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The application of fault seal analysis at the Solokha field, Dnieper-Donets Basin, Ukraine – case studies

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Abstract: The Solokha gas field is one of the most valuable hydrocarbon fields in the central axial part of the Dnieper-Donets Basin (DDB). Every new exploration well there has to be highly validated in order to reduce possible drilling risks. In this study, the characteristics of faults, as possible seals, are analysed, based on the latest well and 3D seismic data. Evaluating fault seal risk is a constitutive factor in hydrocarbon exploration and production. For this reason, to reduce uncertainty in the faults' leaking facilities, we used a couple of known approaches, such as juxtaposition analysis, with building Allan diagrams, to determine the relationship between sand-sand juxtaposition and the occurrence of hydrocarbons-bearing sands. We used the Shale Gouge Ratio (SGR) calculation with prediction of clay content distribution along the faults, pressure data analysis, seismic attributes modelling and self-organized map clustering analysis for accurate delineation of sand bodies shape. This represents a complex research method of integration of high-quality depth processing with seismic structural and stratigraphic interpretation and, also, geological modeling. In this paper, we assessed the Jurassic and Visean faults of the Solokha gas field, according to their fluid cross-flow facilities. This research will provide valuable information about the presence of prospective places for hydrocarbon accumulation and will likely impact the well staking process for the upcoming drilling.

Keywords: Dnieper-Donets Basin, Fault Seal Analysis (FSA), hydrocarbon traps

INTRODUCTION

Salt basins, with their complex tectonic history, occur worldwide. Large hydrocarbon deposits are often associated with the presence of salt structures, due to favorable conditions for accumulation and trapping of oil and gas. One of such basins is the Dnieper-Donets Basin, located in Ukraine (the location and boundaries of the basin are shown in Figure 1).

The Solokha area is representative of the DDB, as such. It comprises different types of traps that are associated with salt dome flanks (Savchenko et al. 1979–1982), separated tectonic blocks, unconformities and discontinuities (Tiapkina & Bartashchuk 2011). Obviously, this is possible, as a result of the process of salt rising, which occurred in several stages and was separated by periods of relative calm. These pulsating movements led to the formation of a very complicated structure (Tiapkina et al. 2012, Tiapkina & Okrepkyi 2013).

In this study we applied an integrated geological approach, involving 3D seismic, petrophysical measurements, pore pressure and some other

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available data, with complex geological modeling, to establish the role of faults in the formation of hydrocarbon accumulations in the Solokha gas field. Although Fault Sealing Analysis (FSA) is addressed by many researchers (e.g., Bouvier 1989, Magoon & Dow 1994, Yielding et al. 1998, Manzocchi et al. 1999, Ligtenberg 2004, Bretan 2012), and it is widely considered that about 75% of all hydrocarbon-bearing traps are fault-related, very little attention has been paid to accurate assessments of fault properties at the Solokha field. That is why, throughout the year, we concentrated on providing an evaluation of all the available data, to be able to conclude firmly the presence of possible cross-fault flows at the most prospective hydrocarbon levels. As a result of all these processes, we can presently observe some structural traps with tectonic sealing along normal faults and multilayered hydrocarbon accumulation in Visean and Jurassic intervals.

OIL AND GAS FIELDS IN THE DNIEPER-DONETS BASIN

More than 200 fields were detected in the DDB. It is considered that discovered petroleum volumes are slightly higher than 11.5 billion barrels of oil equivalent (BOE), of which 86 percent is gas (Petroconsultants 1996). About 20 percent of the gas reserves are in the Shebelynka gas field (>650 billion m^3) (Fig. 1), the largest field in the basin. The majority of all the prospects have been explored to the depth of 4–5 km.

In general, it is possible to encounter three major levels of hydrocarbon traps: Basement and Devonian rocks; Carboniferous–Lower Permian clastics; Mesozoic deposits. Due to investigations of the last decade, it is possible to separate another type of hydrocarbon-unconventional gas accumulations in Carboniferous tight clastic rocks (Yuzivska area – Fig. 1).

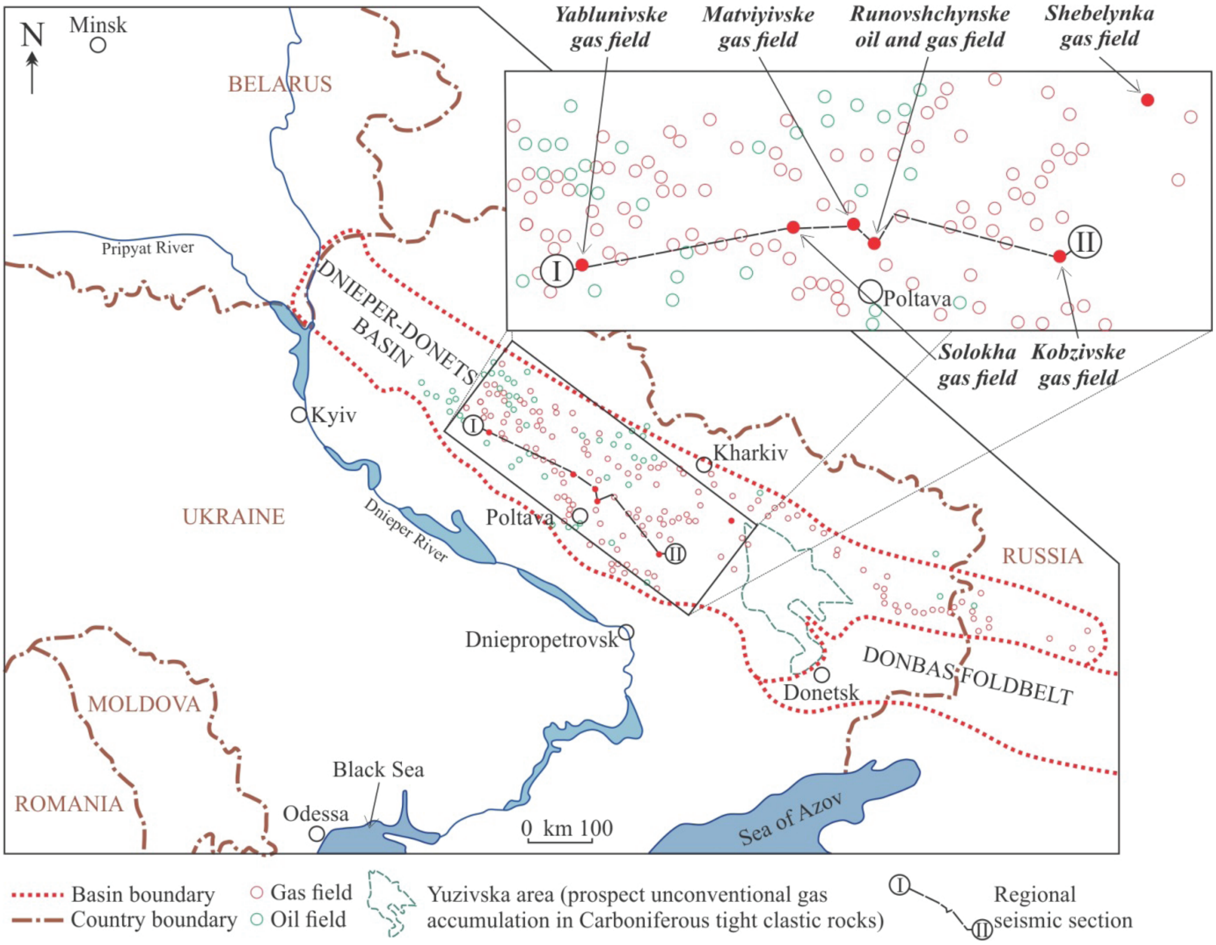

Fig. 1. Location of Dnieper-Donets Basin (modified from Ulmishek et al. 2001)

According to the last researches (Sachsenhofer et al. 2009), at least two, and possibly more, stratigraphic units that contain petroleum source rocks are present in the Carboniferous deposits of the DDB, as follows, Lowermost Upper Visean rocks (“Rudov Beds”, average 5% TOC) and Serpukhovian horizons (up to 16% TOC).

GEOLOGICAL SETTINGS OF SOLOKHA GAS FIELD

The most developed salt bodies occur in the central axial part of the DDB, ranging from pillow to mushroom-shaped diapirs 10–15 km high (Chirvinskaya & Sollogub 1980). A general well-section across Solokha and neighbor fields is shown in Figure 2.

The Solokha field is an area with extensive salt tectonics. This is the reason why we paid attention to the study of its evolution. The main mass of salt in the basin was deposited at the Late Devonian rift stage and then mobilized in the Late Paleozoic post-rift stage. During subsequent post-rift phases of salt diapirism activity, the salt pierced overlying deposits. The salt growth activity, time intervals are correlated with post-rift regional extensional and compressional tectonic events. Major post-rift structural reactivations took place in the beginning of the Late Visean, in the Middle of Serpukhovian and in the beginning of Permian time (Stovba & Stephenson 2003). All of these episodes of salt movement were triggered by extensional tectonic events. Finally, compressional tectonics during the Late Cretaceous to Early Paleogene accelerated the rate of diapirism or strongly deformed some of the diapirs.

The Solokha field is located near the salt dome. Salt also occurs beneath the interval of our study. After paleostructural analysis, several phases tectogenesis and associated halokinesis were identified in the area: the Early Sudeten phase in Late Tournaisian time (denoted as I), Later Sudeten phase in Late Visean time (denoted as II), Palatinate phase in Late Carboniferous time (denoted as III), and Laramide in Late Cretaceous time. Positions of tectonic phases are shown in Figure 3.

DATA AND METHODS

A study of the relationship between the tectonic phases and the time of hydrocarbon migration is very important for successful search for hydrocarbons. Oil and gas deposits, formed at a certain moment of geological history, then respond to tectonic deformations, each time adapting to new structural conditions, reservoir pressure, and the influence of other factors. Hydrocarbon migration up the fault cracks can lead to complete or partial destruction of existing deposits and to formation of new deposits in younger rocks.

During our investigations, we concentrated our attention on two main tasks: delineating structural and tectonic boundaries for the gas trap in the J_{bc} interval and predicting the measures of Visean stratigraphic traps, affected by the faults. Both of these tasks are directly associated with providing the FSA. As such we used a couple of common methods, mandatory to obtain precise geological results.

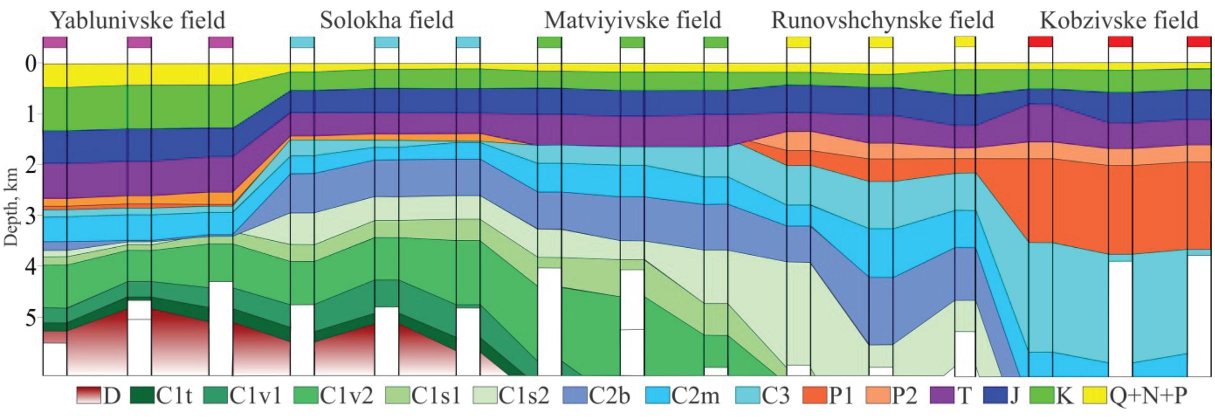

Fig. 2. Well section across Yablunivske, Solokha, Matviyivske, Runovshchynske and Kobzivske fields at line I-II on the Figure 1

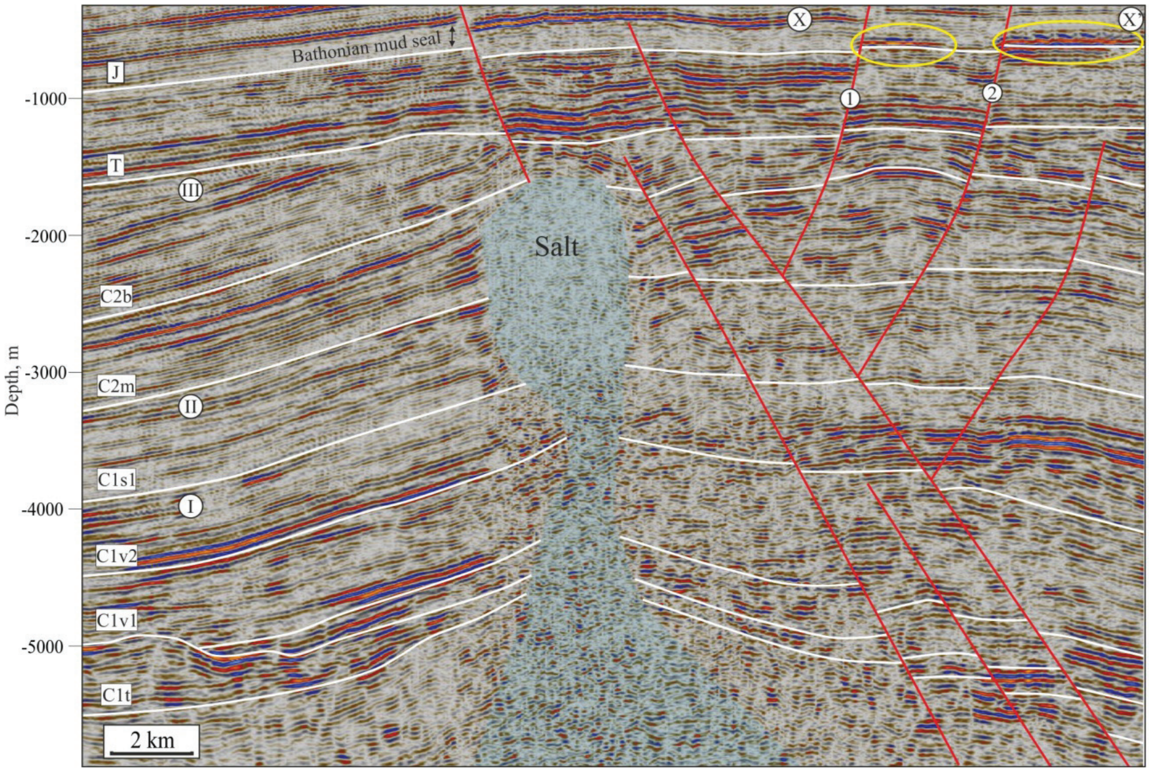

Fig. 3. *Seismic section across the Solokha field. Jurassic reservoir is marked with yellow ovals. Numbers I, II and III refer to the consecutive phases of tectogenesis and associated halokinesis. The numbers 1 and 2 denote faults with sealing properties. The letters X and X' denote a fragment of the section along the line shown in Figure 4*

The first approach includes conduction of an accurate seismic interpretation, within the area of interest. This was the main input for providing juxtaposition analysis (Allan 1989) or Allan diagrams, which can help in the quick initial examination and prediction of fault seal capacity. These can also reveal lithological juxtapositions of footwalls and hanging walls along the fault. An "upgraded" version requires facies model to predict juxtaposition of not only structural horizons, but also facies layers. However, this can be a very time-consuming process, because of the array of thin layers. Hence it is may be difficult to interpret and analyse them all.

The second approach was associated with available pressure data analysis. Usually, this is the most direct indicator of reservoir compartmentalization or existing of fluid flow pathways. Unfortunately, measured pressure data are available only for the Jurassic hydrocarbon interval. The pressure regime of the Visean interval will be evaluated using the pore pressure prediction approach, which engages seismic and well log data. (Considering, this is a heavy workload, the results will be shown in the next paper, related to the Solokha gas field). This investigating will give more geological information about reservoir compartmentalizing.

The third method is the Shale Gouge Ratio prediction. This seems to be one of the most common and accepted approaches (Yielding et al. 1998, 2010, 2012). The approach is very data-consuming, demanding the presence of lithological characteristics of the fault zone, such as shale smear, fault gouge and rock types that are juxtaposed along the fault. It is usually used in the situation when unfavourable juxtapositions exist along the fault plane, so as to predict the possibility of an impermeable fault zone. However, this does not mean that, in the situation when there is no juxtapositions of reservoir rocks, there is no need for such investigation. This is because the existence of two different types of fault seals:

- reservoirs against non-reservoirs, in which the sealing mechanism is working due to the juxtaposition of permeable rock (for example, sandstone) against non-permeable (clay-rich);
- the fault itself serves as a barrier to a permeable rock and prevents further hydrocarbon migration.

How can a particular fault become a sealing one by itself? This mechanism is pretty complicated. Clay-rich material (which is present in both fault blocks – permeable and impermeable) is incorporated into the fault zone, during its incipience. This process is not a prompt one and takes sometimes thousands of years, from the evolution process from flexure shape to fault movement. As a result, clay-rich material "smears" along the fault, creating an impermeable zone. One should emphasize, that different strata and rocks – tensile and brittle, sand and shale – are incorporated into the fault zone, to form a complex "smearing" process. In addition, this process is not well defined in situations of strike-slip fault, thrust belts etc. Hence, there might be a need for additional research.

INTERPRETATION OF THE J_{BC} INTERVAL

Due to the restructuring of the area in Late Cretaceous time and subsequent migration of hydrocarbons along connected faults, favourable structural conditions for hydrocarbon accumulation were formed and subsequently filled in (Fig. 3). It is possible to distinguish three: a large Bajocian sandstone reservoir (J_{bc}) with rather high and stable values of thicknesses, porosity, and permeability; a rather thick Bathonian mud top seal; and favourable ratios of the faults through to the reservoir thicknesses. This Jurassic gas reservoir manifests itself as a "bright spot" (a well-known local high amplitude seismic anomaly, that can indicate the presence of hydrocarbons, and is therefore known as a direct hydrocarbon indicator) on a stratigraphic slice of the envelope cube (Fig. 3).

Aswas mentioned previously, pressure regime analysis is an important part of this investigation. 13 wells were analysed, according to the available pressure data (Fig. 4C). Wells W2, W3, W12 and W13 emerged out of the predicted gas trap. Their pressure ranges from 7.5 MPa to 7.7 MPa. All the other wells revealed gas traps, and their pressure ranged from 8.1 MPa to 8.7 MPa, at lower depths. This comparison confirms that these groups of wells are not in a pressure communication. Hence, structural sealing occurs from the sides, at the depth of about –700 m.

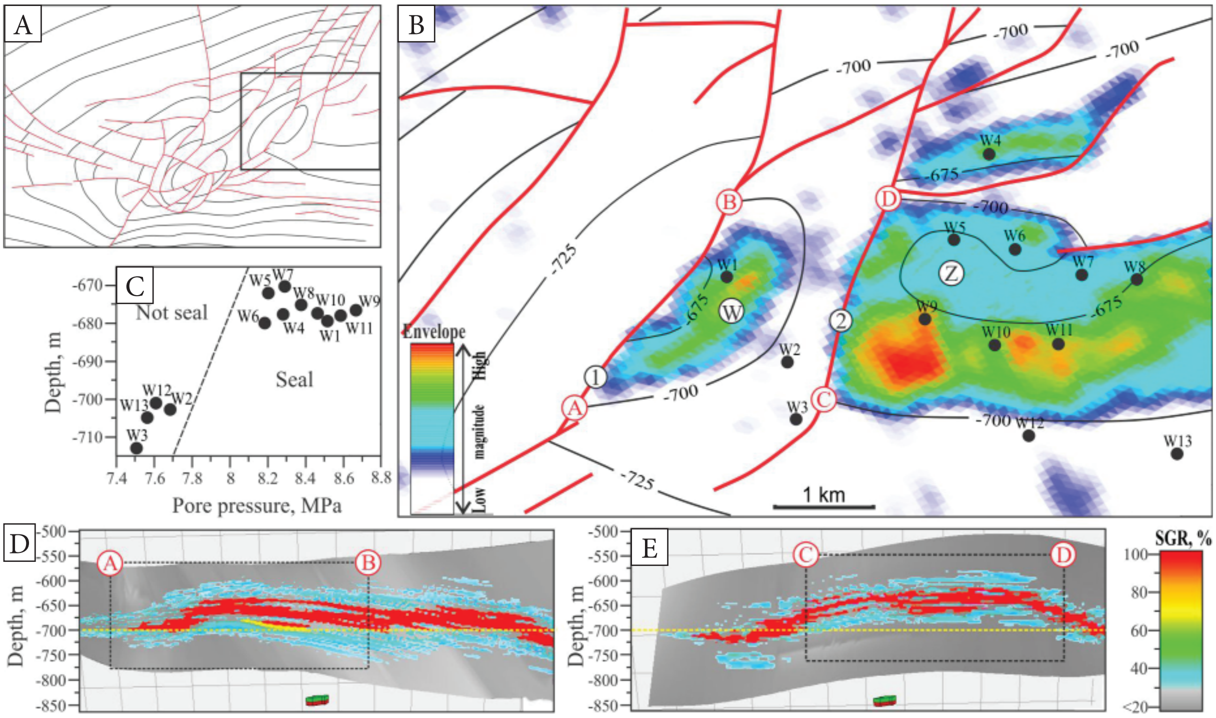

Fig. 4. Composite visualization map of the Jurassic interval, represented by a general structural and tectonic view of the Jurassic horizon (A), stratigraphic slice of the envelope cube, at the level of the sandstone J_{bc} (B), the numbers 1 and 2 denote faults with sealing properties, line X and X' denotes a seismic section across the Solokha field, shown in Figure 3, letters W and Z indicate different parts of the gas trap (C) the cross-plot that shows pore pressure measurements from depth. Figures D and E show the fault clay distribution defined by the SGR, the yellow dotted line denotes a structural level at –700 m

The main idea was to figure out whether it is the solid gas trap or three tectonically separated parts without mutual fault cross-flows. An Envelope amplitude extraction (Fig. 4B) from the seismic data, at the level of the reservoir sandstone, shows that seismic facies of zones, related to the east from faults 1 and 2, differs from what is observed in the surrounding deposits. This figure allows one to delineate the gas trap in a structural sense, at the depth of around –700 m, but leads to another question: whether faults 1 and 2 are sealing or if they can transmit fluid.

Using the Shale Gouge Ratio approach is ideal for this purpose. The SGR calculation needs a V_{shale} model, facies model and faults throw. Facies and V_{shale} models in our case were derived from discrete facies and V_{shale} logs. Later, those well logs were incorporated into the modelling process, based on the Gauss simulation.

Using stochastic simulation, we calculated 100 facies and V_{shale} models, each one with the same geostatistical properties. In general, all the models had a lot in common, because of sufficient amounts of input data. As such, we calculated an average to gain the most probable estimation of the geological environment. Using calculated models and analysed fault throw (which was estimated from the structural model) along the faults, we obtained data shown in Figures 4d and 4e. Red and yellow colours indicate high SGR, with a good probability of fault sealing properties, blue and grey colours – low SGR.

As was mentioned previously, gas traps can be bound in the mean of –700 m. If one looks at the Figure 4e, they will notice, that at this depth, SGR is definitely low, so the probability of fault leakage is high. This statement can assure us that this particular gas trap is a solitary one, and providing a gas injection into part Z can result in fluid cross-flow to the W part.

INTERPRETATION OF THE VISEAN INTERVAL

The presence of Late Visean reservoirs along the whole fold axis is confirmed by numerous wells. However, hydrocarbons remain only at the crest of the structure. Tectonically sealed deposits have been destroyed, due to the lack of sealing properties of faults.

As mentioned previously, any fault can be a transmitter of fluid flow or its barrier. It is worth noting, that in this area, faults also compose lithofacies traps, which were filled, due to lateral migration of hydrocarbons. One of these traps is represented in Figure 5. Considering the paleogeomorphological features of this territory, we are dealing with alluvial deposits, presumably, with the bars. If we apply the classification of non-structural traps by H. Reading (Reading 1978), the nature of the downstream figure schematically recalls with the attached shore bars, in the meandering river beds. This statement allows us to assert that initially the transmissibility of this body was confined by its geometry, but after the next tectonic activation phase, that took place in the Late Visean time, it was compartmentalized, and its containment zone was broken. Hence the question of its sealing properties arises.

The Upper Visean accumulative body, at horizon V-15, interfingers to the deposits in well 2 (that was drilled out of the bar boundaries) and into aggradational rock units, shown in Figure 5D. This accumulative body is represented by a high-porous sandstone, and is divided into three parts, A, B and C, by the faults denoted as F1-F1' and F2-F2'. The productivity of the sandstone reservoir in the footwall block A is confirmed by well 1. The most prospective place for the next well is considered to be block C, but in order to reveal only one well, not of only Visean interval, but of the upper reservoirs as well, it was necessary to confirm the sealing properties of the fault F1-F1' to predict block B prospectivity.

Conduction of a comprehensive fault seal analysis requires a precise delineation of stratigraphic traps, during the exploration process. The above gas-bearing sandstone reservoir manifests itself as a "bright spot", on a stratigraphic slice of the envelope cube (Fig. 5A). In addition, the stratigraphic slice of the acoustic impedance (AI) cube is characterized by low values (Fig. 5B). Figure 5C shows the results of the seismic facies classification process. In this case, we used a self-organizing map (SOM) by Kohonen (2001). His is one of the most effective recognition techniques and is generally used for the classification of seismic facies. The main idea of this approach is that it uses unsupervised learning to produce a low-dimensional (typically two-dimensional, correct and

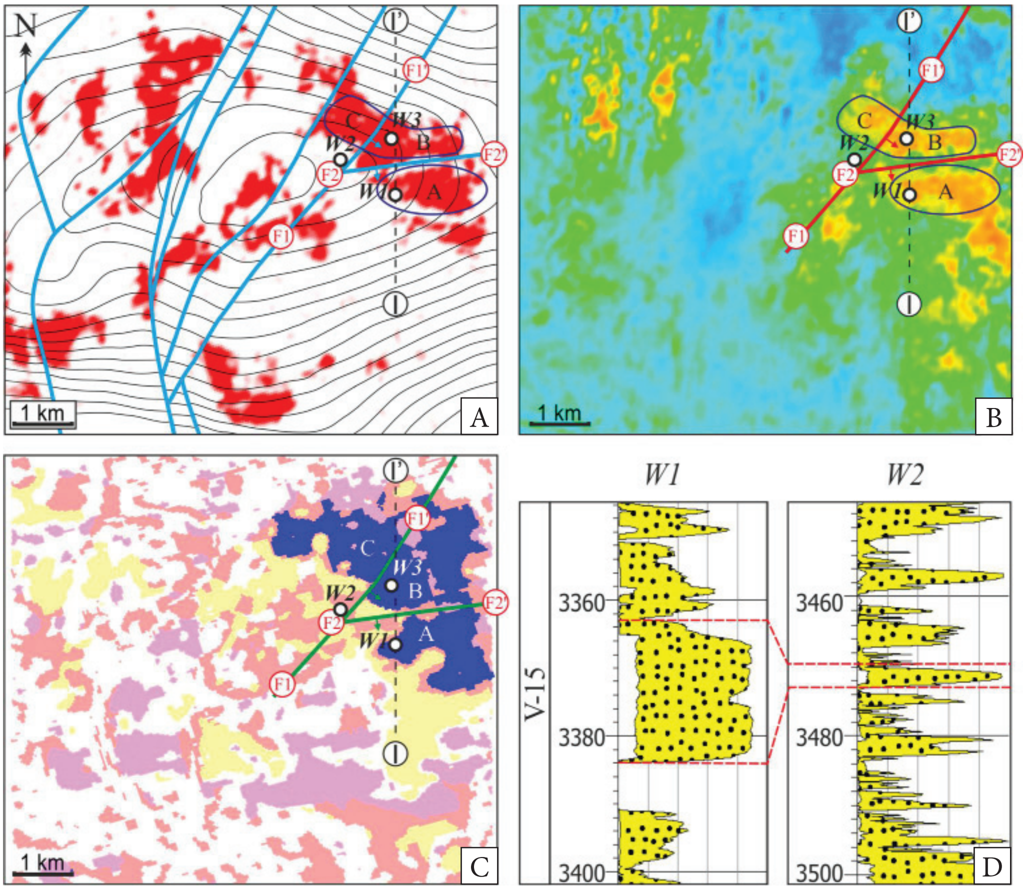

Fig. 5. *Stratigraphic slices of the seismic facies distribution, at the Visean interval: A) the envelope cube, with an overlaid structural plane of V-15 horizon, red colour indicates high amplitudes, blue lines – faults; B) the AI cube, orange colour denotes low values of acoustic impedance; C) the result of self-organized, map clustering analysis, blue colour responds to high-porous sandstone (shore bars in the meandering river beds); D) comparison of the porosity and the sand percentage in wells W1 and W2 of the same sandstone, at horizon V-15. Well W1 revealed a thick, high-porosity (18%) productive sandstone, whereas well W2, revealed a thin unproductive sandstone, with a low porosity. Red dotted line correlates similar sandstones of the horizon V-15. Well 3 is proposed*

representative maps), discretized representation of the input space. Self-organizing maps preserves the original topological structure, within this dimensional space, making it very useful for seismic facies analysis.

Sealing of the trap by faults is shown in Figure 6, as a correlation of the envelope cube section and acoustic impedance cube section, along the line I-I'. In Figure 6A, the fault zone stands out as a loss of seismic regularity, whereas in Figure 6B, the fault zone and both accumulative bodies, A and B, are seen as a single zone of low AI values. This might be evidence of indirect sealing facilities, since low acoustic impedance values may correspond to porous sandstone, as well as to clay components, within the fault zone.

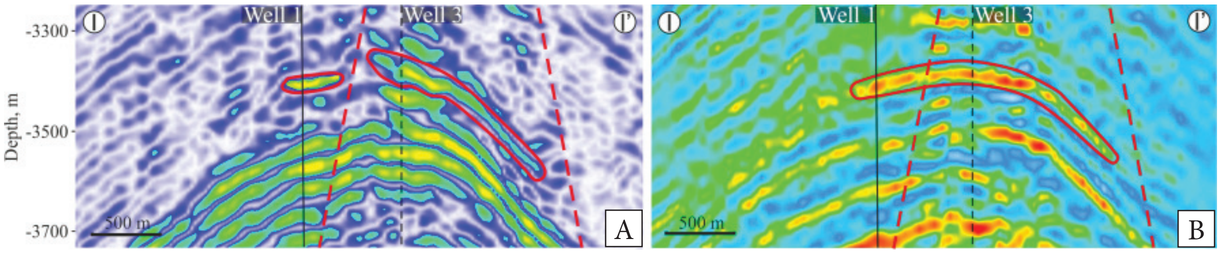

Fig. 6. *An accumulative body with overlaid seismic interpretation depicted on the envelope cube section (A) and the AI cube section, along the line I-I' (B). The red dotted line indicates a fault determined using well and seismic data*

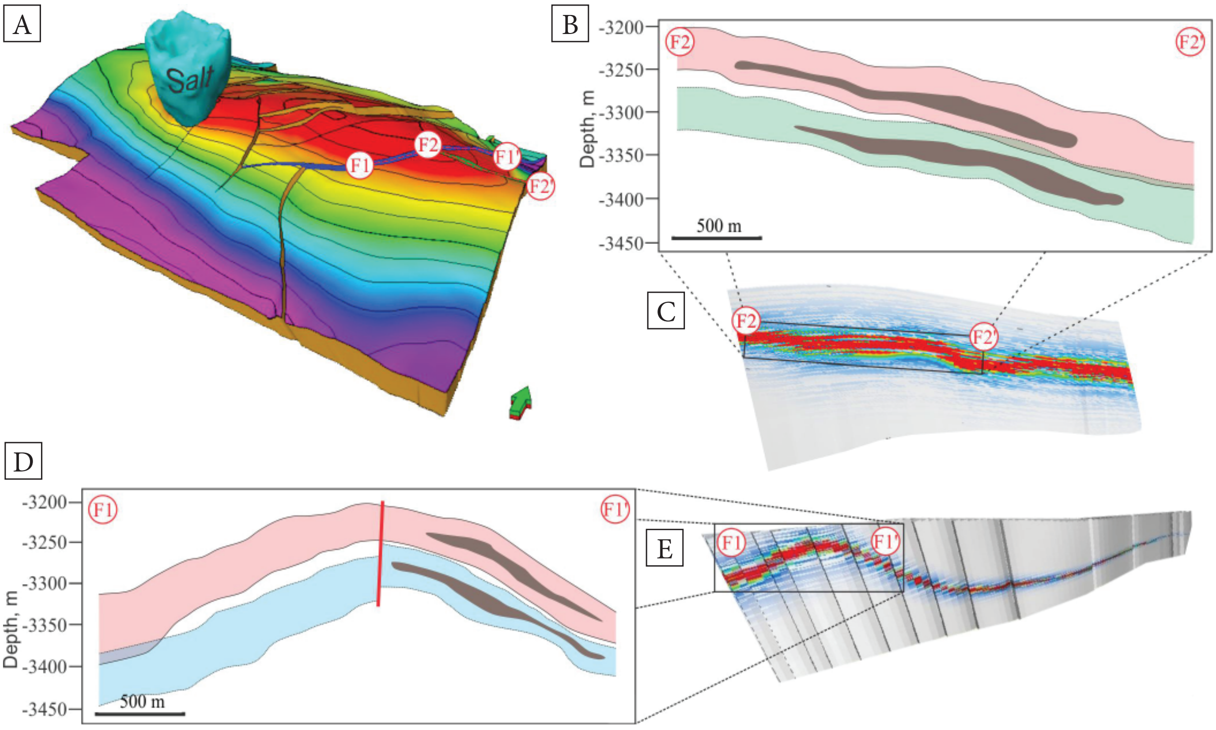

Fig. 7. Composite visualization map of the Visean interval, represented by 3D structural view of V-15 horizon (A), juxtaposition diagrams of the faults F2-F2' and F1-F1' (B) and (D). The footwall layers of the V-15 horizons are denoted by the blue colour, the hanging wall layers are denoted by the light red colour, and the accumulative sandstone is indicated by the brown colour. Figures C and E demonstrate calculated Shale Gouge Ratio of the faults F2-F2' and F1-F1' accordingly, red and green colours denote high SGR, blue and grey – low

In order to find out the type of reservoir contact along the faults F1-F1' and F2-F2', we have built juxtaposition diagram (Fig. 7B, D). Thus additionally enables us to create a projection of productive horizon boundaries, from the neighbor fault blocks to the fault plane, in order to determine its juxtaposition zones.

This approach is a popular one, because of its relevant technological simplicity, and may be used as one of the first steps of the "reservoir-reservoir" juxtaposition determination process. It requires the presence of structural maps (both types – general stratigraphic and productive horizons, thicknesses etc.) or a facies model, which, in our case, was built with the help of stochastic simulation. This implies, that there are no "windows" for hydrocarbon flow, i.e., the two reservoirs do not overlap.

We show a Shale Gouge Ratio, which was calculated for the V-15 productive horizon (Fig. 7). As one can see, the footwall is sealed, not only by its juxtaposition with the impermeable rocks of the hanging wall, but also with a high Shale Gouge Ratio, so the fault is sealing by itself. This suggests that the "smearing" process was "successful", because different geological studies show that fault zones with an SGR > 20% may be thought of as a seal for oil and gas.

CONCLUSIONS

This paper emphasizes that a lot of components are important during the complex fault seal analysis, which is an essential part of research of any hydrocarbon field. With examples from the Solokha field, in the central axial part of the Dnieper-Donets Basin (Ukraine), we have assessed the role of sealing and fluid flow properties of fault zones in the formation of hydrocarbon traps, related to different hydrocarbon levels – Carboniferous-Lower Permian and Mesozoic. One of the most important discoveries was that the Solokha field was previously studied by many researches. However, most of them paid an overwhelming amount of attention to the general seismic and geological interpretation. Only the Allan diagrams were widely used in Ukraine, as the main method of evaluating the fault flow behavior. That is why, this is the first and unique attempt to analyse the problem of hydrocarbon preservation, with the example from Solokha field by the application of FSA modelling.

To summarize the results, it is possible to make the following conclusions:

- Tectonic faults of the Jurassic reservoir represent sealing facilities, only in the upper part of the trap, where SGR values are over 30%. This prevents the fluid cross-flow in the area and the formation of tectonically sealed traps. However, the presence of fluid leaks below –700 m is confirmed by low SGR values, fewer than 30% (Fig. 4). Discernible differences show up in the pressure regimes of offset wells. This means, that all the interpreted fault blocks, that possess a "bright spot" anomaly are interconnected below this structural level. We are dealing with a solitary gas trap. Hence providing a gas injection into one part of it, can result in fluid cross-flow into the others.
- Complex geological interpretation and modelling of the Visean interval proved that its faults fulfill the function of sealing faults, possessing high SGR values. Mapping seismic envelops, acoustic impedance and self-organizing maps (Figs 5, 6) allowed us to carefully delineate a bar accumulative body, which represents three insulated tectonic blocks. Being disjoint (Fig. 7) and therefore possessing its unique pressure regime, each of the blocks should be explored and developed separately.

In general, using a fault seal assessment method, we have created detailed geological models, which allow us to refine the hydrocarbon reserves and improve the development and exploitation process of the fields. The analysis results were compared to the current field data showing significant correlation between them.

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