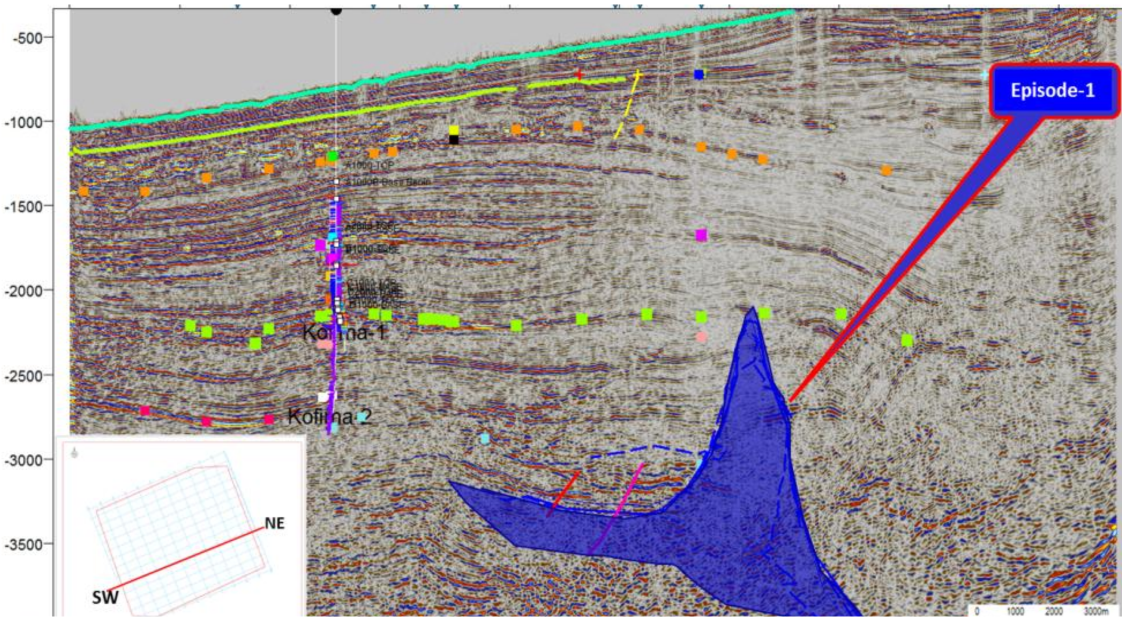


Figure 15: 2D Seismic profile of Episode-1 of the mud diapirism along dipline showing the geometry and magnitude of the shale intrusion

The seismic section below is also a dipline in NE-SW direction. That shows the Episode-2 of the diapir evolution. From results of the high resolution biostratigraphic analysis the fluidized shale bed is from the maximum flooding event dated 9.5ma MFS marked by the *Uvigerina 8* which coincides to the Lower Agbada shales. It is the second depest drilled flooding event in this area. This shale at a time was undercompacted deposit and was later overlain by more matrix rich sediments. The 2D seismic profile of the point source and geometry of this shale diapir is as shown in figure 16.

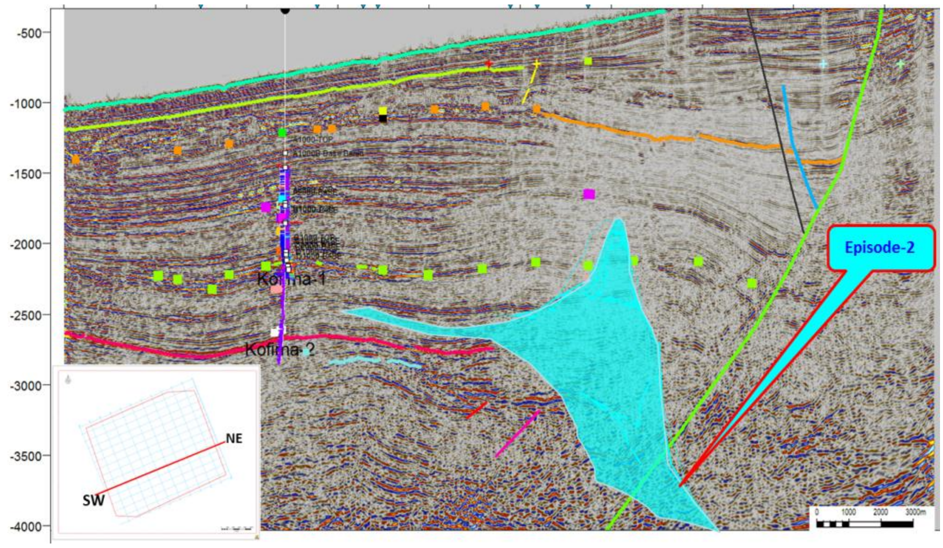


Figure 16: A 2D Seismic profile of Episode-2 of the mud diapirism along Dipline showing the geometry and magnitude of shale intrusion

The seismic section below is a dipline as well oriented in the NE-SW direction. It shows the Episode-3 of the diapir evolution. The high resolution biostratigraphic analysis carried out puts the fluidized shale bed as a maximum flooding event dated 7.4ma MFS marked by the *Globorotalia pseudopima* which also belongs to the Lower Agbada shales. It is the third depest drilled flooding surface to the well TD of Kofima-2. This shale at a point in time was overpresured shale because of rapid sedimentation that befell it during the succeding

Highstand and Lowstand systems tract sediments build-out into the deep ocean . The seismic profile showing the origin and geometry of this shale diapir in 2D is as shown in figure 17.

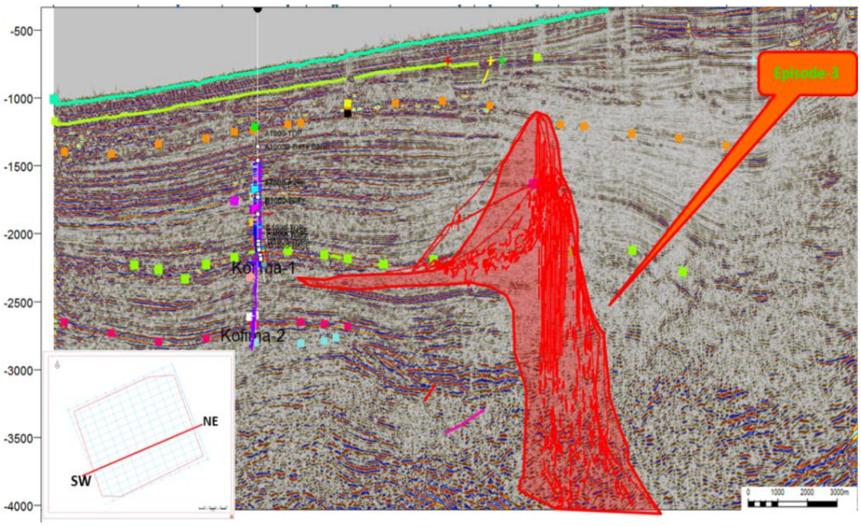


Figure 17: 2D Seismic profile of Episode-3 of the mud diapirism along Dipline showing the geometry and magnitude of shale intrusion

The seismic section below is also a dipline in NE-SW direction. It shows the composite of the shale diapirsm (Episode 1, 2, & 3) of the diapir evolution. An integration of the three is rather seamless as the Shale rheology were similar and did not show much of a difference in amplitude contrast which ensured that all of them had similar sub-transparent signature (that is faint seismic amplitude) The combined 2D seismic profiling of the three different layered sources of the shale diapir and their geometry is as shown in figure 19 below. From this dipline it was observed that the diapir root is more extensive a little way off the regional growth fault trendline. It tappers out basinward as clearly seen then plunges towards the depocenter of the growth fault, just around the rollover anticline's limb. A sharp contrast exists between the geometry of ths diapir along dip from strike as the strike seems to always have a clearer-cut stratal termination against the shale diapir plug(s). From the 2D model of these three different episodes with a high resolution biostratigraphic analysis of Kofima-2 well shown on the seismic section (figure 18) brings us to the following conclusion: Episode -1 evolved from the top of Akata shales as the rapid Agbada sequences was been deposited on top and it is the most extensive, while episodes 2 & 3 evolved from the thick lower Agbada Shales and are less extensive.

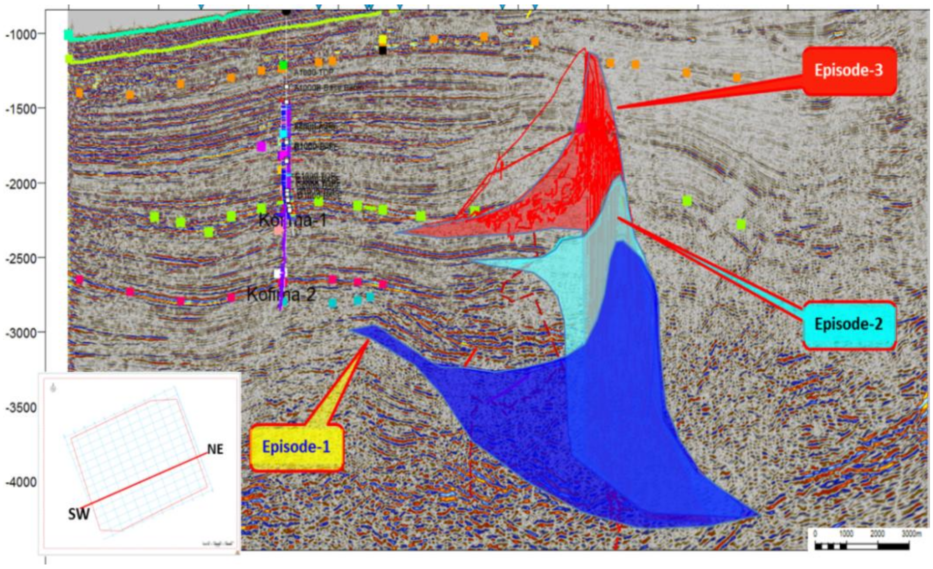


Figure 18: 2D Seismic profile of the composite Episodes (1, 2, & 3) of the shale diapirism along Seismic Dipline showing the geometry of each of them stacked together

An arbitrary seismic section (see insert basemap) was taken relatively along stike in NNW-SSE direction. It shows fully coalesced shale diapirs. Diapir-1 is withing the Southeast and the other in the Northwest areas of the base map. This figure 20 shows the major down to basin faults mapped and the piercement structures evolving from their base and grows right within the weak zones of these faults through time up to 2.7ma MFS. This confirms the fact that it aided the evolution of the diapirs. The various episodes is not distinct here because they have all coalesced as a unit plug. The 2D seismic profiling of the origin and geometry of the shale diapirs is as shown in figure 20 below. The fault that created the weak zones were also mapped as displayed. A few of the seismic horizons mapped are on display for a good understanding of the stratigraphic relationship between the trio; Faults, Diapirs and Strata. Figure 15 above shows switching of the submarine channel at D1000 reservoir. This level also shows indication of detached fan lobe which is typical of channel axial migration.

Summary

Detailed Seismic interpretation and Correlation across faults showed the study area straddles the extensional cum transition Zones of the offshore depobelt. Mud diapirs are most likely triggered by formation of weak Zones as a result of faulting and compressive forces and occurred in three major episodes in Kofima block.

Conclusion

The results from seismic interpretation of faults, horizons, structural model building showed the true image of the subsurface and evolution of complex structures like shale diapirs. The geological impact of shale diapirism on structure formation, fairway evolution was also ascertained. It has been discovered that most shale diapir plugs are made up of several episodes of overpressured mud influx into the latent orifice and coalesce to form single units of diapirs (figure 19).

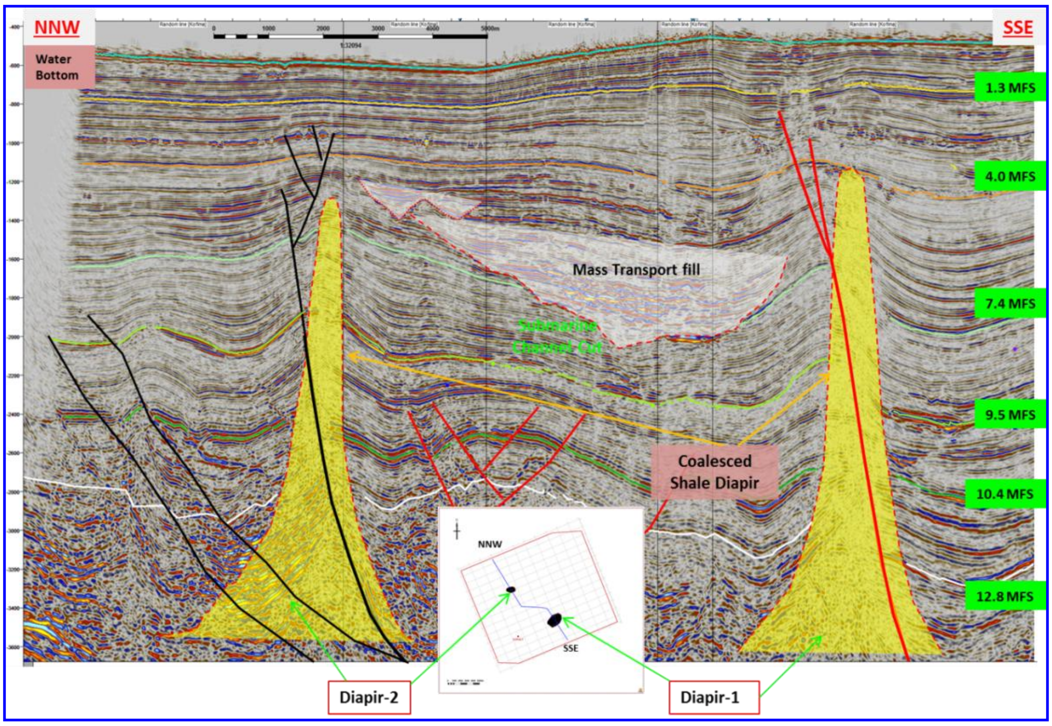


Figure 19: An arbitrary Seismic section connecting two shale diapirs in the study area and their relationship with Faults and Horizons

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