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# THEORETICAL AND EXPERIMENTAL PREREQUISITES FOR DIRECT FORECAST OF HYDROCARBONS BASED ON SEISMIC EXPLORATION DATA (CASE STUDY THE SOUTH CASPIAN AND OTHER BASINS)

*(Представлено членом редакційної колегії д-ром геол. наук Г.Д. Лісним)*

**Background.** *The petrophysical properties of the sedimentary rocks (porosity, permeability, elastic-plastic and acoustic properties, etc.) have been well studied and the results have been sufficiently widely used in the interpretation of geophysical data. Experimental studies completed in recent years as well as intensive technology improvements in data processing and interpretation of seismic data allowed us to explore also the problem of fluid control of petrophysical properties of rocks, which serves as a basis for developing a method of directly forecasting oil and gas accumulations in sedimentary basins. İt is recommended to use a direct seismic method for predicting the productivity of the section in combination with gas-geochemical survey. The aim is to minimize the risk of hydrocarbon exploration in the deepwater part of the South Caspian.*

**Methods.** *Based on an analysis of worldwide experience and the results of experimental studies in the South Caspian Basin (SCB), the direct seismic methods substantiate the high efficiency of direct forecasting of hydrocarbon accumulations in the sedimentary section.*

**Results.** *The analysis of direct determination of hydrocarbons using seismic data in other basins, as well as the results of developmental and experimental validation of proposed methodology, allows us to state its sufficient applicability in the geological conditions of SCB.*

*However, considering high economic and technological risks of drilling in the deep part of SCB (development of abnormally high pressures, high cost of exploration wells, which exceeds $100 million), and attempting to minimize them, it would be beneficial to integrate the seismic method with other direct methods, especially with gas-geochemical surveying.*

**Conclusions.** *The natural exposure of oil and gas on the surface are of great significance to the hydrocarbon exploration since it directly points to the existence of hydrocarbons in sedimentary basins. In the deepwater part of the basin, the presence and nature of oil and gas shows one of the few tools available to assess the prospects of undrilled area. The emergence of new analytical capabilities in recent years allows us to record a very low concentration of migratory gases and increases the efficiency of detection of even low-contrast hydrocarbon anomalies (Elias et al., 2004).*

**Keywords:** *sedimentary section, hydrocarbon accumulations, direct forecast, seismic survey, South Caspian Basin.*

## Background

The history of development and modern geological position of SCB resulted in the formation of a unique oil and gas basin characterized by intense, still-present physical and chemical processes in the rock-fluid system. Oil and gas presence in SCB is associated mainly with sediments of Lower Pliocene-Productive Suite (PS). Hydrocarbon resources identified here are unevenly distributed and mainly related to anticline structures of flange units of Cheyrankechmez – South Absheron trough located in the northern part of the SCB. The results of integrated geological-geophysical research and exploration data have shown the existence of exceptionally favorable geological conditions for the generation, migration, and formation of hydrocarbon (HC) accumulations in this part of the basin:

- the high rate of subsiding and sedimentation in the Pliocene-Quaternary time, their large thickness;
- presence in the section of sediments rich in organic matter (OM) and favorable temperature conditions for their transformation into hydrocarbons;
- a favorable combination of time of generation, migration and the formation of HC traps;
- existence of geologic conditions for the subvertical migration of HCs;
- presence of intraformational and regional seal.

All these led to commercial oil and gas saturation in almost all structures in this part of the basin. In connection with this, technology to detect these oil and gas accumulations, based solely on the anticline theory of their formation, was very simplified (identification of seismic structures, followed by drilling exploratory wells), but it was also very effective.

Application of this technology in the south and in the deep part of SCB proved to be ineffective due to the change in the geological conditions of generation, migration of hydrocarbons, formation and preservation of their accumulations. Taking into account the high cost of exploration drilling in the deep part of SCB (the cost of one exploration well is more than $75–100 million dollars), the introduction of technologies that could reduce the economic and technological risk of finding hydrocarbons would be very relevant. One of these ways would be using, along with traditional methods, methods of direct diagnosis of hydrocarbon accumulations based on seismic data (possibly in combination with direct gas-geochemical methods). An established fact of changing of the phase of hydrocarbon state from the flank to its deep parts and forecast of the existence here of mostly gas/gas-condensate fields is the favorable factor for the direct diagnosis of HCs in the deep part of SCB.

**Methods**

Seismic methods have played and continue to play a leading role in the search for hydrocarbons in reservoirs. Advances in the past were based on the detection of traps that could contain hydrocarbons (e.g., anticlines, lenses, tectonic disturbances, serving as the screen on the way of hydrocarbons migration, and reefs). The effect of the pore fluids properties in the seismic field was extensively explored only since the era of detection of the "bright spots" in the early 1970s (Sheriff, 1975), reflecting the content of hydrocarbons in the reservoir. For this reason, various research centers around the world have started laboratory and experimental-methodological studies to explore seismic properties of rocks saturated with various fluids (water, oil, gas) (Elliot, & Wiley, 1975; Batzl, & Wang, 1992; Sinartio, 2002, etc.).

For example, a series of laboratory experiments on wave velocities in two different samples of quartz sandstones of Berea formation (Ohio, USA) – saturated with water, air, and light and heavy oil, depending respectively on the pressure and temperature – was conducted by Z. Wang and colleagues (Wang et al., 1990). The experimental results showed that the velocity of wave propagation depending on temperature changes in the rock samples saturated with heavy oil is different from the same sample saturated with water or light oil. However, the most obvious differences between the values of seismic parameters were noted between the rocks saturated with gas and liquid – values of Vp/Vs (the ratio of compressional and shear velocities) and Poisson's ratio in the gas-saturated rocks are always comparatively lower.

A significant decrease in the velocity of seismic waves and change of other seismic parameters in the presence of gas in the rock was observed by other researchers (Batzle et al., 2004; Barton, 2007; Goloshubin et al., 2002).

As suggested by G.J. Blackburn (1986), even a small amount of gas is sufficient to create the necessary contrast in the value of the impedance in comparison with water- or oil-containing sandstone.

As an example, fig. 1 shows the trend of the change of the reflection coefficient curves for the model of the reservoir saturated with gas and saline water (Batzle et al., 2004). Their difference is obvious. However, it should be noted that sometimes the gas-saturated water can be a false indicator of hydrocarbons (Han, & Batzle, 2004). In general, it is believed that pore fluid affects Vp more than Vs (Mavko et al., 2005; Alvarez, 2007).

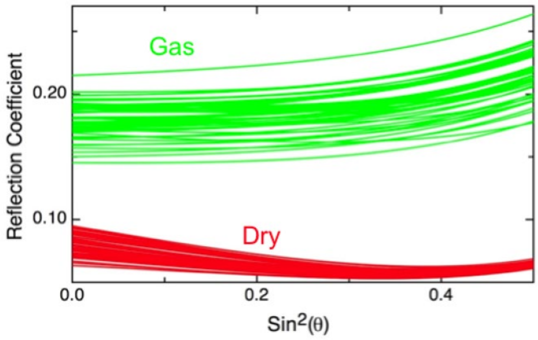



**Fig. 1. The reflection coefficients for models of the reservoir containing certain amounts of gas (green), and only saline water (red) (Batzle et al., 2004)**

The influence of gas on the seismic parameters was also found during a series of laboratory experiments covering the injection of $CO_2$ in the rock-reservoirs (Xue, & Ohsumi, 2004), which showed a significant decrease in P-wave velocity (from 6.1 % to 10.6 %) (Harris et al., 2006) and changes in transit time and amplitude of the reflected waves (Daley et al., 2007). The capabilities of seismic data for the diagnosis of gas is illustrated by the results of monitoring $CO_2$ injection at Weyburn field in Canada (White, 2004) and in an aquifer at the Sleipner area in Norway (Chadwick et al., 2007) (Fig. 2).

The values of Vp impedance measured in a thick soft-sand interval of well in the North Sea, the upper part of which is gas-saturated and the lower – oil- and water-saturated, were examined based on porosity and gas saturation (Fig. 3).

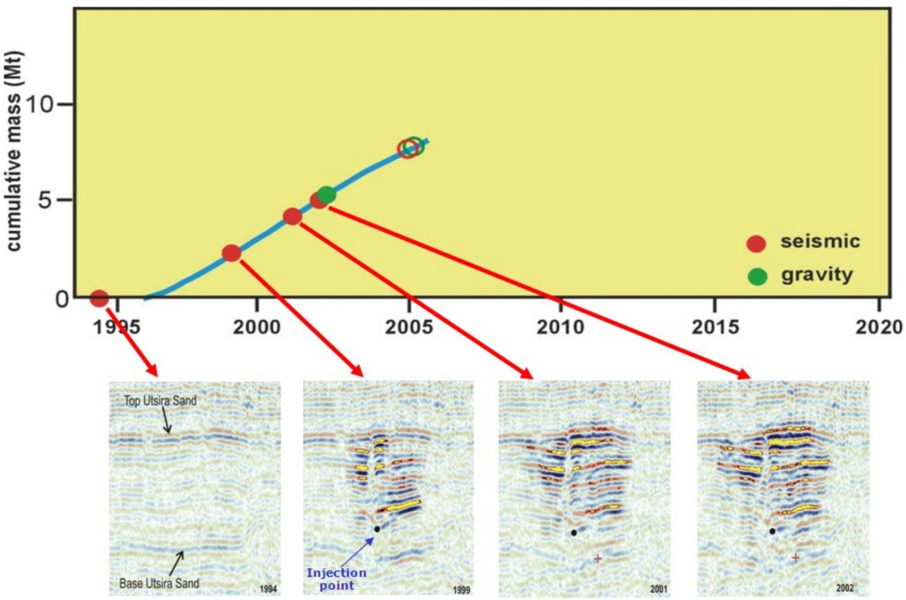



**Fig. 2. Seismic monitoring of CO2 injection in an aquifer at Sleipner storage, the central North Sea (Chadwick et al., 2007)**

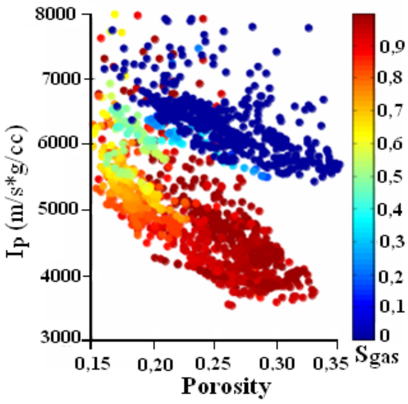



**Fig. 3. Impedance versus porosity is a thick soft-sand interval color-coded by gas saturation. The presence of gas in the pore space produces a strong decrease in the impedance. The rest of interval is filled with oil and water (Walls, & Dvorkin, 2005)**

The presence of the gas in this well causes dramatic reduction of the impedance due to the strong difference between the bulk modulus of gas (about 0.08 GPa in this example), oil (about 0.8 GPa), and water (about 2.8 GPa) (Walls, & Dvorkin, 2005).

The influence of pore fluids on seismic properties of rocks, identified in laboratory and field experiments, formed the basis for development of methods for direct detection of hydrocarbons from seismic data, which have been tested in various basins of the world (Alvarez, 2007; Shikhaliyev, 2005; Blom, & Bacon, 2009 and others). This became technically possible due to progress made in recent years in improving the quality of acquired seismic data and the tremendous progress in their processing and interpretation.

The term of direct diagnosis of hydrocarbons started to be used in seismic exploration more than 50 years ago. In the past 20 years, extensive experiments have been conducted to measure the abnormal attenuation and velocity dispersion (AVD method) of seismic waves in the oil and gas fields, using borehole and surface data. These experiments confirmed the changes in the noted parameters of hydrocarbon-saturated sediments. AVD method was successfully applied in various parts of Russia, China, Vietnam, and Latin America, with the exception of the northern Caucasus, where the abnormal attenuation was caused by the water, heavily saturated with carbon dioxide (Rapoport et al., 2004).

At present, the most widely used method for prediction of gas in the reservoir is AVO method (Amplitude Variation with Offset), which is basically an improved version of the method of "bright spots" (Batzle et al., 2004 and others). At the same time, it's established that the Class 3 AVO anomaly better reflects the gas saturation of sediments (Hilterman, 2003).

However, there is the opinion that the method of AVO is not sufficiently effective at greater depths. For example, many wells drilled offshore Gulf of Mexico in the AVO anomalies detected only non-commercial gas accumulation (the so-called problem of "fizz-water" – gas-saturated water) (Walls et al., 2006).

According to Simmons and Backus (1994), the use of converted waves has the greater potential for differentiating lithology of rocks and fluids saturating them than the method of AVO (Fig. 4).

Application of a universal interpretation system in the offshore hydrocarbon exploration, which combines the methods of determining the amplitudes and spectra of seismic signals (Millahn et al., 1979), has shown the clear correlation between high-amplitude anomalies and gas zones. The authors believe this can be used in combination with other data, which will reduce the cost of exploration and increase the rate of success.

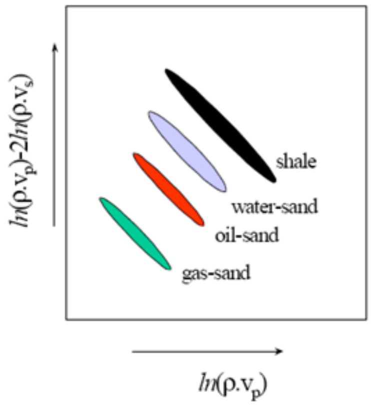



**Fig. 4. The combination of shear (ρVs) and compressional (ρVp) impedances for differentiating lithology of rocks and their saturation with various fluids (Simmons, & Backus, 1994)**

An example of seismic data analysis from offshore of the Netherlands (Permian/Triassic deposits) (Bloml and Bacon, 2009) shows the presence of clear direct hydrocarbon indicators, which were used to assess the prospects of undrilled areas and forecast the expected type of hydrocarbons. Types of hydrocarbons, expected in each prospective area, were predicted on the basis of comparison of early results of simulation and actual seismic observations. Success of exploratory drilling as a result of this approach has been improved. All three recently drilled exploration wells found hydrocarbons in areas previously assessed as promising.

An example of Ay-Pim oil field in Western Siberia shows that amplitude, which depends on frequency, and phase reflection properties can be used for detection and control of thin layers of oil-saturated beds and delineation of oil-water contact (Goloshubin et al., 2002) (Fig. 5).

The attenuation coefficient of seismic data is a good tool to identify gas reservoirs (Walls et al., 2003, 2006, etc.). The experimental results in the Gulf of Mexico on more than 90 wells drilled in 20 areas, showed the effectiveness of direct prediction of oil and gas reservoirs (tally of seismic data with the results of drilling was more than 90 %) (Walls et al., 2003).

The 3D seismic prediction of potential oil and gas zones with the results of drilling was observed in western China (Hu et al., 2005).

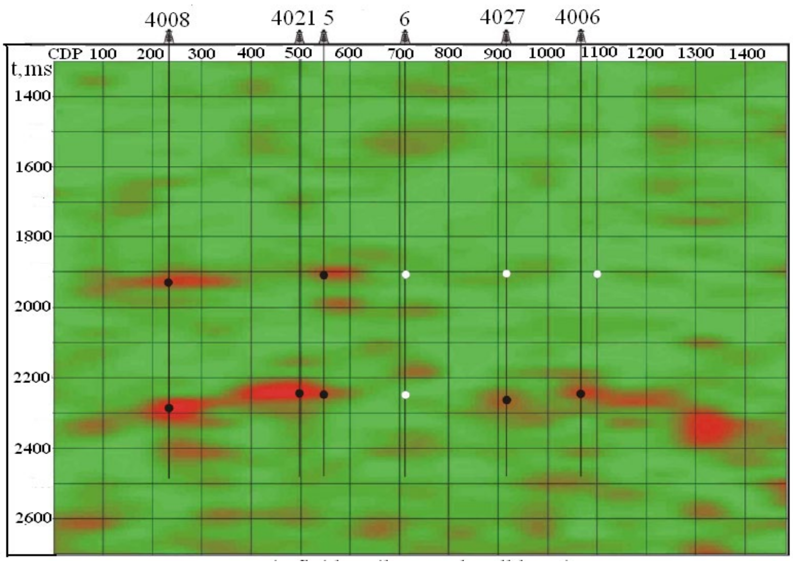
According to statistics based on drilling of 65 wells at 6 oil fields in China with total depth (TD) at depths of more than 5 km, the success of the direct diagnosis from the seismic method was 73 % (Hu et al., 2005).

It's established (Klimentos, 1995) that in the sandstones saturated with liquid fluid attenuation of the S-wave is approximately the same as P-waves, whereas in the gas-saturated intervals the P-wave attenuation is much stronger than the attenuation of the S-wave (Fig. 6).

***Methodical basis of research in SCB***

In this research a methodology, technology and software package "REZAYR" for integrated data processing and interpretation of seismic and well-log data was used (Shikaliyev et al., 1994; Shikhaliyev, 2005).

This technology is based on the implementation of mathematical methods of analysis and interpretation of seismic data executed in an interactive way and enables us, as a result of an iterative process, to clarify or determine such important geological and geophysical characteristics of the 2D section as: stratigraphic boundaries; values of formation velocities and trace velocities; the values of effective porosity and bulk clay volume; the average value of grain diameter and the delimitation of lithofacies boundaries; construction of geoacoustic and effective geological models of section; and prediction of reservoir properties and their productivity.




**Seismic fluid attribute and well locations**

**● - there is oil**

**○ - there is no oil**

**Fig. 5. Low-frequency processed reflection data for Ay-Pim oil field in Western Siberia (Goloshubin et al., 2002)**

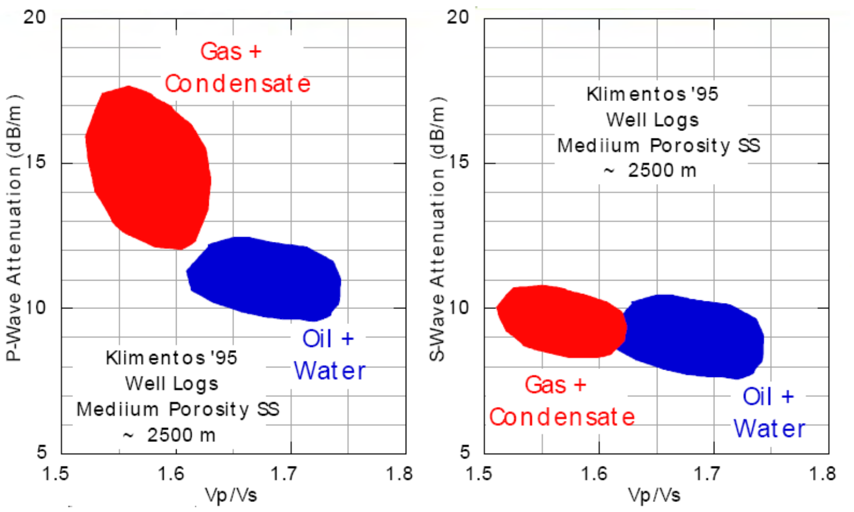



**Fig. 6. The P-wave and S-wave attenuation in liquid-saturated sandstone and gas-saturated intervals (Klimentos, 1995)**

The method does not require a priori knowledge of the velocity characteristics of the section, but its effectiveness increases significantly when acoustic logging data, vertical seismic profiling, and well-velocity survey data are available.

A synthetic seismogram, built from these data, is compared with the real seismic traces at the stake of the profile, where the well is located (Fig. 7).

The integrated process of tying synthetic and real seismic trace continues until the maximum degree of matching is achieved. Based on similar elements of these seismic traces, velocities are determined and used for depth-time conversion of well-log data and tying them back to seismic section.

After this, we construct an effective model of the section and determine predicted values of formation velocities, which are based on the correlation of pseudosonic log velocities with the true velocities in the same intervals, i.e. within the effective model (Fig. 8). The values of the pseudosonic log should be defined with maximum reliability.

During the comparison, the differences in the values of velocities are revealed, their natures are determined, and changes are made accordingly.

Subsequently, using a variety of known functional relationships (Wyllie et al., 1958; Dakhnov, 1982) of petrophysical models as well as the instantaneous dynamic parameters of the wave field, seismic sections are transformed into sections with different petrophysical parameters, based on which reservoir properties of formations are predicted and, if possible, their productivity is determined.

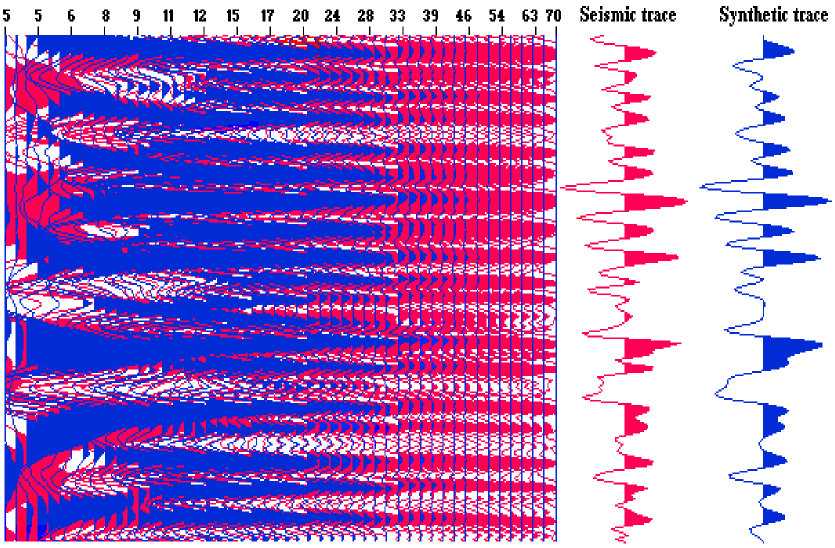



**Fig. 7. Spectrum-time analysis**

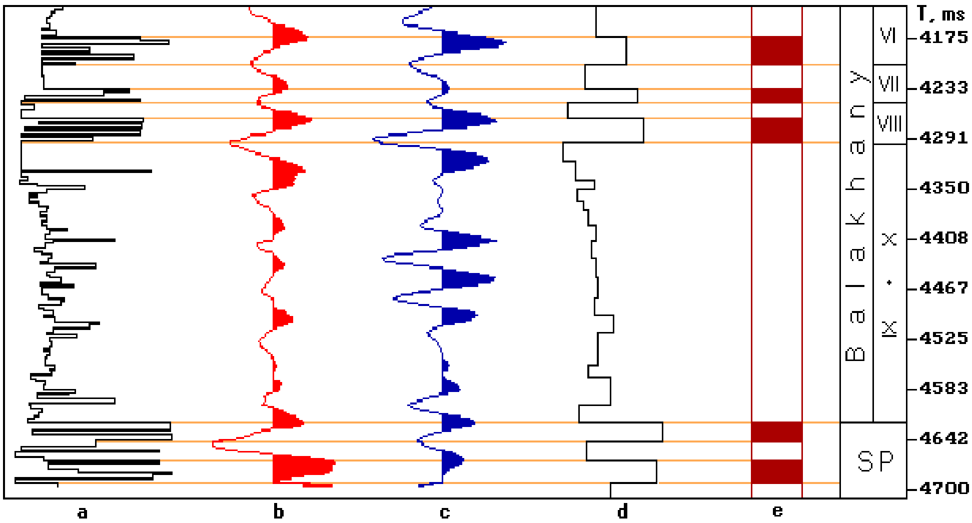



**Fig. 8. Building of an effective model from well-log data:**
a – well-log data; b – synthetic trace; c – seismic trace; d – effective model; e – interval of predicted parameters

Obtained distribution of petrophysical parameters allows us to estimate the total volume of reservoirs in the section, which, on the one hand, is the necessary information for estimation of volume and hydrocarbon reserves of the reservoir, and, on the other hand, is necessary to assess their productivity.

Productivity prediction is solved by different methods. For example, the usual approach to determine the productivity of reservoir is based on the parameters obtained by data analysis from identical areas or from theoretical considerations taking into account a given petrophysical model of the productive reservoir and aquifer (Dakhnov, 1982). Another approach implements a simplified version of the method of pattern recognition in an n-dimensional space. These two approaches, complementing each other, allow us to estimate a zone of ambiguity in the area of oil-water contact. A feature of the methodology is that the well log and seismic data are not interpreted separately, but in the same interpretational cycle.

**Results**

Studies on the direct diagnosis of oil and gas in SCB included developing methodology and a software package for seismic data interpretation and its pilot testing on a large gas-condensate field Shah Deniz, and two prospective offshore structures: Yalama-Samur and Absheron (Fig. 9).

Analyzed seismic profiles were obtained by 2D and 3D seismic surveys. Let's examine the results of this methodology using the example of the Shah-Deniz area (see Fig. 9) with the established commercial oil and gas deposits.

Shah Deniz is a shelf gas condensate structure discovered in 1999. It is situated in the Azerbaijan sector of the Caspian Sea, 70 km south-east of Baku. The water depth in the field is from 50 to 650 m. The gas-bearing area is about 860 km². Production from the first well, with TD of 6500 m and drilled with a stationary production platform at a water depth of 105 m, started on December 15, 2006, with an output of 5.6 million cubic meters of gas per day from Productive series (PS). PS is the main reservoir in SCB and accounts for more than 90 % of current hydrocarbon production.

To study the Shah-Deniz, we used the time section of one of the 3D profiles. The quality of the section is high enough and reflects well the main elements of the geological elements of the section (Fig. 10). The interpretation of the data included identification of seismic horizons corresponding to various suites of PS.

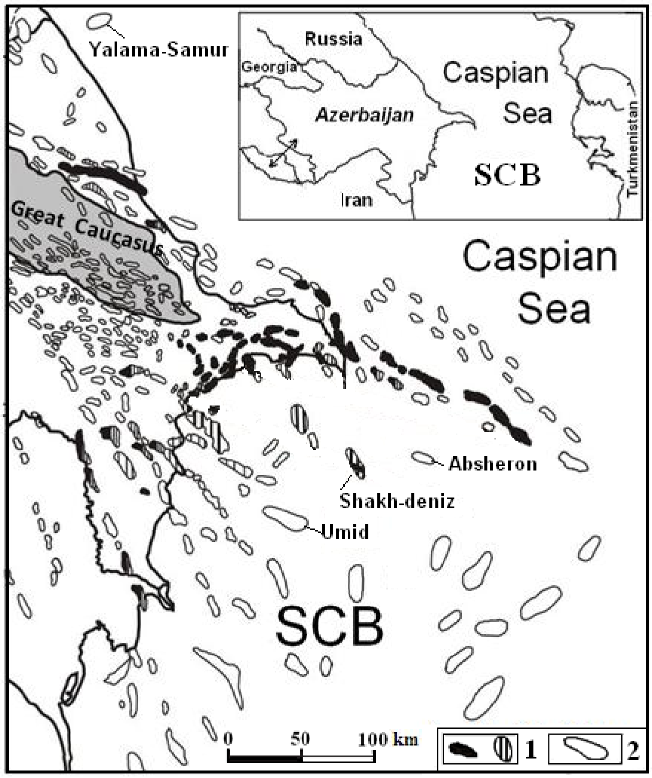



**Fig. 9. Scheme of location of SCB and studied fields:**
1 – productive structures; 2 – prospective structures

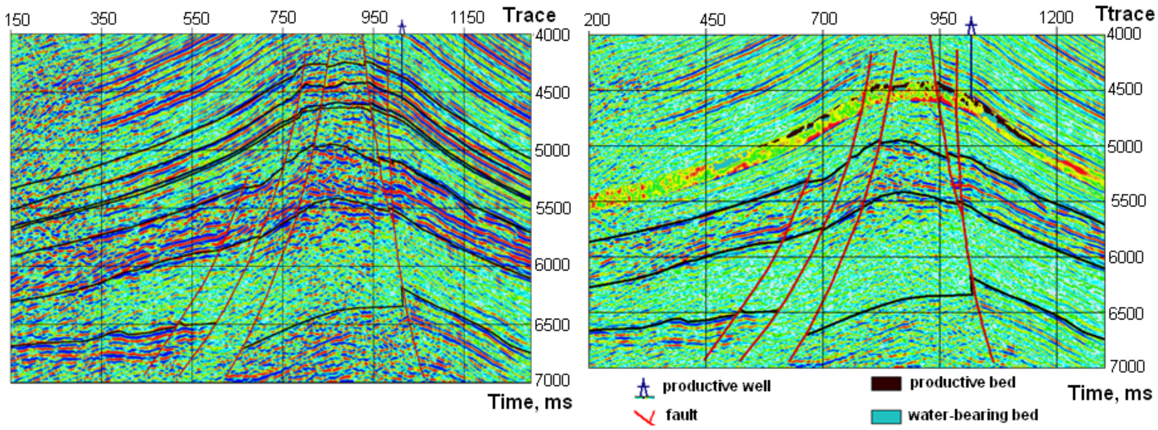



**Fig. 10. Shah-Deniz field. A fragment of time section (left) and predict of productivity**

An integrated interpretation of seismic and well data using the above methodology has allowed us to get a more detailed estimation of petrophysical parameters (velocity, porosity, sand/clay content, etc.) of deposits and to predict the main productive areas in the studied profile (see Fig. 10). These areas belong to the "Pereriva" suite of the PS. Comparison of the projected areas with the location of actual productive zones, identified by the exploration well, showed their satisfactory agreement (see Fig. 10).

The good correlation of seismic data with data obtained from the drilling of Shah Deniz served as a good precondition for the extensive introduction of the developed methodology for prediction of hydrocarbon zones in SCB structures with not-yet-clarified prospects, such as the Yalama-Samur, Umid, Absheron and et. al.(see Fig. 9). The results of direct diagnosis of the productivity of the Yalama-Samur structure are described below.

The Yalama-Samur structure is located on the border of Russian and Azerbaijan sectors of the Caspian, representing a geological uplift perspective for oil and gas. The first exploratory appraisal well drilled on this structure (block D-222) was unproductive. Studies on the direct diagnosis of hydrocarbons in this block were conducted on the 2D profile, crossing the area in sublatitudinal direction (Fig. 11).

The peculiarity of the task of evaluating the petrophysical characteristics in this case was the fact that the well was located at a considerable distance from the analyzed section (about 30 km) and, despite the relative calm of the geological environment, its characteristics were difficult to use correctly.

However, available information on the structure was sufficient to assess velocity characteristics of deposits, and some volumetric parameters of rocks. Based on this, the seismic section was transformed into a parametric section of formation velocities (Fig. 11), and then sections of distribution values of the coefficients of effective porosity and sand were compiled.

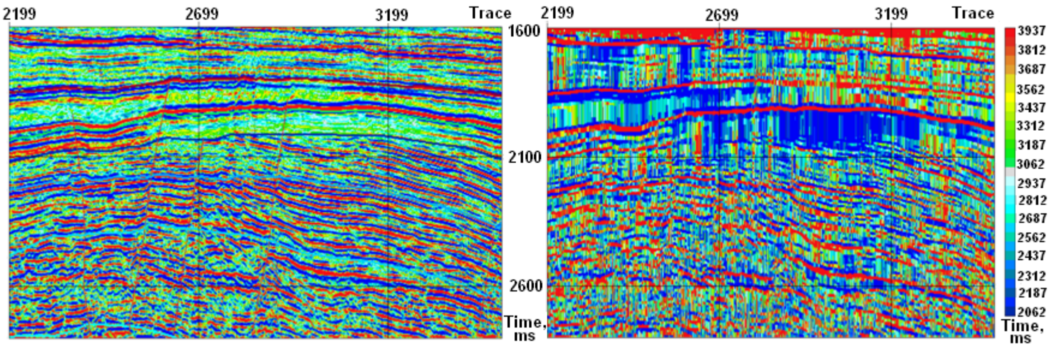



**Fig. 11. A fragment of time section (left) and formation velocities of Yalama-Samur structure (right)**

Based on comprehensive analysis of seismic data interpretation results, in combination with other geological and geochemical data, the conclusion was made that the structure is not of commercial interest (Guliyev et al., 2007). Nevertheless, the second exploration well was drilled and turned out to be also unproductive, thus confirming results from seismic data prediction.

**Discussion and conclusions**

It is important to note that there have been attempts to apply this integrated method (Schumaker et al., 1999). Thus the use of geochemical method in integration with the results of 3D seismic in Canada has increased the success rate of drilling to 71 %, while the success of using only seismic data was approximately 34 %. In South America, the integration of the two methods provided a 95 % success rate of drilling and reduced the cost of exploration to 43 % (Schumaker et al., 1999).

V. Gabela et al. also believes that a good precondition for a substantial increase in the success rate of finding hydrocarbons can be achieved through the integration of seismic data with direct near-surface gas-geochemical methods. As a proof, he presented the analysis of the results from 196 wells drilled within vicinity of the geochemical anomalies. It was found that, in 92 % of cases, the drilling within the positive geochemical anomalies revealed the presence of commercial accumulations of hydrocarbons, while the wells drilled within the limits of negative anomalies turned out to be unproductive in 95 % of cases (Gabela et al., 2003).

It should be noted that in Azerbaijan the surface gas-geochemical exploration have been conducted on the industrial scale, both onshore and offshore. The analysis of the results showed that the effectiveness of positive prediction here is 75–87 %, while the success of negative prediction reaches 95–100 % (Feyzullayev et al., 2008).

An example is a local process of sub-vertical hydrocarbon discharge above the south-eastern subsidence of the Bahar petroleum bearing structure (Bahar-2 area) in the South Caspian, which formed anomalous concentrations of methane and the sum of its homologues in the bottom layers (depths up to 100 m) (Fig. 12).

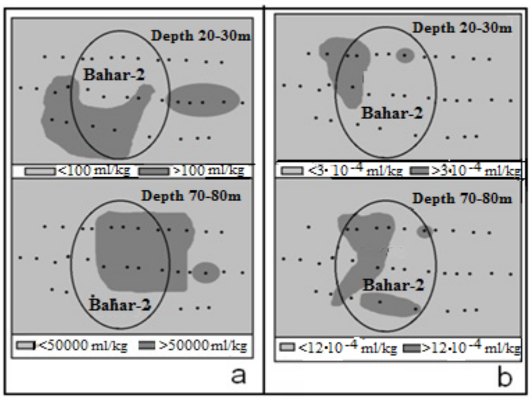



**Fig. 12. South Caspian. Distribution of methane (a) and the sum of methane homologues (b) in the bottom layers (to a depth of 100 m) of the Bahar-2 area**

The above-mentioned serves as a convincing basis for recommending the combination of direct seismic and gas-geochemical methods for the exploration in the central part of the deep part of SCB.

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# ТЕОРЕТИЧНІ ТА ЕКСПЕРИМЕНТАЛЬНІ ПЕРЕДУМОВИ ПРЯМОГО ПРОГНОЗУВАННЯ ВУГЛЕВОДНІВ НА ОСНОВІ ДАНИХ СЕЙСМОРОЗВІДКИ (НА ПРИКЛАДІ ПІВДЕННО-КАСПІЙСЬКОГО ТА ІНШИХ БАСЕЙНІВ)

***Вступ.*** ***Петрофізичні властивості осадових порід (пористість, проникність, пружно-пластичні та акустичні властивості тощо) були добре вивчені, а результати досить широко використовувались при інтерпретації геофізичних даних. Експериментальні дослідження, проведені останніми роками, а також інтенсивне вдосконалення технологій обробки та інтерпретації сейсмічних даних дозволили нам також дослідити проблему контролю флюїдами петрофізичних властивостей порід, що слугує основою для розробки методу прямого прогнозування покладів нафти та газу в осадових басейнах. Рекомендується використовувати прямий сейсмічний метод для прогнозування продуктивності розрізу в поєднанні з газогеохімічною зйомкою.***

***Мета. Мінімізувати ризик розвідки вуглеводнів у глибоководній частині Південного Каспію.***

***Методи.*** ***На основі аналізу світового досвіду та результатів експериментальних досліджень у Південнокаспійському басейні (ПКБ) обґрунтовано високу ефективність прямого прогнозування покладів вуглеводнів в осадовому розрізі за допомогою прямих сейсмічних методів.***

***Результати.*** ***Аналіз прямого визначення вуглеводнів за допомогою сейсмічних даних в інших басейнах, а також результати розробки та експериментальної перевірки запропонованої методології дозволяють стверджувати про її достатню застосовність у геологічних умовах ПКБ.***

***Однак, враховуючи високі економічні та технологічні ризики буріння у глибоководній частині ПКБ (розвиток аномально високих тисків, висока вартість розвідувальних свердловин, що перевищує $100 млн), та намагаючись їх мінімізувати, було б вигідно інтегрувати сейсмічний метод з іншими прямими методами, особливо з газогеохімічною зйомкою.***

***Висновки.*** ***Природні виходи нафти та газу на поверхню мають велике значення для розвідки вуглеводнів, оскільки вони прямо вказують на існування вуглеводнів в осадових басейнах. У глибоководній частині басейну наявність та характер нафтогазопроявів є одним із небагатьох доступних інструментів для оцінки перспектив нерозбуреної ділянки. Поява нових аналітичних можливостей останніми роками дозволяє фіксувати дуже низьку концентрацію міграційних газів та підвищує ефективність виявлення навіть низькоконтрастних вуглеводневих аномалій (Elias et al., 2004).***

***Ключові слова:*** ***осадовий розріз, вуглеводневі поклади, прямий прогноз, сейсморозвідка, Південнокаспійський басейн.***

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