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Structural and stratigraphic mapping of Emi field, offshore Niger Delta

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The Niger Delta, where oil and gas are predominantly trapped in sandstones and unconsolidated sands in the Agbada formation, ranked among the world's major hydrocarbon provinces. The traps, structure and stratigraphic, could be very subtle and complex and are therefore, difficult to map accurately. The degree of reliability and precision of the mapping can be greatly enhanced by integrating seismic data with well logs commonly used independently in hydrocarbon exploration and exploitation studies. In this paper, seismic data were integrated with well logs to define the subsurface geometry, stratigraphy and hydrocarbon trapping potential of Emi-field, off shore Niger Delta. Lithologic units were identified on the logs and correlated across the wells. The stratigraphic cross-sections produced show a general lateral continuity of the lithologic units across the field. Seismic-to-well ties revealed that, high amplitude reflection events correspond to sand units, whereas, low amplitude reflection events correspond to shale units. Four horizons, H_1, H_2, H_3 and H_4 were mapped and structure contour maps produced for each of the horizons. Closures considered as good hydrocarbon prospects were identified and delineated. Stratigraphic plays such as pinch-outs, unconformities, sand lenses and channels are also suspected. The integration of seismic data with well logs proved to be a useful tool in structural and stratigraphic mapping and in predicting lateral and vertical variations in the lithologic units.

Key words: Seismic, structural interpretation, well logs, Niger Delta, stratigraphic mapping, integration.

INTRODUCTION

The Niger Delta is ranked among the major prolific deltaic hydrocarbon provinces in the world and is the most significant in the West African continental margin. Oil and gas in the Niger Delta are principally produced from sandstones and unconsolidated sands predominantly in the Agbada formation. The goal of oil and gas exploration is to identify and delineate structural and stratigraphic traps suitable for economically exploitable accumulations and delineate the extent of discoveries in field appraisals and development. These traps could be very subtle and complex and are therefore, difficult to map accurately. Significant advances in seismic and borehole geophysics has made it possible to map such structural and stratigraphic configurations with high degree of reliability

and precision.

Seismic profiles provide almost a continuous lateral view of the subsurface by defining its geometry and providing an estimate of the acoustic impedance which is related to the formation densities and velocities. However, vertical details are limited due to lengthy duration of the individual seismic wavelets and the occurrence of overlapping wavelets from closely spaced reflectors. On the other hand, vertical resolution of the physio-chemical characteristics of the geologic formations of boreholes can be obtained from well logs. But well logs are limited in their definition of lateral variation of subsurface parameters. Thus, the degree of reliability in mapping complex structural and stratigraphic plays would be greatly enhanced by combining seismic data with well logs (Barde et al., 2002, 2000; Adejobi and Olayinka, 1997), as lateral facies changes, vertical lithologic transitions will easily be detected. In addition, the risk associated with finding oil and gas in subtle and

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complex structural/stratigraphic places will be greatly minimized because such integration will help to discriminate between poor and rich reservoirs.

In the present work, 3 D seismic reflection data were integrated with well logs so as to define the subsurface geometry, stratigraphy and hydrocarbon potential of Emi-field, off-shore Niger Delta. The aims of the study include characterization of the subsurface geometry and stratigraphy, determination of hydrocarbon trapping potential of the field and identification and delineation of possible hydrocarbon prospects in the field. The study is based on forty-two 3 D seismic reflection lines (twenty-seven cross-lines shot parallel to the direction of dip and fifteen in-lines shot parallel to the strike direction) and composite logs of eight wells in the field. The composite logs comprise of gamma ray, SP, resistivities, calliper, sonic and neutron-density logs.

Geological setting of the field

Emi field is located in the offshore depobelt (temporally and genetically related families of growth fault trends or macro-structures) of the Niger Delta (Figure 1) and covers an area of 58.24 km^2 (Figure 2). The Niger Delta, situated at the apex of the Gulf of Guinea on the west coast of Africa, covers an area of about 75 000 km^2. The geology of the tertiary Niger Delta province has been described by several workers (Short and Stauble, 1967; Weber, 1971; Weber and Daukoru, 1975; Weber et al., 1978; Evamy et al., 1978; Doust and Omatsola, 1990; Haack et al., 2000). Basement tectonics related to crucial divergence and translation during the late Jurassic and Cretaceous continental rifting probably determined the original site of the main rivers that controlled the early development of the Delta. The Cenozoic development of the delta is also believed to have taken place under approximate isostatic equilibrium. The main depocenter is thought to have been at the triple junction between the continental and oceanic crust where the delta reached a main zone of crustal instability.

The Niger Delta is a large arcuate delta of the destructive, wave-dominated type and is composed of an overall regressive clastic sequence which reaches a maximum thickness of about 12 km in the basin centre. The Delta's sediments show an upward transition from marine pro-delta shales (Akata Formation) through a paralic interval (Agbada Formation) to a continental sequence (Benin Formation). These three sedimentary environments, typical of most deltaic environments, extend across the whole delta and ranges in age from early tertiary to resent. A separate member, the Afam clay member, of the Benin formation is recognized in the eastern part of the delta and is considered as an ancient valley fill formed in Miocene sediments. The formations are strongly diachronous (Murat, 1970) and cut across the time stratigraphic units which are characteristically

S-shaped in cross-section. Most economically exploitable hydrocarbon in the delta is believed to be trapped within the Agbada formation.

Structurally, the Niger Delta shelf developed as a prograding extensional complex overlying a ductile substrate which probably composed largely of over pressure marine shales. The onshore growth fault systems have been described by Doust and Omatsola (1990) as a series of major growth fault bounded depobelts or mega-structures thought to be transient basinal areas succeeding one another in space and time as the delta prograde southward. The extensional system is dominated by "tepee" structure in which landward-dipping growth faults intersects seaward-dipping in complex interlocking fault networks (Figure 3). The most striking structural features of the Cenozoic Niger Delta complex are the syn-sedimentary structures which deform the delta largely beneath the Benin sand facies. These structures, regarded as the product of gravity sliding during the course of deltaic sedimentation, are polygenic in origin and their complexity increases generally in down delta direction (Merki, 1972). The syn-sedimentary structures, called growth faults, are predominantly trending northeast to southwest and northwest to southeast (Hosper, 1971). Associated with these growth faults are rollover anticlines, shale ridges and shale diapers which are caused by shale upheaval ridges. Mud diapers are the most common and occur on the landward side of the growth faults restricting sedimentation on the up-thrown side of the faults and enhancing sedimentation on the down-thrown side. Most of the faults are listric normal; others include structure-building growth faults, crestal faults, flank faults, counter regional faults and antithetic faults.

In general, the offshore Niger Delta has the characteristic shelf slope break of growth fault modified ramp margins. Trap configuration in the offshore Niger Delta is controlled by gravity driven systems of linked extensional growth faults and compressional toe thrusts initiated during the Paleocene when the modern Niger Delta was formed (Duncan and Townsend, 1997). The present day shelf is dominated by long counter regional faults. Further offshore, there exist a back-to-back fault trend along the shelf edge and upper slope. Down the slope, there are examples gentle folds, with thrust and diapers sometimes cutting the sea bed (Figure 4).

Oil and gas are predominantly trapped by roll over anticlines and fault closures. Stratigraphic traps of palaeo-channel fills, regional sand pinch-outs and truncations, crestal accumulations below unconformity surfaces, cayon-fill accumulations above unconformity surfaces, incised valley and low-stand fans have been recognized (Orife and Avbovbo, 1982; Kruise and Idiagbor, 1994). Hydrocarbon distribution in the Niger Delta is complex with gas-to-oil ratio generally increasing southward away from the depocentre within a depobelts (Evamy et al., 1978) and is primarily controlled by thermal
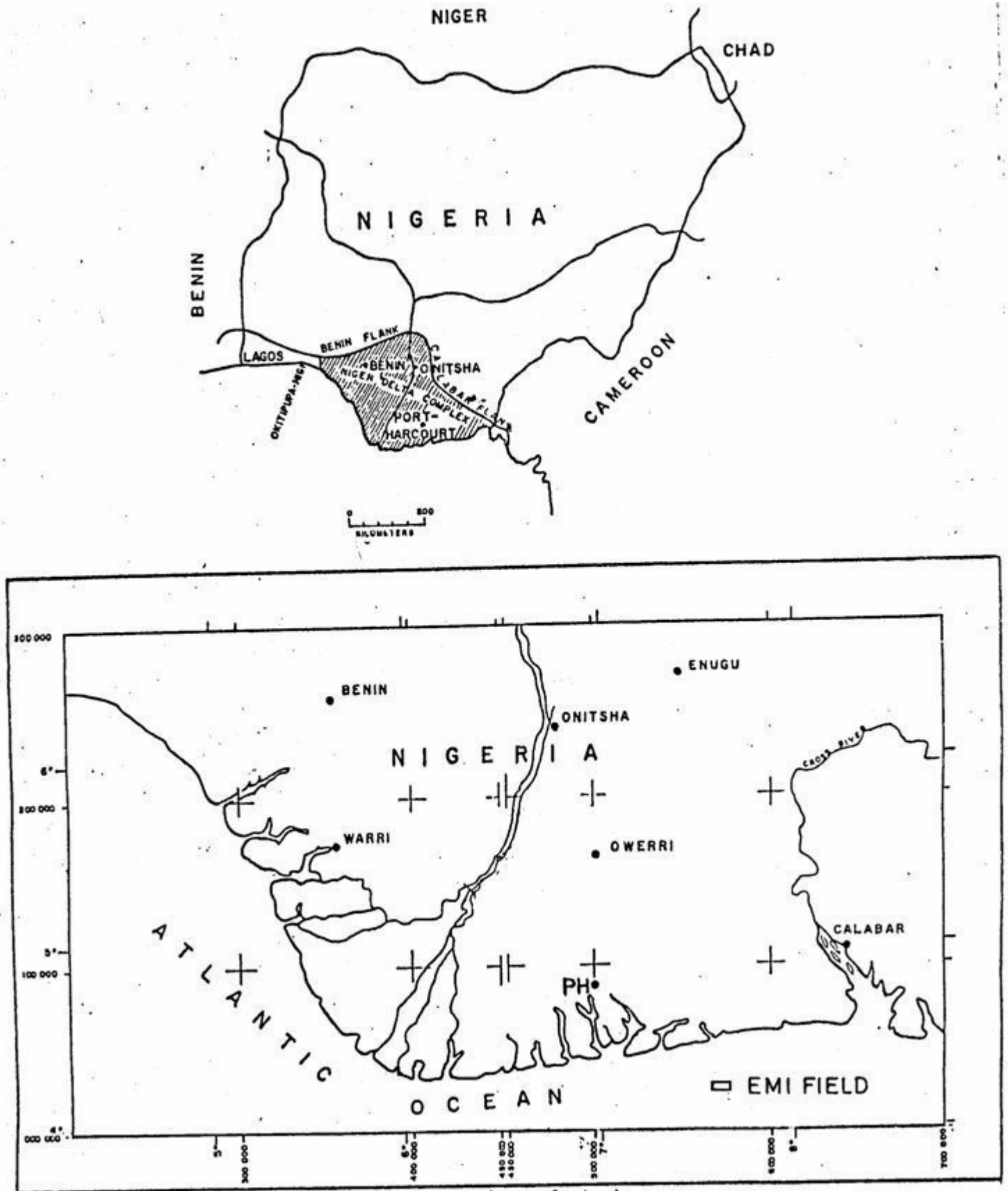
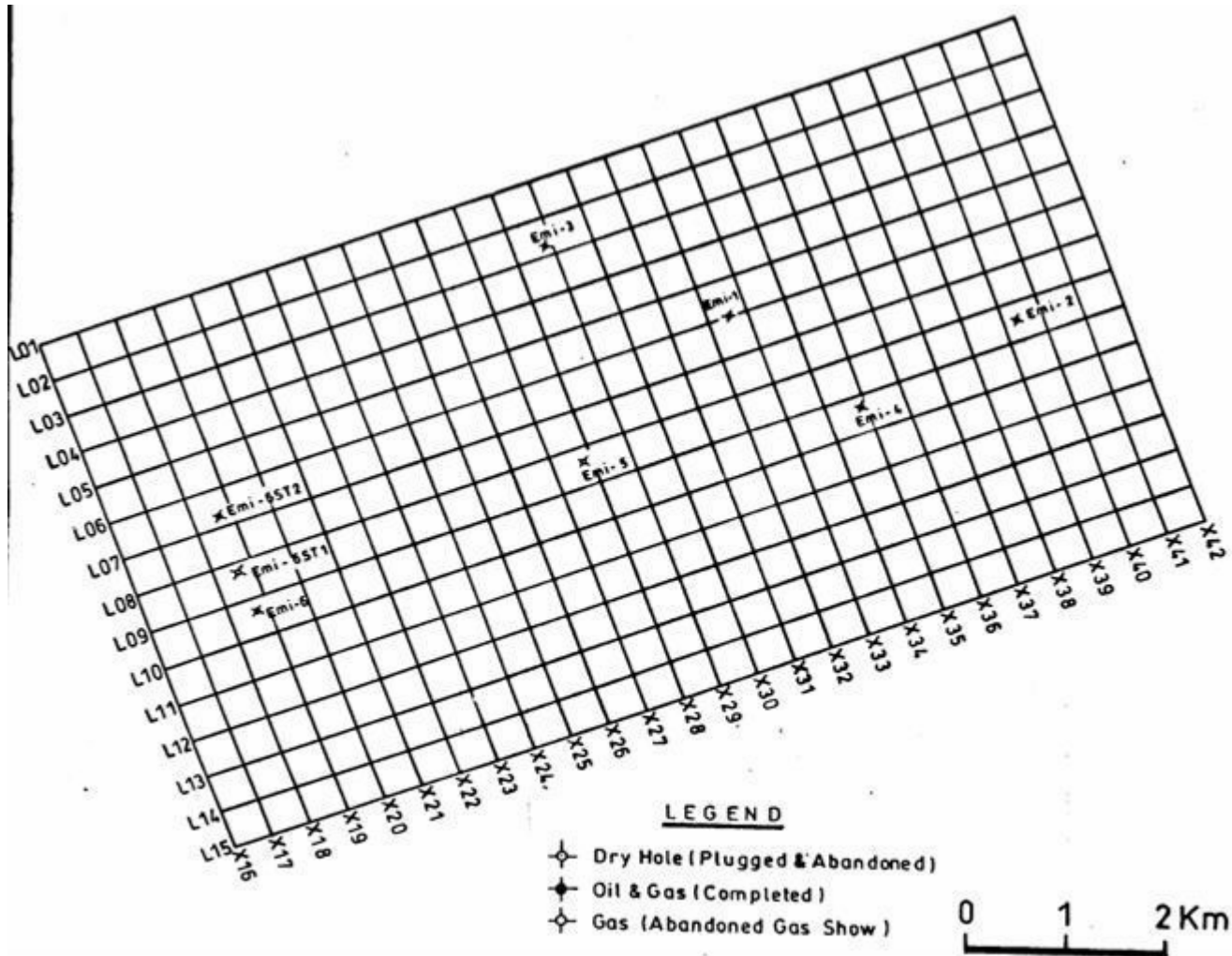**Figure 1.** Map of Niger Delta showing the location of the study area.

Figure 2. Base map of the study area showing well locations and seismic lines.

history of the source rocks, source rocks quality, migration and sealing quality. In addition, the timing of traps formation could be a factor that controls the distribution of hydrocarbon (Chukwueke, 1997).

Trap configuration in the deep water Nigeria is controlled by gravity driven system of linked extensional growth faults and compressional toe thrusts initiated during the Paleogene, when the modern Niger delta was formed (Haack and May, 2000). Most of the reservoir facies in the offshore Niger Delta are related to an aggrading lowstand complex where a slow relative rise in the sea levels allows sediment input to keep pace with the creation of accommodation space over a long period of time. A thick expanding edge of coarse clastics is trapped on the shelf behind the counter regional faults and most of the sediments are therefore, deposited on the shelf, indicating that the sand content and gross sediment input reduces dramatically with increasing distance from provenance. Much of the section of the delta shelf consists of alternating stacked cycles of

low-stands slope fan and low-stand prograding wedge deposits. Good reservoir sand units may occur in either of the two main low-stand system tracts.

METHODOLOGY

Data available for the study include forty-two 3D seismic sections, which covers an area of 58.24 sqkm on a scale of 1:250000. Twenty-seven of the seismic lines are cross-lines shot parallel to the dip direction and the other fifteen are in-lines which were shot parallel to the strike direction. The spacing between the seismic section for both the in-lines and cross-lines is 400 m (Figure 2). A continuous velocity log of Emi-3 well and composite logs for six wells and two sidetracks wells which consist of gamma ray, SP, caliper, resistivities and neutron-density logs were also available for this study.

Emi-1, Emi-3, Emi-4 and Emi-5 wells were selected for study based on data quality and continuity and depth column covered by logs. The gamma ray, SP and resistivities logs were used in identifying the lithologies (within the Agbada Formation) penetrated by the wells. The resistivities logs and neutron-density logs were used in distinguishing between saline-bearing water formations an
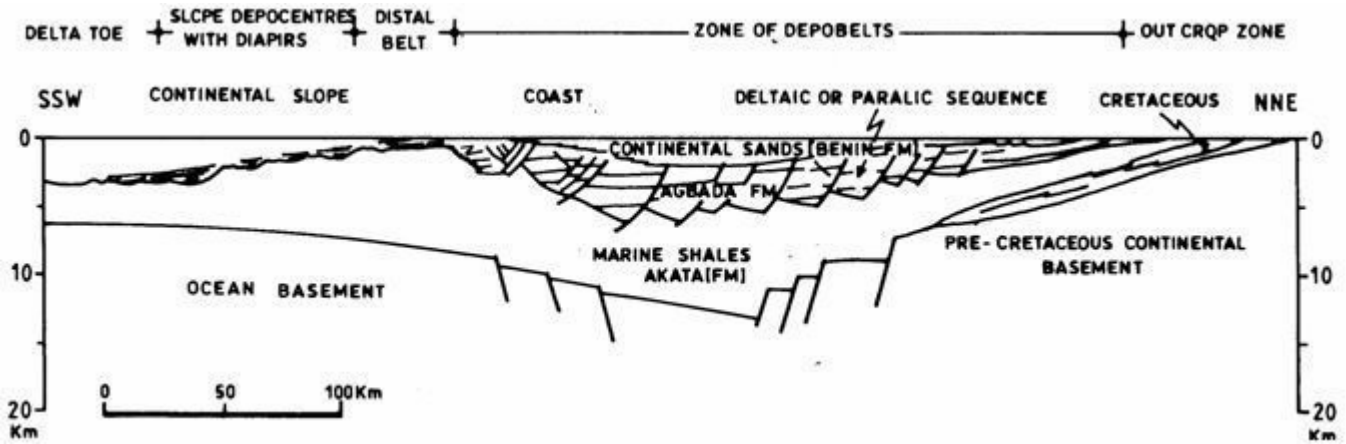
Figure 3. Schematic section through the axial potion of the Niger Delta showing the relationships of the tripartite division of the tertiary sequence to basement (Doust and Omatsola, 1990).
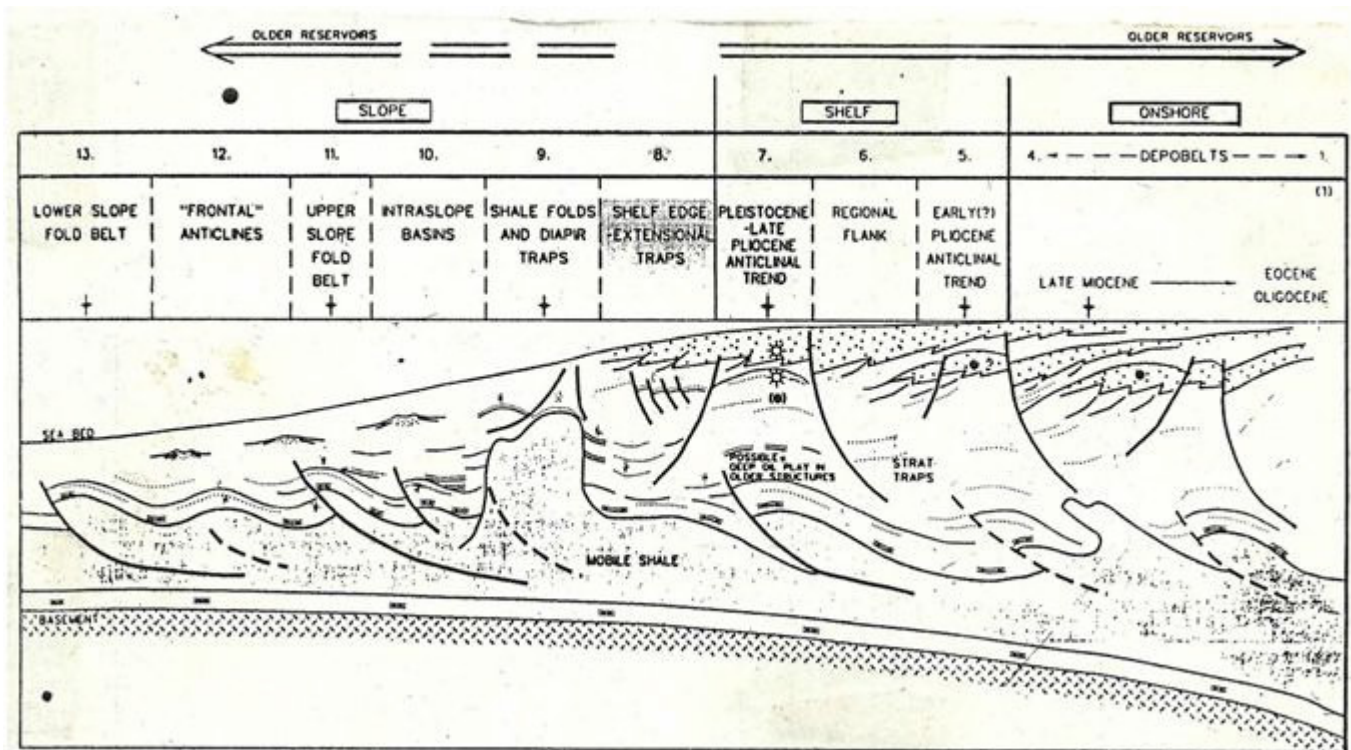

Figure 4. Niger Delta schematic structural profile of the deep water area characterized by listric extension faults gentle folds thrusts and diapirs (Ojo, 1996).

hydrocarbon pay zones. Measured depth (MD), measured thickness (MT), sub-sea true vertical depth (SSTVD) and true vertical thickness (TVT) of each of the stratigraphic units were determined and the wells were carefully correlated. Stratigraphic cross-sections were drawn through Emi-3, Emi-1 and Emi-4 wells and Emi-4 and Emi-5 wells to depict the lateral variations of the horizons within the limits of the data provided.

The lithofacies interpreted from well logs were matched against reflection events from seismic sections. The selection of reflection events from the seismic sections was based mainly on amplitude

and continuity of such reflections, especially in areas where there were no well control. Consistency was ensured in all the data sets. The continuous velocity log of Emi-3 well was used to obtain the vertical travel time in milliseconds and the vertical depth from which the time-depth relation curve was obtained (Figure 5). Lithofacies (horizons) within the well logs that show hydrocarbon prospect were selected for mapping. The depths/thicknesses of these horizon were converted to two-way travel times using the time-depth relation curve. The corresponding seismic reflection events that show reasonable amplitude and continuity were selected. Four
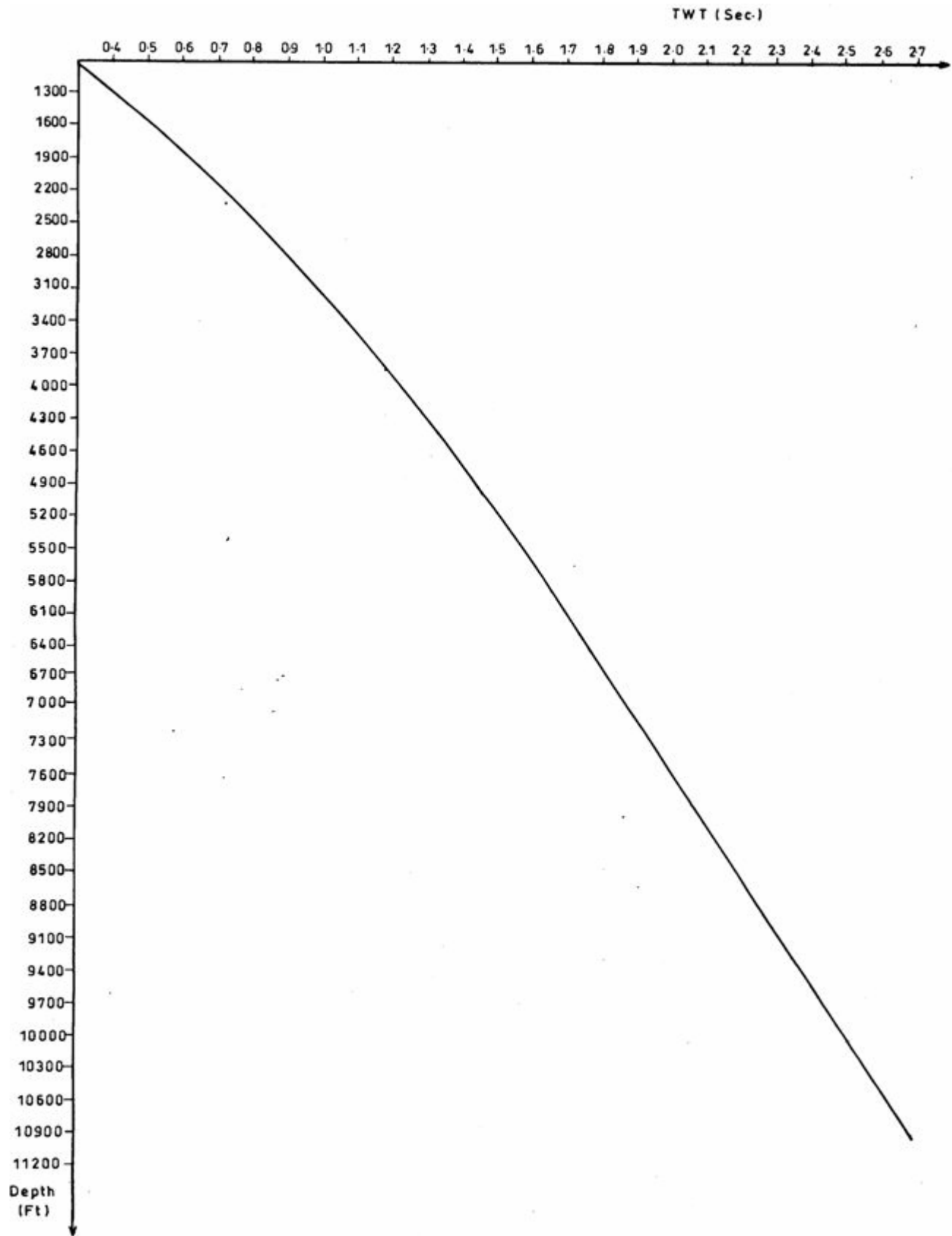
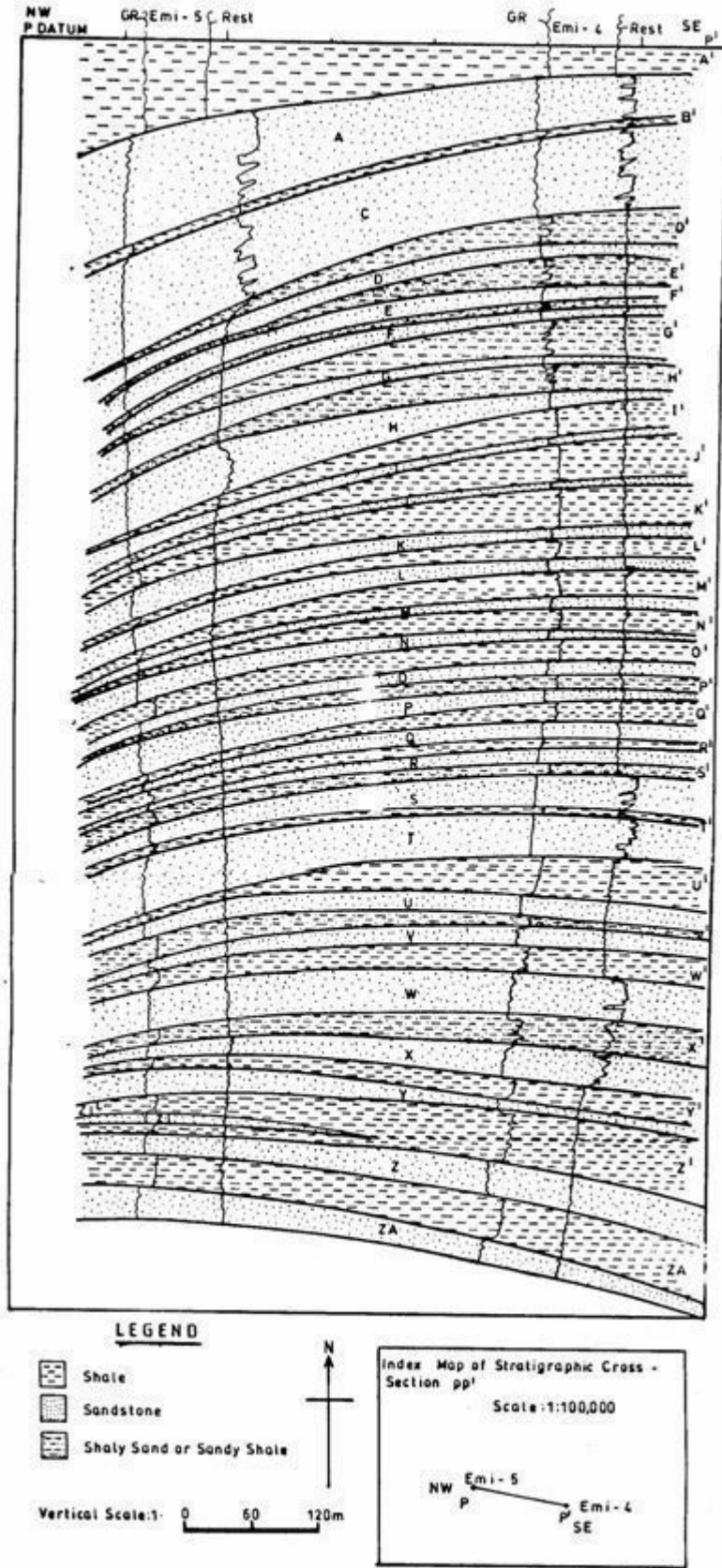**Figure 5.** Time-depth relation curve.

Figure 6. Stratigraphic cross-section showing lithologic units: (a) across Emi-5 and Emi-4 wells and (b) across Emi-4, Emi-1 and Emi-3 wells.
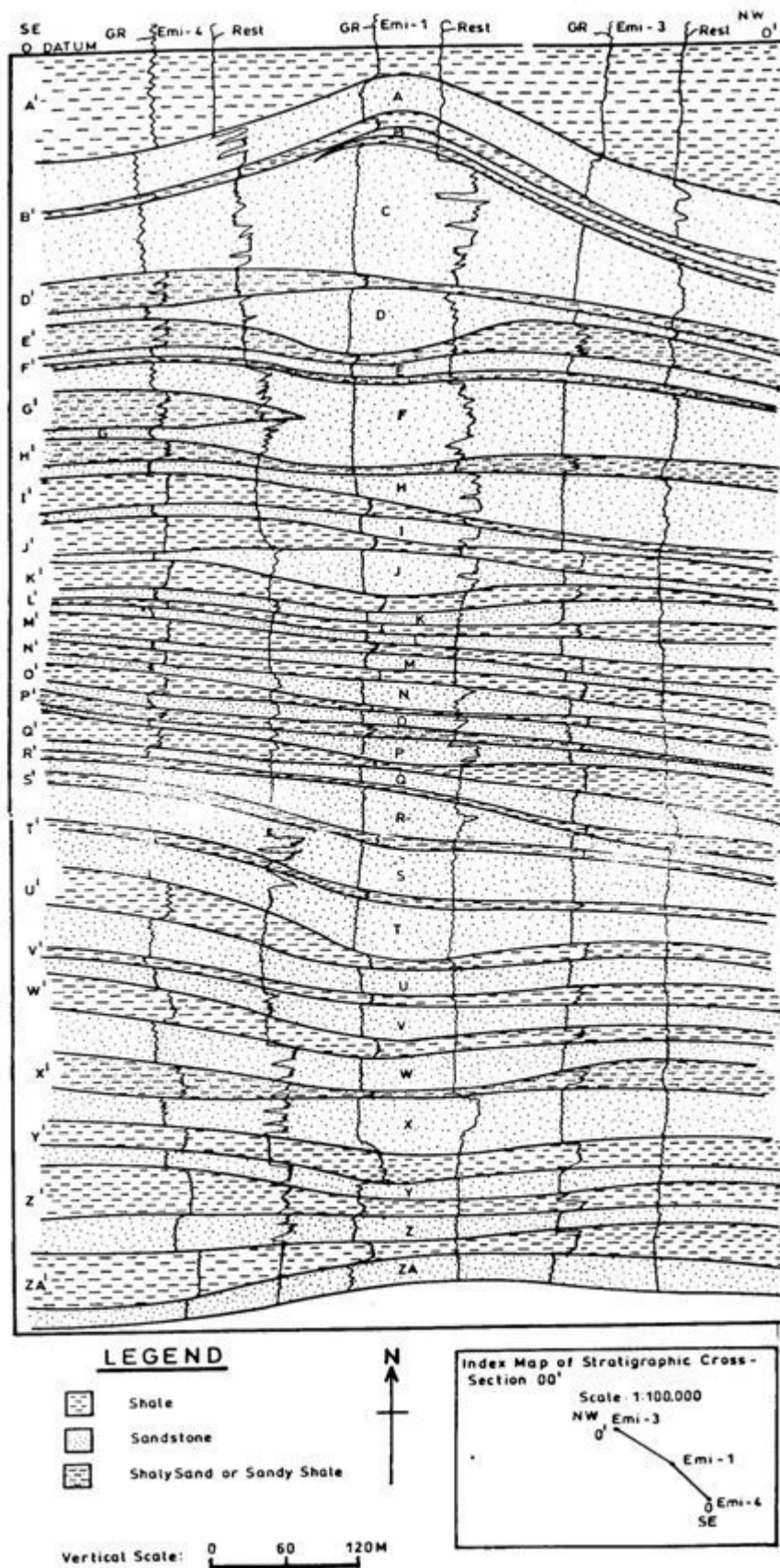
Figure 6. Continued.

horizons, H_1, H_2, H_3 and H_4, were selected in all and were distinguished from each other with the aid of different colour-marker pencils. Each of the horizons selected for study were correlated through all the seismic sections. Major faults were identified base mainly on break in reflection events or abrupt termination of reflection events and marked on the cross-lines. Consistency of the fault traces at all levels was ensured. The time-depth relation curve was then, extrapolated to a two-way time of about 2700 ms, so as to obtain depth information for horizon H_4 (the deepest of the horizons selected).

The horizons selected on the cross-lines and the in-lines were tied at their intersection points. This was done, ensuring consistency in all the lines of intersections and in all the seismic sections which cover the entire survey area. The analysis was rechecked in areas where there were misties or closure errors, thus, reducing the misties. The horizons chosen were digitized using a scale appropriate to the seismic sections and structured contour maps were then produced for each of the horizons. The variable nature of the seismic signals as well as the varying structural styles of rock deformation was taken into consideration while contouring. The fault traces were posted to the structure contour maps produced. The faults' throws and directions were obtained from the seismic sections and correlated with well logs where there were well controls.

RESULTS AND DISCUSSION

Seismic interpretations and stratigraphic cross-sections

All the seismic sections were migrated and this allows for the tying of seismic sections at the intersection point between the cross-lines and in-lines. Most of the major faults picked on the seismic records are counter regional growth faults which are characteristics of the self edge, offshore Niger Delta (Ojo, 1996). These counter regional faults (F_1, F_2, F_3, F_4, F_5 and F_6) are trending west-east and dipping south-east. Two regional growth faults F_1' and F_2' trending north-south and dipping south-west were also picked. The throw of the major faults ranges from 46 to 79 m (150 to 260 ft), while that of the minor faults ranges from 24 to 36 m (80 to 120 ft). This throw is appreciable and could have produce migration pathway for hydrocarbon. The horizons mapped are laterally continuous on the seismic records and formed a closed loop along the tie lines. Horizons H_1, H_2 and H_3 correspond to the stratigraphic units C, K and X on the stratigraphic cross-sections produced (Figure 6). Horizon H_4 is not shown on the stratigraphic cross-sections, because it was not penetrated by most of the wells correlated. However, Emi-5 well penetrated this horizon as a match of his well with seismic section showing that the horizon is a sand unit.

The stratigraphic cross-section through Emi-4 and Emi-5 wells is shown in Figure 6a, while that of Emi-4, Emi-1 and Emi-3 wells is shown in Figure 6b. Primarily, twenty seven sand and shale units of varied thicknesses were observed and denoted as A, B, C… ZA and A', B', C'… ZA', respectively. Most of the units are laterally continuous, though few cases of pitch-out/wedge-out are evident. There is a large vertical displacement of the shale facie A' between Emi-4 and Emi-5 wells. The stratigraphic cross-section through Emi-4 and Emi-5 wells, tend to be more horizontal and parallel to one another than those of the cross-section through Emi-4, Emi-1 and Emi-3. This is because Emi-4 and Emi-5 are more or less in the same strike direction compared to Emi-4, Emi-1 and Emi-3. Thickening and thinning of lithofacies are more prominent in Emi-1, the reservoir units are thickening whereas the shale facies are thinning out. Most of the shales units in Emi-4 are thickening. The variations in lithofacies thickness observed could be attributed to variation in sediment supply, rate of sea level rise and fall, paleogeomorlogy, synsedimentary tectonism or error in data processing. In spite of these variations there exists a good correlation between the wells.

The identification of lithofacies on the seismic sections was based primarily on the amplitude of seismic reflection events. The high amplitude and continuous reflection were found to correspond to sand units, whereas the low amplitude reflections were found to correspond to shale facies. Poor continuity and relatively low reflections were attributed to shaly sand or sandy shale units. Seismic amplitudes are proportional to normal incidence reflection coefficient and thus, lateral/vertical changes in reflection amplitude correspond to lateral/vertical changes in lithology. Changes in amplitude along a continuous reflector may be related to changes in the pore fluid in the formations. Few cases of misties were observed and are attributed to soft shales due to the unreliable description of the virgin formation and excessive filtering of the seismic data.

Structure contour maps

The structure contour maps of the horizons mapped, H_1, H_2, H_3 and H_4 are presented in Figures 7 to 10, respectively. They show a system of rollover anticlines associated with growth faults. The faults appeared crescent-shaped with the concave side being towards the down-thrown block. The crestal faults (synthetic and antithetic) show less curvature in the horizontal plane and are generally steeper in the vertical plane. The throw of the major faults rages from 40 to 60 ms corresponding to 150 ft (46 m) to 260 ft (79 m). The growth faults are sub-parallel to one another and strikes in the west-east direction. The faults are sealing on the up-thrown side of the fault zone where most of the hydrocarbons could be trapped.

Horizon H_1, which correspond to the stratigraphic unit C on the stratigraphic cross-sections with true vertical thickness (TVT) of 443 ft (135 m), 205ft (62 m), 226ft (68 m) and 282 ft (86 m) in Emi-1, Emi-3, Emi-4, Emi-5 wells, respectively, reveals faulted and folded anticlinal closures (I and II) and fault assisted closures (III, IV, V, and VI). The structural closure I and II both closes by 400 ft
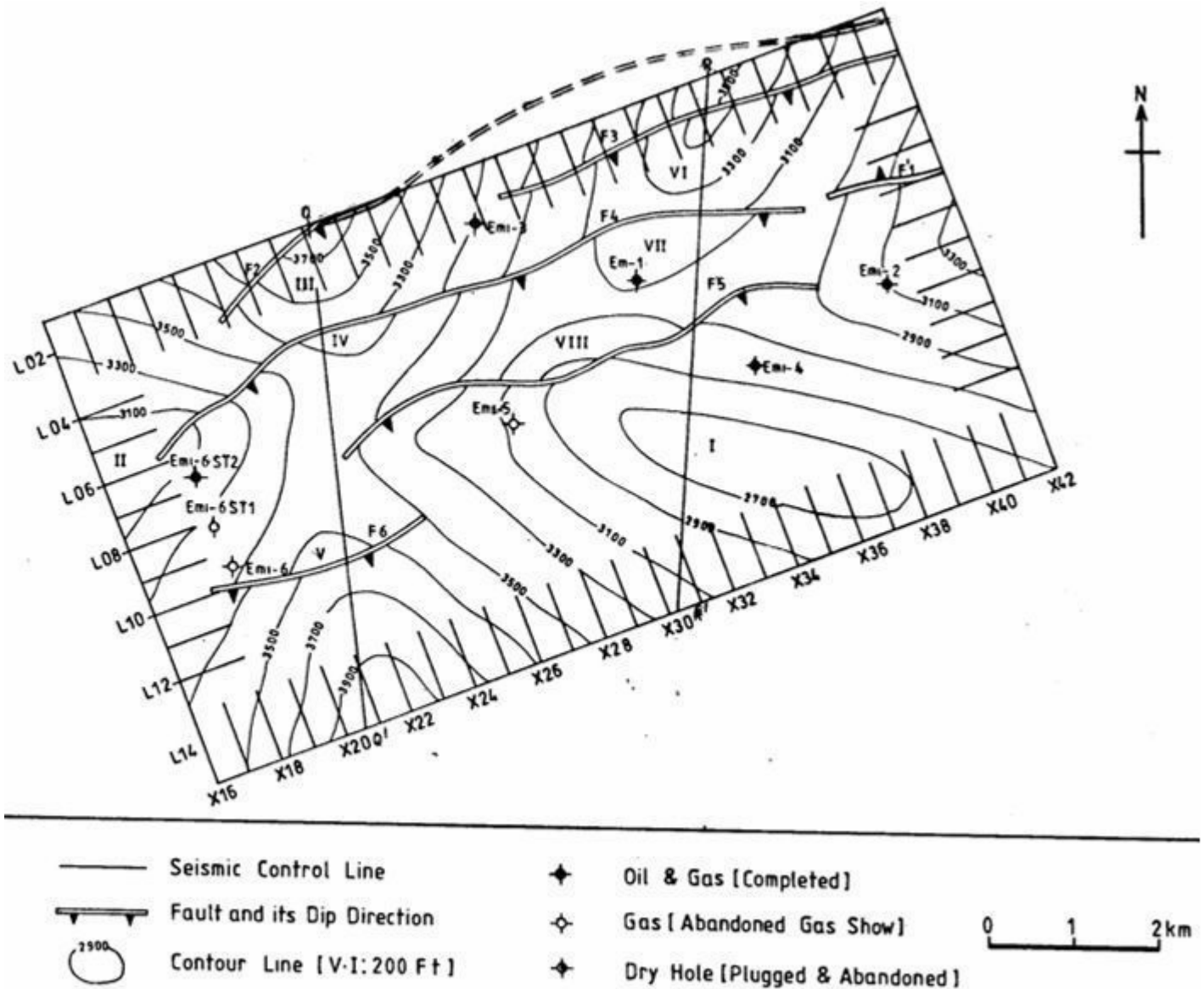
Figure 7. Structure contour map of horizon H₁.

(121 m), respectively. The faults may have serves as migratory paths for hydrocarbon into the structural closures and the reservoir units at large. Cross-sections through its structure maps also suggest a system of growth faults, roll over anticlines and folding. Similar structures are observed in Horizons H_2, H_3 and H_4 (Tables 8 to 10). Unconformities are also evident in the structure map of H_4. These closures serve as good traps for hydrocarbon and are therefore possible hydrocarbon prospects.

Conclusions

The result of the stratigraphic cross-sections drawn

shows that, the horizons are laterally continuous, however, pinch-outs/wedge-outs are evident. The horizons mapped are all within the Agbada formation, where most of the hydrocarbon is believed to be trapped in the Niger Delta. Anticlinal closures and fault assisted closures regarded as good hydrocarbon prospect areas have been delineated in the structure contour maps. Trapping of hydrocarbon by means of simple closure is independent of the presence of faults and trapping in fault closures is assisted by sealing faults in which the fault plane and the sediments dip in opposite directions. Apart from the structural traps delineated, other stratigraphic pays including pinch-outs, unconformities, sand lenses and channels were also suspected. The integration of seismic data and well logs proved to be a useful and valid
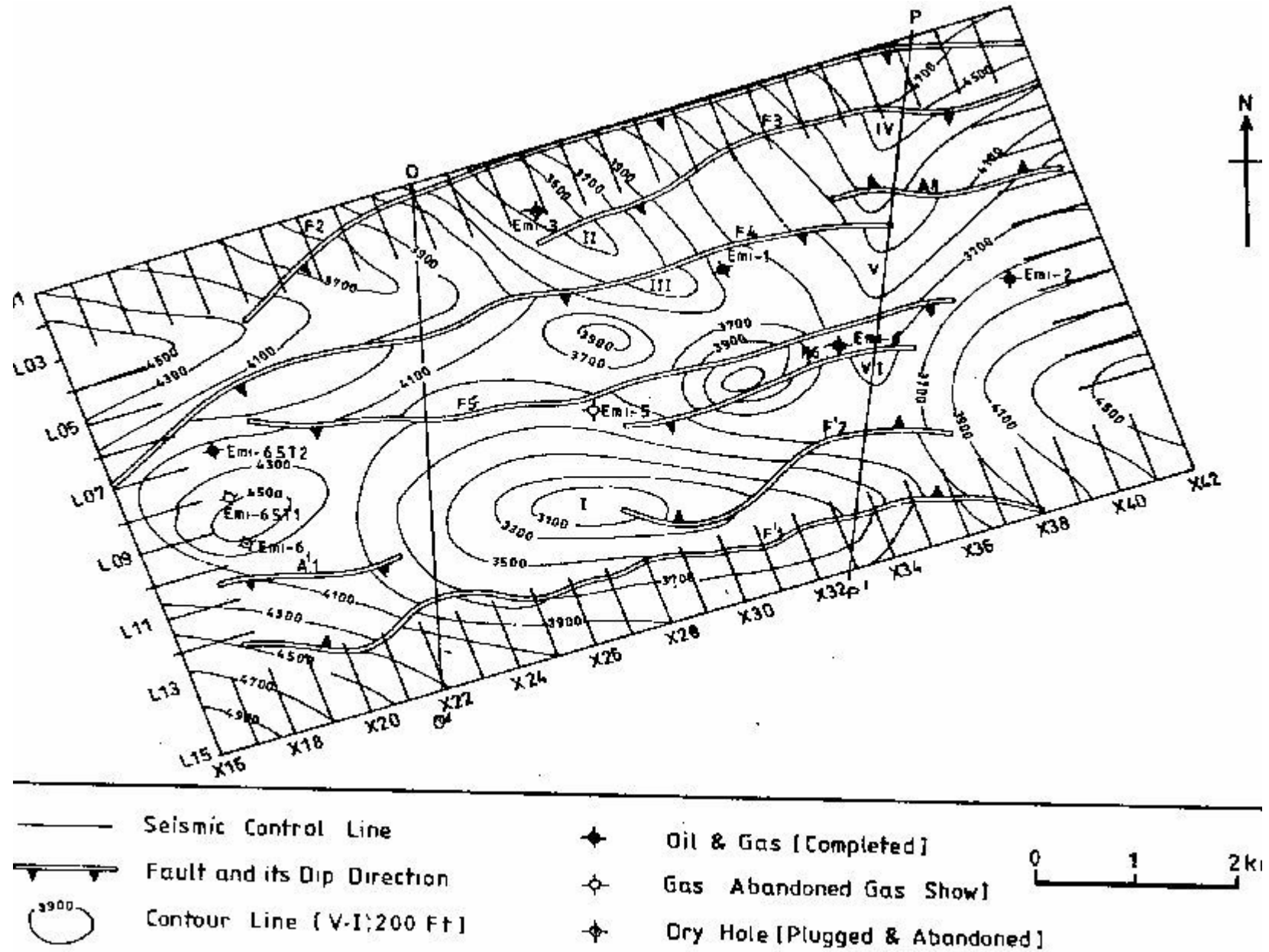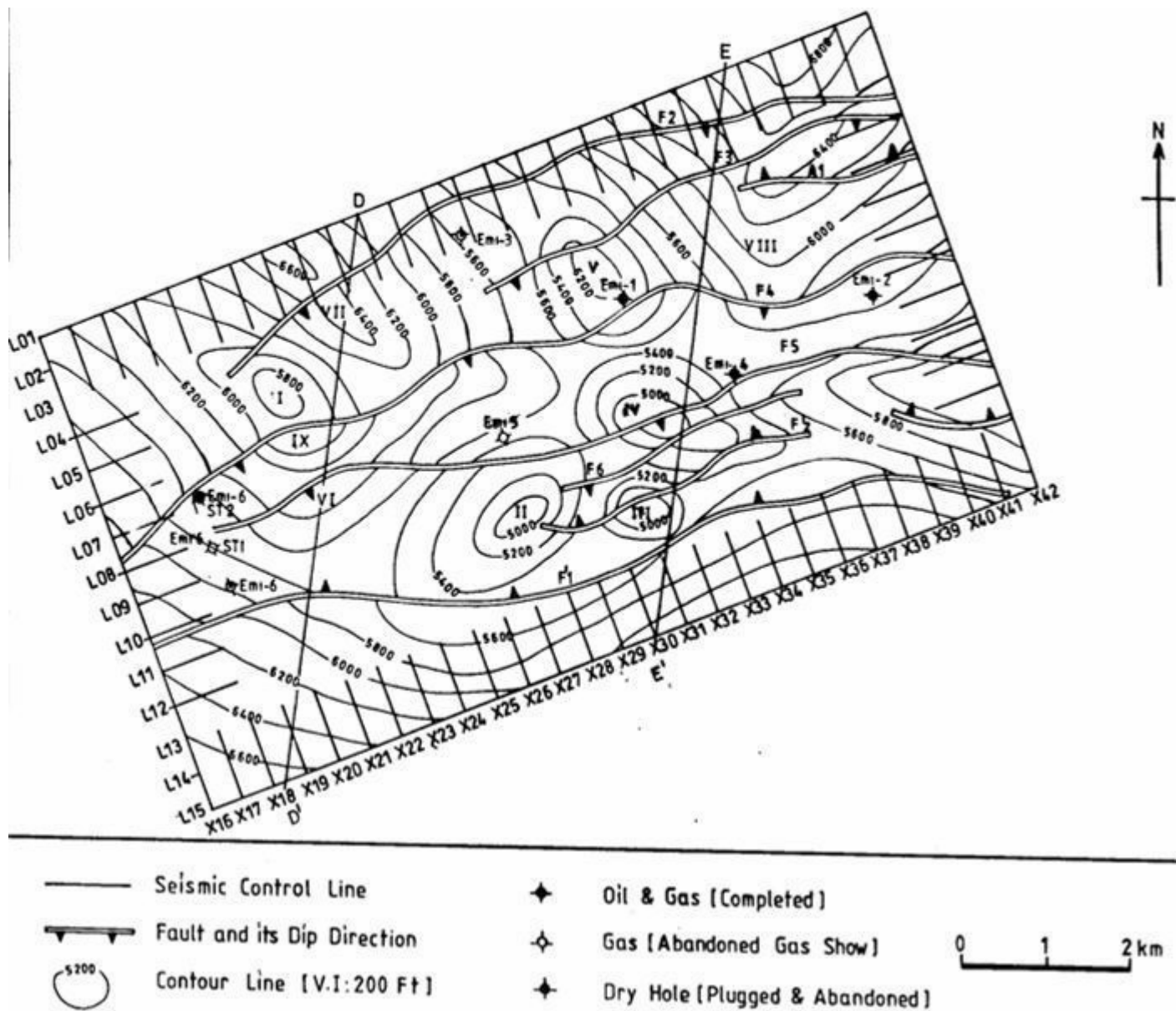
Figure 8. Structure contour map of horizon H$_2$.

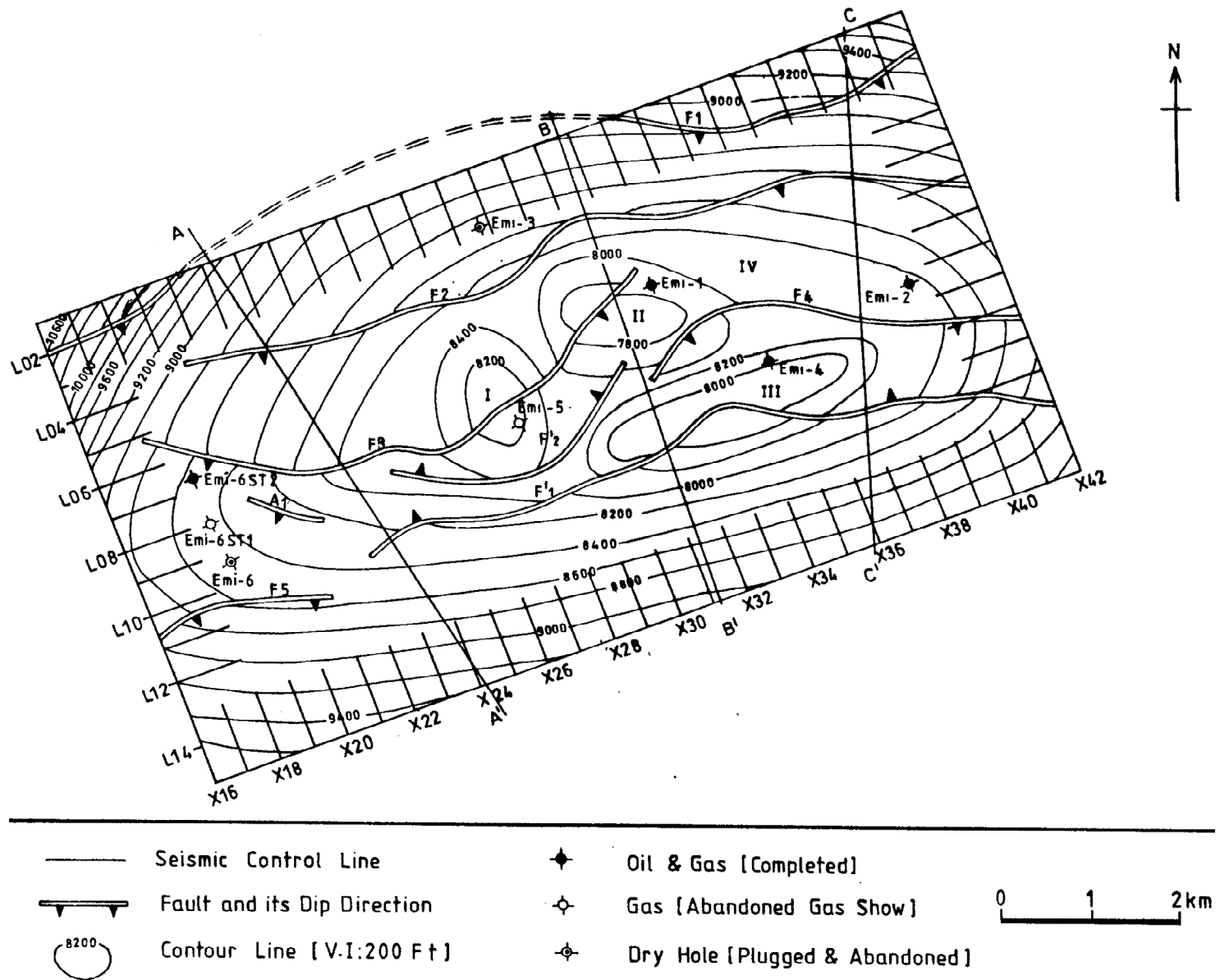**Figure 9.** Structure contour map of horizon H₃.

Figure 10. Structure contour map of horizon H₄.

tool in structure and stratigraphic mapping. These stratigraphic pays may not be effectively mapped with manual interpretation and there is usually a great risk in finding oil and gas in these subtle stratigraphic traps.

The integration of seismic data with well logs was successful in defining the subsurface geometry, stratigraphy and hydrocarbon trapping potential of the field. The technique proved to be useful in structural and stratigraphic mapping and in predicting lateral and vertical variations in the lithologic units reasonably. Hydrocarbon prospect areas were delineated in the structured maps produced. The growth faults may have acts as migratory paths for hydrocarbon from the underlying Akata formation. Thus, it is necessary to integrate all exploration and evaluation tools so as to effectively explore the study area and optimize well locations. Amplitude variation with offset (AVO), seismic attributes analysis and seismic inversion should be carried out in the study area to better discriminate the lithology, characterize the reservoirs and define the hydrocarbon types.

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