УДК 550.834 DOI: https://doi.org/10.24028/gj.v47i1.306149

Exploration of hydrocarbon traps using two methods within the Bogatoika area of the Dnieper-Donetsk Depression — comparison of geological results

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Received 13 June 2024

The paper aims to show the efficiency of a novel estimation technique for oil and gas in reservoirs in complicate-constructed (non-anticline) traps. In contrast to traditional techniques, which require tracing two horizons to estimate a complicated trap, this one uses only one horizon that crosses the reservoir.

The new technique is based on investigating seismic waves' absorption. Absorption was found to be very sensitive to changes in the percentage of gas in the pore reservoir. As a result, the seismic spectrum is depleted of high frequencies. Therefore, absorption is an important characteristic of rocks, complementing information about their velocity and reflective properties and increasing the efficiency of geological interpretation of seismic data. For numerical characterization of a medium's absorption properties, the coefficient of absorption, logarithmic absorption decrement, and quality of medium Q (the quality factor Q or simply Q) are utilized. Recently, the concept of Q-quality been increasingly used in foreign literature.

Quality factor can be expressed through the maximum value of elastic energy E_{max} stored in the sample during a period of load and energy losses ΔE during the same period. For large values of Q, which are usually observed in practice, Q is inversely proportional to the absorption coefficient, taking into account the proportionality coefficient.

As stated above, the new method uses the phenomenon of seismic waves absorbing when they cross reservoirs with hydrocarbons.

The algorithm is close to the expression structure obtained by Hauge in 1981 for exploration of well materials provided that there is no interference in the medium of investigation. It allows to measure Q from surface seismic reflection data. We adapted it to continuous measurements along the trace. It also compensates for the reflectivity's corrupting impact.

The second one is presented in a good a seismo-paleo-geo-morphological (SPGM) technique. The second technique confirms that sand bodies within the Late Serpukhovian substage are the reason of anomalies appearing as a result of the seismic waves absorption research.

To prove this, two structural maps were built at the base of paleo-tectonic and paleo-geomorphological reconstructions (the SPGM technique). Their interpretation and comparison with the map derived from seismic waves' absorption data show that the new technique can be applied while prospecting for hydrocarbon traps. It is planned to continue its approbation within other areas.

Key words: absorption of seismic waves, paleotectonic and seismo-paleo-geo-morphological reconstructions, SPGM technique, Bogatoika field, Late Serpukhovian sub-stage sediments.

Citation: Shadura O.M. (2025). Exploration of hydrocarbon traps using two methods within the Bogatoika area of the Dnieper-Donetsk Depression — comparison of geological results. *Geofizychnyi Zhurnal*, *47*(1), 149—164. https://doi.org/10.24028/gj.v47i1.306149.

Introduction. Choosing a technique to search for nonstructural traps with hydrocarbons is still a problem. Structural constructions are powerless for lithological, stratigraphic, facial, and other trap types as such methods of mapping depositional interfaces' surfaces do not allow to fix the boundaries of the lithological replacement of reservoir rock onto host rock mass [Babadagly et al., 1988; Karpenko, 2000]. Also, it is necessary to note that non-anticline (weak) traps within deep horizons have better conditions for the preservation of hydrocarbon pools compared with typical anticline ones [Karpenko, 2000]. One of the conditions of trap existence is its filling, sealing, and existence in such form till disbandment.

In general, an environmental trap can occur within a «pure» monocline in a frame of some modern structural plane along the roof of the productive layer and even within negative noses. Areas with a great gradient of thickness of the geologic complex, which include productive layers, are the most promising as concerns zones of reservoir rocks pinch-out. Bay-shaped forms of such areas are promising for conditions for hydrocarbon trapping. Just these areas of «heavy gradients» of consolidated origin are characterized by spatially conservative sedimentation. This makes them promising within some productive horizons simultaneously or at least within one of them [Babadagly et al., 1988; Karpenko, 2000].

Therefore, a new technique for searching for nonstructural hydrocarbon traps was elaborated some years ago. It is based on the phenomenon of absorption of seismic waves' energy during propagation through a porous environment filled with gas or oil. As a result, the seismic spectrum loses high frequencies. This effect and stages of the method's creation have been described in detail [Tyapkin, Shadura, 2009; 2010a—c, 2011, 2017; Tyapkin, et al., 2011; Shadura, 2011; Shadura, Tyapkin, 2011, 2019].

The new method was used to delineate the gas pool within the Late-Serpukhovian sediments at the Bogatoika area, located within the eastern segment of the Dnieper-Donetsk Depression (DDD) edge zone (the eastern part of Ukraine). The results are compared with findings based on elements of the seismic-paleo-geo-morphologic (SPGM) method for the same area [Babadagly et al., 1988; Karpenko, 2000; Nedosekova, 2002].

In addition, the thickness analysis of the Late-Serpukhovian sediments with the point of view of such tectonitians as Khain V.E. and Mikhailov O.E. has been executed in the paper also [Khain, Mikhailov, 1985].

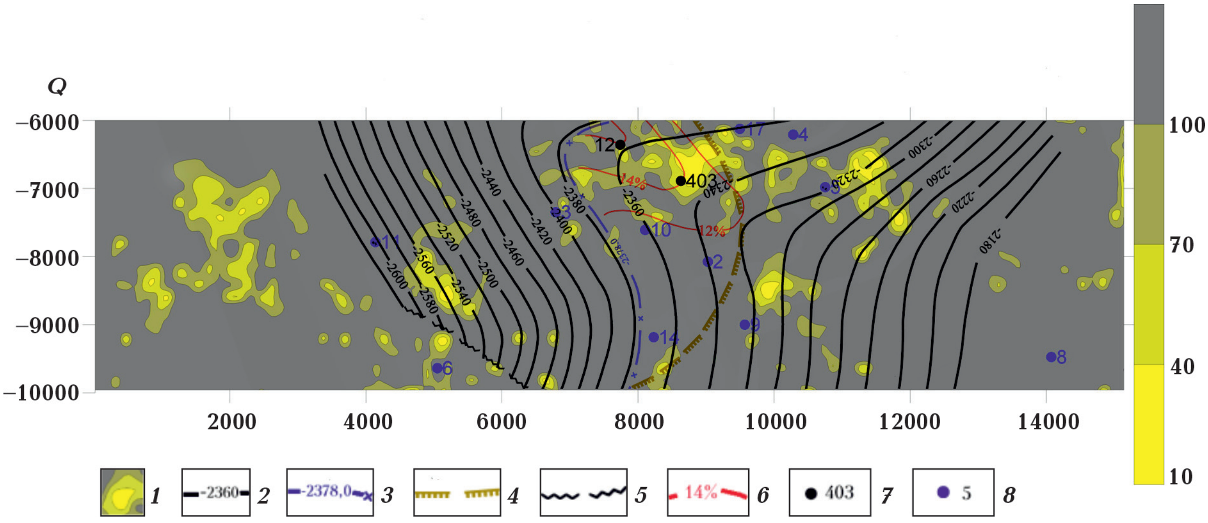

Fig. 1. Map of medium *Q* changing along horizon C-1 within the Bogatoika area: *1* — changes of parameter *Q*, *2* — contour line of roof of productive horizon C-1, *3* — contour line of gas-water surface, *4* — line of lithological replacement of a reservoir, *5* — boundary line of horizon washout, *6* — contour line of equal values of porosity, *7* — producing well, *8* — barren well.

Geological characteristics of the Bogatoika area. The Bogatoika gas condensate field is located within the eastern segment of the DDD edge zone — the eastern part of Ukraine. Administratively, it is mostly located within the Dnipropetrovsk region.

Geologically, the Bogatoika area is located within the southern near-edge part of DDD over the Orelsk protrusion nose of the basement, which has a block structure. The main tectonic element here is the southern edge fault. The Bogatoika structure strikes to the south from the dislocation (Fig. 1).

The Bogatoika gas-condensate field is a complex fluid-conducting and fluid-accumulating system. It was constructed help to buried inverted structures of Late Devonian (the Frasnian fault, the Late Famenian flysch-terrigenous deposits) with the assistance of block tectonics of the basement, volcanic, and reef-carbonate structures and block displacements.

It was opened in 1955 by seismic works by the land seismic party 6/55. During these works, the South-Pereshchepino salt stock and the Bogatoika structural nose were identified at the base of the apparent horizon and the reflecting one in Carboniferous period sediments [Ivaniuta, 1999].

According to the deposit atlas, drilling of parametric well 403 started in 1973. During its testing in 1975, an influx of gas was received on a scale of 96 000 m^3/day through the diaphragm of 8 mm from carbonate rocks of the Tournaisian stage (productive horizon $T\text{-}2^1$, interval 4520—4567 m). The pool was accepted on the State balance sheet the same year.

A number of geophysical investigations were conducted here from 1973 to 1999. They discovered the brachy-anticline structure of the north strike of 2.7—1.7 km^2, with an amplitude of 50 m along the eroded surface of Devonian. Its amplitude diminishes to 25 m in the Tournaisian section, and only a structural nose is recorded in the Lower Visean deposits. The anticline is complicated by tectonic dislocations up to 40—60 m in the Tournaisian and Devonian rocks, which are not traced at all within the Early Visean section [Ivaniuta, 1999].

In the end, a number of gas condensate deposits (Б-13, С-1, С-2, В-21— В-24, В-25, В-26, $Т\text{-}2^1$, $Т\text{-}2^2$, Т-3, Д-1) were revealed by prospecting within the Bashkirian, Serpukhovian, Visean, Tournaisian, and Devonian sediments. A deposit of the Bashkirian sediments of Middle Carboniferous period (B-13) is located within the Ekaterininska area (the eastern part of Bogatoika field). The accumulations of lithological traps in sandstones of the Visean stage have also been taken on state balance. The rock reservoir of the Tournaisian stage represents a carbonate formation with porous-fracture-cavern holding capacity. Reservoirs of other productive horizons are composed of sandstones with a porous type of trap.

The Pereshchepino Depression occurs southwest of the Bogatoika structural nose among the largest structural forms. The South-Pereshchepino salt stock is located to the southwest of it. Here, the Devonian salt almost comes out to the surface. It occurs at a depth of 600 m and is overlapped only by the Paleogene-Anthropogen sediments.

Features of the structure of the hydrocarbon trap in the Serpukhovian deposits. Sandstone sediments of the Serpukhovian stage of the Early Carboniferous period are potential gas reservoirs, taking into account pay zones C-1 and C-2.

As reported by the Ukrainian State Geological Prospecting Institute at the State Geological Institution «Poltavaneftegazgeologiia», productive horizon C-1 has a thickness of 30—50 m and is related to the roof of Serpukhovian section. It is located 5—10 m below the surface of the stratigraphic unconformity on the slope of Pereshchepino structure where the layer-reservoir is washout partly, and it is almost completely washed-out in the vicinity of well 6.

Productive horizon C-2 of common thickness 40—50 m underlays the productive horizon C-1 by 40—60 m.

The cap rock for horizon C-1 is a terrigenous clay dense rock mass with a thickness of up to 20 m that overlays the Serpukhovian section. The rock mass interbedding between horizons C-1 and C-2 is clay-aleurolite dense rocks.

Early investigations within this zone conducted by the Complex thematic group (office crew) of the «Poltava-neftegazrazvedka» Trust report that «layers of sand beds are inconsistent in thickness and homogeneity and their porosity and permeability change abruptly along short distances». Additionally, taking into account the breakdown of mode while operating wells during geophysical investigations, they concluded that the reservoirs within the Bogatoika area could be associated with lithological traps. This prediction makes this area promising for hydrocarbon exploration.

Features of the seismic waves' absorption study within the area of investigations. Reservoir forecasting based on seismic waves absorption was done for 3D data. The area of investigation was 224 km^2. The signal accumulation multiplicity at each common depth point (CDP) was 24. The step between the CDP points along the x axis was 20 m, and along the y axis — 40 m.

3D data have several advantages over data from a rare system of CDP profiles.

Observations along in-lines and cross-lines (grid) make it possible to suppress surface interference waves along both axes. The same applies to multiple and diffracted waves. It also becomes possible to get rid of all kinds of noise by area filtering. The last ones arise in the process of mathematical operations.

Provided that wells with vertical seismic profiling locates within the study area, it is possible to build a cube of seismic waves' velocities varying within these spatial frames. This yields more accurate spatial models compared to CDP-based models.

As was already mentioned, the contouring of a reservoir is based on seismic waves' absorption during their passage through a porous trap with hydrocarbon. Some part of elastic vibration seismic energy transforms irreversibly into thermal and other kinds of energy. The media in which elastic energy is lost are called inelastic or absorbing [Nomokonov et al., 1990].

Absorption turned out to be very sensitive to changes in the percentage of gas in the pore reservoir [Winkler, Nur, 1982].Therefore, it is an important parameter that complements the data on rocks' velocity and reflective properties and makes the geological interpretation of seismic records more efficient [Averbukh, 1982].

For numerical characterization of a medium's absorption properties, the coefficient of absorption, logarithmic absorption decrement, and medium quality Q (the quality factor or simply Q) are used. The concept of medium quality has been increasingly used in foreign literature [Červený, Pšenčik 2008; Raji, Rietbrock, 2013].

The coefficient of absorption α characterizes the relative decrease in oscillation amplitude while increasing path length [Nomokonov et al., 1990]:

$$\alpha = -\left(1/u_{(x)}\right)\left(du_{(x)}/dx\right),$$

where α is the absorption coefficient, $u_{(x)}$ — is the oscillation amplitude at the point x; $du_{(x)}/dx$ is the change of vibration amplitude per unit length at point x.

While fulfilling amplitude measurements in two arbitrary points x_i and $x_{i+1}\left(x_{i+1}\rangle x_i\right)$ [Nomokonov, et al., 1990]:

$$\alpha = \frac{1}{x_{i+1} - x_i} \ln \frac{U_{(x_i)}}{U_{(x_{i+1})}}.$$

The logarithm of amplitude ratio on a distance equal to one wave period length λ is called the logarithmic decrement of absorption ϑ(ω) [Gurvich, 1981]:

$$\vartheta(\omega) = \ln \frac{A(x)}{A(x+\lambda)} = \alpha(\omega)\lambda(\omega)$$

where $A(x)$ is the amplitude of the wave at point x, $A(x+\lambda)$ — the amplitude of the wave at a point removed from the point x to a distance equal to the wavelength λ, and ω is the frequency.

The quality factor of the environment can be expressed via the maximum value of elastic energy $E_{\max}$ stored in the sample during a period of load and losses of energy during the same period ΔE [Aki, Richards, 2002].

As to new technique algorithm, it is based on the normalized moments of the signal spectrum [Tyapkin et al., 2011]. It has advantages over algorithms using spectrum relation. Beyond other innovations, these integral characteristics make the estimation of absorption more robust to the impact of the influence of various noises (except for the case of interference with ghosts).

The algorithm uses the first and second normalized moments of the power spectrum of some part of a seismic record. The first normalized moment of the power spectrum means the average frequency (signal frequency at the peak of its spectrum). The second normalized moment of the power spectrum means the spectrum's variance (width) (distance between spectrum end points at the level equals to half of its maximum amplitude). Both parameters are sensitive to the depletion of high frequencies because of absorption.

The basic formula contains a ratio of the spectrum's width to the derivative of the average frequency of the desired signal in absence of noise. In other words, the behavior of this ratio with depth is:

$$Q(t) = \delta\varpi(t) \Big/ \frac{d\left[\Delta\bar{\varpi}(t)\right]}{dt},$$

where $Q(t)$ — medium quality; $\delta\varpi(t)$ — the second central normalized moment of the power spectrum over some of the seismic trace (spectrum width);

$$\delta\varpi = \tilde{\varpi}^2 - \bar{\varpi}^2,$$

where

$\bar{\varpi}^2 = \dfrac{\int_0^\infty \omega^2 |S(\varpi)|^2 d\varpi}{\int_0^\infty |S(\varpi)|^2 d\varpi}$ is the second initial normalized power spectrum;

$\bar{\varpi} = \dfrac{\int_0^\infty \omega |S(\varpi)|^2 d\varpi}{\int_0^\infty |S(\varpi)| d\varpi}$ is the first initial normalized power spectrum;

where $S(\varpi)$ is the complex Fourier spectrum; $\Delta\bar{\varpi} = \bar{\varpi}_{synt.} - \bar{\varpi}$, where $\bar{\varpi}_{synt.}$ is the first initial normalized moment of the power spectrum of the same part of the synthetic trace, simulated in the zone without absorption; $\bar{\varpi}$ — the first initial normalized moment of the power spectrum of the interference interval of the real trace.

To find $\bar{\varpi}_{synt.}$, a site was selected within the well's area with no deposit along the C-1 horizon. Thus, we can state that the resulting wavefield contains the absorption effect caused only by thin layering.

The resulting difference curve $\Delta\bar{\varpi} = \bar{\varpi}_{synt.} - \bar{\varpi}$ looks rather rough. To smooth it and the $\delta\varpi(t)$ curve, a weighting function of the form $w(t) = \sin\dfrac{\pi(T+t)}{2T}$ was used (Fig. 2). However, the resultant curves for frequency and spectrum width remained insufficiently smooth even after this treatment, making differentiating difficult.

Therefore, the next step was to approximate both curves with a polynomial of degree N of the form: $f(t) = \sum_{i=0}^{N} at_i$ before differentiation. Here, $a_0, \ldots a_n$ are the coefficients of the polynomial. However, even this approximation does not prevent from negative values of the difference frequency due to the presence of thin layering, which is meaningless from the physical point of view. Therefore, restrictions on derivatives have been introduced while obtaining the approximated curves.

Thus, for the difference frequency curve, a condition was introduced that the resulting curve should only be positive. It takes place because the probing signal is depleted due to

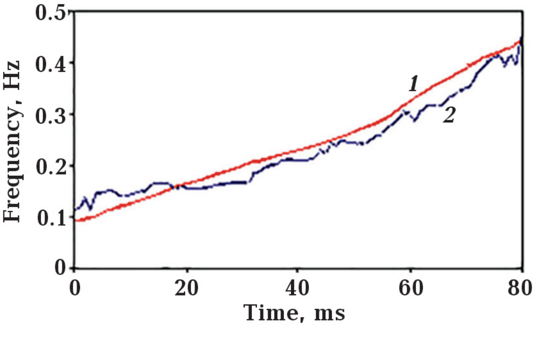

Fig. 2. Estimations of $\Delta\bar{\varpi}(t)$ obtained with (*1*) and without (*2*) introducing weighting function $\omega(t)$.

high frequencies when propagating into the lower half-space, and so the difference curve can only be positive (Fig. 3).

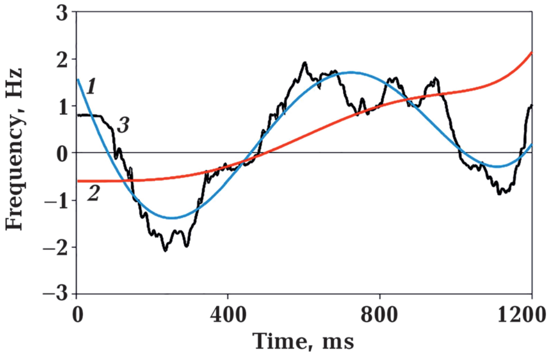

Fig. 3. Unconstrained (*1*) and constrained (*2*) polynomials approximating $\Delta\bar{\varpi}(t)$ (3).

The second condition was that the difference curve was within the range inherent to the study area. These framework values were of the form: $\delta\omega(t)/Q_{max}$ and $\delta\omega(t)/Q_{min}$, where Q_{max} and Q_{min} are, respectively, the maximum and minimum acceptable values of Q in the study area.

In the case of the spectrum width, a restriction was introduced so that the derivative had to be only negative. This is dictated by the fact that when a signal propagates deep into the Earth, its spectrum becomes depleted due to the loss of high frequencies and gets narrower.

Since the method come to analysis of a signal's average frequency changes during its propagation in the medium, it is called the frequency shift method.

To get knowledge of stage of new technique elaboration, the reader can look through papers [Tyapkin, Shadura, 2009, 2010a—c, 2011, 2017; Tyapkin et al., 2011; Shadura, 2011; Shadura, Tyapkin, 2011, 2019]. Results obtained with this technique are demonstrated below.

The results obtained in a study of seismic wave absorption. Obtained on using based on the seismic wave absorption investigations new technology, the resulting map was constructed while tracing a seismic event in the roof of Late Serpukhovian sediments which stratigraphically allocates to productive horizon C-1.The anomalous zone on this map gravitates towards the apical part of structural nose in the vicinity of productive along horizon C-1 wells 12 and 403 as expected. Here, the anomalous zone touches wells 3 and 10 only by its southern edge. We can also see the trend of its spreading in the west direction. This coincides with the earlier predicted direction of reservoir expansion. Also, it is more typical for sandstone C-2.

We can see in Fig. 1 another anomaly to the west from the conditional line well 6 — well 11 and a group of anomalies to the west of them. In this way, clastic materials of the structure nose, after subsequent washout and transportation, become apparent in the absorption field within the trough between the South-Pereshchepino fold and the Bogatoika anticlinal bend. The authors of previous studies have also been inclined to this assumption.

The anomaly to the east from well 5 is located within a separate block within the Ekaterininska area.

Well 14, productive within horizon C-1 according to well logging data, is located outside the anomaly contour, although it is productive along horizon C-2. At the same time, we can see a small-scale anomaly just under well 14 in Fig. 1.

The initial assumption regarding this strange behavior of the anomaly in the area of well 14 was that well 14 is located within a paleo-estuary that branched off from the main sand body.

The Serpukhovian stage can be related to a group of shallow-water (marsh) facies. The presence of mudstone, together with inclusions of coal material and imprints of the remains of sea grasses and limestones with the remains of animals, are reasons for such a conclusion. Thus, it is possible to state that these facies' areas of spreading may not have an isometric form [Busch, Link, 1985]. It is also indicated by the braided (complex, interlacing) pattern of anomalies based on seismic exploration with utilization absorption of seismic waves by porous medium with hydrocarbons along horizon C-1 (see Fig. 1). Evidently, the anomaly to the north of well 9 is a consequence of the under-compensation of the interference wave.

It is typical that all productive wells 12 and 403 are located within the main anomaly zone with lower *Q* values, and all non-productive wells are within zones with high *Q* (see Fig. 1). As the coefficient of absorption is in fact inversely proportional to the *Q* factor, all productive wells (12 and 403) are in the zone of high absorption (see Fig. 1).

It should be noted that the maximum flow rate of wells 12 and 403 is 40 and 64 thousand cubic meters per day, respectively. A *Q* value of 98 arbitrary units corresponds to well 12, and a *Q* value of 50 corresponds to well 403. Note that both values were read from the map in Fig. 1 with a small step between lines of equal *Q* values, which was equal to 1 *Q*. Hence, conventional coefficient of absorption of 0.01 corresponds to well 12, and 0.02 one corresponds to well 403 (Fig. 4). A plot of these data emphasizes the obvious fact: hydrocarbons are accumulated in the rocks with high porosity (and permeability) and so with high absorption. The higher the absorption in the vicinity of a well, the more hydrocarbons within this site and, accordingly, the higher the efficiency of the well.

All this allows us to suppose that as lacustrine-marsh facies spread within the Bogatoika structure just in the Late Serpukhovian period of sedimentation, the anomaly zone is due to the presence of a sandstone body.

To conclude, the distribution of the quality factor *Q* within horizon C-1 is in good agreement with the results of layer C-1 uncovering and does not contradict results of early investigations.

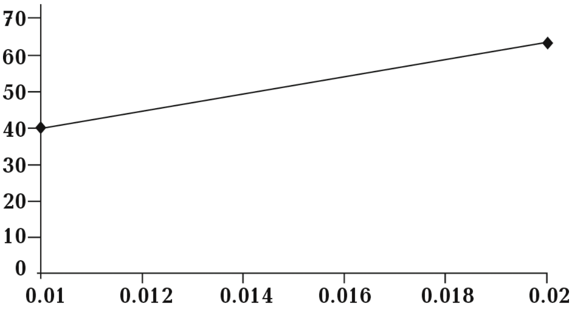

Fig. 4. Plot of relation between well production and conventional coefficient of absorption. Axis *Y* — gas production volume, thousands m^3/day, axis *X* — absorption, conventional units, well 12, well 403 (well 12 at the beginning of the figure).

Results of hydrocarbon trap forecasting based on elements of the SPGM technique. The close connection between a sediment body's morphostructure and internal formation composition is the basis of the SPGM technique [Babadagly et al., 1988]. The concept of morphostructure includes in itself the thickness of the sedimentary complex together with the configuration of its external surfaces. The internal structure includes the lithological composition and sheeting (stratified) structure. Comparative analysis of thicknesses of sedimentary rock masses of various ranks is its main methodological technique.

Establishing the paleotectonic and paleogeomorphological mechanisms of the formation of sedimentary complexes provides the very basis for the SPGM technique.

As a whole, the SPGM-technique is destined for revealing and mapping depositional and stratigraphic hydrocarbon traps which are controlled by angular unconformity surfaces inside of the sedimentary complex [Karpenko, 2003].

The technique consists of the following stages:

– tectonic-sedimentation seismic stratification of the sedimentary section;
– quasi-synchronous inter-well correlation of polyfacies horizons;
– mapping seismic geological horizons;
– paleotectonic reconstructions;
– paleogeomorphological reconstructions;
– methods for delineating hydrocarbon traps.

Tectonic-sedimentation seismostratification of the Bogatoika field's sedimentary section. In this part we divide the sedimentary section into sedimentary complexes that correspond to tectonic epochs and phases. We also mark paleoplanation and unconformity surfaces.

The Serpukhovian deposits were formed during the Rudnogorsk tectonic orogenic-phase. It began at the boundary between the Visean and Serpukhovian stages and ended at the boundary between the Serpukhovian and Bashkirian stages during the Hercynian tectonic cycle. Deposits of the Middle and Upper Carboniferous are associated with the syneclise-platform regime of lithosphere development in this area.

The mode (regime) of development of the Earth's crust — tectogenesis — is an inalienable component of the evolution of the planet. As V.I. Korinnyi writes, tectogenesis is «an assembling of geological phenomena in the progressive development of the tectonosphere which is characterized by the natural evolution of the mobile region from the initial stage of the geosyncline to its completion within the fold and fold-block processes and associated orogenesis» [Korinnyi, 2017].

Each tectonic phase is composed of two regimes. Large-scale transgressions of seas due to syncline bowing of the crust, as well as warping in adjacent areas of the platforms, are typical for the first regime (the so-called thalassocratic regime). Thick strata of siliceous-volcanogenic, slate, carbonate, and other formations are accumulated this way. The second (geocratic) regime is the period of geosyncline transition to the orogenic stage of development, characterized by great tectonic activity. Massive uplift of the Earth's crust and regression of the seas, rock deformation, formation of mountainous relief instead of a geosyncline, violent magmatic activity, seismicity, metamorphism took place during this period [Korinnyi, 2017].

According to [Karpenko, 2000], during the Rudnogorsk tectonic orogenic phase in the DDD, the Early Serpukhovian sedimentary complex was formed against the background of an intensification of the process of the paleo-relief bottom of the sedimentary basin parting, regression of sea, as well as prevalence of continental-facies conditions over marine ones. Therefore, hydrocarbon deposits should be expected in the sediments of the Early Serpukhovian stage, which are connected mainly with deposits of channel-alluvial land systems and coastal-deltaic straight clinoform formations under the internal-Serpukhovian surface of unconformity.

Meanwhile, the Late Serpukhovian sedimentary subcomplex was formed against the background of topography shoaling of the sedimentation basin bottom, as well as sea regression. For instance, the lower part of the sub-complex in the volume of sediments within the interval of horizons C-9-C-6 has mainly a reverse clinoform structure. Gulf-shaped paleo-lowlands within monoclines were covered by sediments of this subcomplex. The upper sediments of the Late Serpukhovian subcomplex were formed during significant planation of the paleo-relief. They mostly have a cover structure and form hydrocarbon traps mainly with participation of considimental paleo-uplifts (traps of deformed paleo-uplifts). Within the Bogatoika field, the Serpukhovian sediments are represented by sandstone horizons C-1 and C-2.

In general, it is believed that macrocycles beginning with transgressive and ending with regressive stages of development are more common. This took place in the DDD during deposition of the Late Visean, Late Serpukhovian and Late Bashkirian substages.

As to their thickness, according to the Poltava stratigraphic allocation, the thickness of the Lower Serpukhovian substage ranges from 665 m (well 8) to 713 m (well 11), the upper one: from 522 m (wells 6, 8) to 600 m (wells 2, 10). Overall, it ranges from 1180 m (well 8) — 1290 m (well 2). The thickness of the Early Serpukhovian is 830 m, of the Late one — 505 m; total thickness is 1335 m in the Mazharovska well 493 and 717, 563, and 1280 m in the Katerininska well 623, respectively.

Deposits of Early Carboniferous belong to the syneclise regime of development from the point of view of tectonic-sedimentary stratification [Korinnyi, 2017]. According to Korinnyi, «...by syneclise regime, we mean rates of subsidence that lead to the formation of mainly plicated dislocations with a small amplitude (a few — the first tens of meters) faults and extended monoclinal slopes».

As seismic reflector due to unconformity boundary between the Serpukhovian and Bashkirian stages is used in this study, it should be mentioned that the Bashkirian deposits were formed in platform conditions. The platform regime of the basin's development is characterized by minor differences in the rates of warping of neighboring sections of the basin, during which there was no formation of either disjunctive or plicate structural forms [Korinnyi, 2017]. The covering sedimentary associations were formed mainly during the platform regime in shallow-shelf conditions.

Confirming the presence of sand formations as a whole within the Upper Serpukhovian substage by the SPGM technique is a problem has been put in the paper. Therefore, we will not deal with the issue of breaking up the Serpukhovian strata into separate beds. We will make a stratigraphic allocation only for the reflecting target horizons at the base of the Serpukhovian deposits, within the boundary separating the lower and upper substages, and reflecting the seismic boundary between the Serpukhovian and Bashkirian stages. For these purposes, we will resort to a fragment of a paleontological allocation (breaking up), which is representative of the entire DDD and was mentioned by Karpenko I.V. during research investigations, as shown in Table.

This breakdown is based on the idea that exogenous changes in the Earth's biosphere and exogenous tectonic changes in the Earth's lithosphere are practically synchronous. Only a slight lag between the tectonic changes and the start of biological transformations is possible since tectonic transformations namely are a trigger for the latter in the biosphere. It is also believed that such a paleontological layer as a stage is determined only by the exogenous tectonic regime.

Therefore, according to Table, our target horizons are the next ones: $V\text{б}_2^{3\text{-П}}$, $V^{B_1^3}$, $V^{B_2^1}$.

As we are dealing with the rock mass of the Late Serpukhovian as a whole, we omit the chapter «quasi-synchronous inter-well correlation of poly-facies horizons».

Bashkirian	Lower	Kinderscotian (1.3) Kin	clayish carbonate Б-12		Lowering	
Serpukhovian	Upper	Alportian (2.8) Alp	carbonate-clayish sand C-3,C-2,C-1	↓ Sudetian (322.8) ↑ (5.5)	final shallowing	$V\text{б}_2^{3\text{-П}}$ $V^{B_1^1}$
		Chokierian (2.7) Cho	clayish sandstone C-5,C-6		initial shallowing	$V^{B_1^2}$
		Arnsbergian (2.8) Arn	carbonate clayish C-9,C-8,C-7	↓ ↑ (4.6)	final lowering	$V^{B_1^3}$
	Lower	Pendlian (1.8) Pnd	coal-bearing C-23...C-16 (B-12...B-6)		initial lowering	$V^{B_2^1}$
Visean	Upper	Brigantian (3.1) Bri	clayish-carbonate deposits B-16...B-14	↓ Rudnogorian (332.9)	stability	

Notes: The table is adopted from the report under contract No. 396 «To develop methodological techniques for detection and mapping of non-structural traps with hydrocarbons and for forecasting the characteristics of reservoirs with carboniferous deposits within the DDD» under the leadership of Yu.K. Tyapkin, I.V. Karpenko, V.M. Lakhniuk, Kyiv, 1994.

The work was carried out within the framework of the Ukrainian State Geological Research Institute as part of the State Geology Committee of Ukraine.

↓ — compression, ↑ — extension, B-24—B-14 — numbering of regional horizons, (3.1) — duration of stage in time in millions of years (third column); (5.5) — duration of other complexes.

Mapping seismic geological horizons. In this case a high accuracy of structural mapping is needed because paleotectonic and paleogeomorphological reconstructions operate with thicknesses of formations and their derivatives [Karpenko, 2003]. This is caused by the fact, that in the process of subtraction of one surface from another mistakes in the position of the contour lines on resultant surface becomes greater two or more times.

The surface of the unconformity at the top of the Upper Serpukhovian deposits was used in our paleogeomorphological reconstructions to determine paleorelief at the beginning of the Bashkirian deposits formation.

Interpretative complex «OpendTect» was utilized for mapping reflecting surfaces and 3D survey data processing within the Bogatoika field. As a result, the next three maps were built: the seismic reflecting surface at the bottom of Serpukhovian stage (Fig. 5), seismic reflecting surface at the boundary between the Early and Late Serpukhovian substages (Fig. 6), seismic reflecting surface at the bottom of Bashkirian sediments (coincides with the roof of Late Serpukhovian substages sediments) (Fig. 7).

As we can see from Fig. 5, seismic reflection time from the bottom of the Serpukhovian stage (horizon $V^{B_2^1}$) is 2.135—2.518 s, for the boundary between the Early and Late Serpukhovian substages it (time) is varying within 1.801—2.255 s (see Fig. 6), for the subsurface of the stratum of Bashkirian stage it is varying within 1.513—2.026 s (see Fig. 7).

As was noticed early, these reflecting surfaces were used for forecasting hydrocarbon traps at the Bogatoika area within the Serpukhovian stage at the base of the SPGM technique. In accordance with special features of the SPGM technique, these maps were later transformed to *.grd format.

Paleo-reconstruction on the example of Late Serpukhovian deposits of the Bogatoika area. ***Paleotectonic reconstructions.*** «Outer boundary surfaces of paleo-levelling of sedimentary complexes of different ranks for determining the average rates of subsidence of the basin bottom …» is utilized in that technique [Karpenko, 2003].

At the time of the Serpukhovian sediments' formation within the Bogatoika area, there were formed three scoured surfaces which are considered as surfaces of paleo-levelling: at the bottom of Serpukhovian stage, along the boundary between the Early and Late Serpukhovian substages, and at the bottom of Bashkirian sediments.

The Upper Serpukhovian deposits were formed during the next three eras: Alportian, Chokierian, and Arnsbergian. The Lower Serpukhovian deposits were formed during the Pendleian era.

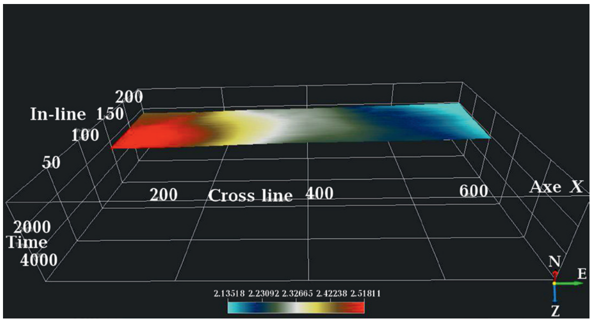

Fig. 5. Seismic reflector in the bottom of the Early Serpukhovian substage (by OpendTect).

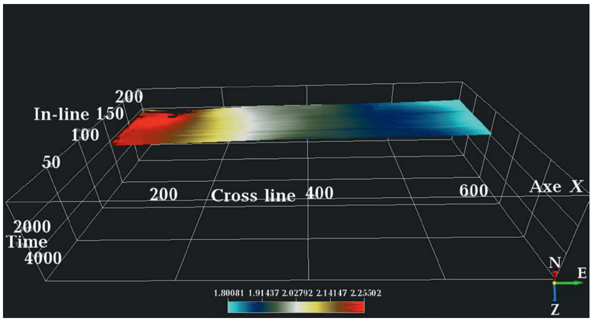

Fig. 6. Seismic reflector in the bottom of the Late Serpukhovian substage (by OpendTect).

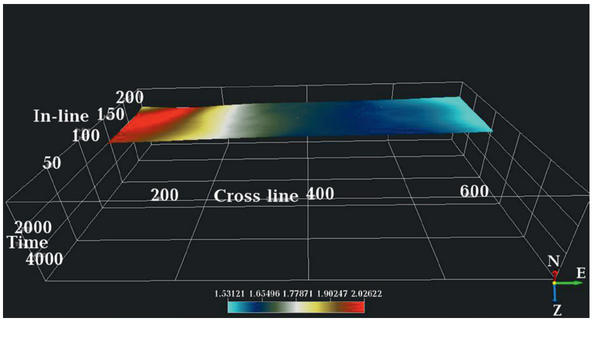

Fig. 7. Seismic reflector in the bottom of the Bashkirian substage (by OpendTect).

As was written above, the upper deposits of the Upper Serpukhovian subcomplex were formed with significant planation of the paleo-relief. It has mainly cover structure and forms hydrocarbon traps mainly in the form of the consedimental paleo-uplifts (traps of deformed paleo-uplifts).

Bogatoika deposits have a limited area. Thus, it can be studied within the smallest of *T*-phase cycles of the sedimentary strata such as a horizon, a sub-horizon, a family of layers. They can be identified by seismic exploration [Karpenko, 2003].

The rate of subsidence of the basin bottom can be characterized via the thickness of the sediments then formed due to such a phenomenon as an equilibrium profile in shallow water conditions.

The thickness map of Late Serpukhovian deposits was developed and analyzed (Fig. 8).

Here, maximum values of thickness can be seen along the conventional line connecting well 3 and well 14. They are productive wells within the perspective sandstone C-2. Assumed traces of thalwegs are passing in the direction of maximum values of thickness in the vicinity of productive wells 3 and 14 (Fig. 9). One of the thalwegs is crossing productive well 2 according to the predicted sandstone C-2. Lines of thalwegs have a tendency towards intersection in the vicinity of well 3 and to the south from it as well. This

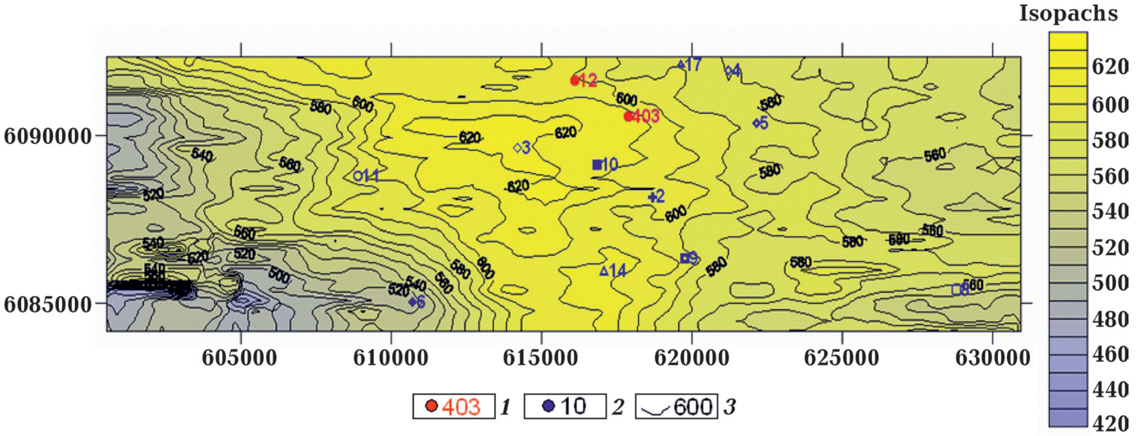

Fig. 8. Thickness map of the Late Serpukhovian substage: *1* — producing well within horizon C-1; *2* — barren well within horizon C-1; *3* — lines of thickness equal meanings of the Late Serpukhovian substage. Axes *Y* and *X* — conventional geographic coordinates. Structural complications in the lower left corner are caused by presence of the South Pereshchepino salt stock.

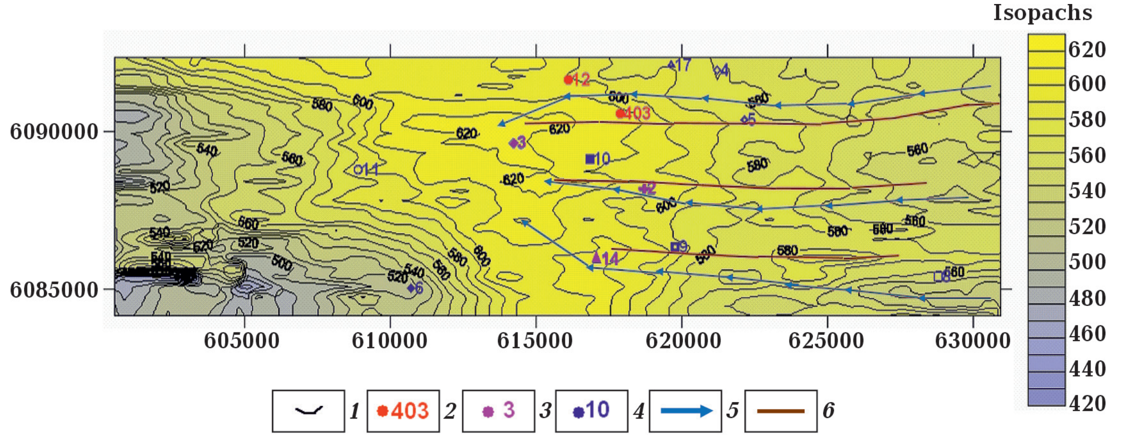

Fig. 9. Thickness map of the Late Serpukhovian substage: *1* — iso-pachous line of Late Serpukhovian substage sediments; *2* — producing wells within horizon C-1; *3* — producing wells within horizon C-2; *4* — barren wells within Late Serpukhovian; *5* — line of thalwegs; *6* — line of interstream areas. Axes *Y* and *X* — conventional geographic coordinates. Structural complications in the lower left corner are caused by the presence of the South Pereshchepino stock.

phenomenon is prospecting character on hydrocarbons.

Perspective wells 12 and 403 along gas-bearing sandstone C-1 are situated up-dip as to the zone of maximum values of thickness of the Late Serpukhovian. In this case, one needs to remember that the Late Serpukhovian sediments contain two sandstones within this area: C-1 and C-2. Thus, we can observe their summary effect on the map of thickness. Therefore, wells 12 and 403 are outside the zone of maximum thickness because sandstones C-1 and C-2 are not collinear in the space.

As to the productive well 14, initially it was assumed to be within an estuary. However, looking at the thickness map with traces of supposed thalwegs, one gets the impression that it is located separately. By the way, this is also indicated by the anomaly in the vicinity of well 14, shown on the map in Fig. 1. It should be noted that in this case, the absorption study took place along the reflecting horizon allocated in the vicinity of the productive sandstone C-1.

Paleogeomorphological reconstructions. Paleorelief of surface of unconformity is used in the process of paleogeomorphological reconstructions.

Within the Upper Serpukhovian strata in the Bogatoika field, sand bodies were predicted based on the concept of coefficient of paleogemorphological conditions (tectonic-sedimentation equation in the SPGM technique). The coefficient of paleogemorphological conditions can be expressed via the ratio of the average rate of sedimentation of the subcomplex $\Delta h(C)$ to the average rate of subsidence during the accumulation of sediments of the entire sedimentary complex ΔH between two paleo-levelling surfaces (V). In that case, the following three variants are possible: compensated sedimentation of deposits of the subcomplex Δh (when $\bar{C} \approx \bar{V}$), under-compensated ($\bar{C} < \bar{V}$), or over-compensated sedimentation — the formation of an accumulative body ($\bar{C} > \bar{V}$) [Karpenko, 2003]. Therefore, a map of the ratio of the thickness of the Upper Serpukhovian sediments to the thickness of the sediments of the entire Serpukhovian was constructed for forecasting purposes (Fig. 10). This section should be classified as under-compensated one ($\bar{C} < \bar{V}$) according to the thickness ratio values.

At the same time, an anomalous zone with increased ratio values is notable in the central part of the map. This zone is due to the presence of sand bodies in the section, which are less susceptible to compression than clays ones. Wells 12 and 403 are at the edge of the anomalous zone. This is explained by the effect of non-collinearity in the section of two productive sandstones: C-1 and C-2.

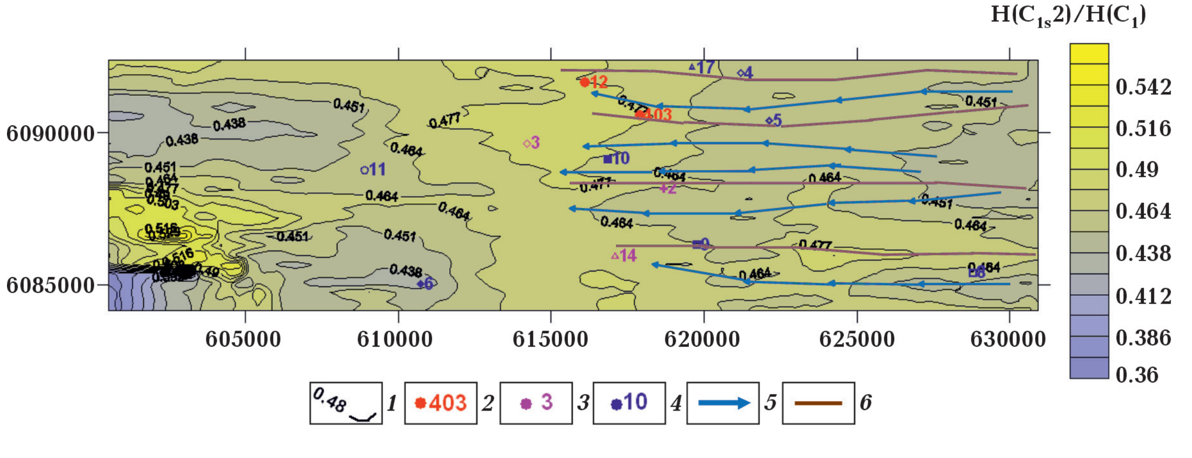

Fig. 10. Ratio map of thicknesses of the Late Serpukhovian substage to all Serpukhovian: *1* — ratio line of thicknesses of the Late Serpukhovian substage to the whole Serpukhovian; *2* — producing wells within horizon C-1; *3* — producing wells within horizon C-2; *4* — barren wells within Late Serpukhovian; *5* — line of thalwegs; *6* — line of interstream areas. Structural complications in the lower left corner of the map are caused by the presence of the South Pereshchepino stock.

The anomalous zone in the western part of the map is due to the presence of the South Pereshchepino stock in the absence of exploration wells. This is why making stratigraphical location (reference) of seismic horizon was impossible.

From the structural maps for reflecting horizons VI_3 (D_3fm), Vb_4 (C_1t), and other based on the «Report under agreement No. 18-GF-00 for carrying out 3D seismic surveys within the Bogatoika area of the near-edge zone of DDD» of 2004, it follows that the body under investigation is located within a monoclinal slope in the area of the structural nose. The SPGM technique aims to contour exactly this kind of sand formation under such geological conditions.

Thus, one can conclude that just the presence of the sand body is the reason for an anomaly formation on the map of the distribution of absorption of seismic energy within horizon C-1 (see Fig. 1).

Analysis of the Late Serpukhovian sediment thickness with point of view of tectonics. Accumulation of sediments is a consequence of deposition basin bottom lowering. This process took place within the Bogatoika field during a period of formation of Late Serpukhovian sediments in shallow-water conditions as was stressed earlier. As famous tectonicians V.E. Khain and A.E. Mikhailov pointed out in [Khain, Mikhailov, 1985], «analysis of thicknesses in certain conditions allows obtaining not only qualitative but also quantitative assessment of vertical movements. The thickness of sediments is in accordance with the size of the tectonic settling of basins' bottoms within shallow epicontinental seas and on the shelves of the underwater margins of continents. This is explained by wave activity, which prevents the accumulation of sediments over some level referred to as «the equilibrium profile». If the surface of sediments reaches the equilibrium profile, their further accumulation is impossible without basin bottom subsidence creating space for possible sedimentation. Due to this, the tectonic settling becomes the regulator and measure of thickness of sediments. Just such sinking makes it possible to accumulate such thick strata of purely shallow-water sediments...» In particular, they claim that «such conditions are typical for platform regions where sea bottom depth is rarely more than 50 m, characteristic for outer zones of geosyncline which corresponds to the shelf of the continental margins». As the Serpukhovian deposits were formed in shallow-water conditions, therefore the thickness analysis from the position of [Khain, Mikhailov, 1985] is quite acceptable for the Bogatoika gas condensate field.

Additionally, the Serpukhovian sediments were affected by deuteric alterations, leading to their thickness deformations. In the conditions of the Bogatoika field, such changes may include the following: 1) consolidation of sediments under the influence of the overlying layers and 2) subsequent washout of sediments. The above-mentioned authors emphasize further that «compaction affects mainly pellite and aleurolite sediments. It proceeds at a rapid pace immediately after sedimentation until the process of sediment accumulation of that stratigraphic interval stops. And thus, subsidence is compensated there and then by further sedimentation. However, compaction continues, especially for clays. A detailed analysis of thickness should consider this phenomenon as, in some cases, the difference between the initial and finite thickness can reach 35—50 %».

Let us look at the map in Fig. 8 (the thickness map of the Late Serpukhovian sediments). The maximum thickness values are in the central part of the map (depocenter). Thickness decreases in the eastern and especially western parts of the map. Rimming of high values of thicknesses is observed in the northern and especially southern parts of the map. Such a phenomenon is connected with the secondary compaction of sediments along the perimeter of the sand body because of the high percentage of clay and aleurolite content here [Khain, Mikhailov, 1985]. The location of productive and forecast wells in this area indicates this reason indirectly. Thus, productive wells 12 and 403 and perspective on well logging data 2, 10, and 14 ones within efficient horizon C-1 are just within the zone of large thickness. The same can be said about productive wells 2, 3, 14, and perspective according to well logging the well 12 along sandstone layer C-2. Well 14 is somewhat isolated.

Considering the poor sorting of sand deposits of the Early and especially Late Serpukhovian substages and their dark coloration, it is possible to suppose, according to [Khain, Mikhailov, 1985], that the land submerged fast. Coal detrital matter indicates the presence of drift waters. At the same time, as Khain and Mikhailov point out: «in very shallow basins with an abundant supply of clastic material, the arches of growing anticlines are characterized by increased sand content».

All this indicates the presence of sand formations exactly at the anomaly's location according to seismic wave absorption (see Fig. 1).

Conclusions. It is proved that the reason for an anomaly arising in terms of absorption of seismic waves is a sandstone body within horizon C-1 of the Bogatoika area. The anomaly was found by a novel technique aimed at investigating seismic waves' energy absorption. A sand body's presence was also proven by seismopaleogeomorphologic (SPGM) technique.

The new technique is recommended in conditions of development of nonstructural traps of hydrocarbon.

Acknowledgments. The author would like to thank Ph. D. Marmalevskyi N.Y. and Ph. D. Karpenko I.V. for their help and support while working on the paper.

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Розвідка вуглеводневих пасток двома методами в межах Богатойської площі Дніпровсько-Донецької западини — порівняння геологічних результатів

О.М. Шадура, 2025

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Мета статті — показати ефективність нової розробленої методики для оцінювання запасів нафти і газу в пастках складної конструкції (неантиклінальних). На відміну від традиційних методик, згідно з якими для оцінювання складнопобудованої пастки

необхідно простежити два горизонти, у запропонованому методі використовується тільки один горизонт, що перетинає поклад.

Перша методика є новою, розробленою на підставі дослідження поглинання сейсмічних хвиль. Було виявлено, що абсорбція дуже чутлива до зміни відсоткового вмісту газу в пористому резервуарі. Як наслідок, сейсмічний спектр збіднюється на високі частоти. Тому поглинання є важливою характеристикою гірських порід, що доповнює інформацію про їх швидкісні та рефлективні властивості та підвищує ефективність геологічної інтерпретації сейсмічних даних. Для чисельної характеристики поглинальних властивостей середовища застосовують коефіцієнт поглинання, декремент логарифмічного поглинання та якість (добротність) середовища *Q* (*Q*-фактор або просто *Q*). Останнім часом у зарубіжних наукових публікаціях все частіше використовують поняття *Q*-якості середовища.

Коефіцієнт добротності можна виразити через максимальне значення пружної енергії E_{max}, що зберігається у зразку протягом періоду навантаження, і втрат енергії протягом того самого періоду *E*. Для великих значень *Q*, які зазвичай спостерігаються на практиці, параметр *Q* обернено пропорційний коефіцієнту поглинання з урахуванням коефіцієнта пропорційності.

Застосований алгоритм є близьким до структури вираження, отриманої в публікації [Hauge, 1981], для дослідження свердловинних матеріалів з припущенням відсутності інтерференції.

Запропонований метод дає можливість виконувати вимірювання добротності на підставі відбиттів за даними поверхневої сейсморозвідки. Він адаптований з метою зробити вимірювання безперервними в часі вздовж траси. Розроблено також метод для введення компенсації за спотворювальний вплив кратних відбитих хвиль.

Друга методика — добре зарекомендована сейсмопалеогеоморфологічна (СПГМ) технологія. За її допомогою підтверджено, що згідно з даними досліджень поглинання сейсмічних хвиль причиною виникнення аномалій є піщані тіла в межах пізньосерпуховського під'ярусу.

Для підтвердження цього на підставі палеотектонічної та палеогеоморфологічної реконструкцій (СПГМ-технологія) побудовано дві структурні карти. У результаті інтерпретації та порівняння з картою, побудованою за даними дослідження поглинання сейсмічних хвиль, зроблено висновок щодо можливості застосування нової розробленої методики під час пошуку вуглеводневих пасток.

Ключові слова: поглинання сейсмічних хвиль, палеотектонічні та палеогеоморфологічні реконструкції, SPGM-технологія, Богатойське родовище, відклади пізньосерпуховського під'ярусу.