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Seismic attribute analysis for oil field characterization in Côte d'Ivoire sedimentary basin

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Abstract. A seismic attribute can be defined as any parameter or observation retrieved from available seismic data that directly or indirectly enhances and deepens understanding of data processing and interpretation in hydrocarbon exploration. Indeed, seismic attributes contribute to better understanding of geological structures, petrophysical properties, fluid content and their differentiation in a simplified but more detailed form that enables the determination of their presence in reservoirs as well as the spatiotemporal distribution of subsurface geological elements. This work studies the application of various seismic attributes to identify and describe the oil and gas potential of the license area. This site is characterized as a deepwater alluvial fan on the end-slope fan on the Turonian stage based on regional seismic data, whereas the 3D seismic data clearly determining the boundaries of the stratigraphic trap indicate the likelihood of hydrocarbon saturation. Analysis of dynamic characteristics of seismic waves confirmed the presence of oil and gas-bearing indicators that imply the high potential of the reservoir. The study showed how seismic attributes retrieved from 3D seismic data can qualitatively provide valuable information about subsurface geological features. This, research is highly promising for hydrocarbon exploration based on the results of the combined seismic attribute analysis. However, even if this study is deemed sufficient for drilling an exploratory well, it may be useful to propose other geophysical methods to be integrated into this study that could improve the assessment. For example, electrical methods are known for their effectiveness in direct detecting of fluids in reservoirs and have proven their efficiency in Western Siberia, Russia.

Keywords: Côte d'Ivoire sedimentary basin, turbidites, seismic attributes, rock physics, amplitude versus offset (AVO) analysis, alluvial fan, Lamé parameters, rock properties, fluid saturation

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Анализ сейсмических атрибутов для характеристики нефтяных месторождений в осадочном бассейне Кот-д'Ивуар

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Резюме. Сейсмический атрибут можно определить как любой параметр или наблюдение, извлеченное из имеющихся сейсмических данных, которое прямо или косвенно способствует улучшению и углублению понимания обработки и интерпретации данных в разведке углеводородов. Действительно, сейсмические атрибуты помогают лучше понять в упрощенном, но более детальном виде геологические структуры, петрофизические свойства, содержание флюидов и их дифференциацию, чтобы определить их присутствие в коллекторах и пространственно-временное распределение подземных геологических элементов. Представленная работа основана на исследовании применения различных сейсмических атрибутов для выявления и характеристики нефтегазового потенциала лицензионного участка. Выбранный объект характеризуется как глубоководный конус выноса на концевом склоне туронского яруса на основе региональных сейсмических данных, а данные 3D-сейсмики, четко определяющие границы стратиграфической ловушки, указывают на вероятность насыщения углеводородами. Анализ динамических характеристик сейсмических волн подтвердил наличие нефтегазоносных признаков, что свидетельствует о хорошей перспективности резервуара. Исследование показало, как сейсмические атрибуты, извлеченные из 3D сейсмических данных, могут качественно предоставлять ценную информацию о геологических особенностях недр. Таким образом, проведенное исследование имеет большие перспективы для разведки углеводородов, основанные на результатах, полученных в ходе комбинированного анализа сейсмических атрибутов. Тем не менее, даже если данное исследование будет признано достаточным для бурения поисковой скважины, может быть полезно предложить и другие геофизические методы для интеграции в это исследование, которые могли бы улучшить оценку. Например, электрические методы известны своей эффективностью в прямом обнаружении флюидов в пластах и доказали свою эффективность на основании их применения в Западной Сибири в России.

Ключевые слова: осадочный бассейн Кот-д'Ивуар, турбидиты, сейсмические атрибуты, физика горных пород, AVO-анализ, конус выноса, параметры Ламе, свойства пород, насыщение флюидов

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Introduction

In seismic surveys, the conditions of data collection and processing used for interpretation often make it difficult to explore for oil and gas structures directly. In this regard, the analysis of seismic attributes proves to be a valuable solution that facilitates the work of geologists and geophysicists [1]. A seismic attribute can be defined as any parameter or observation extracted from available seismic data that contributes directly or indirectly to improving and deepening understanding of data processing and interpretation in hydrocarbon exploration. Attributes can be calculated from seismic traces either before or after summation.

Prior to summation, attributes study the behavior of individual seismic traces relative to displacement and azimuth in time or depth and provide additional insight into the physical properties of the formation, as well as predict the content of hydrocarbons directly. Attributes before summation include both instantaneous and wave attributes, root-mean-square velocity (RMS), energy and amplitude absorption (AVO attributes), group and phase velocities, and dispersion measurements.

Attributes after summation are attributes calculated based on the statistical characteristics of the traces involved in the summation, using kinematic corrections or migration [2]. In this regard, it is important to understand that seismic attributes are special measurements of dynamic, kinetic, statistical and geometric parameters of seismic traces.

Attributive analysis allows us to study the following characteristics of the section:

– structural characteristics: parameters of the geometry of structural surfaces (tilts, azimuths, faults, etc.);

– material characteristics: lithology, facies, fluid saturation, intensity, etc.).

The objects of attribute analysis are:

– sedimentary (seismic) complexes (time intervals);

– formations (seismic reflecting horizons, reflections, waves);

– oil and gas deposits, reservoirs.

This work is aimed at showing the usefulness and importance of analyzing seismic attributes in oil exploration. Indeed, seismic attributes help to better understand geological structures, petrophysical properties, fluid content and differentiation in a simplified but more detailed form in order to determine their presence in reservoirs and the spatiotemporal distribution of underground geological elements [1]. The results of this work demonstrate that the analysis of seismic attributes can optimize the profitability of oil fields, thereby minimizing the risks of failures and accidents during drilling, and also helps to make more informed decisions by reducing costs.

Materials and methods

Currently, there is no comprehensive list or generally accepted classification of seismic attributes. However, various literary sources contain interesting classifications that can serve as a basis or tool for their analysis [3]. Seismic attributes can be divided into three main groups: physical, geometric, and combined.

Physical attributes are seismic measurements that are directly related to wave propagation, lithology, and other physical parameters. They include both instantaneous and wave attributes.

Geometric attributes provide an assessment of the reservoir structure, its heterogeneity, and also define geometric specific indications of lithology (such as parallel bedding, convergent and divergent zones, and unconformities) and are commonly used in stratigraphic interpretation.

Combined attributes integrate physical and geometric attributes and provide unique information about the characteristics of the reservoir: its morphology, heterogeneity, and specific types of lithology. These include chaotic reflection areas, combined geometric and physical attributes for sandstone and shale areas, carbonate layers, and the reliability of the segmented section assessment [2]. Attributes can be represented in the following forms:

– section: this form represents traditional representation of an instantaneous seismic attribute, often depicted in real time in conjunction with conventional seismic traces;

– reflection is a form for extracting an attribute directly from a seismic reflection (horizon) or in its vicinity;

– volume is an object for extracting a volume attribute extracted from a seismic cube.

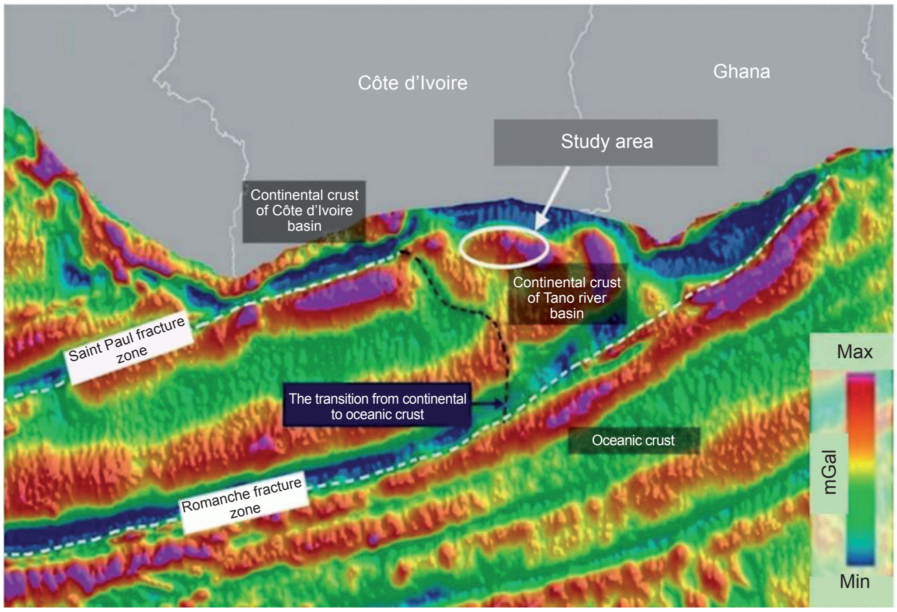
Brief description of the SSG license stie. The prospective SSG target is characterized as a deep-water alluvial fan on the end-slope fan on the Turonian stage based on regional seismic data obtained during well drilling, and 3D seismic data clearly define the boundaries of the stratigraphic trap, indicating the likelihood of hydrocarbon saturation with a higher potential for oil. The SSG site is located near the centre of the Tano – Côte d'Ivoire basin in the northeastern part of the Gulf of Guinea shelf. The object is located between a modern continental shelf cliff and a lower slope (Fig. 1, *a*). The water depth within the license area varies from approximately 200 m in the northeast corner to 2500 m in the southwest corner. The SSG object is located in the southeastern quadrant of the license site at a depth of approximately 2000 m. The SSG-0 well was drilled 25 km to the northeast, in which signs of oil were found in thin Campanian and Turonian sandstones. Several wells have been drilled in the vicinity of this promising object, both in the Ivory Coast sedimentary basin and in the neighboring Tano – Ghana basin. These wells serve as analogues for calibrating some useful data. The main target area is the upper Turonian alluvial fan. All license areas located in the vicinity cover two large four-sided structural zones, SSG-1 and SSG-2 (Fig. 1, *b*), located on the modern upper slope, under which there are inclined fault blocks of the Albian stage.

3D seismic survey, time and depth data processing. The survey of seismic data covered 2000 km^2 of the central part of the license area and was designed to visualize a large four-sided structure in reservoir formations of the Albian and Turonian stages. The survey was carried out using a vessel and two sets of seismic guns with a pressure of 2000 psi and a maximum power of 2600 psi, as well as eight cables 6 km long with an interval between groups of 12.5 m. As part of this survey, 9 second recordings were obtained with a sampling interval of 2 ms to provide sufficient data to visualize the target horizons at great depths that occur in the southern part of the block.

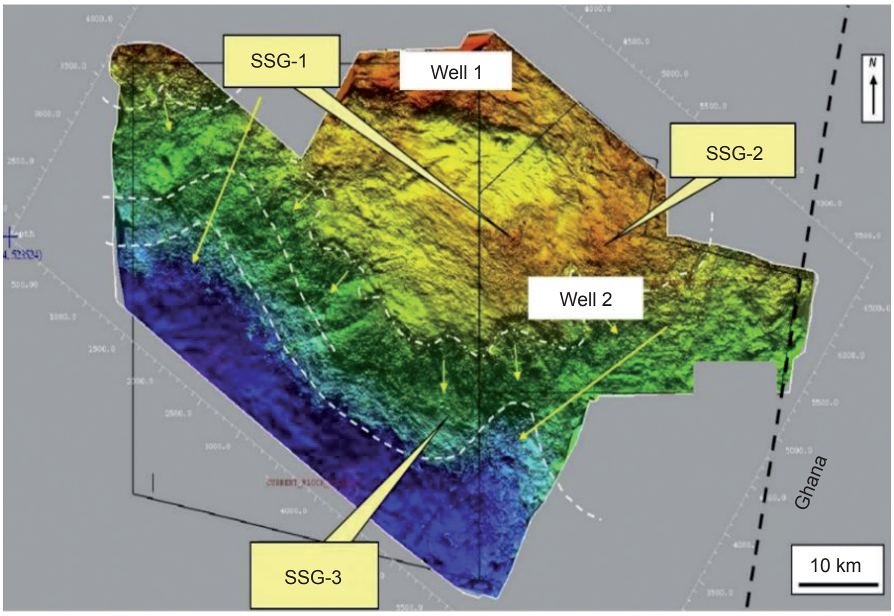
The survey was completely processed using the Pre-Stack Time Migration (PSTM) method. PSTM is a seismic transformation technique used to position reflections accurately before summing individual seismic traces. This method is very good for detecting moderate changes in lateral velocity within a geological region [4–6].

After completion of PSTM processing, the non-aggregated data were processed by Pre-Stack Depth Migration (PSDM) method, which is usually aimed at creating accurate maps in areas with complex underground geological structures and is ideal for extreme lateral velocity changes [7, 8]. This comprehensive approach to processing allows for separate interpretation of data on time and depth scales, which makes it possible to compare errors or risks associated with depth conversion.

Turbidite fan deposits of the Turonian and Santonian stages wedge out on the sides of these structures, while younger ones, from the Campanian to the modern stage, have large complexes of slope canyons – Bassam canyon in the west and Assini canyon in the east – cut through and lie on the lateral slopes of old structural uplifts (Fig. 2). The SSG object is



a



b

Fig. 1. Location of the study area relative to the Cote d'Ivoire sedimentary basin:
a – Bouguer reduction gravity anomaly map of the Gulf of Guinea (according to source [2] with authors' modifications);
b – SSG license site in Albian structure indicating post-Albian deposits
Рис. 1. ***Расположение исследовательского участка относительно осадочного бассейна Кот-д'Ивуар:***
а – карта гравитационных аномалий Гвинейского залива в редукции Буге
(согласно источнику [2] с изменениями авторов);
b – лицензионный участок SSG альбской структуры, указывающий на постальбские отложения

located in the Assini canyon system and represents the return of the rocks of the Turonian stage and the underlying complexes of slope alluvial fans of the Cenomanian stage, which are unconformable above the Albian sediments.

The SSG license area is a stratigraphic trap formed by a complex of slope channels and turbidites of slope alluvial fans filling a large canyon system cutting into the edge of the shelf of the Upper Cretaceous period. The early deposits in the emerging canyon system consisted of turbidites of the upper slope alluvial fan fed by complexes of slope channels. A series of episodes of canyon filling began at the beginning of the Campanian stage and continued until the Maastricht stage. The expected reservoirs are

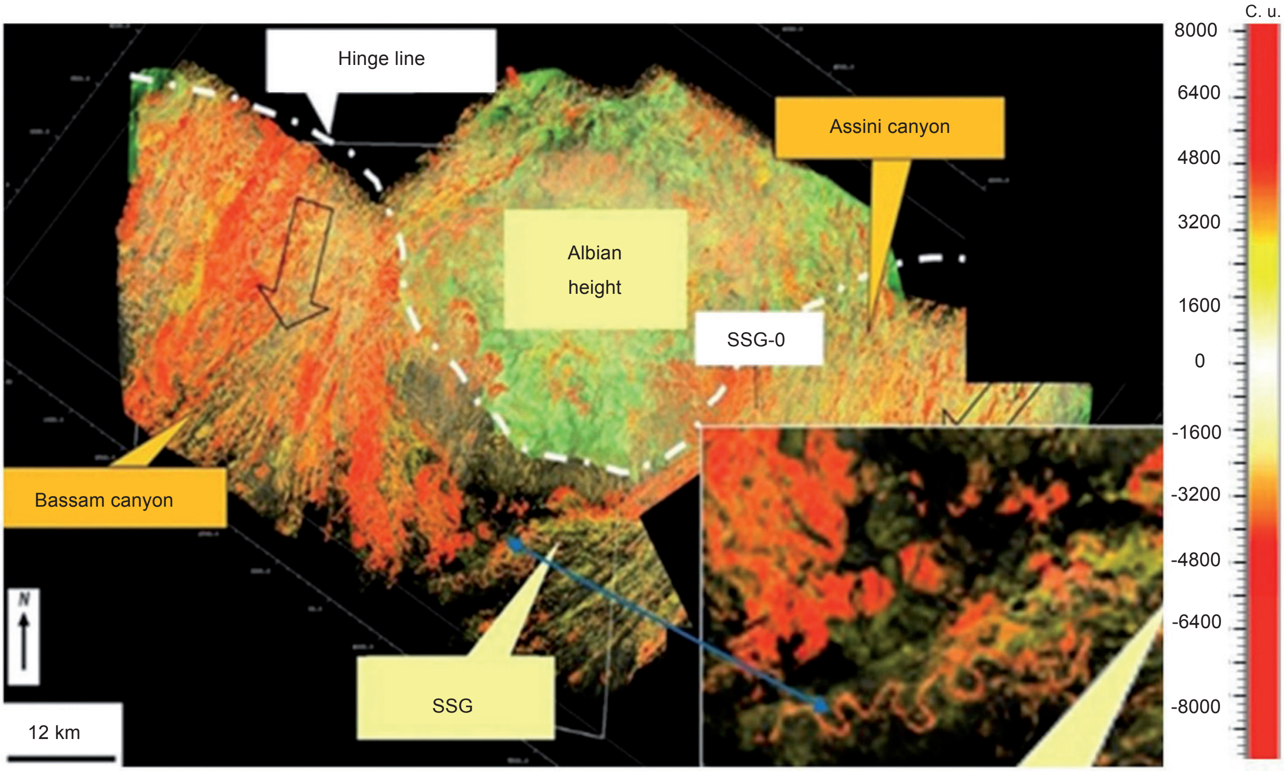


Fig. 2. Amplitude vectors (amplitude values and reflector tilt) of Cenomanian and Turonian reflectors showing the influence of the Albian uplift
Рис. 2. Векторы амплитуд (значения амплитуды и наклон отражателя) сеноманских и туронских отражателей, демонстрирующие влияние альбского поднятия

sheet-like alluvial fans in the Upper Turonian stage, which become more sinuous and channel-like in the lower Turonian and Cenomanian stages. The interest in turbidite reservoirs is due to the fact that the traps formed there have very good properties, which is well known in the main oil and gas provinces. The gravitational flow of sedimentary rocks in turbidite lobes, as well as grain gradation in reservoir rocks, very often lead to high porosity. Thus, turbidite lobes create a favorable environment for the accumulation of hydrocarbons from a geological, structural and petrophysical point of view, namely tectonics, sedimentary rock transfer systems, entrapment of petroleum and geomorphological structures [9–13].

The analysis of the SSG-0 well provides the most essential information for understanding the oil and gas system of the SSG site. The SSG deposit system is a stratigraphically captured sequence of combined complexes of channel and coastal sediments of the Campanian stage, which are the main targets. These sediments were deposited in a large deep-water canyon, with channel and coastal sediments trapped upward (to the north) and sideways (to the east and west) by wedging with the fall ending to the south. Along the faults and immediately above the fall, there are clear indicators of the presence of gas fluids, which additionally confirms the influx of hydrocarbons to the area of the SSG object. These fault systems can also provide a mechanism for the leakage of a significant amount of gas formed as a result of the ongoing burial of Albian parent rocks in the external burial zone, which makes it possible to preserve early charged oil columns [14, 15].

The use of seismic attributes to characterize the geological structure of the SSG site. This work is based on a study of the use of various seismic attributes to identify and characterize the oil and gas potential of the SSG site located in the Turonian strata of the Côte d'Ivoire sedimentary basin in the Gulf of Guinea. The following attributes were used to get a general idea of the physical properties of a promising SSG object.

The AVO method (amplitude depending on the angle of incidence of the wave) studies how the strength of the seismic reflection changes depending on the distance (displacement) between the source and receiver. AVO analysis reveals the properties of rocks below the surface (such as porosity, density, lithology, and especially fluid content) and usually acts as a direct indicator of hydrocarbons [16]. It is based on the Zoeppritz equations [17], which describe the reflection coefficients at different angles of incidence, which makes it possible to detect anomalies such as “bright spot” anomalies. The Zoeppritz equations and their approximations, developed several years later, are fundamental equations relating reflection amplitudes to rock properties (P-wave velocity, S-wave velocity, density) and angle of incidence, forming the basis of AVO analysis, since they help to deduce the exact amplitudes of the reflected P-wave as a function of angle [16].

The $\lambda\rho$ attribute is theoretically derived from the Lamé parameters and primarily indicates the content of pore fluid and incompressibility in reservoirs, and low values often signal gas bearing zones (hydrocarbons) or unconsolidated sands, distinguishing them from brine-filled sands or shales, which makes it crucial for hydrocarbon exploration.

The coefficient $\mu\rho$ is an indicator of shear hardness related to rock hardness, lithology, and is commonly used to distinguish between shales, brine–filled sands, and oil and gas-bearing sands.

The *P*-impedance or Pseudo Poisson’s ratio is an estimate of the elastic properties of a rock used to identify hydrocarbons based on seismic data such as P- and S-wave velocities or AVO intersections/gradients, instead of direct laboratory measurements. It is a method of mapping changes in fluid content by approximating the true Poisson’s ratio to distinguish lithology and fluids.

The Poisson’s ratio *v* quantifies how much a material deforms in the presence of transverse deformation during axial compression. It is calculated based on the speeds *P* (V_P) и *S*-waves (V_S) according to the formula:

$$\mathrm{v} = \frac{1 - V_s^2/V_p^2}{2}.$$

This helps characterize reservoirs, making it possible to distinguish rock types, identify fluids, and detect faults.

Acoustic impedance Z_P helps to distinguish lithology, assess porosity, and detect the presence of fluids. It is defined as the product of the velocity of the longitudinal waves V_P and volume density ρ [1].

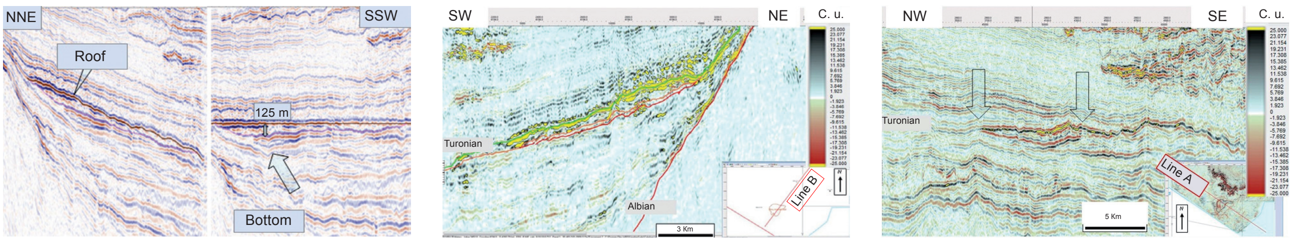
The root mean square (RMS) amplitude value makes it possible to identify areas containing hydrocarbons and characterize formations by measuring the average energy of seismic reflection over a certain time interval, which helps to accurately identify anomalies indicating the presence of oil/gas or fluid changes, especially in combination with other attributes and well data for detailed mapping and monitoring. It helps to distinguish between gas, oil and water, track the movement of fluids (as in 4D seismic) and understand the conditions of sedimentation, which is crucial for exploration and production [18, 19].

Results and discussion

The interpretation of all seismic volumes was carried out using the Kingdom Suite software from Seismic Micro Technology. Mapping and extraction of attributes were performed using PSTM data. The promising SSG object was identified based on available 3D seismic data, data from nearby drilled wells, as well as a set of seismic attributes, as indicated above. This is an alluvial fan of Turonian stage with anomalous amplitudes in the PSDM data, especially in the long-range angular summation. The PSDM data helped to identify and identify the unique morphology of the outflow cone. Although the promising SSG object shows a moderate southern fall, when the upper part of this Turonian cone is aligned, it becomes obvious that the base thickens with thinning in the south-west and west directions (Fig. 3, *a*). The SSG perspective object was identified using processed angular decays (near, middle, and far angles) to facilitate the distinction of horizons with increasing amplitude with angle/displacement (AVO). The analysis of angular decays with displacement confirmed the presence of an oil and gas bearing feature demonstrating an increase in amplitude with an angle (displacement), which is consistent with the known accumulations of oil and gas in the basin (Fig. 3, *b*). Figure 3, *c* is a line of near decay amplitudes showing the laterally northwesterly-southeasterly propagation of the alluvial fan sequence of the upper slope of the prospective SSG object. The analysis of seismic data on the prospective SSG object demonstrates a clear behavior of AVO with displacement, characterized as a response of third-term AVO for potential Turonian oil and gas reservoirs and suggests a high probability of hydrocarbon saturation.

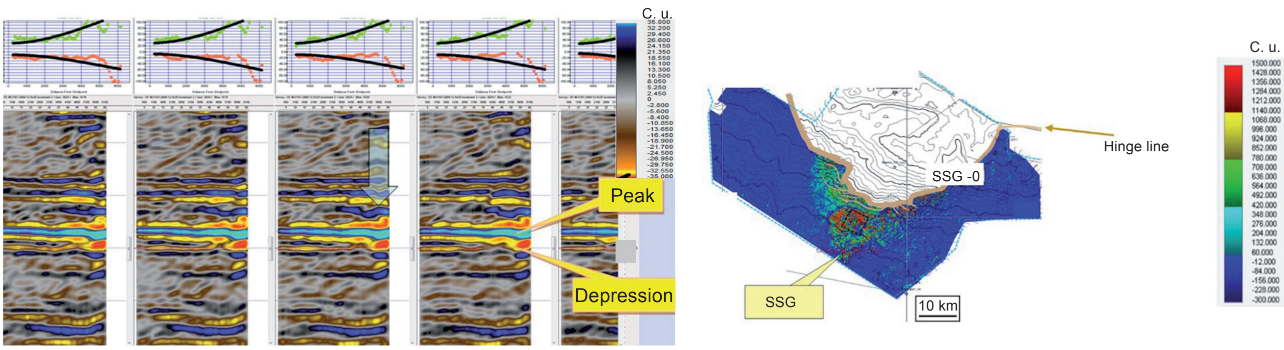
Figure 4 shows a clear AVO anomaly in the area of a promising SSG object [20].

Additional seismic processing was performed to invert the data. Inversion data calibrated based on qualitative well logging data can help visualize potential reservoir formations, tire formations, and trapped hydrocarbons [21, 22]. The inversion data processing was completed prior to summation, and all 3D surveys served as input data for this process. Seismograms with the total depth of the seismograms with the total depth of the point were prepared and kinematic corrections were made. These seismograms, in turn, were introduced into various algorithms that generated key data, including the $\lambda\rho$ attribute, $\mu\rho$ coefficient, *P*-impedance, and Poisson's ratio. Then this data was calibrated using SSG-0 well logging materials, adjusted for the greater depth



a *b* *c*

Fig. 3. Seismic profiles showing the prospective SSG site:
a –. structural dip line (left panel) with aligned seismic data above the Turonian stage (right panel);
b – B line (far-near) × far-field amplitude versus offset (AVO) screening volume;
c – A line located near the stack shows the east-west extent
Рис. 3. Сейсмические профили, демонстрирующие перспективный объект SSG:
a – линия структурного наклона (левая панель) с выровненными сейсмическими данными поверх туронского яруса (правая панель);
b – линия Б (дальняя – ближняя) × объем скрининга AVO на дальнем расстоянии;
c – линия А, расположенная рядом со стеком, показывает восточно-западную протяженность



a *b*

Fig. 4. Prospective SSG site displaying amplitude versus offset (AVO) anomalies:
a – strong AVO anomalies in the Turonian;
b – regional delineation of the upper Turonian horizon × far AVO screening volume
Рис. 4. Перспективный объект SSG, демонстрирующий аномалии AVO:
a – сильные аномалии AVO в Туроне;
b – региональное выделение верхнего туронского горизонта × дальний объем скрининга AVO

of occurrence in SSG, and regional calibration information to identify anomalous values. However, due to the lack of data on Turonian reservoirs (such as powerful, exceeding seismic resolution, oil and gas bearing and flooded reservoirs) this calibration is still qualitative. Nevertheless, the *P*-impedance / Poisson's ratio crossplot (Fig. 5, *a*) compares the data points at the SSG object with the data points from the SSG-0 well. The scatter crossplot demonstrates anomalous values within the SSG site and the absence of anomalous values in the SSG-0 well, which indicates the presence of oil and gas bearing sandstones in the SSG object area. Figure 5, *b* is a map of extraction intervals (+/- 10 ms) at the upper boundary of the Turonian stage (sequence of the upper alluvial fan) from the volume of the attribute $\lambda\rho$, obtained by the inversion method before summation. Anomalous values of $\lambda\rho$ are observed within the SSG site, indicating the presence of porous oil and gas sands with a resolution higher than seismic. Geological model of sedimentation history in the SSG area, it is confirmed by images obtained by prestack inversion method. Figure 5, *c* shows a slope line showing an anomaly in the upper part of the cone of wedging with a clear wedging upward and lateral continuity, indicating the presence of an oil and gas reservoir with a resolution from 20 to 30 m higher than seismic.

Figure 6 shows the interval extraction of the RMS force of the amplitude decay at a large

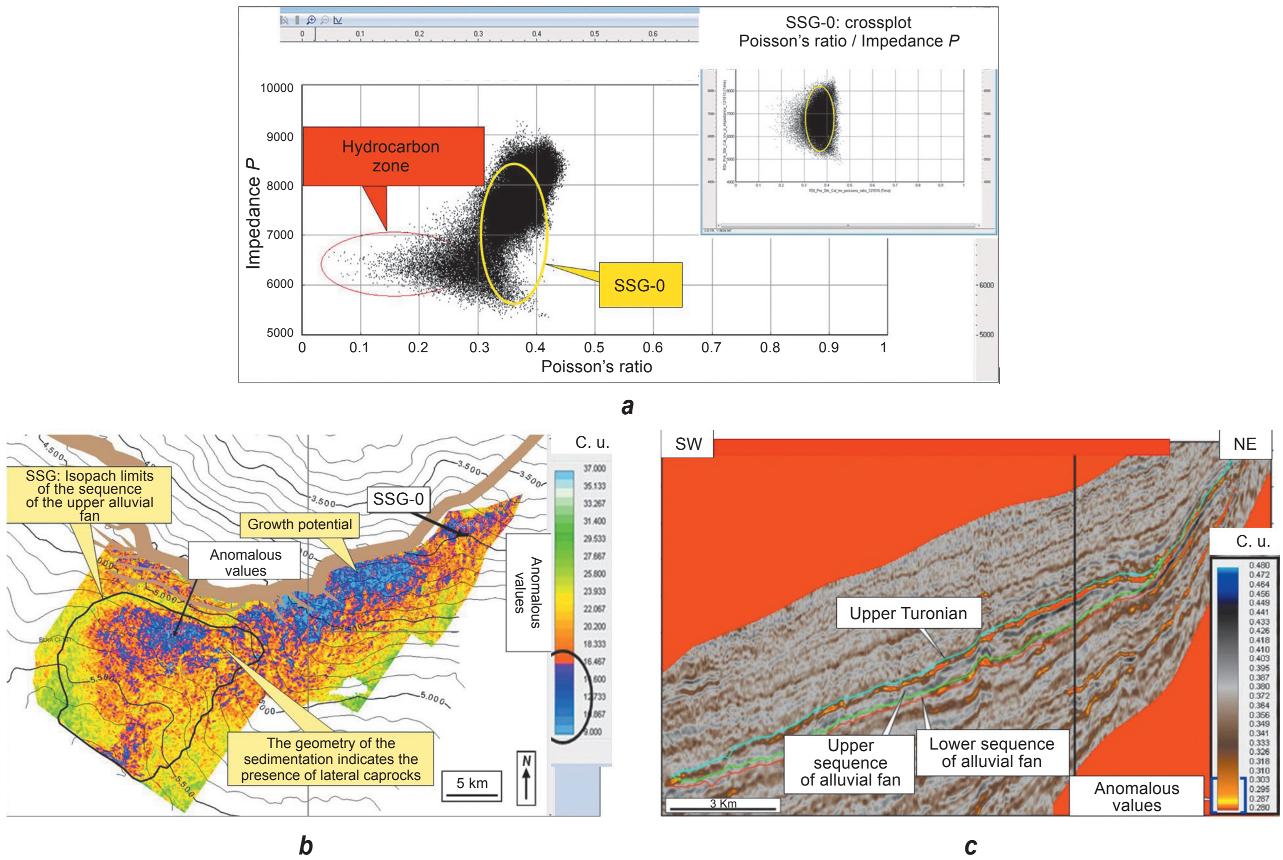


Fig. 5. Parameters demonstrating petrophysical characteristics of SSG site rocks:
a – prestack inversion calibration: impedance P / Poisson's ratio crossplot comparing SSG and SSG-0 site characteristics;
b – retrieval interval $\lambda\rho$ (+/- 10 ms) obtained from the inversion volume before processing the upper boundary of the Turonian stage data shows anomalous negative values (blue-orange);
c – slope line through the SSG site with prestack inversion with Poisson's ratio

Рис. 5. Параметры, демонстрирующие петрофизические характеристики пород участка SSG:
a – калибровка методом инверсии до суммирования: кросс-плот рассеяния импеданса P / коэффициента Пуассона, сравнивающая характеристики объектов SSG и SSG-0;
b – интервал извлечения $\lambda\rho$ (+/- 10 мс), полученный из инверсионного объема до обработки данных по верхней границе Туронского яруса, демонстрирует аномальные отрицательные значения (сине-оранжевый цвет);
c – линия наклона через участок SSG с инверсией до суммирования с коэффициентом Пуассона

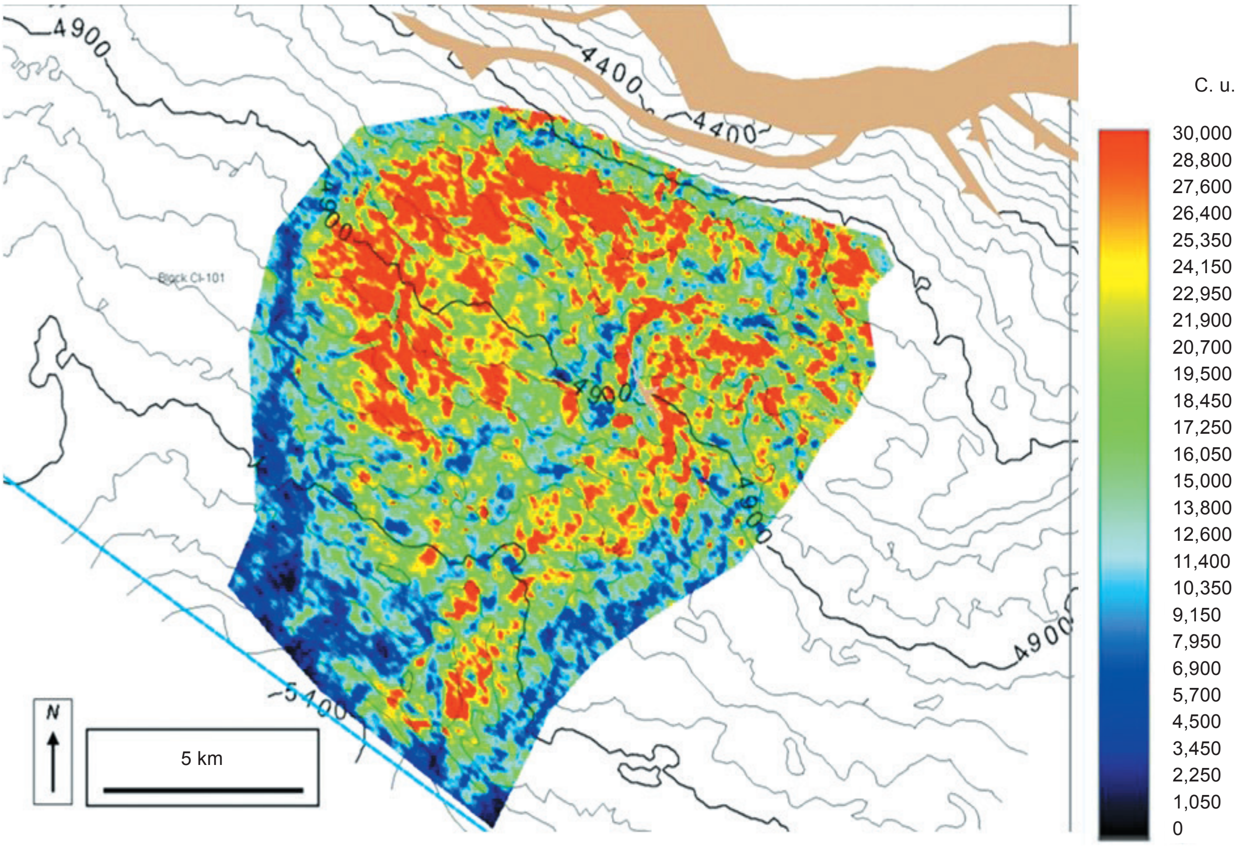


Fig. 6. Total root mean square (RMS) amplitude of oscillations in the SSG area measured from the top to the base of the alluvial fan on the slope
Рис. 6. Суммарная среднеквадратичная амплитуда RMS в районе участка SSG, измеренная от вершины до основания конуса выноса на склоне

angle, demonstrating a high amplitude force (RMS) over the entire cone. This indicates a good continuity of the reservoir, as well as the presence of a certain AVO signature with an increase in amplitude with an angle (displacement).

Conclusion

This paper demonstrates that seismic attributes are a key tool for characterizing and optimizing oil fields. The study showed how seismic attributes extracted from 3D seismic data can qualitatively provide valuable information about the geological features of the subsurface, namely, to map, identify and characterize a promising SSG object, conduct a comparative and similar study with data from neighboring already drilled wells, determine the presence and content of fluids in formations, identify and isolate morphology, the structure, continuity and boundaries of the formation, as well as determine the properties of the formation rocks. The analysis of PSDM, PSTM and prestack inversion seismic data provides excellent determination of the morphology and hydrocarbon potential of a promising SSG object. The results of the petrophysical analysis also confirm the potential for hydrocarbon saturation. Anomalies in the AVO prove the presence of hydrocarbons in the pore fluid. Thus, this study has great prospects for hydrocarbon exploration based on the results obtained during the combined analysis of seismic attributes. Nevertheless, even if this study is considered sufficient for drilling an exploration well, it may be useful to suggest other geophysical methods for integration into this study that could improve the assessment. Electrical methods are known for their effectiveness in direct detection of fluids in formations and have proven effective in Western Siberia in Russia. In this case, it would be advisable to try this approach in the Gulf of Guinea.

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