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ORIGINAL ARTICLE

Gas channels and chimneys detection using post-stack seismic attributes, simian field, offshore west Nile Delta, Egypt

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Abstract

The West Delta Deep Marine region has substantial prospects for extracting oil and gas. The area is also known for its distributed and disconnected channel systems and gas chimneys. The Simian field is particularly intriguing within this region. Gas chimneys and pockmarks are frequently observed on the seafloor. Pockmarks are formed when gas or fluid is released, causing depressions. These characteristics have the potential to influence the stability of the seabed and present hazards to oil rigs in proximity. To reduce the risks associated with these hazards, it is essential to have a thorough comprehension of the geological characteristics involved. The primary objective of our study is to identify and delineate gas channels and chimneys and the associated geologic features through the analysis of seismic attributes and the construction of three-dimensional models. By applying multiple seismic attribute classes such as the cosine of the phase, variance, and envelope, the detection of these hazards and associated features can be improved. We were able to identify and isolate areas of high-intensity brightness in the vicinity of the Simian gas channel. These high-intensity brightness zones serve as clear indicators of gas seepage and the movement of gas. In addition, there is substantial evidence of gas being discharged from a high-pressure zone upwards to the seafloor through the gas chimney and eventually creating pockmarks that pose a serious hazard area to the hydrocarbon production process. Upon completion of this study, after linking the presence of the subsurface marine geological features and the hazardous risk these features might propose. The optimal site within the study area for the placement of an oil rig with the aim of mitigating the impacts of capillary action is recommended. The results enhance risk avoidance and regulatory measures in this highly significant field.

Keywords Offshore Nile delta · Gas chimneys · Gas channels · Seismic attributes · Hazard evaluation · Simian field

1 Introduction

The WDDM is in the Mediterranean Sea, north of Egypt. WDDM is situated within the concession of Egypt. It is known for its substantial reserves of hydrocarbon resources and is located approximately 125 km NE of Alexandria. Simian Field is found at the northwest edge of the offshore region, around 120 km away from the Alexandria shoreline in the WDDM concession, at coordinates of latitudes 31° 42′ 12’’ and 32° 19′ 58’’ N and longitudes 30° 7′ 12’’ and 31° 4′ 48″ E (Fig. 1). The Simian channel is positioned at the late Pliocene [13].

Gas chimneys and gas channels are significant geological features linked to the movement of fluids in the Earth's underground. Gas chimneys, notable as vertical disruptions in seismic data, signify the upward flow of fluids, such as hydrocarbons, they can occur due to the discharge of high-pressure gas or cracks in the sedimentary column. These occurrences are particularly important in locations such as WDDM since they have an impact on the production of gas hydrates and seafloor seepage. Gas channels serve as pathways for the movement of gases from source rocks to reservoirs, and they play a crucial role in the discovery of energy resources and the evaluation of geohazards. In addition, associated features like bright spots. The presence of

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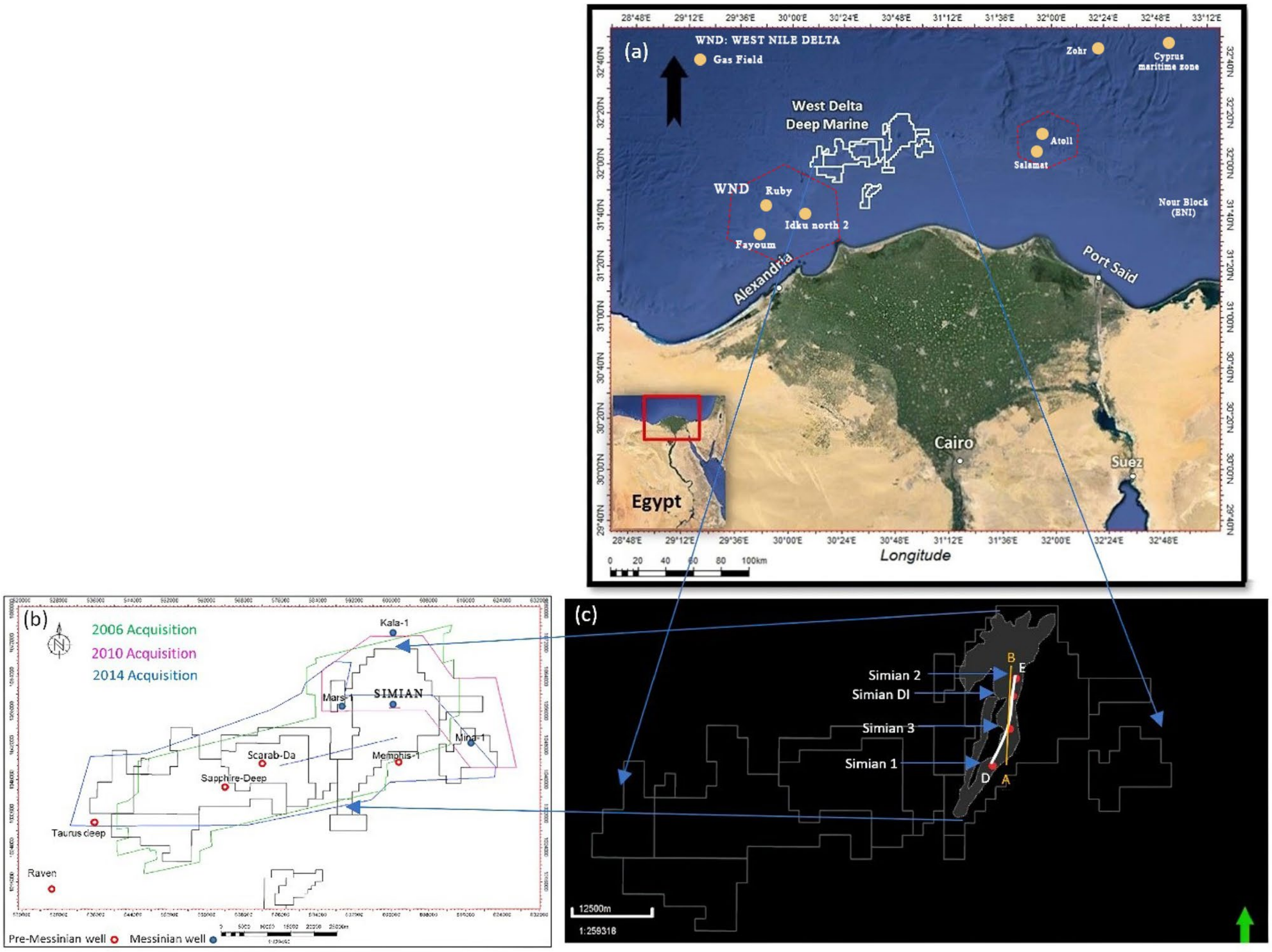


Fig. 1 **a** The Study area and map of Egypt shows the location of the WDDM concession, modified from Google Earth. **b** The WDDM concession was modified after [10]. **c** Locations of provided wells' data in this study and A-B, D-E seismic cross-sections

bright spots in seismic data indicates the likely existence of hydrocarbon deposits in close proximity and also supports the idea of gas seepage.

In seismic data, Gas chimneys and gas channels and their associated geological features are interpreted by the high amplitude or the high energy regions, since each geological feature has its characteristics and properties, Geophysicists can spot the geological features from the seismic sections, by applying advanced geophysical techniques like seismic attributes, Geophysicists extract and interpret these features from the seismic sections.

Seismic attributes are crucial for differentiating between hydrocarbon-bearing areas and non-productive areas. Accurate identification of reservoir boundaries in the Nile Delta is especially important due to the restricted connectivity of hydrocarbon reservoirs at the WDDM, which hampers conventional seismic data interpretation. The discharge of fluids under high-pressure results in the creation of significant geological formations, such as seabed Pockmarks. The WDDM often exhibits these characteristics, Pockmarks are typically situated above gas chimneys, resulting in a gradual release of gas. Assessing the potential hazards associated with pockmark activities is essential for offshore installations, operations, and drilling to prevent catastrophic incidents in the future. Moreover, the existence of gas channels has the potential to improve the refilling of nearby gas chimneys, highlighting the significance of understanding these subterranean dynamics. Four seismic attributes have been implemented in this study, the phase attribute, when used in conjunction with the cosine function, is valuable for representing and understanding intricate structural patterns. The variance attribute is primarily used to detect discontinuities, faults, and chaotic regions in the data. The envelope attribute is employed to compute the total instantaneous energy, encompassing both the real and imaginary constituents, of seismic traces. Furthermore, the RMS attribute exhibits a strong sensitivity towards hydrocarbon-bearing zones, making it a valuable tool for identifying areas of interest. The utilization of seismic attributes and 3D models can proficiently illustrate the reservoir properties and structural characteristics within the designated study area.

Petrel is a robust subsurface modelling software developed by Schlumberger. It empowers geoscientists and reservoir engineers to seamlessly transition from exploration to production. Key features include geological modelling, where users can create accurate 3D representations of stratigraphy and structures and petrophysical modelling. Petrel can apply Seismic attributes to the provided seismic data to obtain better information about subsurface features, allowing for a more thorough understanding of the geological and structural properties of the reservoir. As a result, this leads to an improved understanding of the reservoir's properties and a more accurate representation of the reservoir in models. The key part of geophysical exploration involves the serious examination of faults and subsurface characteristics using 3D model dissection. Using advanced 3D techniques in Petrel allows for precise identification and tracking of geologic features in the subsurface. By dissecting the 3D model along different planes, one can obtain a precise visualization of geologic features like gas channels, gas chimneys, pockmarks, domes, and fault zones, and their potential for causation. This level of specificity offers a crucial understanding of the structural soundness of the underlying layers.

Seismic attributes and 3D modelling are used together to gain insight into the location and creation of pockmarks, which are evidence of past or current fluid escape and potential instability of the seabed. The comprehensive 3D visualization enables a meticulous evaluation of subsurface conditions, facilitating the positioning of drilling infrastructure in stable regions. This integrated methodology not only mitigates operational hazards such as seabed sinking but also guarantees the structural soundness of wells. Geophysicists can utilize these advanced techniques to make well-informed decisions that improve safety, safeguard the reservoir, and ensure the long-term success of production activities.

In July 2021, a subaquatic gas pipeline experienced a rupture in the Gulf of Mexico, resulting in the release of natural gas into the adjacent water. The gas bubbles that managed to escape rose to the surface of the sea and ignited without any external ignition source, causing visible flames. On a natural phenomenon scale, the gas leak gathers at the domes located on the subsea surface and subsequently leads to their collapse due to the high pressure, resulting in the formation of pockmarks afterwards (Fig. 2). Hypothetically, the ignition of the gas can occur due to the friction between the discharged gas and the surface of the sea. Conversely, the depressions formed at the seafloor have a direct impact on the stability and operational safety of the surrounding offshore oil rigs. These incidents can have environmental consequences because they may cause damage to marine ecosystems and pose safety hazards to nearby vessels and workers.

The main theme of this study is to delineate the hazardous geological features to improve both the safety and efficiency of oil and gas exploration and production. The study utilizes the integration of seismic attributes and 3D modelling to gain a comprehensive comprehension of subsurface characteristics, including gas chimneys and pockmarks. By employing this comprehensive approach, geophysicists can effectively and precisely identify and steer clear of dangerous areas, thus mitigating the risk of accidents and minimizing any potential negative effects on the environment. Furthermore, the study aids in maximizing the positioning and structure of wells, resulting in enhanced resource extraction efficiency and decreased operational expenses. In conclusion, the research results enhance the dependability, security, and efficiency of oil and gas activities, guaranteeing improved resource management and reduced risks.

2 Geological background

2.1 The WDDM concession

The WDDM concession in Egypt is an area of great potential for gas and oil exploration approximately 30 to 40 trillion cubic feet of natural gas and significant oil reserves according to the Egyptian General Petroleum Corporation (EGPC). Covering approximately 1366 square km with water depths ranging from 150 to 1200 m, the hydrocarbons in the Nile Delta are primarily found in the Neogene-Quaternary sequence [22, 34], which consists of the Miocene, Pliocene, and Holocene sedimentary successions (Fig. 3) [2].

2.2 Structural settings

The structural pattern of the study area is influenced by three major trends:

- The NW-oriented Temsah trend.
- The NE-oriented Rosetta trend. [35]
- The E-trending faults identify the boundaries of the Messinian salt basins.

Faults are primarily responsible for controlling the southern margin of the Upper Miocene salt basin. This is evident from the abrupt change in structural styles across an E-W lineament, where the stable southern platform transitions into a rotated northern fault block zone.

The Simian exhibits a blend of stratigraphic and structural attributes. The reservoir demonstrates stratigraphic closure along its entire length and a combination of dip and reservoir pinch-out at its southern boundaries. The claystone of the El

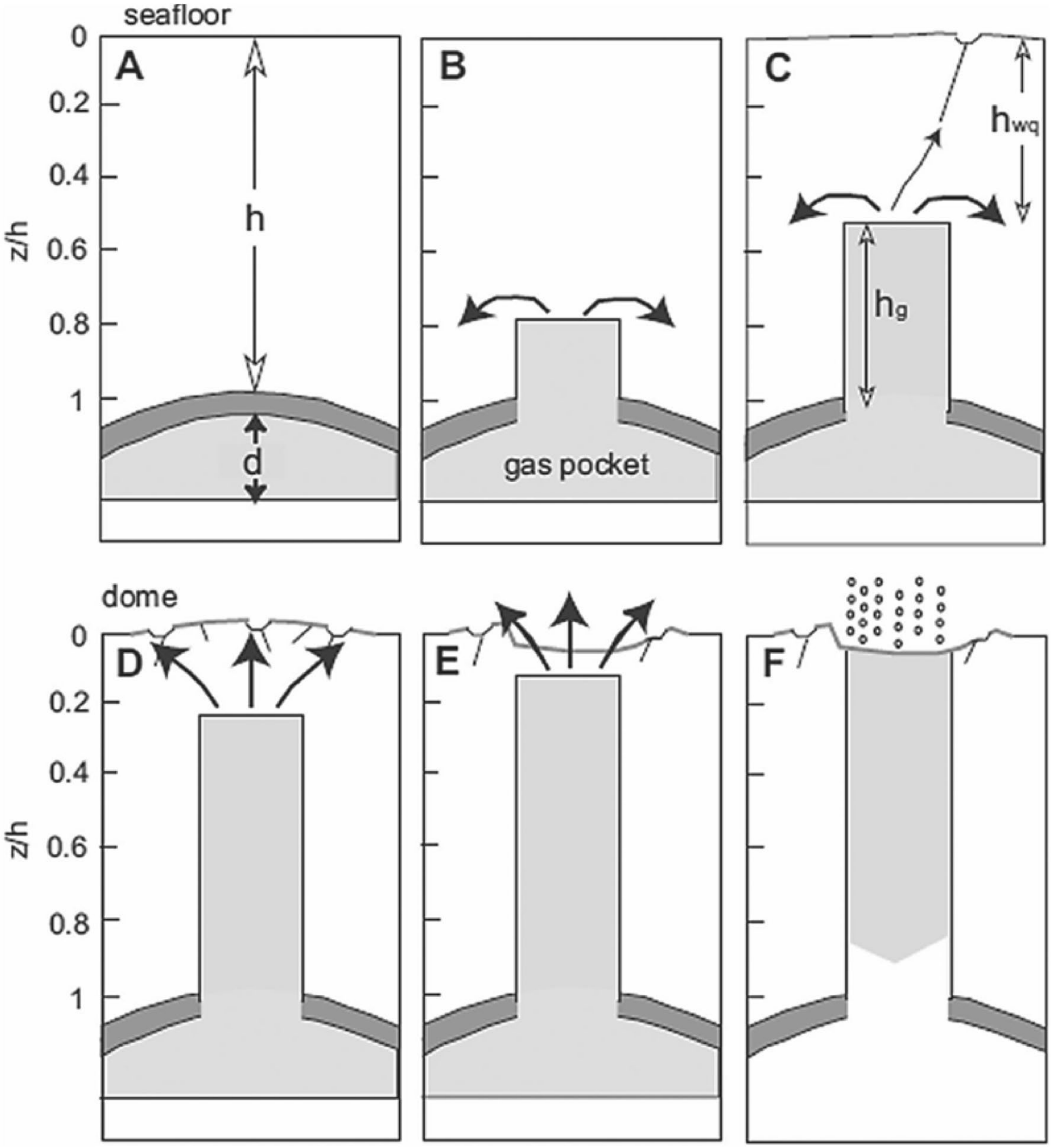


Fig. 2 Schematic depiction of the development and the movement of a gas diapir towards the seafloor [6]

Wastani Formation serves as both the upper and main lateral barriers [13]. The Simian gas field is located in the eastern section of the WDDM concession and contains gas that dates back to the Pliocene era. It is situated at depths that vary between 500 and 1500 m. The current alignment of the Nile Delta offshore anticline (NDOA), which extends in an east-northeast to west-northwest direction, and the Rosetta fault, which extends in a northeast-to-southwest direction [12], have been influenced by important tectonic events. The rotational movement of the African plate towards the Eurasian plate has resulted in the formation of these structural features through wrench tectonics [11].

The North of Egypt region occupies a crucial role in the plate tectonic evolution of the eastern Mediterranean basin. Positioned on the northern margin of the African plate, this region stretches from the subduction zone neighbouring the Cretan and Cyprus arcs to the Red Sea rift basin, which diverged from the Arabian plate [8]. Deep-water reserves in the area have primarily been discovered in Cenozoic and Mesozoic sandstone reservoirs, accounting for approximately 90% of the reserves. In deep marine environments, shale is the predominant form of top seal, although its presence alone is not sufficient as seal integrity poses a significant risk. Source rock potentiality is significant in deep

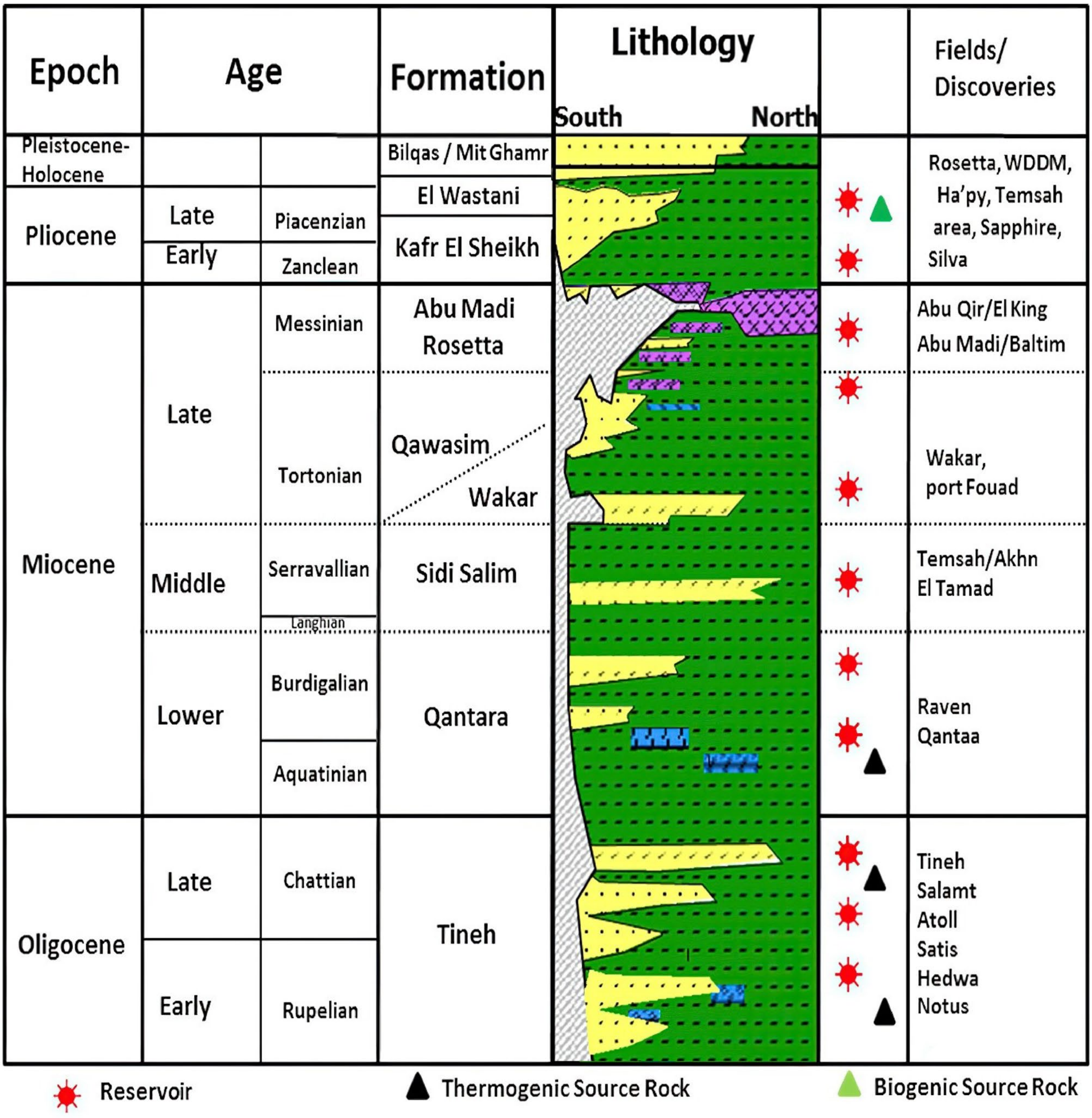


Fig. 3 The Nile Delta stratigraphic column and the hydrocarbon system in the region [35]

marine environments, with most source rocks ranging from the Mesozoic to the Cenozoic ages. These rocks can come from the continents or the oceans. They include lacustrine, terrigenous deltaic, and deep marine deposits linked to major transgressions or relative increases. As a result, hydrocarbon compositions vary and can include biogenic gas, waxy oil, Sulphur-rich oil, and asphaltenes.

The WDDM has a slope channel complex system that was deposited during the early Pliocene (Fig. 3) [42]. The stratigraphic succession of the Simian Field consists of the Bilqas Mit Ghamr, El-Wastani, and Kafr El-Sheikh formations (Figs. 4 and 5), with the El-Wastani formation serving as the primary producing reservoir in the field.

Presently, the Upper Miocene and Pliocene sections are considered to be the main reservoir targets in the Mediterranean Block [1, 33]. Throughout the Oligocene to Pliocene-Pleistocene periods, gas is generated and accumulated at various levels within the stratigraphy. The primary reservoir of the Upper Miocene, equivalent to the Upper Messinian, is found in the Abu Madi Formation. On the other hand,

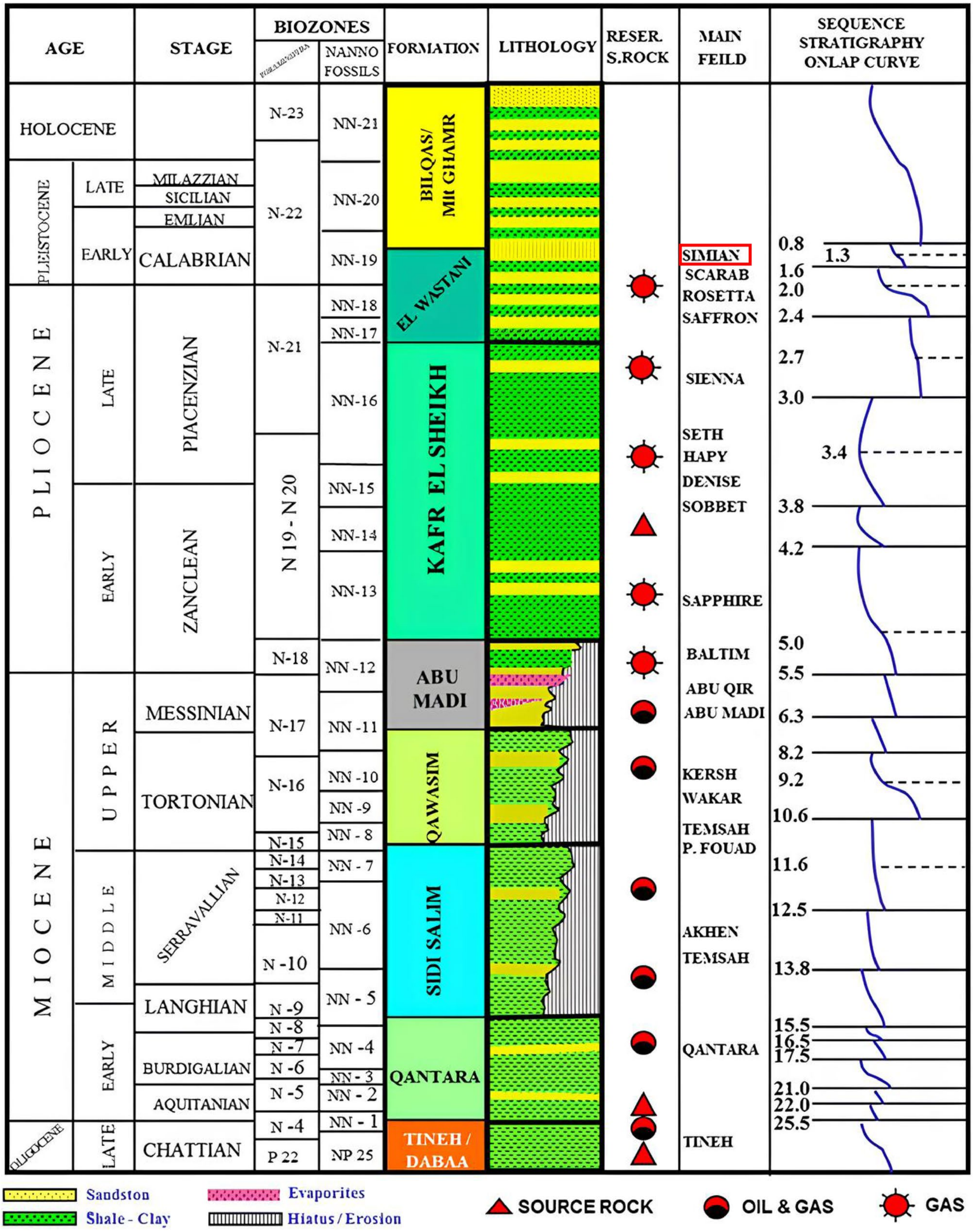


Fig. 4 The litho-stratigraphic column of the WDDM concession, which includes the Simain field [45, 46] [50]

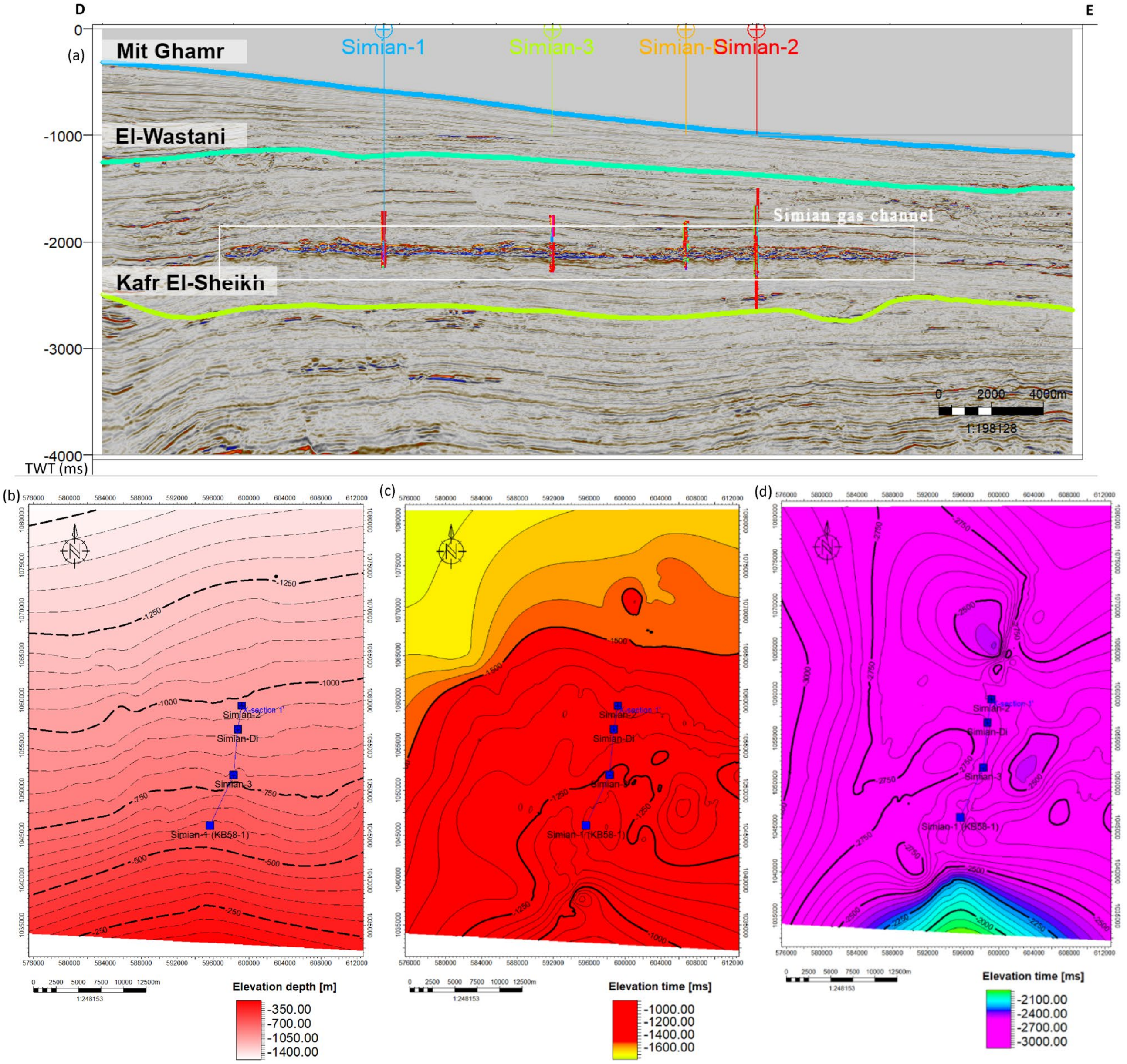


Fig. 5 **a** DE seismic section showing the main gas channel and well data, (**b**, **c**, and **d**) show the surface maps of the picked horizons Mit Ghamr, El-Wastani, and Kafr ElSheikh respectively

reservoirs of the Pliocene are primarily represented by the Kafr El Sheik and El Wastani Formations [1]. These findings provide essential insights into the hydrocarbon system within the Nile Delta region.

2.3 Gas chimneys and pockmarks

Identifying near-surface gas accumulations is essential for offshore activities, such as drilling and installing equipment. The presence of pockmark activities near existing platforms can result in highly dangerous events with the potential for catastrophic consequences. The occurrence of pockmark activities is determined by the continuous presence of gas and the durability of the pathway through which it is released. Engaging in these activities can result in the discharge of a substantial volume of fluid, leading to a catastrophic occurrence (Fig. 2) [44].

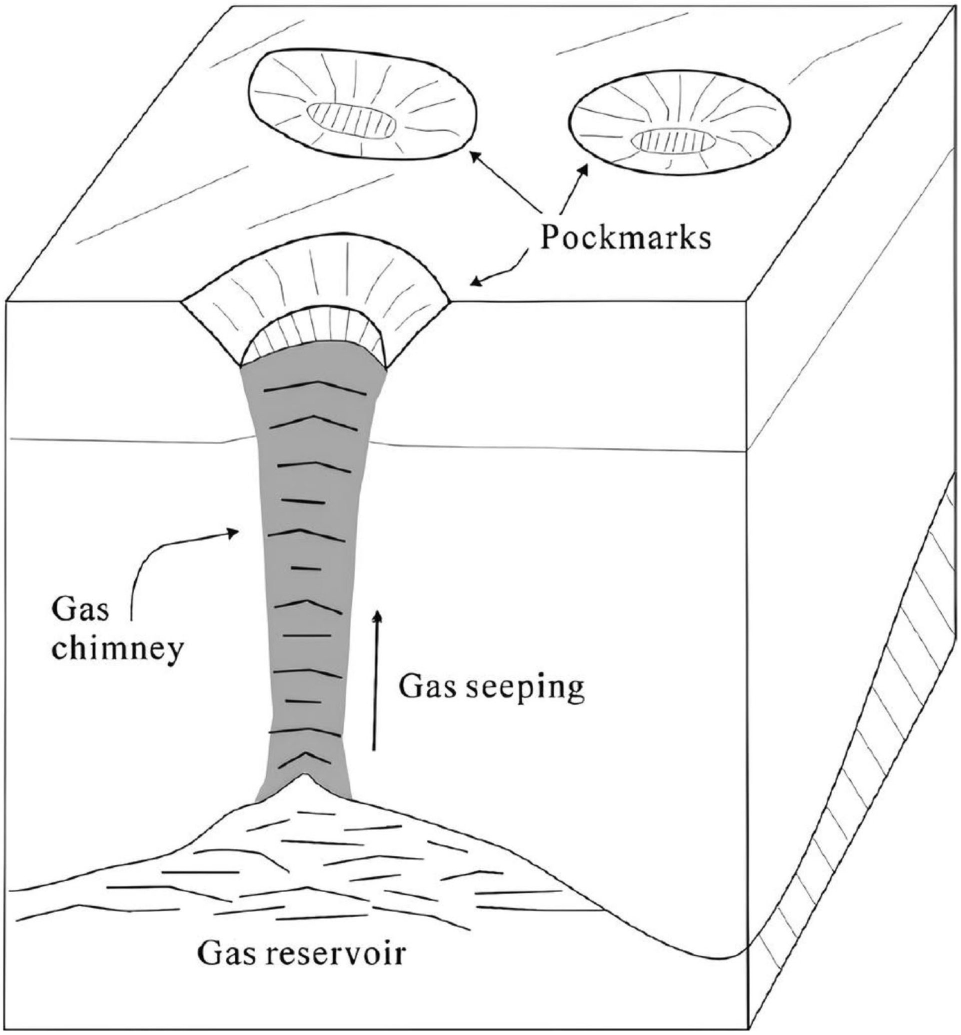
The escape of high-pressure fluids is the cause of significant geological features, including seabed pockmarks. They serve as preliminary indicators of explosive gas eruptions [28]. The presence of gas hydrates has been revealed by the seismic reflection profiles of ocean floor sediments [30]. Pockmarks are identified by a gas plume situated in their centre [31, 32]. Near-surface gas is the most prevalent cause of blowouts, as indicated by a study conducted by the Norwegian research organization SINTEF (22% of 172).

Gas chimneys are an inadequate data zone because seismic energy is dispersed by the scattered gas in the cap rocks above the leaking reservoir. There are several locations in the Pliocene that contain thermogenic gas, which is definitely produced by units that existed before the Messinian period. This has been confirmed by a geochemical study conducted by [55]. The chimneys found in the Nile Delta exhibit structural and morphological characteristics that are often seen in volcanic eruptions [5]. Fluids ascending through a sedimentary sequence can cause rocks to fracture or undergo chemical changes, resulting in the formation of gas chimneys due to the presence of connate gas. When the fluid reaches the surface, it creates pockmarks (Fig. 6), the presence of gas induces variations in the compressional velocity field, leading to the dispersion and degradation of a seismic wave as it passes through. Gas builds up until its pressure is high enough to penetrate the seal. The seal subsequently malfunctions entirely, resulting in the discharge of a significant portion of the collected gas into an ascending gas chimney [17].

Pockmarks are geological formations resulting from the release of fluids through the seafloor, which leaves sunken depressions on the seabed and serves as evidence of seepages in different sediment layers (Fig. 6). In addition, the significant magnitude of the gas release incidents can have a physical impact on the sinking of ships due to the loss of buoyancy caused by rising bubbles underneath them. It can also lead to the collapse of rigs and platforms, where the gas might disrupt the structures or activities even before it reaches the bottom. Seafloor seepages can be found in several geological settings, including the continental shelf, the deep ocean, and the slope in between [19].

In 2010, Cathles, Su, and Chen presented an illustration of how gas release leads to the expansion of microscopic fissures, intensifies seabed erosion, and increases venting velocity. This ultimately results in a forceful release of gas, forming a single pockmark [6]. (Fig. 2) Demonstrates the gradual development of the pockmarks; (A) illustrates the

Fig. 6 Gas chimneys often have pockmarks on their surface. The persistent and gradual release of gas through the chimneys supports the growth of vent communities, which in turn generate carbonate mounds inside the pockmarks [6] [18]



confined gas under high pressure that results in the seal rock (dark grey) bending. (B) The seal fails when the gas is sufficiently dense and under enough pressure to penetrate the seal rock. Gas is then transported to the upper layers via a chimney, and ater (represented by arrows) is charged as the chimney travels through the sediments to the seafloor. Areas that are saturated with water are characterized by a translucent color. (C) The seafloor begins to deform, and minor faults and fractures begin to form. The buried pockmark or chimney reaches approximately halfway to the seafloor. (D) Subsequently, the deformation of sediment above the chimney increases, fluids begin to escape through the seafloor, the seafloor assumes a dome shape, and pockmark formation becomes more frequent. (E) The associated fractures and collapses, as well as the minor pockmarks, merge into a "full-grown" (F) pockmark.

The interpretation and study of fluid flow in sedimentary basins are crucial for many environmental, ecological, and safety purposes [7, 14, 57]. The movement of fluids that have migrated through chimneys and shallower faults around chimneys can have an impact on the potential instabilities of slopes [52]. This can pose a hazard to human operations and significantly affect offshore drilling operations in terms of safety, environment, and cost [29].

3 Methodology

The digital datasets acquired from Rashpetco Oil Company encompassed data from four wells and 20 2D seismic lines. In addition, checkshots were used to establish a correlation between seismic data and well data in order to improve the accuracy of the final interpretations. The methodology employed in this study can be visualized in (Fig. 7).

3.1 Conventional interpretation

After importing the data, the well logs were matched to the seismic data. This process involves connecting the different layers identified in the well logs and then establishing a relationship between these layers and the seismic data by utilizing the checkshot information. Ensuring the accurate correlation between the well and seismic data was a crucial step in this process (Fig. 8). By accurately correlating the well logs and seismic data, the seismic lines were used to identify and outline the structural and tied stratigraphic features. Once the well logs and seismic data have been accurately correlated through Synthetic seismogram showing the expected seismic response based on the checkshot data. These help in understanding how accurate the seismic data should look if the checkshot model aligned with the seismic section. (As shown in Fig. 8).

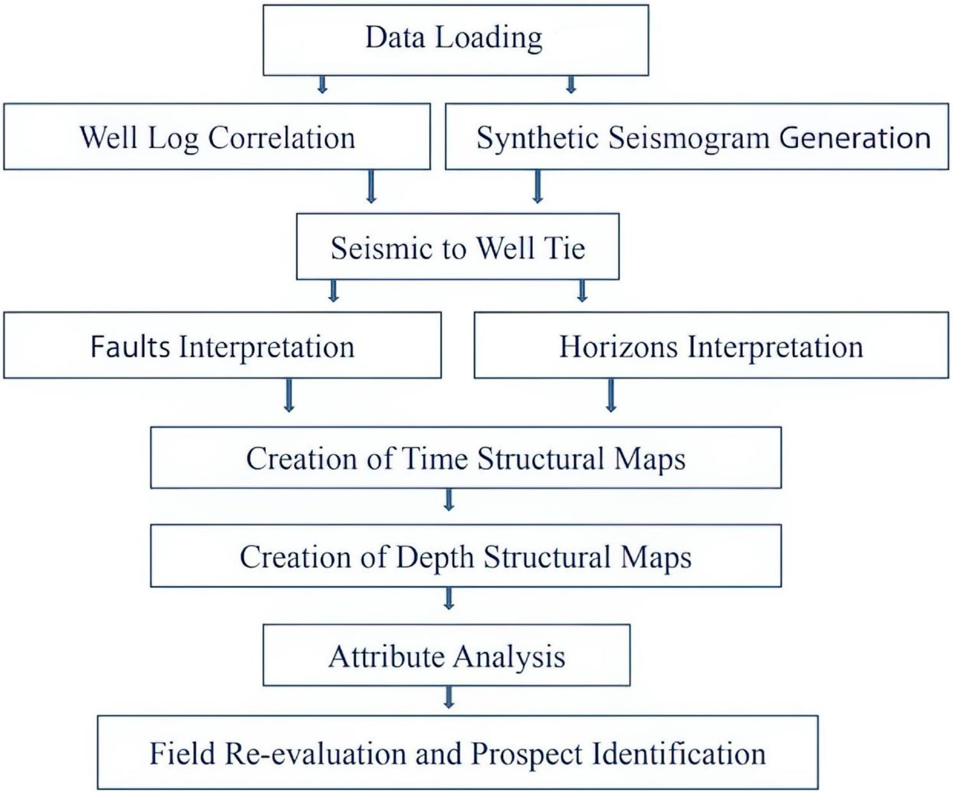


Fig. 7 Flowchart of the main steps performed in the present work

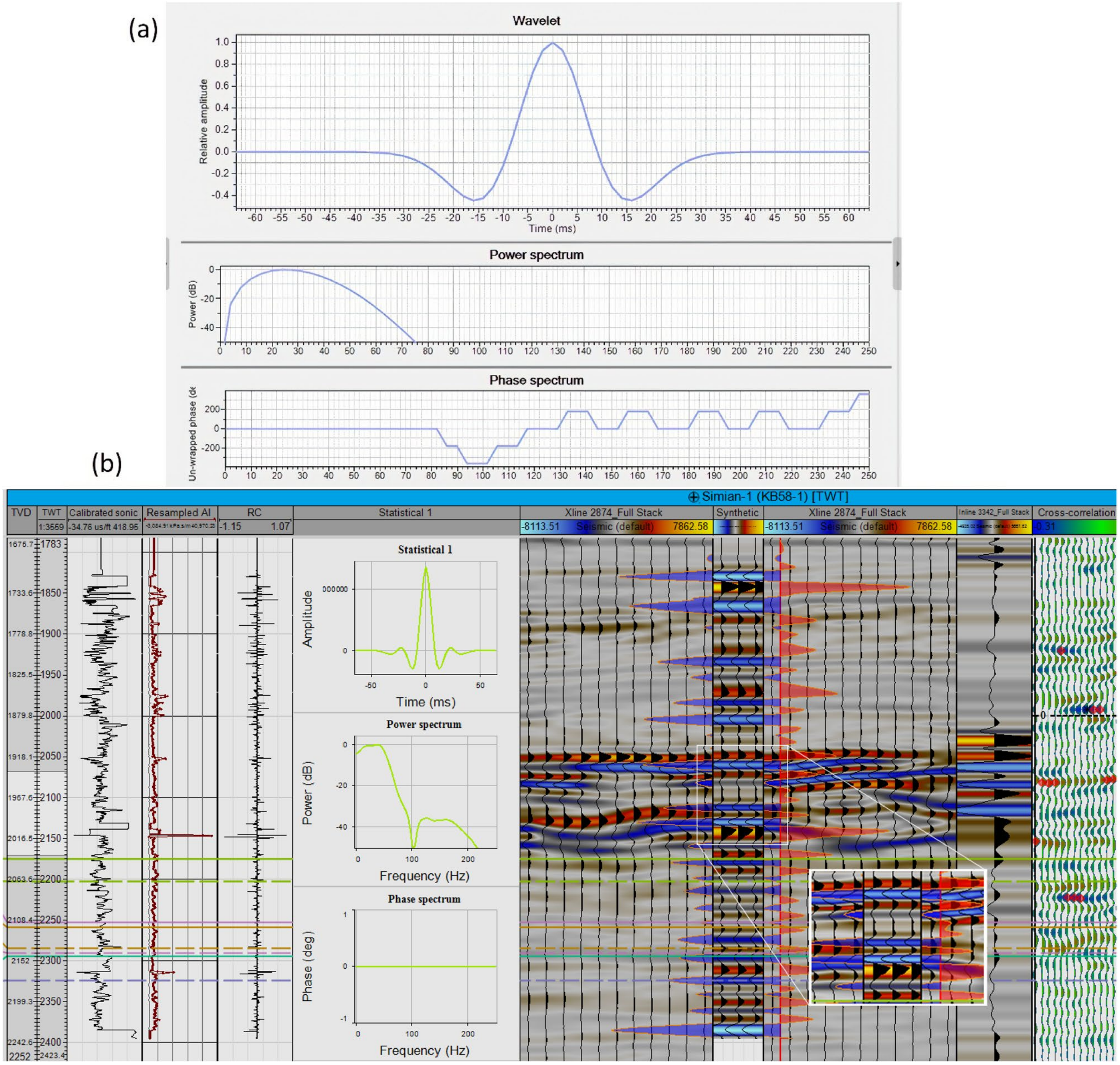


Fig. 8 **a** Analytic wavelet with time response on top, respective power spectrum at mid, and unwrapped phase at the bottom, **b** the well-tie by petrel software using simian-1 well and the extracted analytic wavelet

Traditional horizon interpretation entails the selection of horizons and structural characteristics, such as geological faults. In order to accomplish this, an interpreter initiates the process by identifying noteworthy reflections and subsequently generates colour maps using two-way time (TWT) as a basis. These color maps facilitate the extraction of valuable information regarding subterranean geological characteristics. However, what if we require a more sophisticated approach to visually augment or quantify noteworthy characteristics? Now, we will discuss the non-traditional analysis of seismic data using seismic attributes.

3.2 Seismic components

Seismic data contains amplitude, frequency, geometry, and texture data [8, 23]. Seismic attributes play a crucial role in interpreting seismic reflections by amplitude values and all geological features observed in the data [8]. Seismic attributes have been widely used to characterize faults and identify hydrocarbon reservoirs [8, 24, 37–39, 55, 56]. Amplitude attributes, such as Root Mean Square (RMS) and average energy, are particularly useful for stratigraphy and reservoir properties [8]. Bright anomalies in amplitude attributes often indicate the presence of hydrocarbons [26].

Seismic attributes like trace-to-trace similarity and amplitude (or energy) are key in identifying chimneys and other geological features [16]. These attributes can help identify irregular sedimentary bodies, faults, bright spots, and other features that may not be easily detected through conventional interpretation.

3.3 Seismic attributes

Seismic attributes are quantitative measures of specific seismic characteristics and play a vital role in interpreting seismic reflections by quantifying the amplitude and shape features observed in the seismic data [8]. Seismic attributes have found widespread application in characterizing faults and identifying hydrocarbon reservoirs [11, 27, 56]. In particular, amplitude attributes are very useful and reliable for solving problems related to stratigraphy and reservoir properties, especially in thin-bed reservoir settings [15]. Root Mean Square (RMS) in this study discriminates between high and low energy levels which is effective for identifying hydrocarbon prospects, as they indicate the presence of bright anomalies.

In chimney identification, the initial step involves leveraging seismic attributes that markedly improve detection methods. Extracting various seismic attributes such as RMS, envelope, chaos, variance, and cosine of the instantaneous phase is particularly effective for identifying irregular sedimentary bodies, gas chimneys, faults, bright spots, pockmarks, and other associated features. These attributes are essential as they facilitate the detection of features that may not be readily identifiable through conventional interpretation and horizon picking alone.

3.3.1 Cosine of the phase attribute

Is considered a geometric attribute that offers the advantage of smoothing oscillations between peaks and troughs (Fig. 11b). It is particularly useful in improving the continuity of reflectors and enhancing the visualization of faults and stratigraphic boundaries [9]. It also aids in imaging structural complexities. In this study, there are various complexities, such as shallow fault zones, gas chimneys, domes, pockmarks, and their associated features in the original seismic dataset (Figs. 10 and 11). These complexities can have an impact on the lateral continuity of reflectors. By utilizing the cosine of the phase attribute, you can better understand and visualize these complex geological features.

3.3.2 Variance attribute

Is a geometric attribute that is utilized to calculate the local variance of the seismic signal. It is primarily used for detecting faults, and chaotic zones in the data. The variance attribute plays a significant role in enhancing the visualization of shallow faults near gas chimneys and pockmarks (Fig. 11a) compared to the Cosine of the phase attribute (Fig. 11b). It is particularly valuable in improving the imaging of fault zones and major sequence boundaries [43]. Additionally, the variance attribute is crucial in measuring the dispersion of waveforms around the mean value, making it one of the key factors in waveform analysis.

3.3.3 Envelope attribute

The envelope attribute is recognized as the most reliable and stable (Fig. 13a) [8]. It calculates the total instantaneous energy (including both real and imaginary components) of a complex seismic trace, with the imaginary part derived from the Hilbert transform [54]. Studies have demonstrated the envelope attribute's effectiveness in analyzing seismic signals in shallow offshore regions, regardless of their amplitude levels. It proves especially valuable in identifying and studying bright spots, which denote areas of distinct reflectivity. Unlike other attributes, the envelope attribute is phase-independent, offering detailed insights into reflectivity contrasts. Elevated envelope values typically indicate potential gas accumulation, changes in lithological and depositional environments, and the presence of bright spots [4, 25].

3.3.4 RMS attribute

The RMS attribute plays a crucial role in extracting information about the energy content of seismic data. It is particularly sensitive to hydrocarbon-saturated zones and can be utilized to identify prospective areas (Fig. 13b) [24, 41]. Typically, the RMS attribute is obtained by calculating the root mean square of the original seismic trace amplitude. It serves as a valuable gas indicator, enabling discrimination between high-amplitude zones (bright spots), low-amplitude regions, and chaotic areas (such as gas chimneys) on the seismic profile [25].

4 Results and discussion

The research study in the Simian field aims to identify the precise positions of deep seafloor pockmarks, gas chimneys, faults, and other structures associated with these phenomena (Figs. 9, 10, 11, 12 and 13). Different seismic attributes were employed to process and extract information, leading to the creation of improved 2D seismic sections. These sections were subsequently analyzed to identify both direct and indirect indications of near-surface gas presence by examining various seismic attributes.

Figures 12 and 13 Present seismic data that shows bright spots, intensified reflectors, gas chimneys (also known as

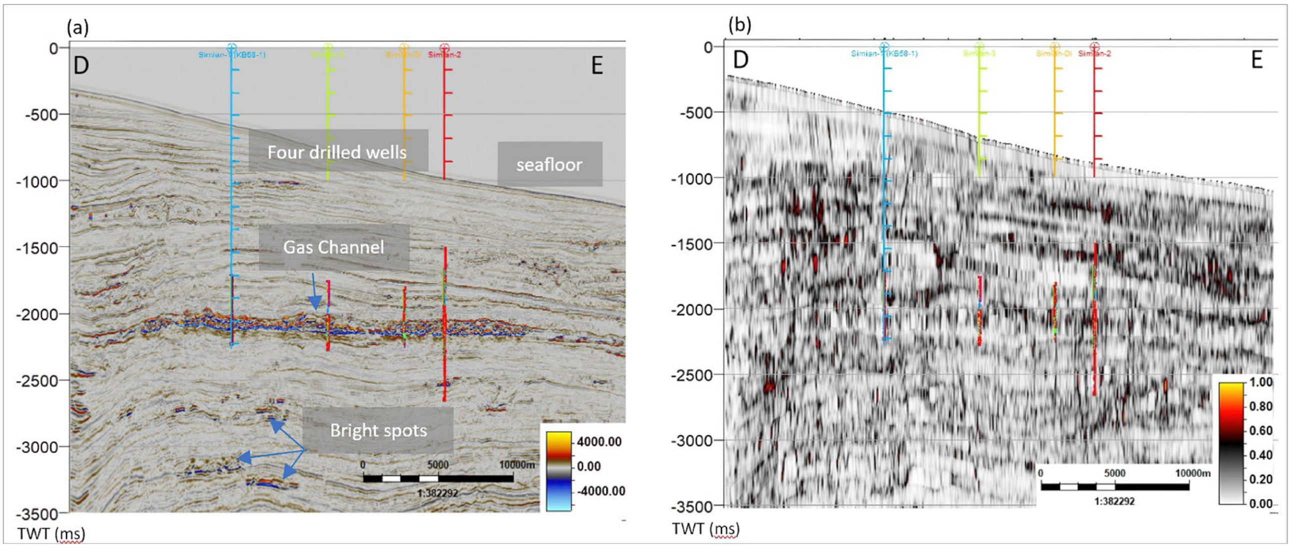


Fig. 9 DE seismic cross-section **a** original seismic amplitude and **b** after extracting the variance attribute

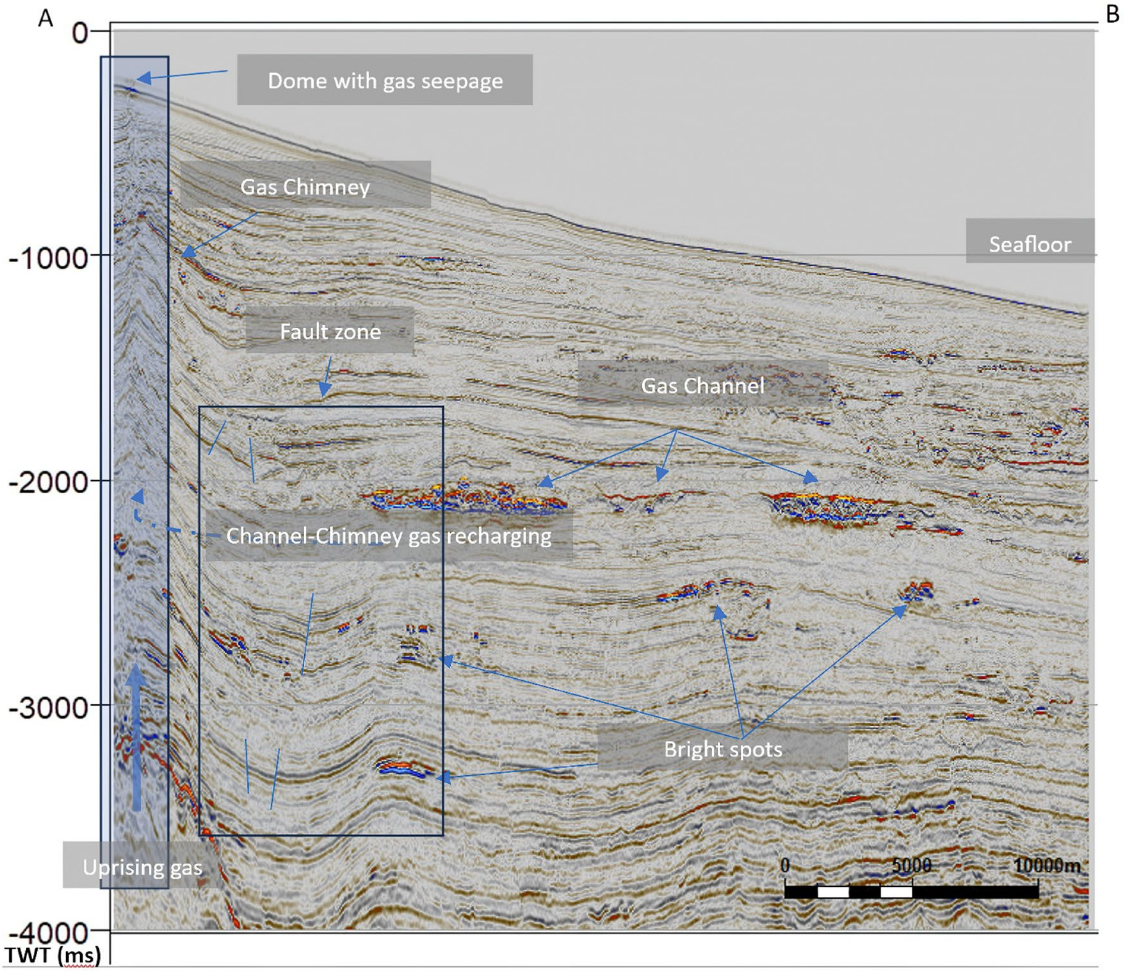


Fig. 10 Interpretation of AB seismic cross-section spotting a gas chimney and its associated features

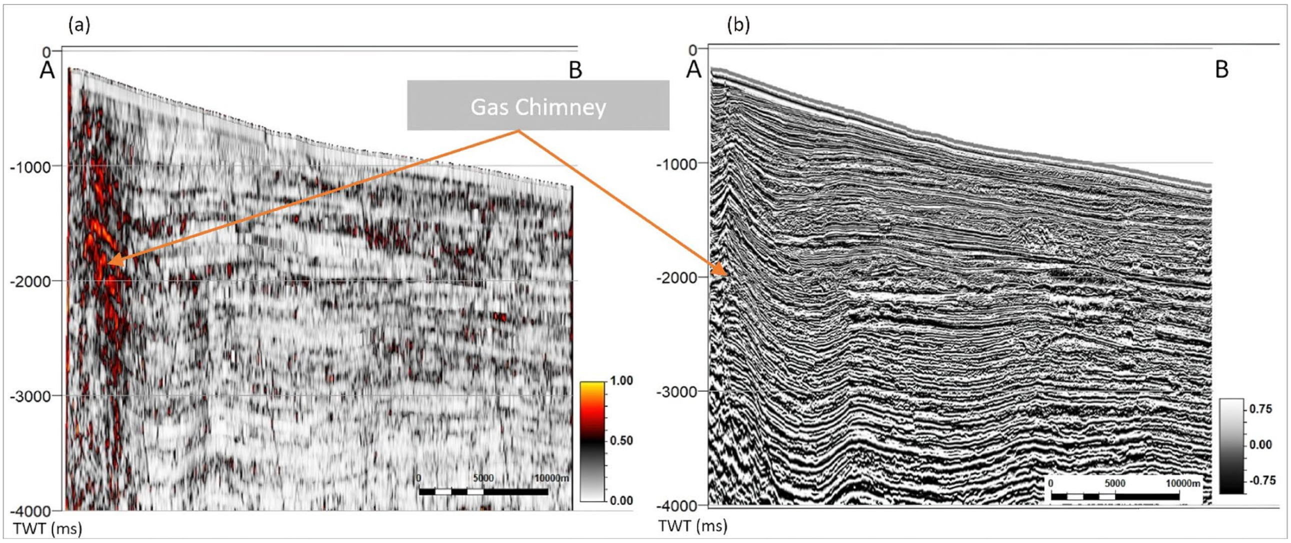


Fig. 11 AB seismic section after the extraction of **a** variance and **b** cosine of the instantaneous phase

"poor data zones"), characteristics of the seabed, seepages, and factors that influence the creation and expansion of pockmarks due to gas venting. The analysis of detailed 2D seismic sections has played a crucial role in identifying features within sedimentary layers. These findings align with prior research on the investigation of gas chimneys, pockmarks, and associated geological characteristics [25, 36, 48].

The gas relocates from source rocks to shallower reservoirs and eventually reaches the seafloor through deep-seated gas chimneys (Fig. 10). This migration process entails the movement of high-pressure fluids through fractured sedimentary layers along gas plumes until they reach the seafloor. This results in the formation of domes accompanied by cracks and faults. These structural characteristics enable the release of fluid, which eventually results in the formation of well-defined pockmarks (Fig. 10). Pockmarks exhibit a range of sizes, encompassing structures such as domes, gas chimneys, and mega pockmarks that extend over several kilometres. The release of gas at the bottom of the sea creates a visible and separate bright reflection.

In summary, the study offers extensive knowledge about the development of gas chimneys, pockmarks and other characteristics found on the deep-seafloor in the WDDM concession area [21, 24–26]. The study indicates that fault zones surrounding these seafloor features have a significant impact on enabling the flow of fluids through fault planes to the seafloor.

4.1 Seismic attributes classes

The seismic attributes are categorized into two main categories. The first category includes amplitude-based attributes, which distinguish features based on their energy content, ranging from highest to lowest amplitude. Bright anomalies, enhanced reflectors, and Bottom Simulation Reflector (BSR) are associated with the highest amplitude content, while the columnar disturbance corresponds to the lowest amplitude.

The second category focuses on geometric attributes like variance and the cosine of the instantaneous phase. These attributes are utilized to enhance the detection of buried pockmarks (BPm) and fault zones associated with them. Gas seepage through gas chimneys (Fig. 10) is visible as macro-seepage and can be identified using seismic data. Figure 12 depicts the presence of vertical and inclined plumes, indicating the migration and accumulation of fluids under high pressure in reservoirs of upper layers (Miocene and Pliocene). Ultimately, the gas ascends towards the seafloor through gas chimneys and along faulted zones.

4.2 Chimneys, associated features, and fluid flow

In the Simian gas field, a 3D seismic model was employed to identify and map the seabed layers such as the Bilqas/Mit Ghamr Formation, El Wastani Formation, and the gas channel reflector (Fig. 11). These findings provide a visual representation of the geological structures and processes associated with gas migration in the area.

The application of seismic attributes has demonstrated its efficacy in identifying and describing the subsurface geological and structural characteristics in the WDDM region, particularly in the Simian field. Through the analysis of multiple seismic attributes and 3D models, we have identified bright spots scattered in the vicinity of the Simian gas channel, alongside the pre-existing gas chimney. These bright spots are indicative of unsystematic gas seepage and migration. Moreover, the existence of a fault zone

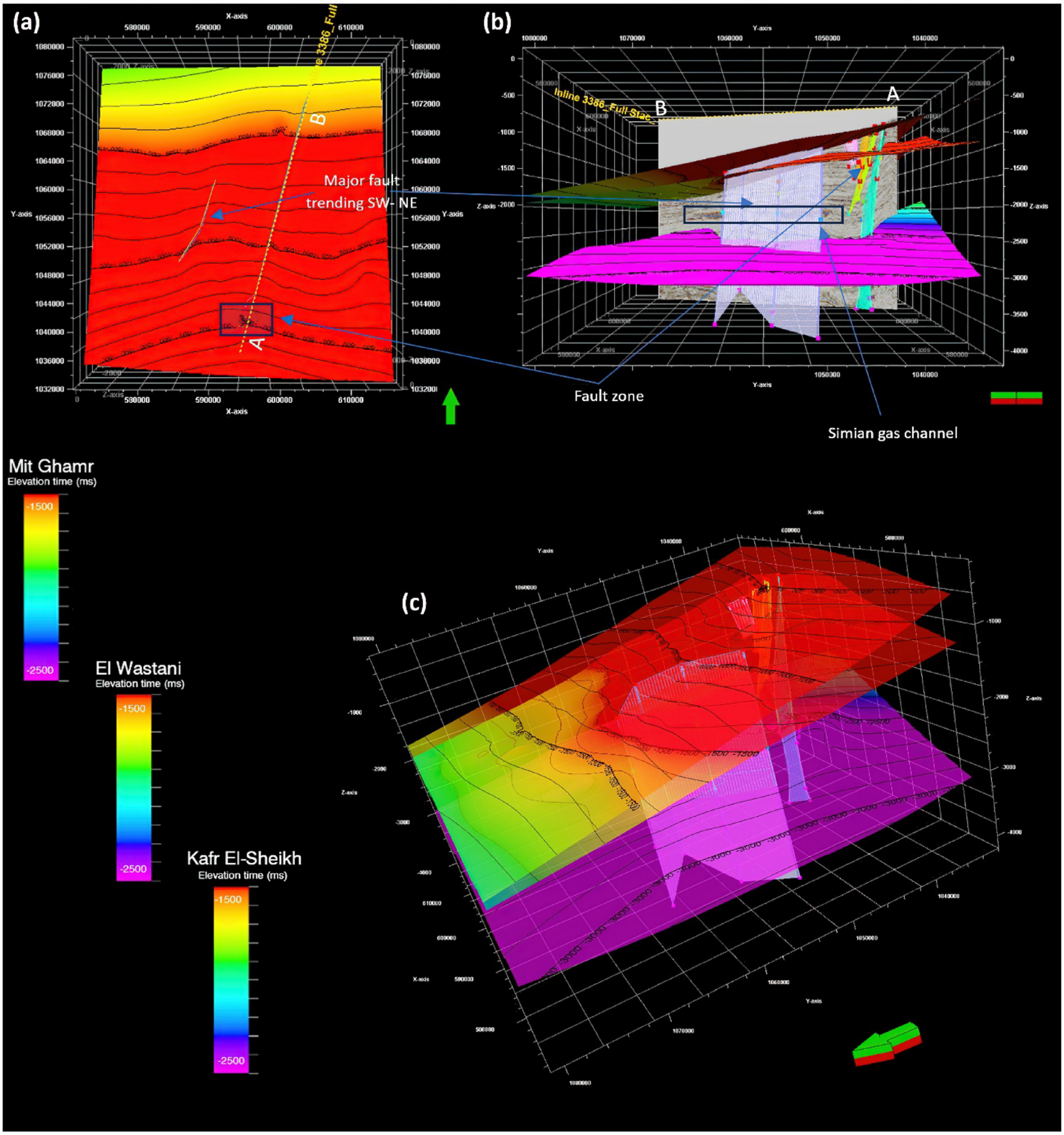


Fig. 12 **a** & **c** 3D Visualization for the three picked horizons Mit Ghamr, El-Wastani, and Kafr El-Sheikh, **b** show the major fault combined with AB seismic section

that has been sheared and cracked in an upward direction, as shown in Fig. 11, near the gas chimney, provides significant evidence of the release of gas from a high-pressure zone to a lower one, specifically the seafloor. This discharge activity is associated with the formation of pockmarks, which are caused by the accumulation and release of gas at the seafloor, which, as discussed, is a huge life risk that should be assessed before and while conducting gas and oil production.

Figure 5 depicts the graphical representation of the three primary formations found in the Mit Ghamir, El Wastani, and Kafr El-Sheikh areas. The Simian gas channel is located between the El Wastani and Kafr El-Sheikh areas. Southward, there is a distinct area where gas is being

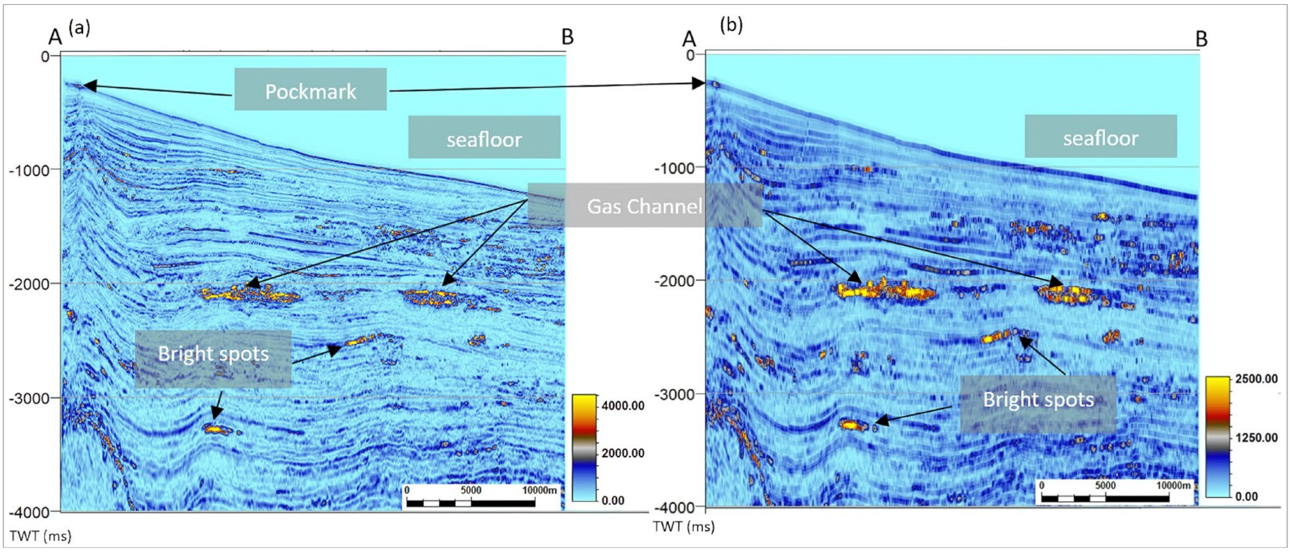


Fig. 13 Bright anomalies and pockmark appear with the highest values of the extracted **a** envelope and **b** root mean square (RMS) attributes

released, which is indicated by the variance seismic attribute (Fig. 11a). The objective of the study was to delineate the gas chimneys and gas channels in the Simian field. By using advanced geophysical methods, we were able to enhance subsurface imaging for the identification of pockmarks, related characteristics, and faults. The gas chimneys serve as the main routes for fluids to migrate from deep underground sources, known as the "kitchen", through the Miocene-Pliocene sequences and up to the seafloor. They serve as preferential paths for hydrocarbon migration from pre-Messinian to Plio-Pleistocene reservoirs. In areas where these reservoirs intersect with gas chimneys, the seafloor above exhibits a bright reflector indicating gas seepage. Pockmarks, on the other hand, are typically formed by the escape of both liquid and gaseous phases, including pore water, hydrocarbon fluid, and hydrothermal solution [40, 48]. The identification of gas chimneys, which are characterized by chaotic seismic signals due to energy absorption and scattering, shows extensive areas of reduced amplitude throughout the pre-Messinian to Pleistocene slope succession. This reduction is due to the diffusion of gas through cap rocks above breached reservoirs (Fig. 10) [53]. It appears that gas chimneys mainly form from hydraulic fracturing caused by the upward movement of gas from deeply accumulated sources under high pressure, due to rapid burial during the Plio-Pleistocene mega sequence deposition. According to [19], Thermogenic gas is generated at considerable depths and then moves into younger sediments, where it gets trapped in smaller reservoirs. Gas can escape through fine-grained surface sediments, with initial fluid escape occurring through small cracks. These early-formed cracks serve as pathways for fluid escape, expanding over time during vertical gas migration and eventually leading to pockmark formation. Pockmarks are commonly linked to bedrock structures [51] and can be found along faults and faulted anticlines [10].

Figures 10 and 12 show gas escaping through faults from shallow depths to the seabed, causing discontinuities in the shallower parts of seismic profiles. Gas chimneys, domes, and buried chimneys act as the main pathways for vertical and lateral fluid migration, appearing as bright spots in the interpreted profiles. The WDDM area shows significant seepage activity, characterized by numerous venting features associated with domes (Fig. 10), pockmarks, and gas chimneys. In Fig. 13, the bright anomalies appear with the highest envelope and root mean square (RMS) values. Enhanced reflections with higher amplitudes in certain regions may result from increased gas saturation within a porous layer surrounded by mainly impermeable layers.

Accordingly, to reduce the risks associated with exploring and interpreting gas detection, it is essential to extract a variety of seismic attributes that are customized to the specific objectives of the study. Different seismic attributes are employed to accurately identify gas zones and important characteristics like gas chimneys, bright spots, and enhanced reflections. The attributes include RMS (Root Mean Square), energy, envelope, chaos, variance, and the cosine of the instantaneous phase. The presence of sediment-saturated gas, even in small amounts, can significantly decrease the acoustic impedance of the surrounding sediment. This leads to the formation of bright spots, also known as enhanced reflectors, on seismic profiles [3, 49]. The presence of large and noticeable anomalies, which suggest possible locations where oil may be leaking, have been identified at fault locations that extend to the seafloor. This highlights the importance of these faults as pathways for oil leakage [47].

Domes are characterized by minor faults and fractures, which are connected to the seeping of gas. This observation aligns well with the findings shown in (Fig. 13). In this figure, a bright, high-amplitude reflection is visible at the top of the dome, exhibiting maximum Root Mean Square (RMS) values that are higher than the surrounding seabed. These geological features are hazardous features and affect the stability of the seabed and indicate the presence of gas chimneys beneath the seabed. Associated with the gas chimneys are fault zones, Fault zones are implemented due to the gas escaping mechanism, When the gas pushes its way up through the sub-surface it creates faults and cracks thus in summary, this creates an interconnected ecosystem where each feature is linked to one another (Fig. 14).

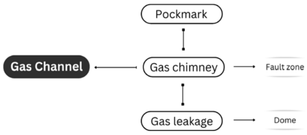


Fig. 14 Illustrates the ecosystem of the associated features of the pockmarks and how each feature is dependent on one another

To minimize risks associated with near-surface gas migration affecting offshore installations and seabed structures in the WDDM concession, it's crucial to integrate drainage piles around platform locations. These piles function as vertical pathways through which gas can safely disperse away from the structures. Incorporating modern techniques such as seismic attributes can further enhance the effectiveness of this approach. The pockmark in our study has a large hazardous zone, so building oil rigs near these formations is dangerous. We advise positioning the rig at a minimum distance of 10 km (Fig. 15). Oil rigs require secure and steady foundations, and the presence of gas chimneys and pockmarks suggests a lack of stability. Seabed collapse or subsidence can occur as a consequence of gas release during drilling or construction activities. This would compromise the integrity of the rig's structure, posing a risk to the crew and the environment.

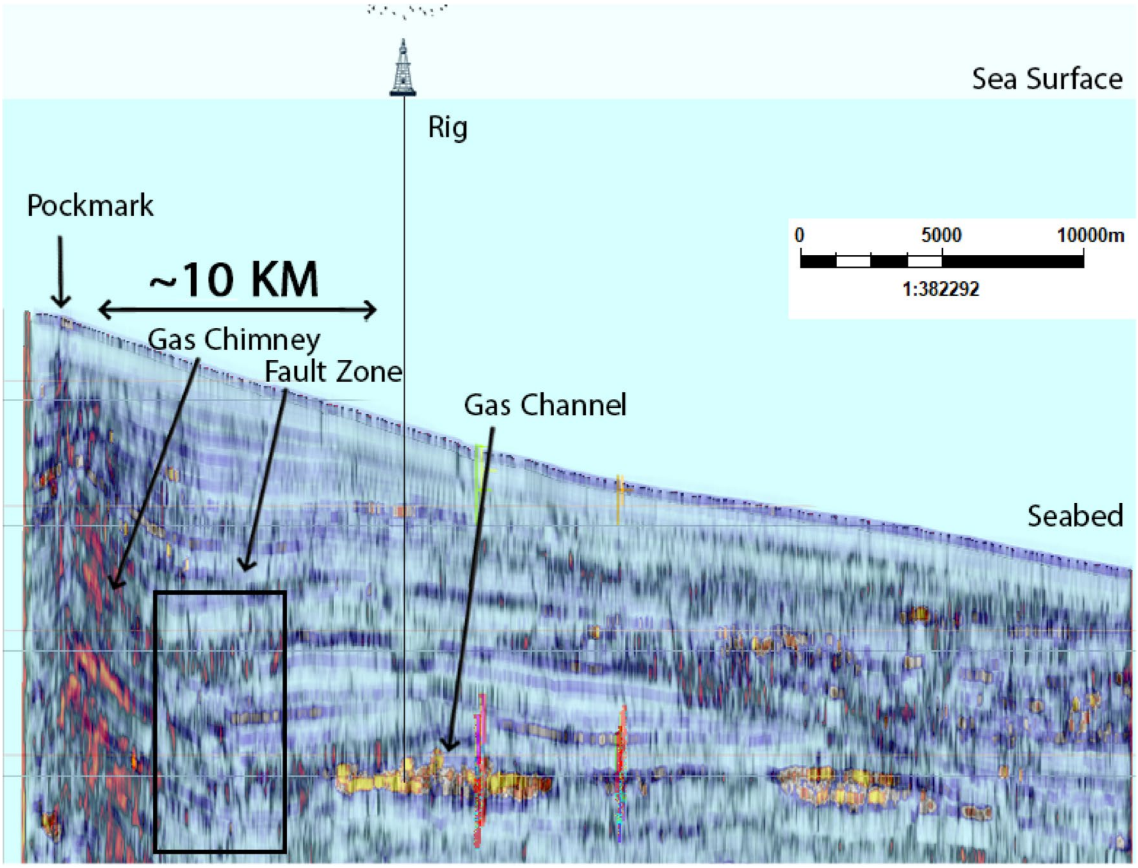


Fig. 15 Combined/Stacked RMS and variance seismic attributes clearly show the hazardous area and the possible safe distance to install the rig

5 Conclusion

The study implemented advanced geophysical techniques to detect gas chimneys and gas channels and their associated geological characteristics, highlighting the vital importance of these sophisticated methods in saving lives. The Simian Field exhibits various seafloor geological formations such as pockmarks, gas chimneys, gas channels, faults, and related seafloor seepage features. A key goal of this article is to highlight the risk of seafloor seepage and illustrate the potential dangers that arise during offshore installations. Pockmarks that develop in close proximity to current platforms have the potential to present a highly dangerous and potentially disastrous threat to offshore installations in the future.

The physics of fluid movement often relies on stratigraphic characterizations, as evidenced by seafloor domes. Pockmark formation is linked to underlying tectonic structures, such as high fault zones. Further exploration may uncover additional details.

The typical dimensions of a normal pockmark range from 1 to 10 m in width and less than 0.6 m in depth. On the other hand, larger pockmarks can be as wide as 10 to 700 m and have a maximum depth of 45 m [20]. Therefore, it is imperative to underscore the critical importance of safeguarding the oil platforms, as this can avert a significant loss of life.

In conclusion, the arrangement of small and large pockmarks is an important indicator of underlying gas chimneys and potential fault zones. Constructing oil rigs near these formations poses significant risks to structural integrity, operational safety, and the environment. To reduce these risks, it is crucial to maintain a safe distance from pockmarks and gas chimneys. Thorough geophysical surveys in site selection are essential to ensure the safe and sustainable development of offshore oil rigs. By prioritizing safety and environmental protection, we can balance energy development and the preservation of our marine ecosystems.

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Author contributions Ahmed A. Abd El-Naby: Conceptualization, Methodology, Software, Data curation, Visualization, Investigation, Formal analysis, Writing-Original draft preparation, Writing-Reviewing, and Editing. Amin Esmail Khalil, Amr Talaat, and Amir Ismail: Conceptualization, Methodology, Investigation, Visualization, Validation, Writing—review & editing, Supervision. All authors have critically reviewed and approved the final draft and are responsible for the content and similarity index of the manuscript.

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Data availability The data produced in this study can be obtained from the corresponding author upon reasonable request.

Declarations

Conflict of interests The authors state that the research was carried out without any commercial or financial ties that could be seen as a potential conflict of interest.

Consent for publication All authors agreed to publish.

Ethics approval Not applicable.

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