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The accurate shape of salt diapir and near-salt commercial hydrocarbon pools: outcome of applying a 3D joint gravity, well-log, seismic inversion, and new paradigm for pool mapping

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Limitations of the seismic method in mapping salt diapirs increase exploration risks while drilling in near-salt areas. An innovative method of 3D joint inverse problem solution for gravity, well-log, and seismic data makes it possible to verify and refine the shape of a salt dome and map hydrocarbon accumulations right beside the salt wall under the salt wing and over the salt dome. It is illustrated by the results for four salt domes in the central axial part of the Dniper-Donets Basin. In half of the cases, joint gravity inversion proved that seismic data provided a reliable salt shape that may be used as the biggest outline. In the other half of the cases, the salt stem outlined by 3D gravity inversion significantly differed from that by 2D and 3D seismic data interpretation. In one case, gravity inversion showed that the size of the salt stem was three times smaller. For all the cases under the salt wing in proximity to the salt dome, near the salt wall, and over the salt dome, localized low-density rock areas were mapped. These areas were associated with commercial

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hydrocarbon pools. A commercial hydrocarbon pool is a hydrocarbon pool with porosity, permeability, hydrocarbon saturation, recoverable reserves, and a production rate that simultaneously are higher than cut-off values, making future drilling and production commercially viable. For one, the salt dome location of the commercial pools was verified by drilling. As a result, a new oil field was discovered and named after Academician Schpak. Also, over the same salt dome, the size of the Runovshina field shallow gas pool outline was six times expanded. Four wells drilling outcomes — three commercial and one dry — fully confirm the correctness of the shape of the mapped commercial pool with a 100 % commercial probability of success.

Key words: salt dome, complete Bouguer gravity anomaly, geologically meaningful 3D density model, joint inverse problems solution, isolated density anomaly, commercial hydrocarbon pool, Dnieper-Donets Basin.

Introduction. Some major hydrocarbon accumulations (hydrocarbon pools) in the Dnieper-Donets Basin (DDB) are associated with salt diapirs. Among them are Rozpashnivske (52 BCM of recoverable gas), Vedmedivske (49 BCM), Mashivske (39 BCM), and Chutivske (12 BCM) gas fields [Ivanyuta, 1998]. Many known accumulations underlie salt wings and are adjacent to salt stems. Moreover, some of them (like Rozpashnivske, Chutivske or Novoukrainske) are associated with steep near-salt blocks with hydrocarbon production within some hundred meters from the salt wall (Novoukrainske oil and gas field). Overlaying salt wings, steep orientations of salt walls and near-salt beds, velocity contrasts, and intensive faulting around the salt make seismic imaging of near-salt structures challenging and petroleum exploration highly risky.

Salts' physical properties do not favor seismic studies. Still, they are beneficial for gravity exploration, as high-amplitude density contrast between salt and host rocks contributes to the reliable reconstruction of salt shape by gravity. Recent advances in gravity interpretation [Kobrunov, Petrovskyy, 1990; Petrovsky et al., 2003; Petrovsky, 2004] utilize full-scale 3D density modelling and full-field 3D gravity inversion, constrained by seismic and well data. They allow for detailed mapping of salt shape and identification of isolated low-density areas associated with hydrocarbon accumulations in immediate proximity to salt.

Method. The approach quantitatively introduces initial geological and geophysical information into the inversion algorithm to get a unique, stable, and geologically meaningful solution (Fig. 1):

– All available data is used to build a detailed, initial 3D density model of the subsurface and to define major uncertainties and structural/density constraints;

– Convex functional J(.) is quantitatively introduced to the inversion algorithm. It contains the initial information and geological constraints. In the case of inversion for one geophysical field, a so-called «Inactive inverse problem solution» is used

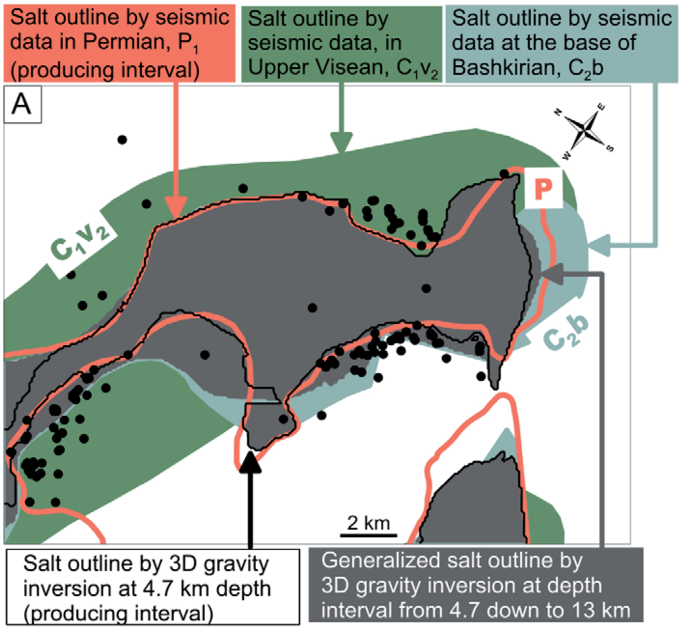
$$\begin{cases} A\big(\xi(\mathbf{r})\big) = u(\mathbf{s}), \\ J\big(\xi(\mathbf{r}) - \xi_0(\mathbf{r})\big) \to \min, \\ \xi(\mathbf{r}) \in D(A) \subset \mathbf{W}, \\ u(s) \in Im(\mathbf{A}) \subset \mathbf{U} \\ \xi(\mathbf{r}), \xi_0(\mathbf{r}) \in M \subset D(A); \end{cases} \quad (1)$$

– In the case of joint inversion for two geophysical fields, a so-called «Active inverse problem solution» is used

$$\begin{cases} A\big(\xi(\mathbf{r})\big) = u(\mathbf{s}), \\ B\big(\eta(\mathbf{r})\big) = y(\mathbf{s}), \\ J\big(\xi(\mathbf{r}) - \eta(\mathbf{r})\big) \to \min, \\ \xi(\mathbf{r}) \in M \subset D(A) \subset \mathbf{W}, \\ \eta(\mathbf{r}) \in N \subset D(B) \subset \mathbf{W}; \end{cases} \quad (2)$$

where $\xi(r)$, $\eta(r)$ — models (density or velocity values in the heterogeneous model or depth to geological or geophysical structural surfaces in the structural model in the point $r \in XYZ$); W — metric space of models; $u(.)$, $y(.)$ — observed geophysical fields or their functionals in the point $s \in XYZ$; U, Y — metric spaces of geophysical fields; $A(.)$: $W \to U$, $B(.)$: $W \to Y$ — in general case non-linear operators acting from models' space W to the spaces of U, Y of geophysical fields; $D(A)$, $D(B)$ — domain of operators $A(.)$, $B(.)$ — open subspace in space W, wide enough to ensure adequate approximation of a true geological model; Im(A), Im(B) — open subspaces in spaces U, Y, wide enough to ensure adequate approximation of geophysical fields $u(.)$, $y(.)$; M, N — set of possible geologically meaningful models $\xi(r)$, $\eta(r)$; $J(.)$: $W \to R$ — Convex functional acting on W and containing prior geological and geophysical information as estimation of uncertainties of

Fig. 1. Fundamental scheme of 3D joint inverse problem solution for gravity, well-log, seismic, and geological data, and estimation of petrophysical and hydrocarbon production properties of commercial hydrocarbon pools.



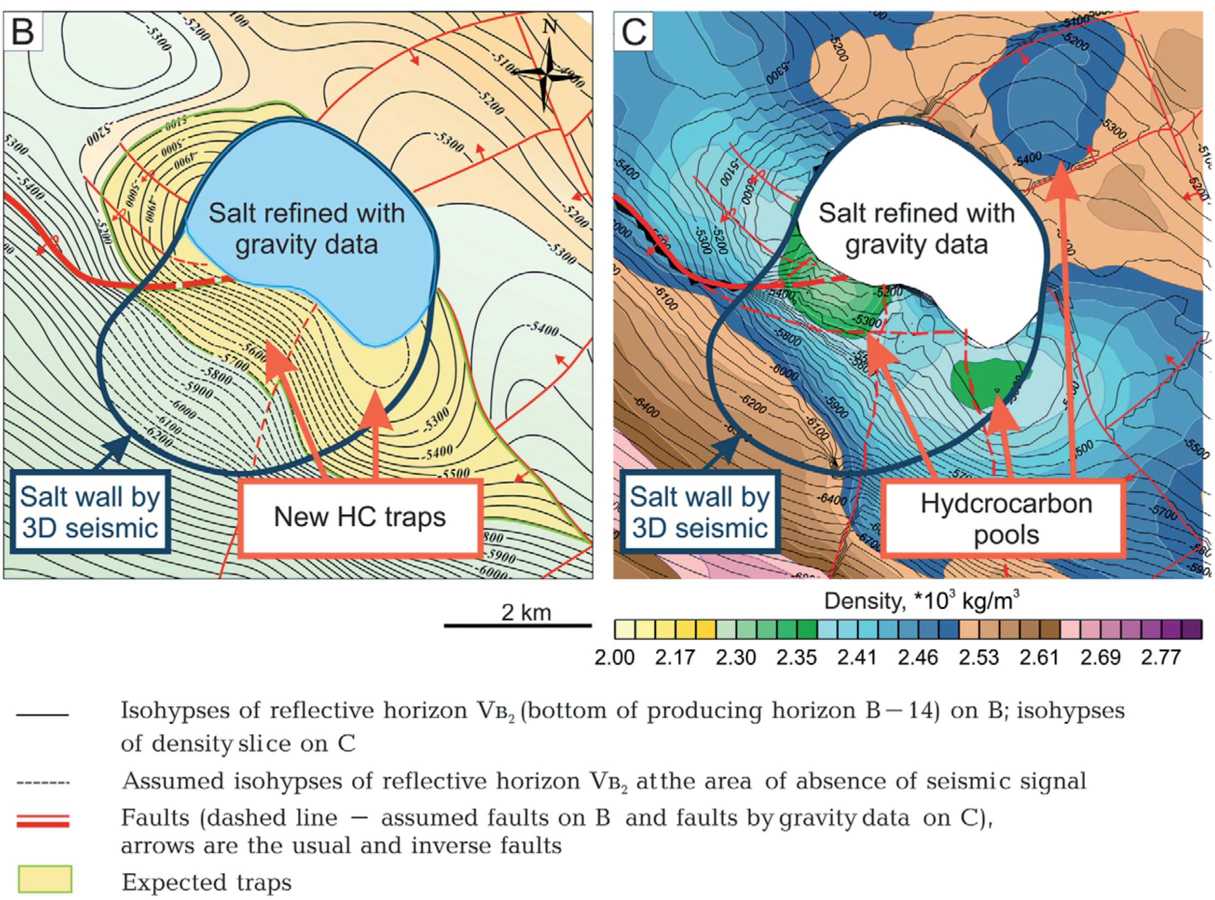


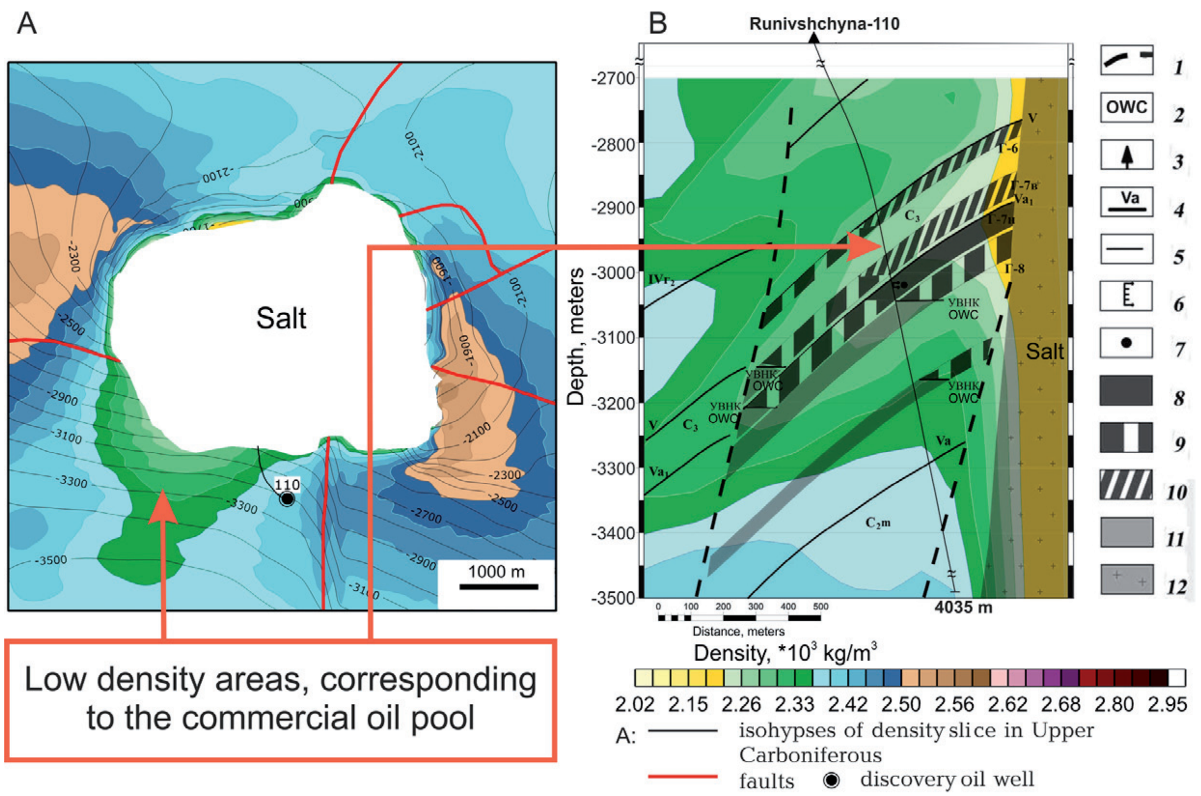
Fig. 2. Two examples of salt diapirs, significantly modified after 3D gravity inversion: A — salt dome within a highly explored area. Black dots indicate deep wells. A prior salt outline was built using wells and 2D seismic data. 3D gravity inversion indicated a much smaller size of salt, especially at depth, with changes varying between 17 and 600 %; B, C — example of new prospect area, covered with 3D seismic survey. 3D gravity inversion revealed an over three times smaller diapir size than the 3D seismic data. The S-W block (previously assumed to be part of the salt stem by seismic survey) is characterized by the density of the hydrocarbon-bearing sedimentary rocks (C). The down dip (from the salt stem) location of new hydrocarbon commercial pools here is analogous to that of the recently discovered oil field named after Academician Schpak (see Fig. 3). Considering the «noisy» character of seismic image here, one cannot exclude a thick salt wing or, alternatively, a deformed block of salt overburden, similar to the objects described in [Petrovska et al., 2021].

initial properties of model; $\xi_0(r)$ — the initial model incorporatingall available prior geological and geophysical information.

– Inversion for the entire geological column, including salt/basement/Moho interface/local density variations of the sedimentary section;

– The use of complete Bouguer (or Free-air) gravity anomaly for the inversion;

– The use of actual physical density, which



B: *1* — faults, *2* — expected oil — water contact (OWC), *3* — exploration well, *4* — seismic interfaces, *5* — stratigraphic boundaries, *6* — well testintervals, *7* — oil infliw, *8* — oil pool, *9* — expected oil pool, *10* — oil saturation by well log interpretation, *11* — water reservoir, *12* — salt

Fig. 3. Identification of the commercial oil pool under the salt wingand near the salt wall. The case for the field named after Academician Schpak: A — 3D density model conformal slice within the Lower Permian — Upper Carboniferous production layer; B — 3D density model of a vertical cross-section through the discovery wellwith results of well testing [Zeikan et al., 2013]. Salt stem size did not change significantly from the estimate by3D seismic data. Light green low-density areas mark the commercial oil pool, identified bythe 3D gravity inversion. The yellow area outlined the salt rocks of the stem. Model validity was proved by the discovery well #110.

ensures the possibility of proper model constraining during the inversion and further petrophysical conversions.

Exploration outcome. Four salt diapirs were studied in the central part of the Dnieper-Donets Basin (DDB). For detailed 3D density modeling and joint gravity inversion, high-precision gravity field measurements with 100×100 m station spacing (1:10 000 scale) were performed for all the cases. To minimize interpolation errors when using the gravity field for joint inversion, gravity stations were placed at the centers of the rectangles that were projections of the future 3D density model's cells to day surface. 3D density models of the subsurface were built from the day surface down to 20—25 km to include salt wind and overburden, salt stem, mothersalt, and basement. The resolution of the 3D density models was 100×100 meters laterally and varied from 50 to 20 m vertically depending on the geological tasks.

Prior sizes of the diapirs' salt stems varied from 5.6 to 19 km by seismic data (3D seismic data in three cases and 2D seismic data in one case). The distances between the three sites are between 10 and 30 km, which might be why all salt bodies have a similar expected structure. However, the results of the 3D density modeling differ significantly.

The 3D gravity inversion outcome for two salt diapirs showed significant changes in the position of the salt wall (Fig. 2). In both cases, the new commercial hydrocarbon pools were mapped in the areas identified as salt-bearing after seismic data interpretation. In one of the cases, the identified accumulations were associated with a new kind of hydrocarbon pro-

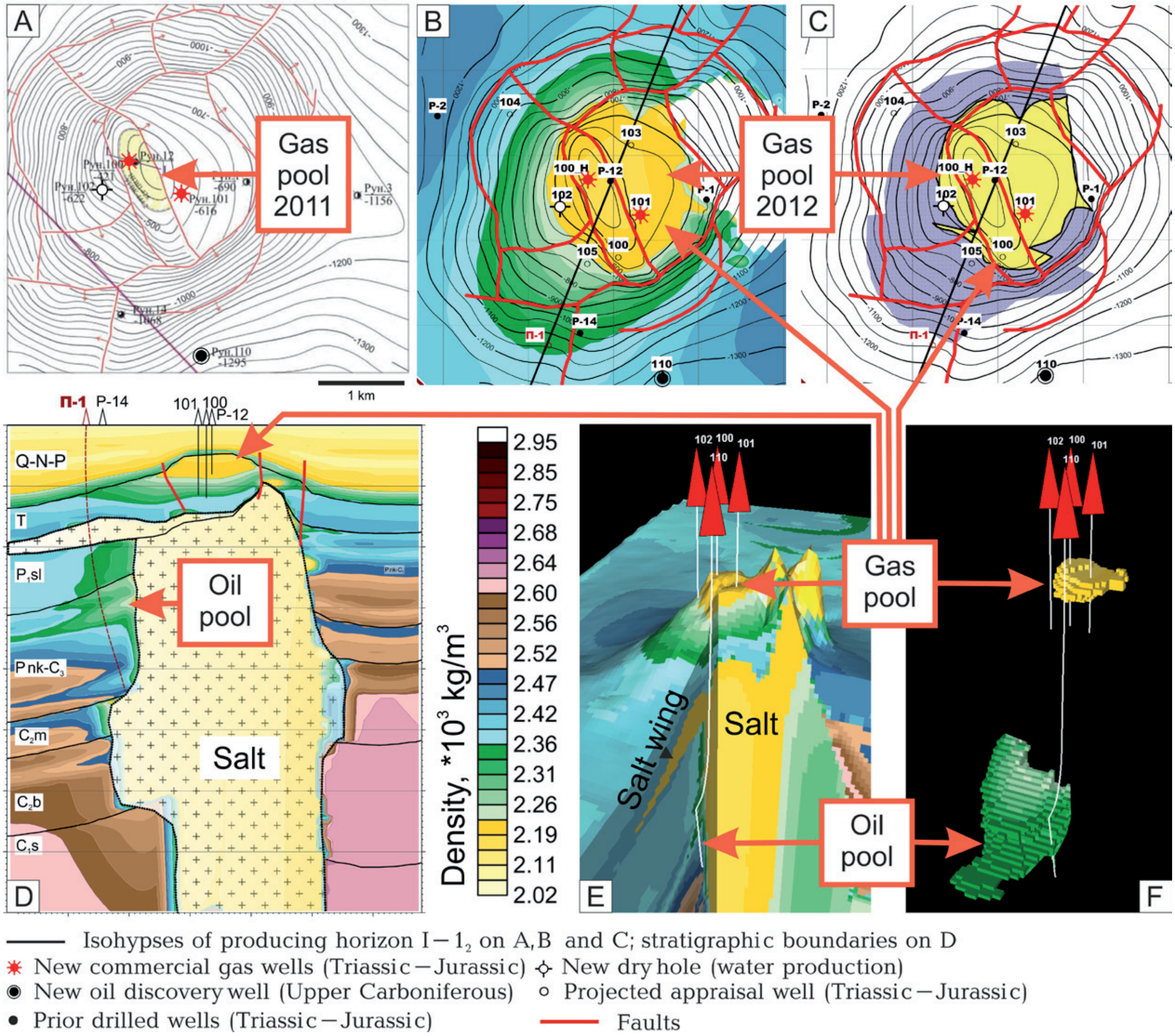


Fig. 4. Identification of the Jurassic-Triassic commercial gas pools of Runovschyna field over the salt dome: A — top of the Triassic producing horizon by 3D seismic data (by Shevchenko O.A., cited from [Svjatenko, 2018]; B — density in Triassic by the results of 3D gravity inversion, 2012. Adjacent Jurassic and Triassic producing horizons are depicted as a single low-density zone, shown in yellow; C — outline of the commercial hydrocarbon pool (yellow area) by the 3D density modeling; D — cross-section along the black line shown at B and C; E — a salt dome and the overlaying gas pool in a 3D density model by the results of gravity inversion (2012), with new drilled wells (2013); F — the shape of the Triassic-Jurassic (yellow body) and Upper Carboniferous (green body) commercial hydrocarbon pools (2012) and new wells drilled in 2013. 3D visualization of E and F performed in GCIS software [Petrovsky et al., 2003].

spective structures — displaced blocks of salt overburden — that represent new prospects for deep drilling in the DDB [Petrovska et al., 2021].

In two cases (50 %), the 3D density model confirmed the shape of salt stems. In 2012, commercial hydrocarbon pools were mapped under the salt wing in proximity to salt stems (in both cases) and over the salt dome (in one case). In 2013, four wells were drilled to test two mapped commercial pools. The oil field was named after Academician Schpak. It was discovered by one well (Fig. 3). Two commercial wells and one «dry» hole confirmed the accuracy of the shape of the mapped commercial hydrocarbon pool in the Runovscyna gas field (Fig. 4).

Conclusion. The four exploration cases illustrated the technique's efficiency in obtaining geologically meaningful 3D density models by deterministic joint 3D inversion of gravity, well-log, seismic, and petrophysical data to map the 3D shape of salt diapirs. In 50 % of cases, gravity inversion proved that seismic data provided reliable salt shapes that may be used as the biggest outlines. However, in the other 50 % of cases, the size of the salt stem was much smaller than previously expected from only the seismic data. In one case, gravity inversion showed that the size of the salt stem was three times smaller. An additional value of the innovative technology was the accurate prediction of the shape and properties of new commercial hydrocarbon pools near the salt wall, under the salt wing, and over the salt dome and caprock, including the areas assumed as salt by seismic data. The license owner drilled four new wells around the diapir studied. The drilling outcome confirmed the 3D model's accuracy and evidenced the method's efficiency for derisking deep drilling by increasing the probability of successfully mapping the commercial pools up to 100 %.

References

Ivanyuta, M.M., Fedyshyn, V.O., Denega, B.I., Arsiriy, Y.O., & Lazaruk, Y.G. (Eds.). (1998). *Atlas of oil and gas fields of Ukraine in Six volumes. Vol. III. Ukrainian Oil and Gas Academy* (pp. 932—958, 986—992). Lviv (in Ukrainian and English).

Kobrunov, O.I., & Petrovskyy, O.P. (1990). Iteration scheme of gravity inversion. *Reports of the Academy of Science of the USSR,* (2), 13—16 (in Russian).

Petrovsky, A.P. (2004). Information support and model concepts of integral interpretation of geological and geophysical data during exploration. *Geophysical Journal, 26*(3), 77—86 (in Russian).

Petrovska, T.O., Petrovskyy, O.P., Tsihovska, O.M., & Trachuk, A.Ju. (2021). Carapaces of the Dnieper-Donets Basin as a New Exploration Target. *SPE Eastern Europe Subsurface Conference*, *Kyiv, Ukraine, 23—24 Nov 2021.* https://doi.org/10.2118/208538-MS.

Petrovsky, O.P., Kobrunov, O.I., Gangenko, N.S., & Sujatinov, V.M. (2003). Automated system of quantitative complex interpretation of geophysical data GCIS as the basis of the Technology of integral interpretation of geological and geophysical information in oil and gas exploration. *Geoinformatyka*, (2), 25—34 (in Ukrainian).

Svjatenko, G.Ye. (2018). Features of geological structure and oil and gas potential of Mesozoic of the Dniper-Donets basin. *PhD thesis*. Kyiv, 247 p. (in Ukrainian).

Zeikan, O.Yu., Hladun, V.V., Maksymchuk, P. Ya., Chepil, P.M., Dudnikov, M.S., Husachenko, V.O., Dovzhok, T.Ye., Vakarchuk, S.G., Kharchenko, M.V., Stryzhak, V.P., & Shevchenko, O.A. (2013). The first oil field discovered by the National Joint-Stock Company «Naftogaz of Ukraine» in the Dnieper-Donetsk Depression. *Geological Journal,* (3), 26—32 (in Ukrainian).

Визначення точної форми соляного діапіру та навколо-соляних покладів вуглеводнів: результат спільної 3D інверсії гравіметричних, свердловинних і сейсмічних даних та нової парадигми картування комерційних покладів вуглеводнів

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Обмеження сейсмічного методу при картографуванні соляних діапірів збільшують ризики під час буріння довкола соляних штоків. Інноваційний метод тривимірного спільного вирішення оберненої задачі для даних гравіметрії, каротажу свердловин і сейсмічних даних дає можливість перевірити й уточнити форму соляного купола та закартувати скупчення вуглеводнів безпосередньо біля стінки соляного штоку, під соляним козирком і над соляним куполом. Це проілюстровано результатами для чотирьох соляних куполів у центральній осьовій частині Дніпровсько-Донецької западини. У половині випадків спільна гравітаційна інверсія довела, що сейсмічні дані забезпечили надійну форму солі, яку можна використовувати як найбільший контур. В іншій половині випадків соляний шток, закартований за допомогою 3D гравітаційної інверсії, суттєво відрізнявся від інтерпретації 2D та 3D сейсмічних даних. В одному випадку гравітаційна інверсія показала, що розмір соляного штоку був утричі меншим. Для всіх випадків під соляним козирком поблизу соляного купола, біля стінки соляного штоку та над соляним куполом були закартовані локалізовані ділянки порід низької густини. Ці ділянки були пов'язані з комерційними покладами вуглеводнів. Комерційний поклад вуглеводнів — це поклад вуглеводнів, в якому пористість, проникність, вуглеводневе насичення, видобувні запаси та початковий дебіт одночасно перевищують граничні значення, що робить майбутнє буріння та видобуток комерційно рентабельними. Для одного з соляних штоків розташування комерційних покладів було підтверджено бурінням, унаслідок чого було відкрито нове родовище нафти, якому присвоєно ім'я академіка Шпака. Крім того, над тим же соляним куполом у шість разів збільшено розмір контуру неглибокого газового покладу Руновшинського родовища. Результати буріння чотирьох свердловин — трьох промислових і однієї сухої — повністю підтверджують правильність форми закартованого промислового покладу зі 100%-ю ймовірністю комерційного успіху.

Ключові слова: соляний купол, повна гравітаційна аномалія Буге, геологічнозмістовна 3D модель густини, спільний розв'язок обернених задач, ізольована густинна аномалія, комерційний поклад вуглеводнів, Дніпровсько-Донецька западина.