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Analysis of seismic gas chimney distribution using artificial neural network – A case of shallow offshore field, Niger Delta, Nigeria

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Abstract

The importance of detecting fluid migration as guide to exploration efforts has been shown using the pattern recognition technique of neural network-derived chimneys from multiple seismic attributes. Valuable insights for robust exploitation decision on the probable characteristics of the hydrocarbon presence, migration, sealing quality of faults, flux/charge rate, leakage and spillage from reservoirs have been provided. Dense clusters of chimneys around faults and fractures exhibit the probable extent of palaeo and recent hydrocarbon flows from Akata and Agbada shales to reservoirs and the effectiveness of the local and regional seals. Reserves depletion and geohazards signatures are rather slim but may develop over time due to hydrocarbons escape to shallow seabed.

Keywords: Seismic Chimney; Migration; Probability; Seepage; Neural Network.

1. Introduction

Several techniques aimed at preventing dry holes and ensuring optimal production of hydrocarbon from any field at the most reasonable cost have and are the still being developed. Since the advent of 3D seismic technology, seismic data have proved to be very useful and successful in exploration and exploitation processes [1-2]. However, many exploration post-mortem studies indicate that seal failure, or limited charge paucity and small hydrocarbon column heights, are common causes of dry holes [3-5]. For hydrocarbon to be generated there must be source rock with high organic content, which must have been subjected to high temperature and pressure, over a long period of time [6]. At the oil window the hydrocarbon generated remains within the source rock until further increase in the temperature and pressure conditions leads to expulsion of the hydrocarbon, which marks the onset of migration [6]. The low density of gas and oil which are the major components of hydrocarbon will naturally result in buoyancy and tendency to flow through any opening or spaces within the rocks to the surface [6]. The free flow of the hydrocarbon will continue vertically until it meets a barrier (seal) that will cause the fluid to flow laterally until another barrier rock is met, thus forming a trap [6]. The migrating hydrocarbons usually leave trails of movement in the subsurface in the form of oil seeps or gas clouds leading to cracking, chemical alteration and deposition of connate gas within their path. These characteristic patterns (trails) are referred to as seismic chimneys [7-11]. Seismic chimney refers to the region on seismic data where low concentration gases escape from accumulations of fluids (oil, gas or brine) and migrate upward through formations [12]. They are haphazard in nature and usually show on seismic sections as regions of fuzzy reflections and amplitude weakness [13]. Seismic chimneys are invaluable for inte-pretations, they have been successfully used for vertical hydrocarbon migration [14], geohazards studies [15] and to detect fault related migration patterns directly in the seismic data. Seismic chimney provides a links for tying the surface expression of seepage to su-pected hydrocarbon traps, hence its usefulness in delineating hydrocarbon migratory pathway [16]. Cluster of chimneys can be an indication of charged reservoirs [17]. Its presence along faults can suggest that the fault is or was opened in the past and can serve or have served as a migratory path [13]. Many gas chimneys are very obvious in the seismic record. However, subtle gas clouds above hydrocarbon reservoirs, deep chimneys related to expulsion from source rocks, and fault-related hydrocarbon migration pathways are often difficult to distin-guish on normally processed seismic data. The diffuse character and weak expression of gas chimneys in seismic data make them difficult to map. Often they are most obvious on vertical seismic sections, but not clear on 3D seismic time slices. Thus a method for detection of gas chimneys in post-stack 3D data was developed [18-19] to improve the identification of gas chimneys in seismic data, map their distribution, and allow them to be visualized in three di-mensions. This semi-automated detection of seismic chimneys utilizing neural networks on several attributes has been applied to several 3D seismic data sets from the Norwegian shelf [7] and the Gulf of Mexico [18] with consistent results. Singh *et al.* [20] interpreted the Maari 3D prospect of the Taranaki basin in New Zealand using chimney technology and were able to improve the understanding of the petroleum system and provide preventive clues for mitigating exploitation hazards. This study is aimed, therefore, at assessing the distribution of seismic chimneys as a means to improving the understanding of the critical elements of the petroleum system for optimal hydrocarbon management plans and decisions on the field.

2. Regional geology of the study area

The Niger Delta basin located in the Gulf of Guinea on the west coast of Africa [21]. It is the African leading oil province that evolved from the pre-Tertiary sedimentary basin, the Benue-Abakaliki Trough (Figure 1a). The trough originated as a failed arm of a triple junction rift ridge system that initiated the separation of South American from African plates. The rifting in the entire region started in the Late Jurassic and persisted into the Middle Cretaceous [24]. Folding in the Campano-Santonian resulted in the uplift of the Benue-Abakaliki Trough to form the Abakaliki high, whilst the Anambra platform was warped from the Anambra Basin. The rifting was then followed by gravity tectonism as the primary form of deformation. Shale mobility induced internal deformation occurred in response to two processes [25]. Firstly, the loading of the poorly compacted, over-pressured, prodeltaic and delta-slope clay of the Akata Formation by the higher density delta-front sand of the Agbada Formation lead to formation of shale diapirs. The slope instability generated by the lack of lateral basin-ward support for the under-compacted delta-slope clays of Akata Formation also led to further deformation. The Benin Formation was then deposited in the depobelts after the completion of gravity tectonics.

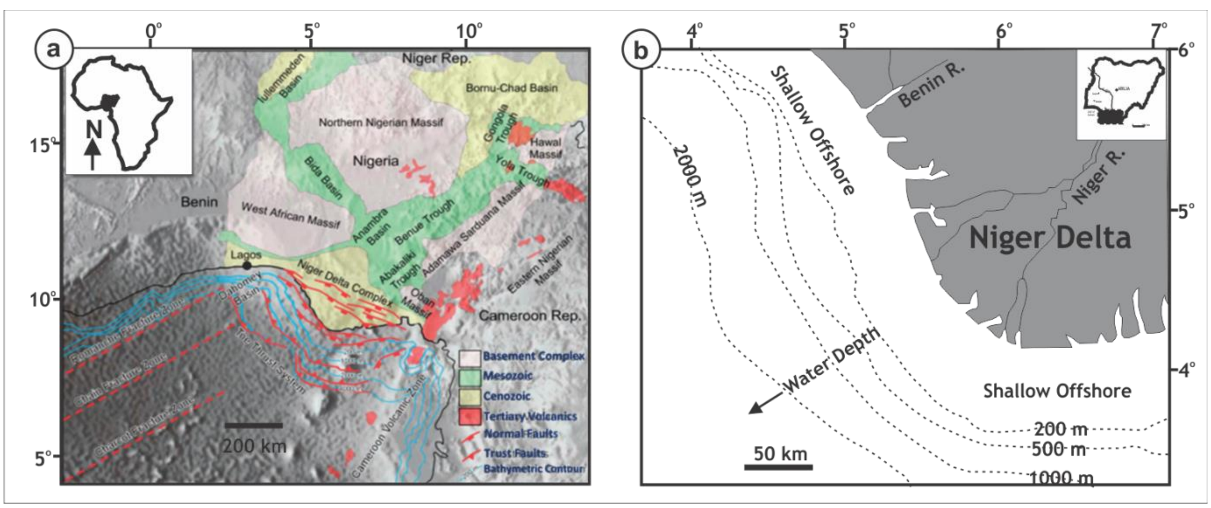

Figure 1. (a) Regional map showing the Niger Delta basin and other Nigerian sedimentary basins [22], (b) Map of western Niger Delta basin, showing the shallow offshore [23]

This tectonism resulted in the formation of complex structures such as shale diapirs, roll-over anticlines, collapsed growth fault crests, back-to-back features, and steeply dipping, closely spaced flank faults [26-28]. From the Eocene to the Present, the delta has prograded southwestward, forming depobelts that represent the most active portion of the delta at each stage of its development [29]. The delta is a coarsening upward regressive sequence of Tertiary clastics that prograded over a passive continental margin sequence of mainly Cretaceous sediments. The Niger Delta Province contains only one identified petroleum system [25] [30] and 11 proven plays. The Agbada group of plays is the main contributor of reserves. The most significant play is Agbada stratigraphic-structural Play [28]. The source rock of the Niger Delta has been an issue of debate among scholars, some are of the opinion that Agbada formation is the source rock [31], and some others believe that the shale within the Agbada formation is a major contributor to the hydrocarbon in the Niger Delta [32]. Nwachukwu *et al.* [33] shows the presence of mature shale within the Agbada formation which contain kerogen that could have been source of hydrocarbon in the western part of the Niger Delta. The hydrocarbons are believed to have been produced in the Akata Formation and migrated up dip through growth faults and accumulated in the Agbada Formation [28]. Researches aimed at the lithology of Niger Delta [29,31,34] have revealed that deposition in the Niger Delta involved fully terrestrial, to intermediate (i.e. paralic) and the fully marine conditions. An extensive but thin lens of sediment which consists of continental, gravelly or very sandy terrestrial deposits upstream, which gradually changed to sandy and clay fluviatile and marine sediments in the paralic environment, which later turn to marine clays is presently formed. The study area is shallow offshore (< 200 m water depth) Niger Delta (Fig. 1b) where about six wells have penetrated some central prospects and hydrocarbon has been reportedly encountered in certain reservoirs at some depths.

3. Methodology

3.1. Neural network methodology

Seismic attributes are invaluable tools of evaluation and enhancement of features in seismic interpretation [35]. Combining several attributes to form meta-attributes [36] using neural network helps in enhancing the geologic feature or quantifying reservoir property of interest. Some of the useful attributes for training the neuron models are energy, similarity, local dip and dip variance [16,21,37-39]. The artificial neural networks have emerged as a promising computing technique that enables computer systems to exhibit some of the desirable brain properties [35]. Just like the brain, it is robust and fault tolerant; flexible and can deal with information that is inconsistent or contaminated with noise. It can handle unforeseen situations and large amounts of input data by quickly extracting relevant properties from the data. It is highly parallel and performs highly. Various types of networks have been applied successfully in a variety of scientific and technological fields. Examples are applications in industrial process modelling and control, ecological and biological modelling, sociological and economic sciences as well as medicine [40]. Within the exploration and production world, neural network technology has been applied to geologic log analysis [41] and seismic attribute analysis. The most general and most widely used neural network model is the 'multilayer perceptron' (MLP). The basic building block of this model is the perceptron [42] – a mathematical analog of the biological neuron. The mathematical expression of the biological neuron can be written as an activation function, A, applied to a weighting function, W, defined as:

$$W(y) = \sum_{i=0}^{L} w_i y_i \quad (1)$$

where y is the neural network input vector written as y_i with i. = 1, …; L and w is the weighting vector w_i with i. = 1, …, L

$$A(W)=\begin{cases}1 & W>0\\ 0 & W\le 0\end{cases} \qquad (2)$$

In MLPs, the binary activation function is often replaced by a continuous function. The most widely used activation function is the sigmoid function defined as:

$$A(W)=\frac{2}{1+\exp(-W)}-1 \qquad (3)$$

In its simplest form, there are three layers; an input layer, a hidden layer and an output layers, and there are no connections between neurons belonging to the same layer. MLPs are trained on a representative dataset, a form of supervised learning. Known examples, consisting of input patterns and corresponding output patterns are repeatedly fed to the network during the training phase. The learning algorithm (back propagation) which is widely used to train this type of network result and the known output by adjusting the weights of the connections. The algorithm has been derived independently by many researchers [43-47]. MLPs have two properties of interest, namely, abstraction and generalization ([35]). Abstraction is the ability to extract the relevant features from the input pattern and discard the irrelevant ones. Generalization allows the network once trained, to recognize input patterns that were not part of the training set [35].

3.2. Chimney processing and interpretation

Chimneys are recognized as vertically-aligned low-amplitude chaotic zones in normally processed seismic data and will often cause a frequency washout or attenuation of high frequencies [35]. Chimney processing and interpretation [7-8,19] is based on using multitude of seismic attributes to train a neural network to highlight chaotic features on the seismic data with vertical orientation. Although chimney can be seen as fuzzy regions within seismic sections, their mapping and extent is usually enhanced by a combination of multiple attributes. Attributes usually vary in their degree of sensitivities to the randomness of gases, but there is no attribute that is sensitive solely to haphazard movement of gases [19,48]. These features can sometimes be linked to gas chimneys, an indication of hydrocarbon migration to a reservoir or expulsion of gas from a reservoir.

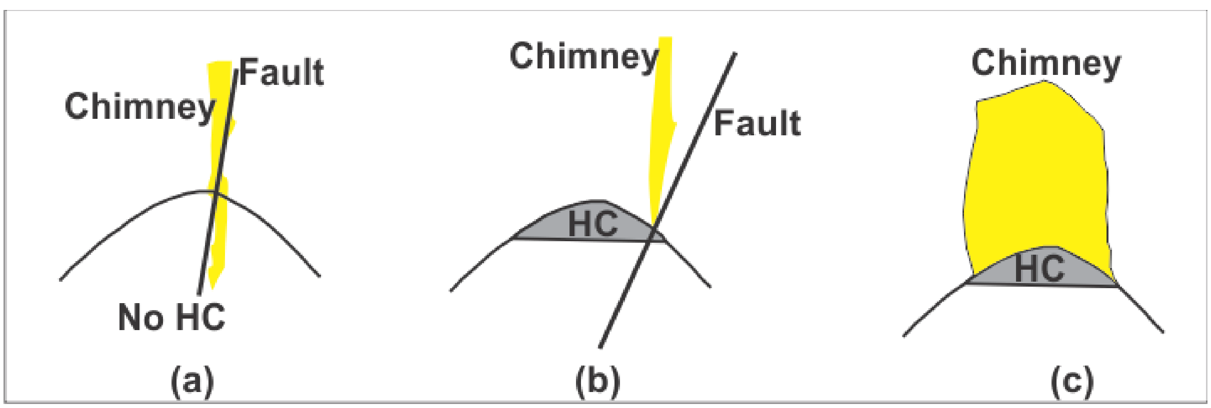

Figure 2. Class sub-division of chimney types [13] showing (a) Breached Chimney - This refers to the chimney observed when fault pass through the crest of a structure. It normally leads to the loss of the hydrocarbon, (b) Edge Chimney - This chimney class is usually observed when the fault passes through the side of the reservoir structure rather than the crest of the reservoir, and (c) Cloud Chimney - This is the type of chimney usually observed on top of an un-breached reservoir

The various types of chimneys that have been observed in different areas have been subclassed based on the presence or absence of visible faults or fractures and the dimension of the chimney. Generally, chimneys are classed into breached, edge and cloud chimneys [13].

Breached (Figure 2a) and edge chimneys (Figure 2b) are essentially associated with visible faults and have circular horizontal cross section of about 100 m in diameter. The presence of this chimney type along faults is an indication that the fault is open or have been opened in the past and that faults are or have been working as migration pathway [13]. The relative positions of breached and edge chimneys to other elements of crude oil formation is very important in interpretation. If the chimney is located at the crest of the structure, only small amount of hydrocarbon will remain in the reservoir but if the chimney is on the flank, the hydrocarbon will still be preserved [13].

Cloud chimneys (Figure 2c) are not usually associated with any visible faults but the presence of micro faults cannot be completely ruled out. Their lateral extent can span several hundred metres [13]. This type of chimney is usually seen at the top of hydrocarbon-charged reservoir or between the source and the reservoir. Cloudy chimneys represent the trail left by escaped gases from solution of upward moving waters trapped by seals or the gases migrating with relatively slow flux rate from the oil kitchen or the top of the reservoir through micro faults and fractures beyond seismic resolution. The migration rate of these gases is usually so low that it is not considered risky for the hydrocarbon remaining in the reservoir, but an indication of the presence of hydrocarbon [13].

4. Analysis and interpretation

This procedure was applied to the study area in the OpendTect™ software environment by generating steering cube [49-50]. The steering cube was computed for the entire seismic data volume using the Background Fast steering (Figure 3).

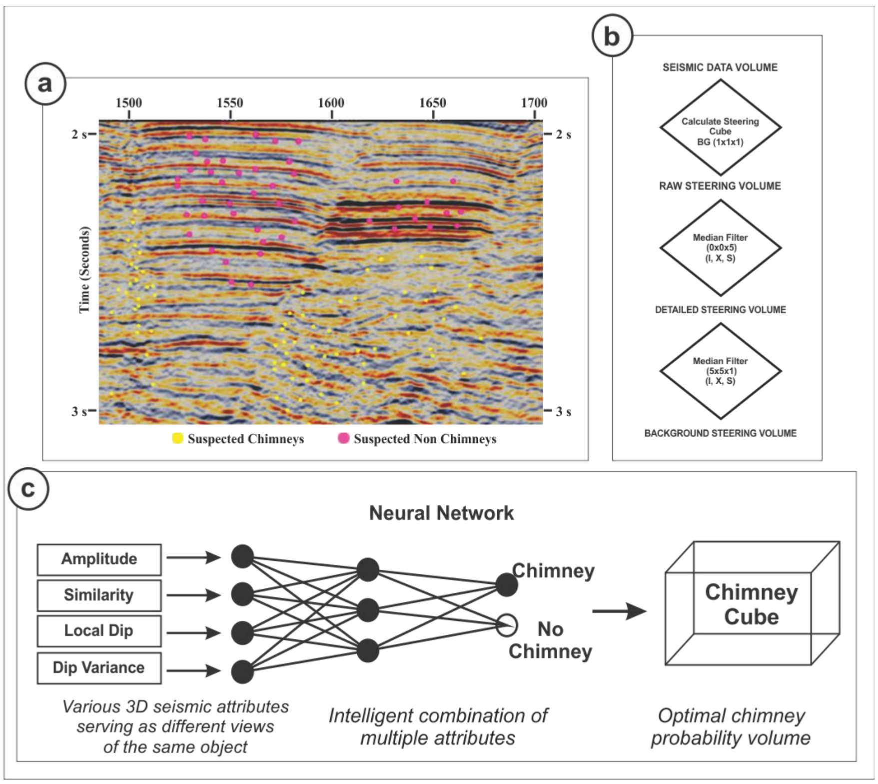

Figure 3. Fluid migration and seepage detection workflow [13] (a) selection of train locations representing suspected chimney and non-chimney areas; (b) flowchart for the generation of the background steering volume where I is inline, X is crossline, S is sample; (c) application of trained neural network to the different seismic attributes to produce optimal chimney probability volume

4.1. Gas flow and weak seals

Figure 4 shows five seismic sections between times 2000 ms and 4000 ms and respective depths 2243.33 m and 5949.70 m.

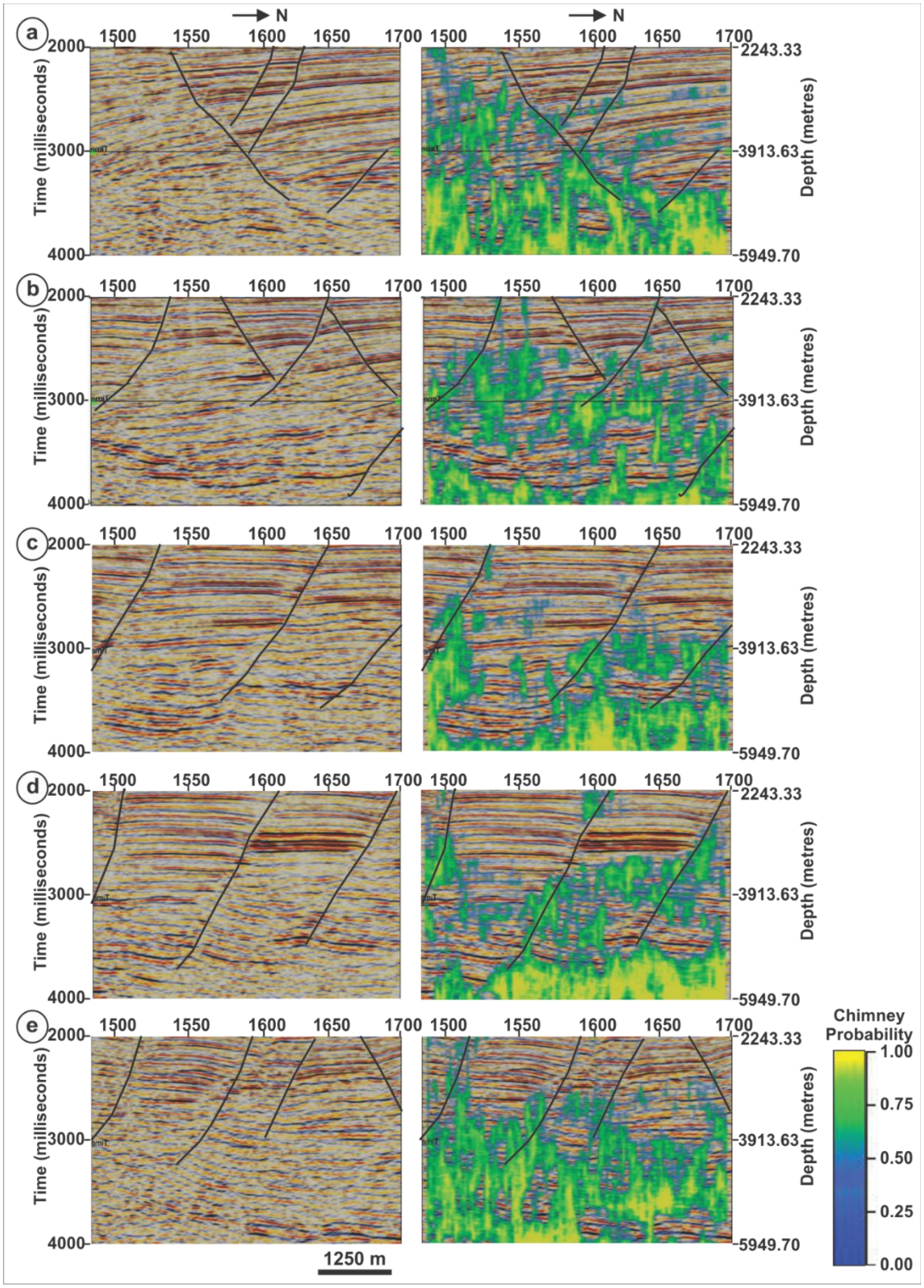

Figure 4. Showing no chimney on the left and chimney on the right indicating vertically migrating fluid on 3-D seismic sections (a) Inline 5810, (b) Inline 5900 (c) Inline 6000, (d) Inline 6100 and (e) Inline 6190

The sections are displayed such that Figure 4a which is inline 5810 is located at the western end while Figure 4e which is inline 6190 is located at the eastern end of the study area. These sections are intersected by the crosslines in a south-north direction. Hydrocarbon has been encountered within this interval in certain reservoirs especially between 2000 and 3100 ms. The seismic sections on the left have no chimney overlay while those on the right have chimney overlay. High probability chimneys are represented by yellow colour and low probability chimneys are indicated by green to blue colour. The chimney patterns vary from one seismic section to another but have higher values at deeper levels greater than 3000 ms (about 4 km). The probability of occurrence of chimney is decreasing upward. This represents migrating hydrocarbons that is able to break through the capillary pressures of overlying sediments [10] with or without faults. These chimneys indicate the quality of seals, the degree of leakage and charge which are all important aspects of determining the quality of prospects [10]. The relation between closure, seal strength and buoyancy provides an important control on the amount of oil and gas present in reservoirs, as well as its hydrocarbon type in multi-phase petroleum systems [52]. This is a useful contributor in the analysis of seal strength, trap closure, and expected hydrocarbon type, based on presence of gas chimneys and other hydrocarbon migration features [52]. For this field, therefore, it seems the charging of the overlying reservoirs [18,53] is relatively high. The quality of seals is high and so significantly less hydrocarbon is expected to migrate to the surface.

4.2. Gas flow and leaky faults

Figure 5 contains time slices with overlay of the fluid migration detection and shows active fluid migration along the faults.

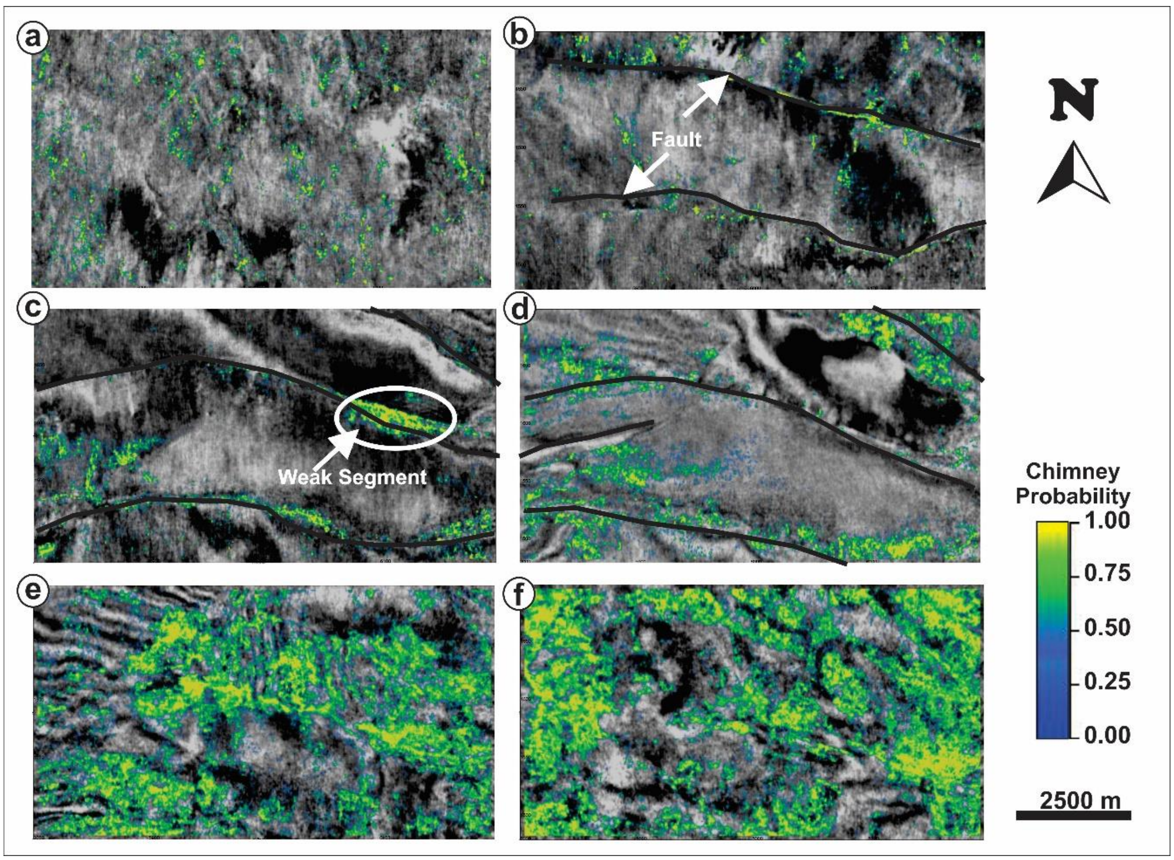

Figure 5. Two-way time slices showing no chimney on the left and chimney on the right indicating probable fluid leakages through faults at (a) 1000 ms (938.78) (b) 1500 ms, (1545.34 m) (c) 2000 ms, (2243.33 m) (d) 2500 ms, (3032.76 m) (e) 3000 ms (3913.63 m) and (f) 3500 ms (4885.94 m)

This type of visualization enhances which faults or fault segments are leaking and which parts are sealing. Seal failure is often associated with areas of locally more intense faulting and higher strain [54] and/or with local lithological variations. Fluid flow in leaking faults predominantly occur through weak sections of the fault zone. Irregularities in fault zones, such as step-overs between the fault segments, fault intersections and bends in fault zones are expected to be weak locations in fault zones and are assumed to be crucial in fluid migration [11]. Gartrell *et al.* [55] have studied fault branch lines in detail and discovered that they are zones of high dilation, in which many open fractures are present and with only minor fault gouge production, and therefore important areas for fluid migration. The presence of chimneys along faults may indicate which faults are likely to be hydrocarbon-migration pathways and in many cases, different fault systems exhibit different signatures in seismic chimney cubes. If a fault is cutting across (or near) the top of a potential hydrocarbon trap, and if gas chimneys or other features indicating fluid migration are present along the fault at the structural high, the prospect can be regarded as a high risk with respect to presence of hydrocarbons [13]. Faults without detected fluid migration are assumed be sealing or having only low-fluid flux [10,13]. In this case, it can be seen that high chimneys values are associated with some zones within the visible faults between times 1500 ms and 2500 ms. These are edge and breached chimneys where segments of the faults appear to be weak and thus act as fluid migration paths. This segmentation in leakage intensity along faults may be related to variations in lithology along the fault or to variations in the pressure regime [10]. The seepage rate should be directly proportional to the weakness of the faults at these zones. At times 1000 ms, 3000 ms and below, the chimneys are not associated with visible faults and are classified as cloud chimneys representing very slow flux rates [10,13].

4.3. Gas flow and potential surface hazard

Table 1 describes the areal distribution of chimneys with time and depth from the time slices (Fig. 5). This is a calculation of the ratio of the area of the proportion of chimney per time slice to the total area of the time slice in square kilometres. The depth was calculated using velocity data. The proportion of chimney in percent varies between about 58% in time slice 5000 ms and about 3% in time slice 500 ms. This is related to the vertical flux rate of the migrating hydrocarbon. In this study, the proportion of chimney (Ch) with depth (D) represents a second-order polynomial with intercept of zero such that

$$Ch = 6.0\times10^{-7} D^2 + 0.0035\, D \quad (4)$$

The higher proportion of the chimneys at deeper level might be due to closeness to hydrocarbon generation and accumulation zones while the decrease at the shallower level might be due to reduction in seepage and high sealing effect of the surrounding formations. The potential for geohazard features is rather slim. Although, the presence of small amount of chimneys on time slice 500 ms (about 423 m) below the surface may be a pointer to the fact some gas might eventually escape, depleting reserves to form pockmarks and other structural geohazard features at seabed over time [56-60].

Table 1. Areal Distribution of Chimney as a function of Two-Way- Travel-Time and Depth)

Time slice (ms)	Depth (m)	Total area (km^2)	Area of chimney (km^2)	Proportion of chimney (%)
500	423.67	55.38	1.85	3.34
1000	938.78	55.38	4.00	7.22
1500	1545.34	55.38	6.45	11.65
2000	2243.33	55.38	9.20	16.61
2500	3032.76	55.38	12.25	22.12
3000	3913.63	55.38	15.60	28.17
3500	4885.94	55.38	19.25	34.76
4000	5949.70	55.38	23.20	41.89
4500	7104.89	55.38	27.45	49.57
5000	8351.52	55.38	32.00	57.78

Figure 6a shows the 3D view of the horizons (H1, H2 and H3) approximating the tops of reservoirs, well logs, seismic section at the background and the chimney overlay while Figure 6b is a chimney cube of the whole seismic volume. These displays are with the view to observing the 3D nature of the chimneys characterizing the vertical migration of hydrocarbon through the formations. The figures confirm that the upward movement of hydrocarbon is pronounced at deeper levels because of the higher values of the chimneys and reduced towards the shallower levels because of the lower values of chimneys. The weak zones of the regional faults and effects of micro-faults within the Agbada Formation could have been responsible for this upward movement at the deeper levels while the increasing quality of regional and local seals upward could be responsible for the diminishing vertical migration of hydrocarbon to the shallower levels.

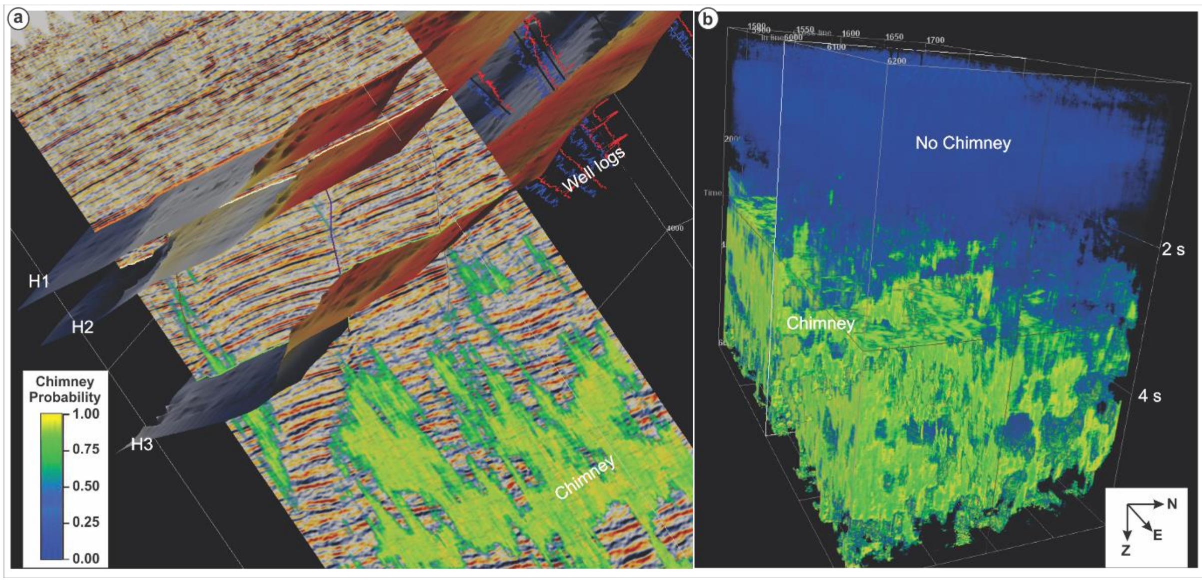

Figure 6. 3D view of vertical chimneys indicating hydrocarbon presence and flow

5. Conclusions

The importance of detecting gas chimneys as guide to exploration efforts have been shown by using the pattern recognition technique of neural network-derived chimneys from multiple seismic attributes. The chimney outputs exhibit the probable extent of active hydrocarbon flow from the source (Akata and Agbada shales) to and between the reservoirs and the effecttiveness of the local and regional seals. The field has both edge, breached and cloud chimneys at different depths. The fault zones that have high chimney values are associated with weak zones that act as conduits for hydrocarbon seepage. This should be a consideration in the effective exploitation of the hydrocarbon resource in the field.

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