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Carapaces of the Dnieper-Donets Basin as a New Exploration Target

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Abstract

New geological structures - displaced blocks of salt diapirs' overburden - were identified in the axial part of the Dnieper-Donets basin (DDB) beside one of the largest salt domes due to modern high-precision gravity and magnetic surveys and their joint 3D inversion with seismic and well log data.

Superposition of gravity lineaments and wells penetrating Middle and Lower Carboniferous below Permian and Upper Carboniferous sediments in proximity to salt allowed to propose halokinetic model salt overburden displacement, assuming Upper Carboniferous reactivation.

Analogy with rafts and carapaces of the Gulf of Mexico is considered in terms of magnitude of salt-induced deformations.

Density of Carboniferous rocks within the displaced flaps evidence a high probability of hydrocarbon saturation. Possible traps include uplifted parts of the overturned flaps, abutting Upper Carboniferous reservoirs, and underlying Carboniferous sequence. Play elements are analyzed using analogues from the Dnieper-Donets basin and the Gulf of Mexico.

Hydrocarbon reserves of the overturned flaps within the study area are estimated to exceed Q50 (P50) = 150 million cubic meters of oil equivalent.

Introduction

Deep petroleum exploration, together with unconventional resources is a strategic onshore focus area for the Ukrainian oil and gas industry to increase domestic production. Today's ambition of Ukraine is to increase gas production from 20.2 bcm (gas production in 2020) up to 31 bcm (gas consumption in 2020) by 2025-2030. Such significant and rapid growth of gas production is only possibly with deep exploration to be prioritized over the shale gas production. The reason is that the production of natural gas from shales is extensive by nature. Even in case if shale gas reserves in Ukraine are significant and proved, and effective low-cost drilling and fracturing technologies are in place, small flow rates (50.000-100.000 m^3/day - shale gas production rate in the US (Selley 2012)) and their rapid decline will require large amount of drilling, making shale gas rather possible long-term perspective in a question domestic production contribution. On the other hand, Ukrainian scientists (Lukin 2014; Shchurov et al. 2018) estimate deep horizons to contain 50% of all undiscovered reserves of DDB, which is the major oil and gas producing region of the country (Fig. 1, 2). The phenomenon of high-quality secondary reservoirs of big depth provides high hydrocarbon flow rates up to 1-2 million m^3/day (Lukin 2014) and, therefore, opens the possibilities for quick production rise. Drilling results from different oil and gas basins of the world prove high hydrocarbon potential of big depth: just to mention deep giant hydrocarbon accumulations at 7-10 km depth in the Gulf of Mexico, US: Tyber oil field (10 685 m), Kaskida oil field (9 900 m), Appomattox oil field (7 910 m) and others.

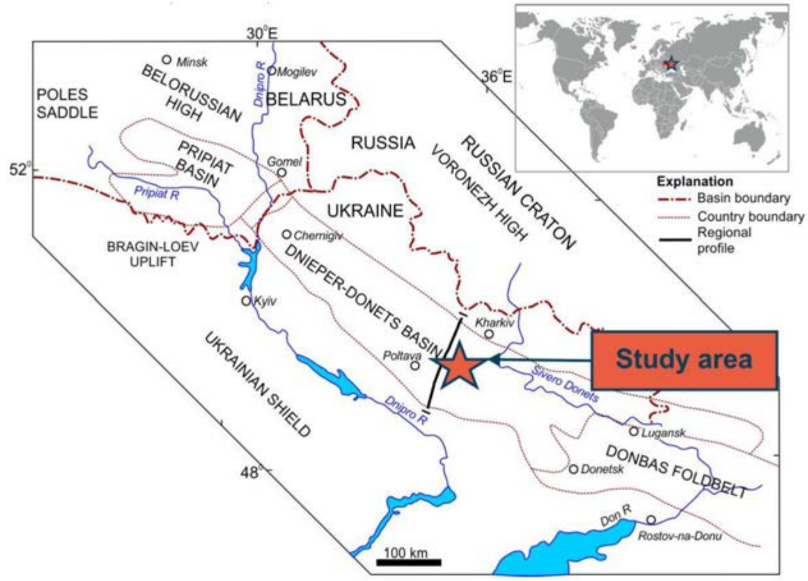


Figure 1—Location of studied area within the Dnieper-Donets basin (map modified from Ulmishek and others (1994), cited from Ulmishek, 2001).

Deep horizons of producing hydrocarbon fields in the DDB (mostly trapped in big anticlinal structures) are being proposed by Ukrainian geologists as the first-priority objects for deep drilling. However, 12 deep wells at Shebelynka giant gas field showed no commercial hydrocarbon inflow at the depth range of 4356-6106 m below the main gas accumulation (Kryvulia et al. 2016). This evidence reservoirs and trapping mechanism at big depth of the DDB to be more complex and differ from currently utilized models, showing the need to reconsider the exploration tactics both in terms of play concepts and identification techniques.

In 2020 high-precision gravity survey was carried out over two big salt domes in the DDB. Consequent 3D gravity inversion and density modeling firstly aimed to define remaining reserves and potential of deep horizons of two HC fields adjacent to the salt dome and being at the final stages of production. Still, this could not be done apart from refining the shape of the salt diapirs.

One of the important geological results of the research was identifying a new type of geological structure - displaced blocks of the former salt overburden. Created 3D density model together with geological data evidence that mapped structures may contain a significant volume of hydrocarbon reserves and become a priority deep exploration target in the DDB.

Background information

Dnieper-Donets basin (Ukraine) is a Late-Devonian rift, filled with pre- and synrift Devonian sequence and overlain with post-rift Carboniferous, Permian, Mesozoic and Cenozoic fill (Fig. 1, 2). It is a salt basin. In the axial part of the depression Devonian salt penetrates over 10 km-thick Carboniferous- Permian sequence (Fig. 3). At the same time axial part of the basin accommodates the biggest known HC fields. The basin is a mature one with over 200 hydrocarbon accumulations under production.

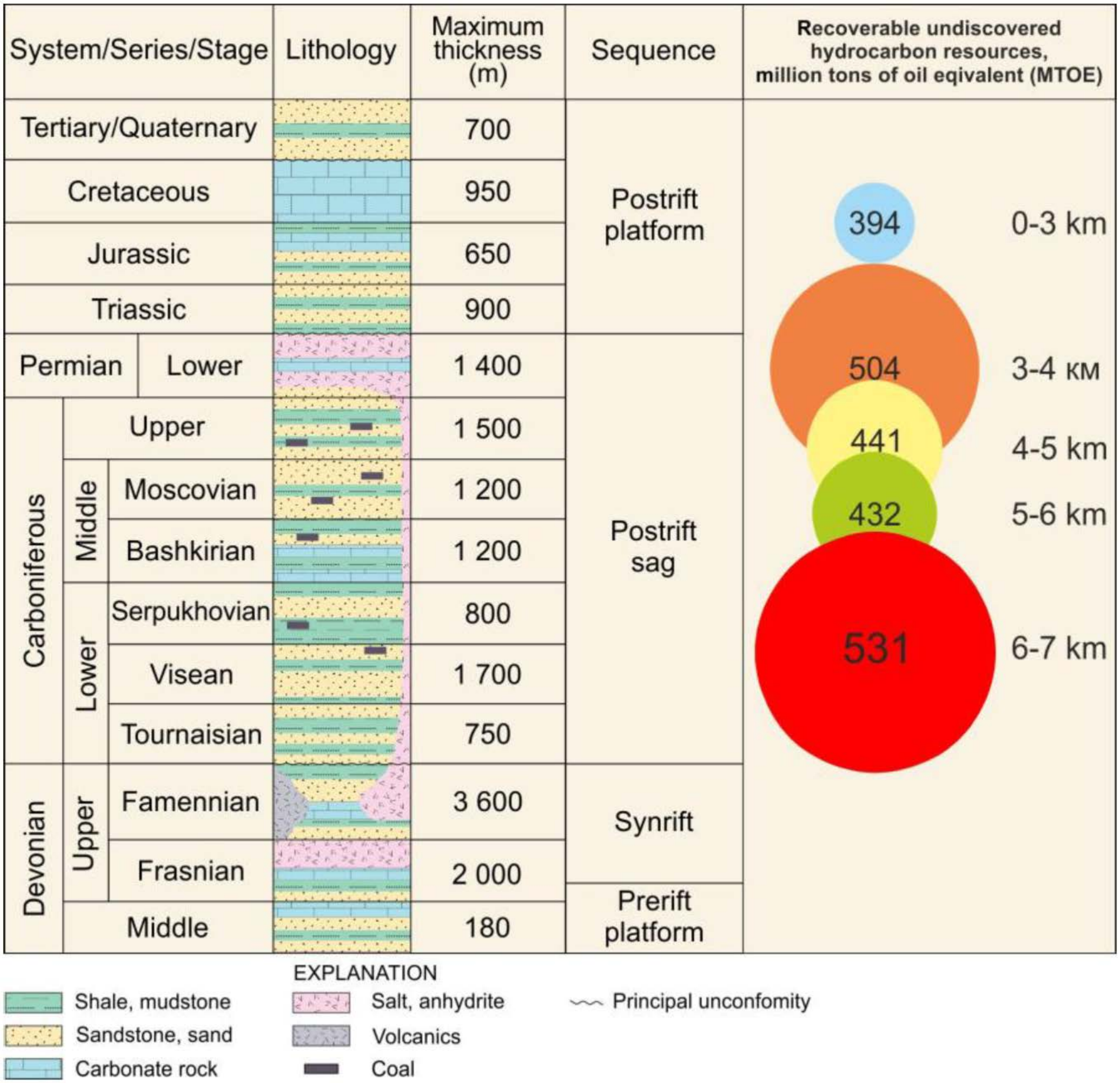


Figure 2—Columnar stratigraphic section of the Dnieper-Donets basin (modified after Law et al. (1998), from (Ulmishek 2001)). Estimates of undiscovered HC reserves after Lukin (2014) and Schurov (2018)

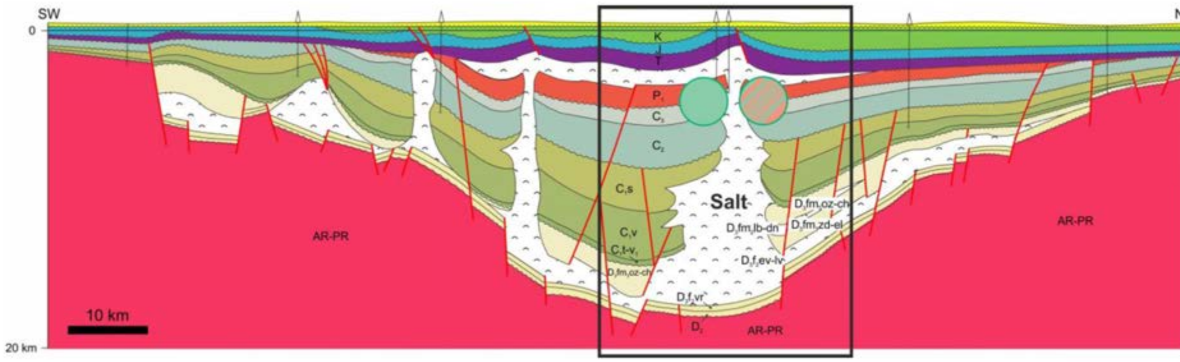


Figure 3—Regional geological cross-section across the Dnieper-Donets basin (modified after Arsiriy et. al., from (Ivaniuta et al. 1998)). Study area is schematically shown by the black rectangle.

Depletion of oil and gas fields emerges a question of the HC potential of underlying deep horizons.

Presented study was undertaken as a part of exploration program of two old hydrocarbon fields at the final stage of development. Oil and gas accumulations are associated with Lower Permian and Upper-Middle Carboniferous sediments under the salt wing and beside the salt wall at 4-5 km depth (Fig. 3). Gas fields are covered with 50- and 20-year old 2D seismic surveys. Both impossibility to obtain 3D seismic data and low confidence of seismic imaging in proximity to salt diapirs were the reasons to introduce non-seismic geophysical methods for subsurface characterization.

High-precision gravity and magnetic data were obtained over an area of 548 sq. km, on the 100×100 meters and 50×100 meters nets respectively, resulting ±0.0069 *mGal* measurement error (standard deviation) for the gravity field and $\pm 0.72nT$ error for magnetic field. Observed data were used for 3D joint gravity inversion together with seismic and well log data (Fig. 4) (Petrovskyy 2004, 2003).

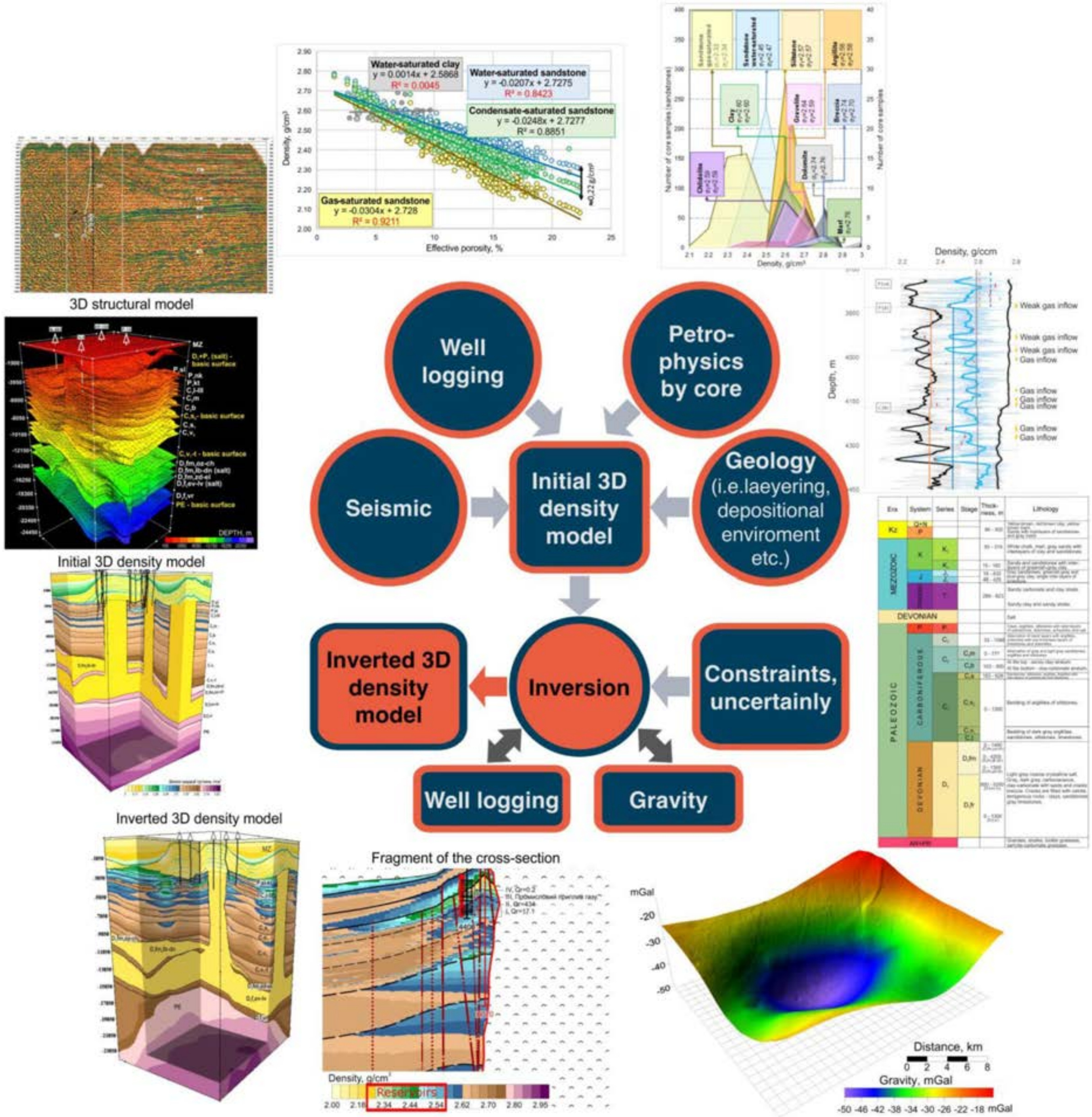


Figure 4—Simplified scheme of the 3D joint inversion of gravity, seismic and well data

Resulting 3D density model (Fig. 5) allowed both to map the shape of the salt diapir, gas reservoirs of the fields under production and to identify knew prospects.

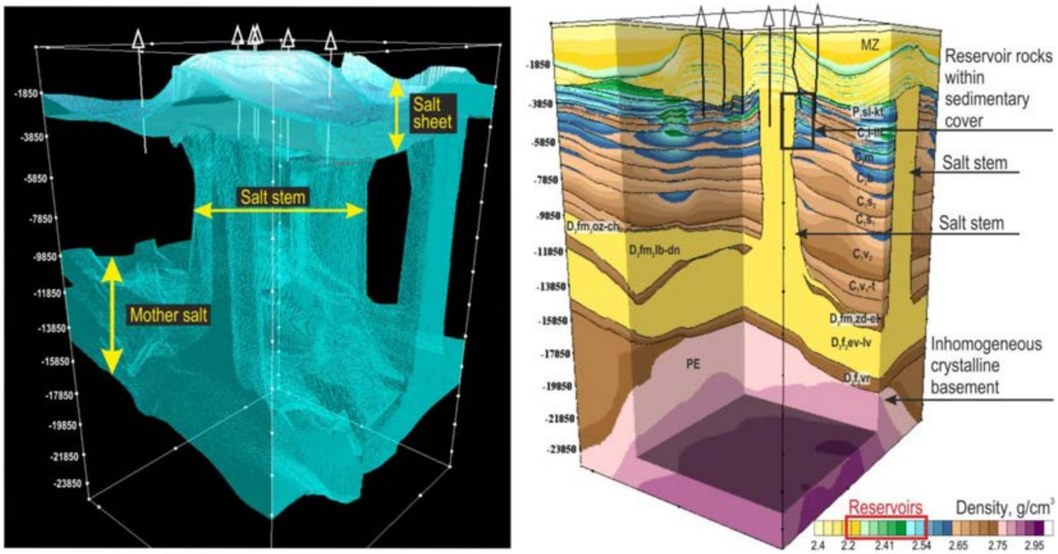


Figure 5—3D salt model (left) and 3D density model resulted from the inversion

Apart from the 3D density model, one of the inversion outcomes is a gravity misfit, which is the difference between the Complete Bouguer anomaly and modelled gravity. The misfit function contains gravity anomalies associated with footprint, undercompensated topography and tectonic features. Presence of the latter is caused by the difference between sharp density change across the fault in the true model and slope-like density change in the approximated model as shown in Fig. 6.

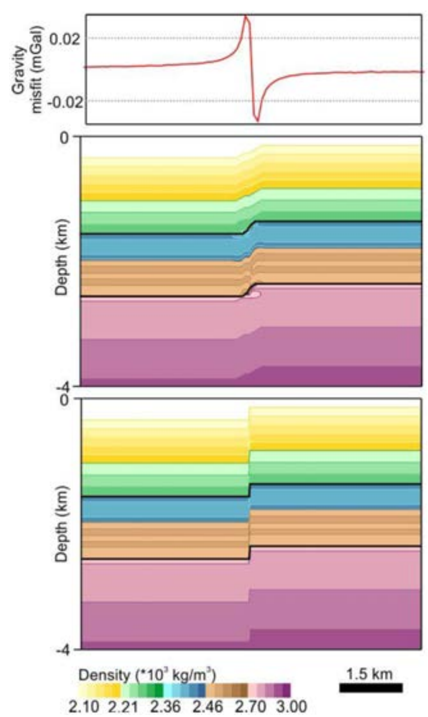


Figure 6—The nature of tectonics-associated gravity anomaly in the final gravity misfit function obtained in the result of the 3D gravity inversion with seismic and well log data: true model is shown below, approximated model is shown in the middle, gravity anomaly associated with the difference between the two models in proximity to fault - at the top

Geophysical criteria for carapaces identification

The shape of the salt diapir

Density contrast between salt and accommodating clastic and carbonate rocks under the salt wing ensured reliable mapping of salt boundary as a result of the inversion. The inverted 3D density model showed that the diapir's size is smaller than previously interpreted from the seismic data (Fig. 7). The axis of the salt dome is inclined towards the Northern flank of DDB (Fig. 7, bottom). Southwestern wall of the salt dome is more gently slopped, northeastern wall is sub-vertical, with negative angle.

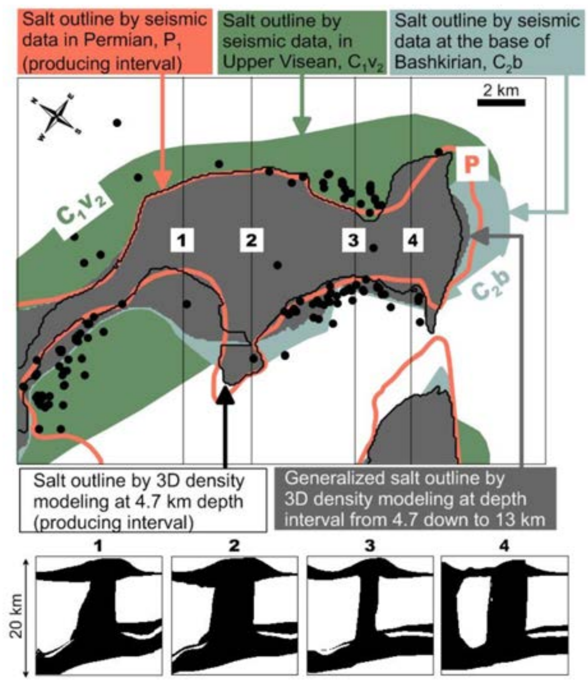


Figure 7—Comparison of salt stem size by inversion results and 2D seismic data interpretation (top). Salt (in black) on the SW-NE cross sections (bottom)

Within an area of lost seismic correlation around the salt dome, we have traced some specific linear elements (Fig. 8, 9), which have no analogs within more than 20 acreages in various parts of the DDB, where high precision gravity surveys were previously carried out. These elements are subparallel along the strike, even when it changes from the sub-latitudinal to the northwestern with 44 degrees rotation around the salt diapir.

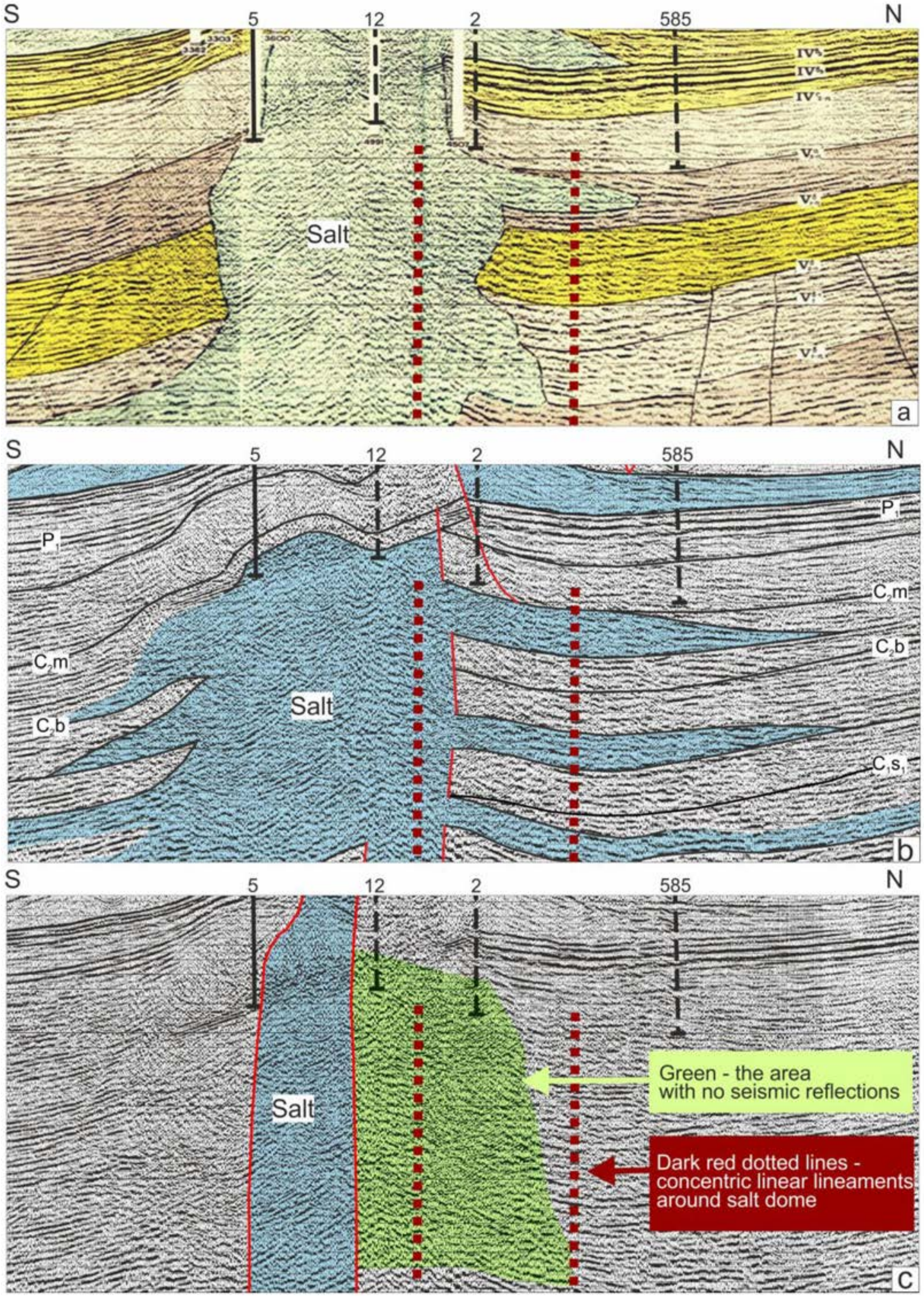


Figure 8—Fragment of the reginal CDP line with salt interpretation by SGE "Ukgeofizyka" (a), Ukrainian State Geological Survey Institute (b) and its comparison with salt stem size in the resulting 3D density model (c). Seismic line position is shown in Figures 1 and 9.

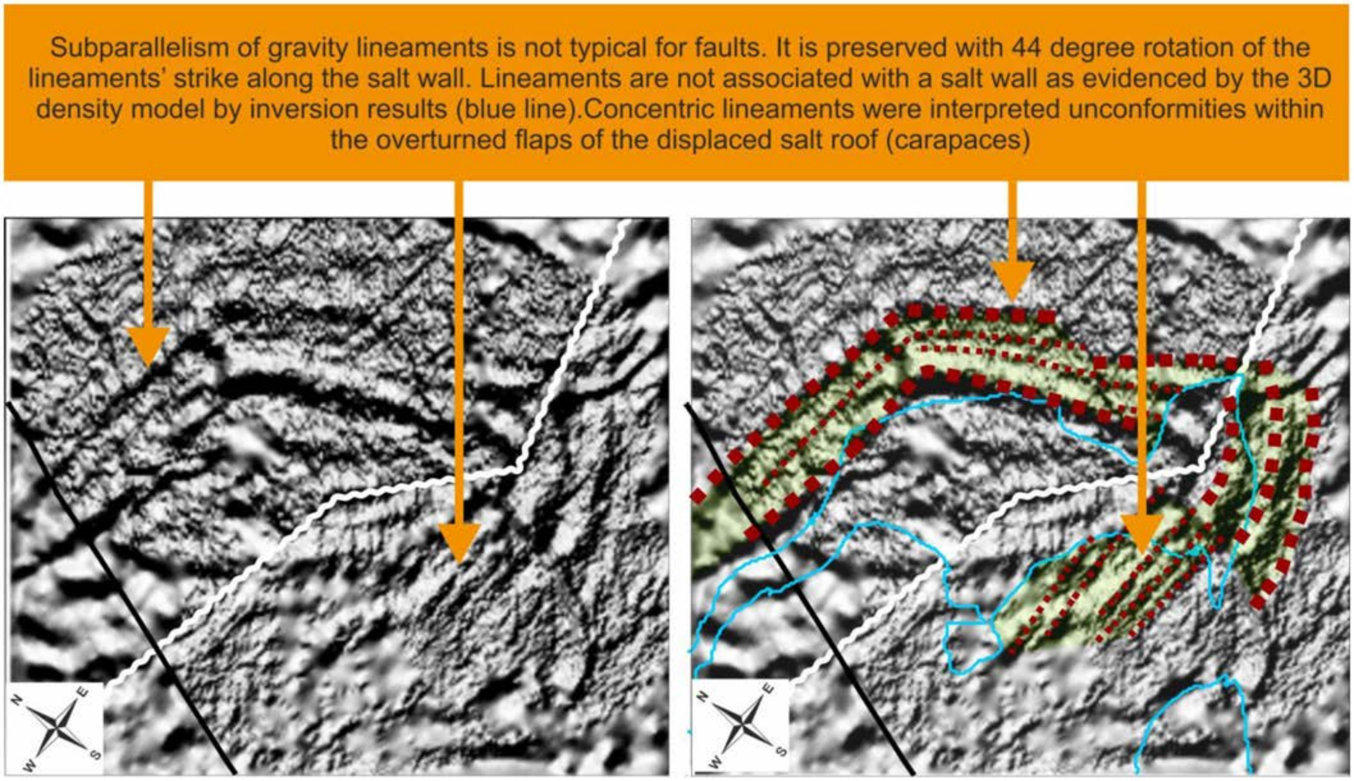


Figure 9—Uninterpreted (left) and interpreted (right) shadow map of the gravity misfit function, resulted from the 3D gravity inversion. Salt wall is shown by blue line. Gravity lineaments are shown with red dotted lines

Superposition of the traced linear elements and unconformable stratigraphic contacts in wells under the salt wing (Middle / Lower Carboniferous sediments below Permian / Upper Carboniferous) resulted in identification of two successions of Moscovian, Bashkirian, Serpukhovian, and Visean aged rocks (while the first three are proved by wells, presence of Visean is presumed basing on the analogy with Skorobagatki-Pesochanskyy diapir, which will be discussed later), separated by the gravity lineaments (Fig. 10b - 10c). In the search for the interpretation model, the upturned collars were discarded by a number of reasons. First and foremost because of the lineaments' geometry at the south-western part of the diapir (Fig. 10b), where contacts are not parallel to the salt wall but approach it at 38-63° angle. Secondly, by the reason there are two adjacent succession of the same age here. Finally, within the segment where lineaments/contacts are parallel to the salt wall, the younger Middle Carboniferous rocks are found closer to the salt wall comparing to the Lower-Carboniferous ones, forming the reverse succession.

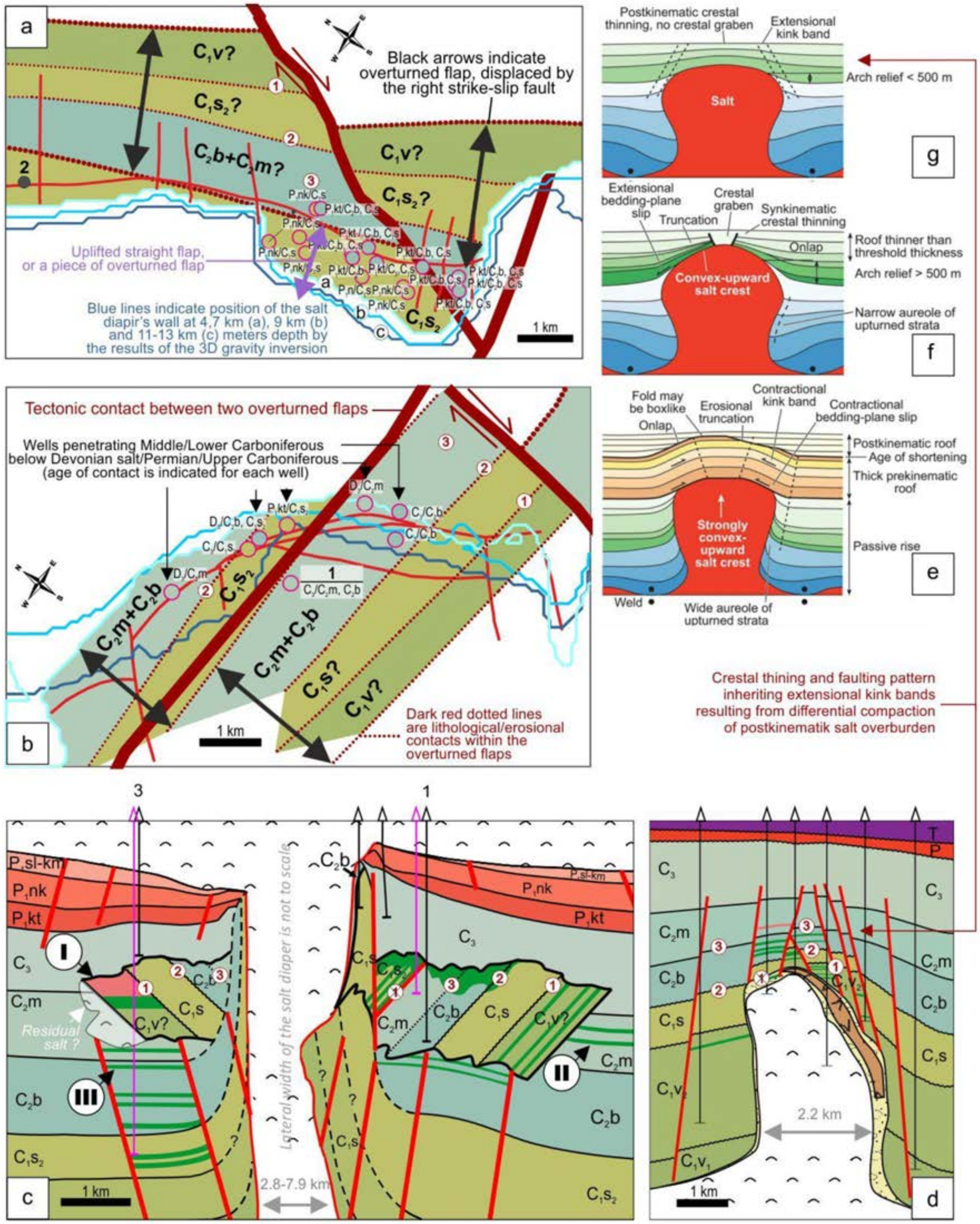


Figure 10—Conceptual model of the overturned salt roof flaps: a - at the south-eastern flank of the salt diapir; b - at its south-western flank; c - conceptual cross-section: I - major expected trap within the displaced blocks of the diapir's overburden themselves (presumably in carbonates of Lower Carboniferous); II - possible traps within the abutting sequence of UpperCarboniferous; III - possible traps within the underlying Middle Carboniferous sequence; 1, 2, 3 - same stratigraphic contacts in (c) and (d), note absence of Upper Visean within part of salt overburden in (d). d - drilled analogue with preserved diapr's overburden (modified from Lukin (2015)), located at the axial part of the Dnieper-Donets basin at shallower depth. Note that in (d) faults inherit an extensional kink bands caused by differential compaction according to diagnostic features of arching by Jackson and Hudec (2017). Diagnostic features produced by halokinesis (b) and active rise (c) (Jackson and Hudec 2017) are shown for comparison.

The key to the interpretation model was a geological cross-section through the Skorobagatki diapir by Lukin (2015, Fig. 10d), showing the same age (Lower to Middle Carboniferous) salt overburden with a fault pattern inheriting extensional kink bands resulting from differential compaction of postkinematik salt roof (according to the models of Jackson and Hudec (2017), Fig. 10g)).

This gave a ground to assume that: (1) the Lower-Middle Carboniferous salt overburden of the Skorobagatky diapir to be an analog (to the studied near-salt displaced blocks), preserved in the original structural position; while (2) the mapped Middle-Lower Carboniferous succession near the studied diapir to be the former salt overburden (Fig. 10d), which was displaced to the near-salt area. Another fact proving the analogy is lineaments occurrence. In particular, one of the mapped lineaments to the south-west from the diapir is located in proximity to two adjacent wells penetrating Bashkirian and Upper Serpukhovian in the upturned position, which may suggest that the high-gradient density boundary (causing the lineament) is related to the Bashkirian carbonate plate and / or stratigraphic unconformity between Bashkirian and Serpukhovian. The last assumption is more reasonable as it explains both absence of lineament at the contact of Moscovian and Bashkirian (where unconformity is regionally absent within the basin) and its presence between Serpukhovian and Visean rocks (Fig. 10 b - 10d).

The area where displaced flaps of salt overburden are mapped is limited by 2.5 - 3.5 km outward from the salt wall. 2D CDP seismic lines across the area show no seismic reflections in the depth interval of Carboniferous where displaced overburden flaps are expected, while overlaying Lower Permian is a perfect reflector (Fig. 11).

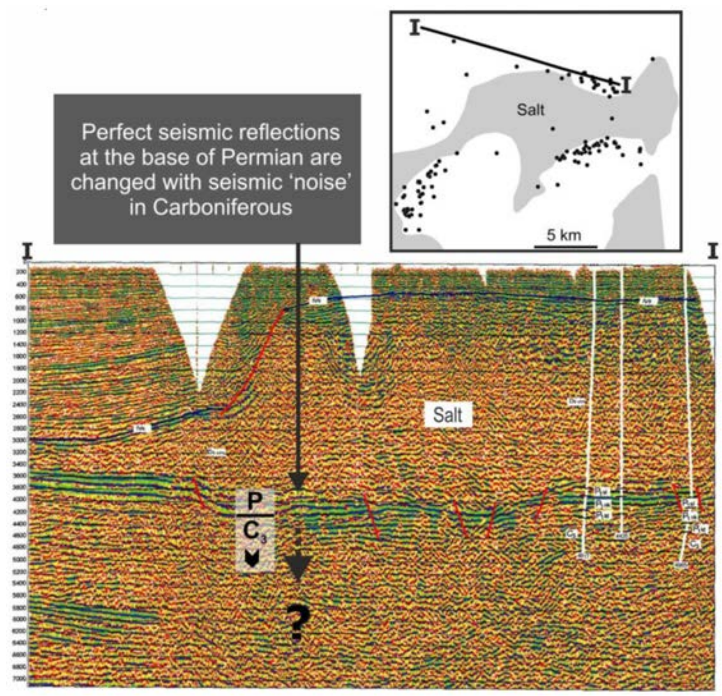


Figure 11—Seismic line to the north-east from the diapir shows no seismic reflections in the depth interval of Carboniferous where displaced overburden flaps are expected, while overlaying Lower Permian is a perfect reflector

The deepest well within the gas field (TVD 6207 meters) is drilled at the south-western flank of the salt dome. Dipping angles by core in Moskovian vary between 25° and 45°, while they do not exceed 17° in Permian (the latter estimate is given for the structural surface in Permian as no core was available).

Angle unconformity allows us to assume that penetrated Moscovian and Bashkirian represent displaced/ overturned succession. In this case, sequential succession of Moskovian and Bashkirian in this well indicates the northern dip of the overturned strata toward the salt wall.

Considering mentioned angels and assuming that the top surface of the displaced flaps is sub-horizontal, their total thickness is estimated between 2,300 and 2,600 meters.

Formation mechanism and time

The possible mechanism of displaced salt roof flaps formation around the diapir is shown in Figure 12. The time of displacement is probably the beginning of Late Carboniferous (Fig. 12b). The assumption is based on the unconformable stratigraphic contacts C3/C1S2, C3/C2K D3/C2m in 22 boreholes at both flanks of the diapir.

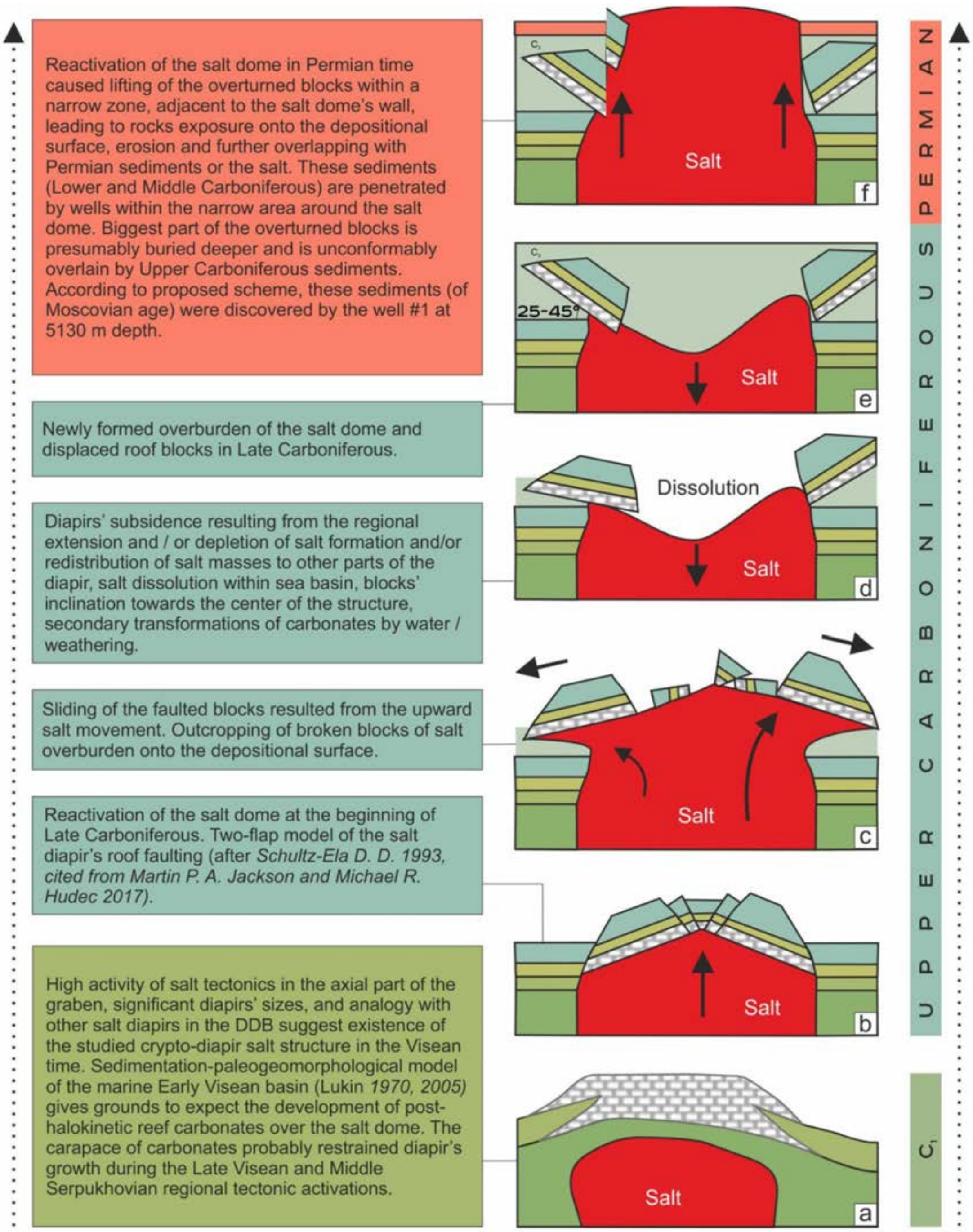


Figure 12—Hypothetical model of displaced salt roof flaps formation around the salt diapir

Structural-tectonic analogues

Displaced strata are known in different salt basins all over the world and are usually referred to as "rafts". Applicably to salt tectonics, the term raft has been used in several basic ways. The closest analogue to the mapped displaced blocks of salt overburden could be rafts or Mesozoic "chips" by Kilby (2008) described for the Gulf of Mexico: "In the Gulf of Mexico, these blocks originate as strata deposited as parallel layers… conformably over autochthonous salt that is later inflated or on actively inflating salt highs (Kilby et al., 2008). After inflation of the salt high, raft blocks are eventually transported laterally (usually basinward) by allochthonous salt movement" (cited from Fiduk et al. 2014). Similar structures are described by Hart et al. (2004). using the term "carapace" for rock formations initially deposited above salt diapirs. The main characteristics of carapaces in the Gulf of Mexico as identified by Hart et al. (2004) are: "(1) strata deposited on salt highs, (2) principally comprised of fine grain sediment, (3) initially form a protective cover to salt, and (4) are readily rafted by spreading salt" (cited from Fiduk et al. 2014). The critical difference between rafts and carapaces is "that rafts can begin forming above autochthonous salt as pre-kinematic or syn-kinematic strata" (Kilby et al. 2008; cited from Fiduk et al. 2014).

Rafts of the Gulf of Mexico have been significantly displaced up to 7 km vertically (in models by Fiduk (2014), Fig. 13) and tens of kilometers laterally (Snedden 2019, Fig. 14). While in the presented case for the DDB vertical and lateral displacements are estimated as 2.3-2.6 km and 3-3.5 km correspondingly.

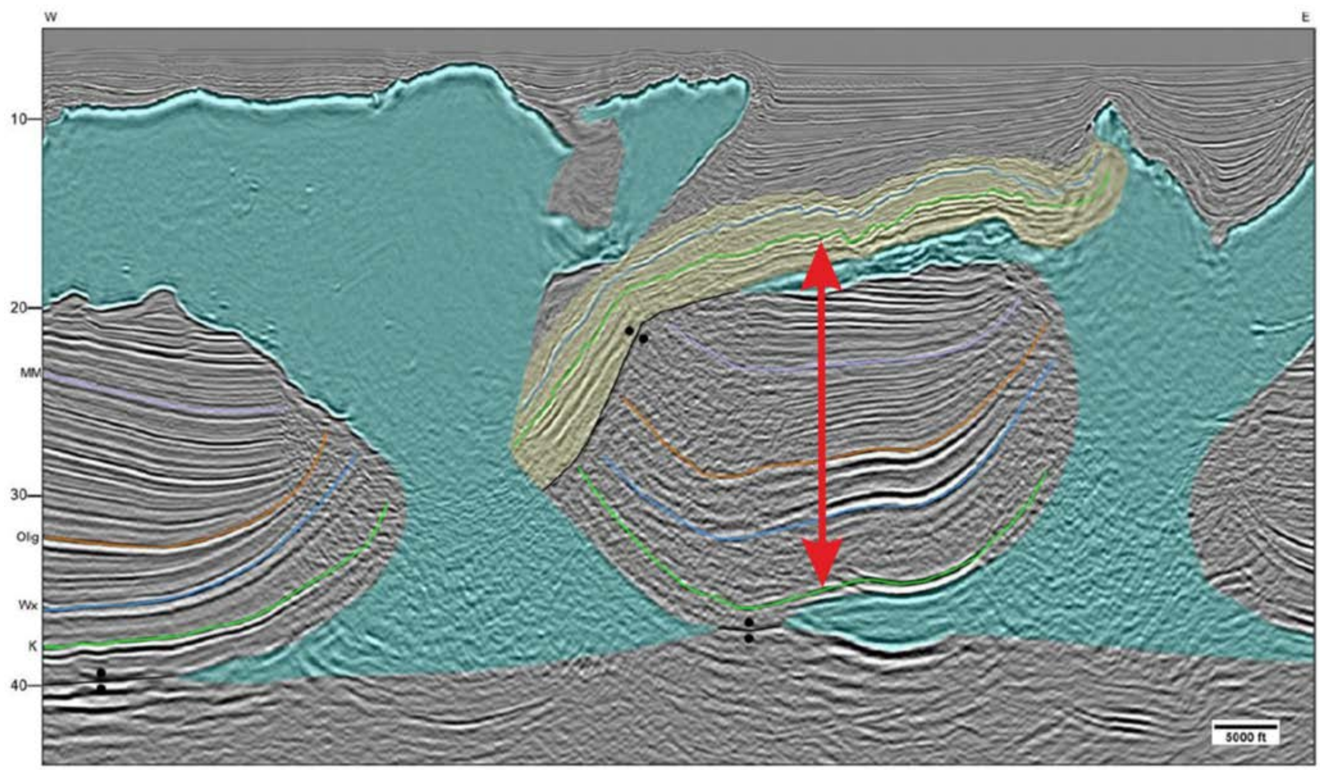


Figure 13—Magnitude of displacement of the rafted blocks in the Gulf of Mexico. West-east oriented seismic line in Walker Ridge showing where a raft has been pulled down into a salt diapir. Red arrow shows vertical displacement of rafted block. Depth scale is in 10,000 ft increments. Vertical exaggeration, 1:1.5. (seismic image modified from Schlumberger Multiclient, cited from Fiduk and Clippard (2014))

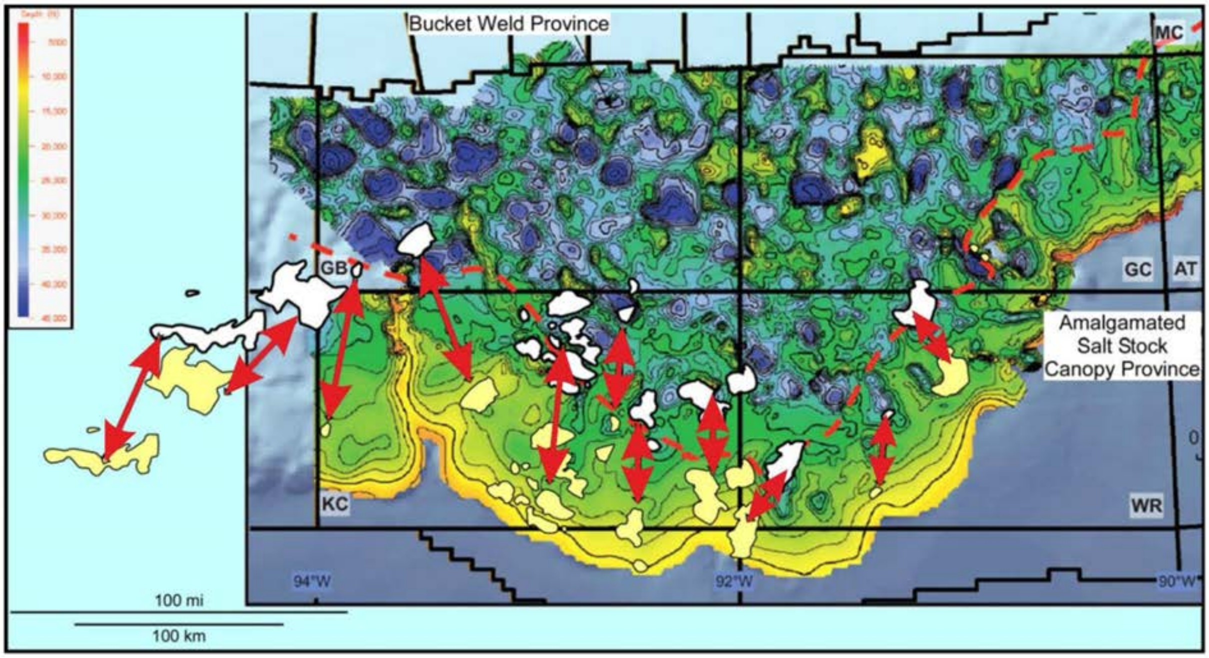


Figure 14—Rafted blocks in the Gulf of Mexico. Top primary basins map with present locations of rafts (yellow) and projected points of origin (white). Red arrows show the direction of transportation suggested by flow lines at the base of the salt canopy. Projection of rafts updip into the bucket-weld province provides many candidate diapirs for the origin of the rafts (map modified from Pilcher et al. (2011), cited from Fiduk and Clippard (2014))

The suggested forming mechanism for displaced blocks of salt overburden assumes they were formed above the salt diapir in the interval of time between two halokinetic events in Early and |Late Carboniferous. So in this context term "carapace" is probably more applicable for use in case of the DDB. Still considering different regional tectonic settings of two basins and different induced forces, analogy between the displaced salt overburden blocks in the DDB and rafts and carapaces in the Gulf of Mexico is limited by the very possibility and amplitude of salt-induced vertical and lateral displacement.

Depth

Reactivation of salt diapir in Permian time led to the uplift of overturned blocks within the narrow zone around the diapir (Fig. 12f), leading to their exposure at the erosion surface, erosion and later burial under Permian sediments and Devonian salt. Exactly these uplifted parts have been penetrated by wells near the studied salt dome (Fig. 10b).

However, biggest part of the displaced blocks are expected to be buried deeper and unconformably overlaid by Upper Carboniferous sediments. The deepest well within the area (indicated as 1 in Fig. 10, all well numbers are conventional) penetrates Moskovian sediments at the depth of 5,130 m.

The initial width of overturned flaps could vary in the range of 2-3 km. The assumption is based on the present day size of the salt diapir and the double-flap-model of the overburden breach. Thus, under 25-45° dipping angles, the estimated depth of the overturned flaps' bottom surface varies at the range of 6,500-7,500 m.

What is the play?

Seal

In the proposed geological model of the displaced blocks, Visean sediments are expected in the outward position, underlying younger Serpukhovian and Middle Carboniferous strata (Fig. 10c). In case, if regionally unpermeable Lower Serpukhovian stratum is present in the cross-section, it can partially seal potential hydrocarbon accumulations in Visean. Majoir (by API classification) hydrocarbon deposits of Kobzivka field (Fig. 15) with 60% out of its 43 Bcm of gas located in producing horizon Г-6[2] of Kartamyshska formation (Kryvulya et al. 2012) proves excellent sealing properties of the Upper Carboniferous shales. Sealing properties of Upper Carboniferous in proximity to salt diapirs is proved by oil accumulation in Г-6 and Г-7 producing horizons of the field named after academician Schpak (Zeikan et al. 2013).

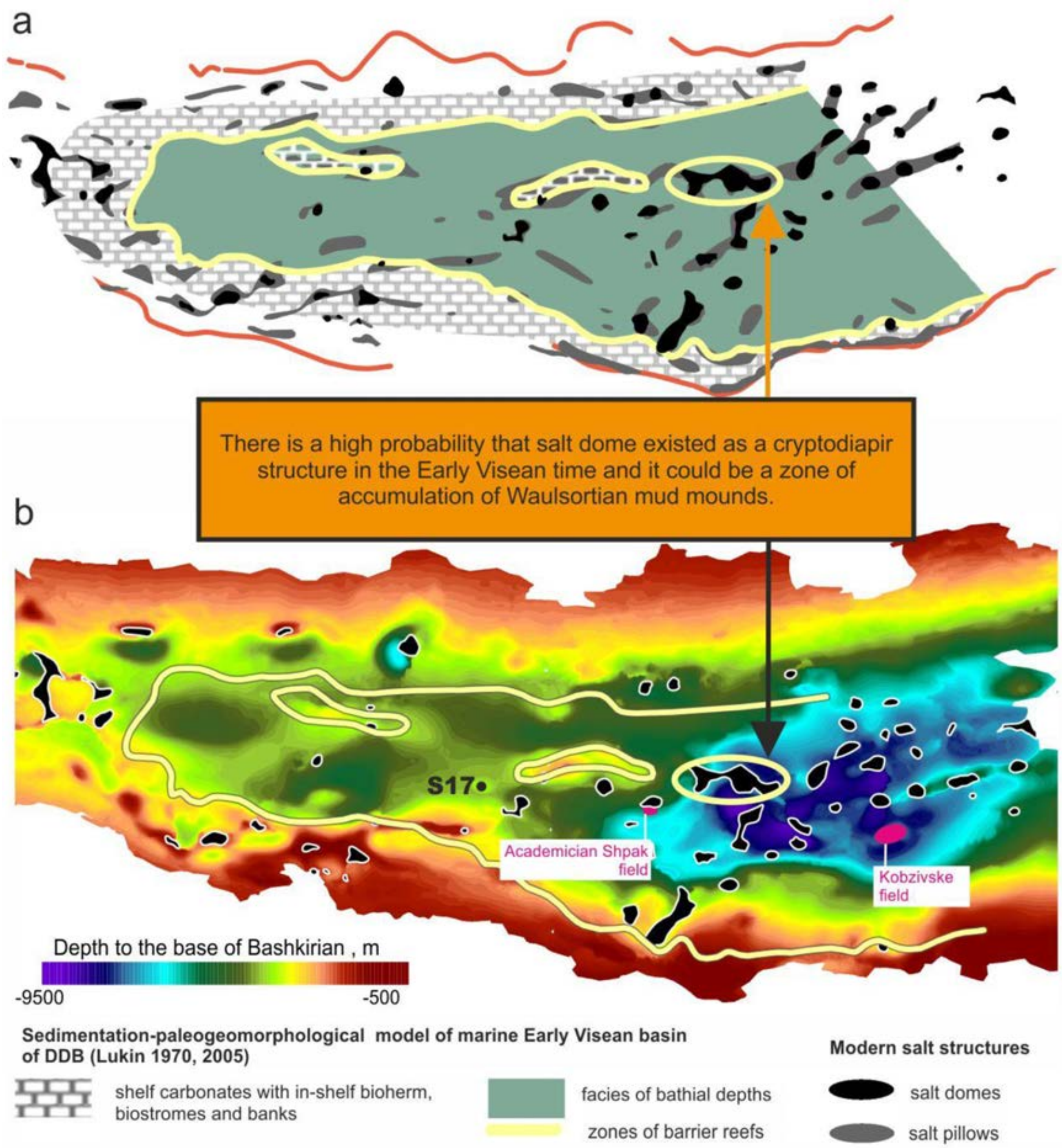


Figure 15—Reef-carbonate formations on the sedimentation-paleogeomorphological model of the Early Visean (C_1va-e_1, XIV and XII microfaunistic horizons) marine basin in the Dnieper-Donets basin (Lukin, 2005) (a); the same on depth map to the base of Bashkirian (b)

Within the study area deep well #1 penetrates producing horizon Г-5-6 at 4760 m depth. It is 340 m shallower the expected depth of the displaced flaps of Middle and Lower Carboniferous.

Reservoirs

The presence of contrast and consistent gravity anomalies, caused by lithology or stratigraphic unconformities, evidences that displaced blocks of salt overburden are preserved as consolidated blocks. By analogy with overburden of Skorobagatky salt diapir, reservoirs of Moscovian, Bashkirian, Serpukhovian, and Visean strata are likely to be present (Fig. 10d).

Tectonic deformations probably induced more intensive faulting and cracking. Depending on depositional environment possible weathering crust could develop.

Another option we considered is Visean carbonates as a main exploration target. Highly active salt tectonics in this part of the graben, together with the analogy with Skorobagatki-Pesochanskyy structure, evidences that studied salt diapir could have existed in Visean time. In this case, the sedimentation-paleogeomorphological model of the Early Visean sea basin (XIV and XII microfaunistic horizons by Lukin et al. (1970, 2005)) makes it reasonable to expect the development of reef-carbonate formations - Waulsortian mud mounds (Lukin et al. 2016) over the salt diapir, which is located at the extension of the Opishnya zone of bioherms and barrier reefs (Fig. 15).

Unlike the Skorobagatki structure, the studied salt diapir is located in the deepest central part of the graben, so we assume that the Visean sequence can be better preserved and thicker than within the Skorobagatki overburden.

The Visean reef carbonates (Waulsortian mud mounds) are characterized by the lowest reservoir properties and high hardness of rocks at shallow depth caused by the early lithification (Lukin et al. 2016). The very presence of hard framing ("carapace") of Visean bioherms, together with the shallower base level of erosion, could be the factors restraining diapir growth in Visean-Serpukhovian time during the Late Visean and Middle Serpukhovian regional tectonic activations, causing growth of many salt diapirs in the DDB according to seismic-based study by Stovba (2003). On the other hand, the high initial hardness of carbonates in the overburden of the studied diapir could be the reason for its fragile deformations, as opposite to plastic deformations of undisplaced overburden of smaller diapirs as indicated by the same author.

Waulsortian mud mounds are characterized by decreasing of their hardness at 3800-4000 m depth and intensive destruction at 5500-6500 m depth (Lukin et al. 2016, Lukin 2020), which is actually the process of forming the reservoir, as proved by well N°17 (S17 on Fig. 15b) at the Semyrenky gas field.

In the case of displaced flaps, secondary porosity is likely to be induced by leaching and metasomatic transformations in carbonates, rocks' brecciation as a result of tectonic deformations and underlying salt dissolution (after blocks have been outcropped at the depositional surface). Metasomatic transformations could cause intensive processes of dolomitization in carbonates. It should me mentioned that the Lower Visean reef carbonates at close proximity to the salt diapir (even if they haven't been displaced) are 70-80% dolomitized (by Lukin, cited from (Vakarchuk 2003). In its turn, increasing the dolomite fracture in limestones up to 50-85% results in a rapid increase of porosity - from 7 up to 30-34% (according to core samples from Mississippi Charles formation by J. Murray, cited from (Vakarchuk 2003)).

So we may conclude that there are geological preconditions for high-quality cavernous-fractured massive carbonate Visean reservoirs to have been formed within the overturned blocks.

Proposed geological model of hydrocarbon bearing Visean reservoirs explains the association of low-density anomalies in the inverted 3D density model with uplifted distal parts of the displaced blocks. No HC potential of the proximal to the salt areas at the north-eastern flank of the diapir is proven by the dry #2 shown in Figure 10a.

One well (indicated with #3 in Fig.10c) was drilled in1976 to the north-east from the salt diapir, within an area of expected HC saturation of the displaced blocks. By the well report (1976), it was stopped at 4,951 m depth in Upper Carboniferous and assumable did not penetrate the Middle-Lower Carboniferous flaps. According to well log data interpretation, there were no targets for well testing in Lower-Permian and Upper Carboniferous at the depth interval of 4034-4951 m.

Except for the reservoirs of the displaced blocks (I in Fig. 10c), hydrocarbon traps can also be associated with abutting reservoirs of Upper Carboniferous (II in Fig. 10c), and/or with the underlying Carboniferous sequence (III in Fig. 10c), which could be the case if the rocks of the displaced flaps are tight or residual salt is present beside the blocks. The expected depth of producing reservoirs ranges from 5100 to 8000 meters.

HC generation

Abiogenic. In terms of hydrocarbon generation, most of Ukrainian geoscientists adhere to the theory of deep abiogenic origin of hydrocarbons. According to this theory, salt diapirs are considered as degassing tubes (Lukin et al. 2018).

Biogenic. The analogy with world oil and gas basins leaves a space for biogenic HC origin at deep parts of the DDB as well.

High thermal conductivity of salt results in temperature increase in salt diapirs' and salt sheets' overburden and its decrease below the salt and beside the salt stem (so-called "salt chimney effect" after Zhuo et al. (2016). Calculations by Mello et al. (1995) for the Gulf of Mexico show that temperature anomalies around salt diapirs reach -85°C.

Considering times bigger size of the studied diapir comparing to one used by Mello, and as early as Devonian salt deposition/emplacement, together with big mother-salt thickness (depositional maximums of 5.7 and 2 km for Devonian and Permian correspondently, according to Stovba and Stephenson (2003), these can cause bigger temperature anomalies in the deep axial part of the DDB and "larger the restraint in the maturation level because the thermal anomalies induced by the salt have more time to affect the maturation history of source rocks" (Mello et al. 1995).

It is interesting to note, that the highest grades of katagenetic transformations within the deep Carboniferous strata at Shebelynka giant gas field are observed in wells Y°200 and Y°500 drilled at the crest of the structure, just above the salt diapir. While in wells Y600 and Y°800 at the flank of the structure the same sediments are less katagenetically transformed (Kryvulia et al. 2016). And further from the crest within the Western Shebelynka structure Mykhailov (2014) indicates an "extremely low vitrinite reflectance" of Paleozoic rocks in depth interval of 4.5-5.5 km evidencing low grades of katagenetic transformations (Fig. 16).

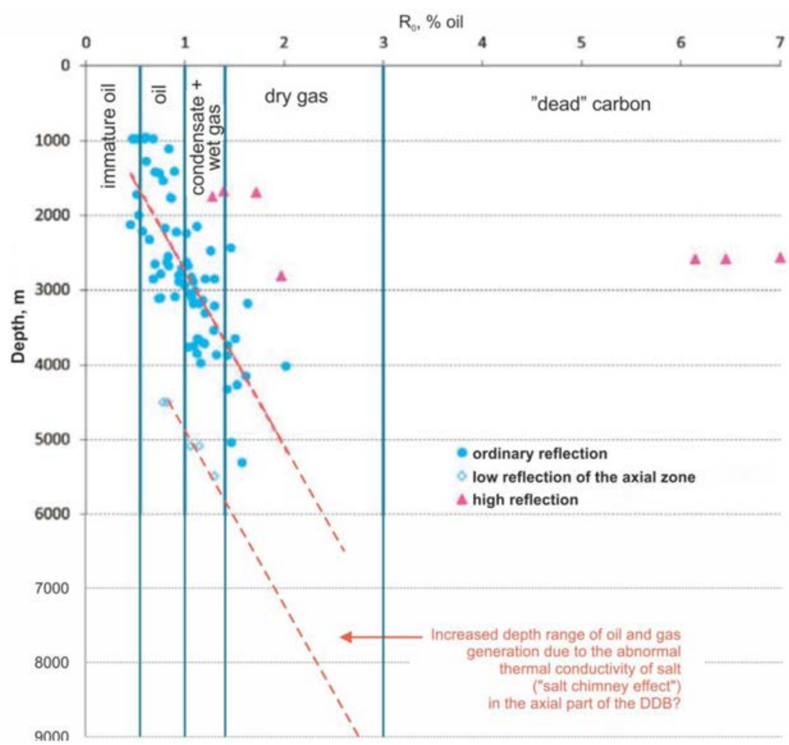


Figure 16—Vitrinite reflectance in Paleozoic depending on depth within DDB (data by Mykhailov V.A. (2004)) (a), undiscovered reserves of the Dnieper-Donets basin (data from (Shchurov 2018))

Back to abiogenic?. While the "salt chimney effect" allows deepening the oil window, it is still not enough to explain oil giants at 7-10 km depths, with reservoir temperature reaching 177°C (Appomattox accumulation in the rafted block as an example, deepwater Gulf of Mexico, according to data of U.S. Department of the Interior, Bureau of Ocean Energy Management (2020), which is beyond the range for the oil window. This probably allows discarding the charge-temperature parameter as not critical for deep exploration, also in the DDB.

Geophysical hydrocarbon indicators and hydrocarbon resources

Core data show that both clastic and carbonate Carboniferous gas reservoirs of the displaced blocks should have clear negative density anomalies comparing to the accommodating rocks (Fig. 17). It is a physical precondition to identify gas reservoirs in the inverted 3D density model.

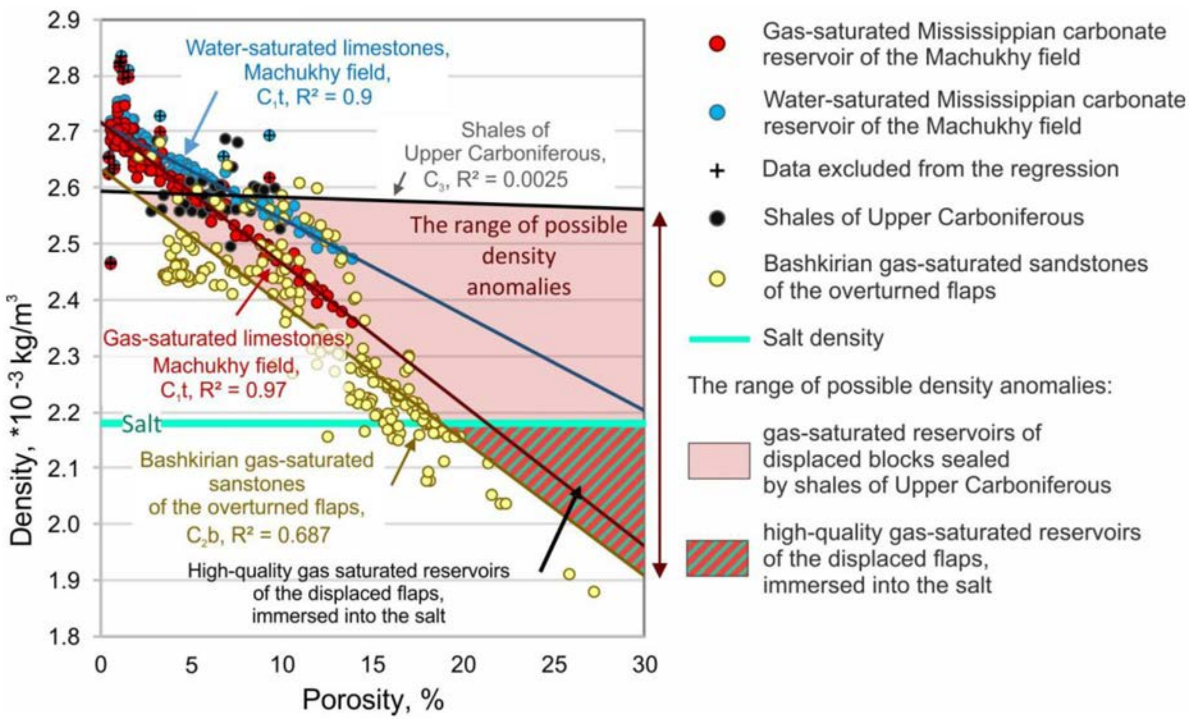
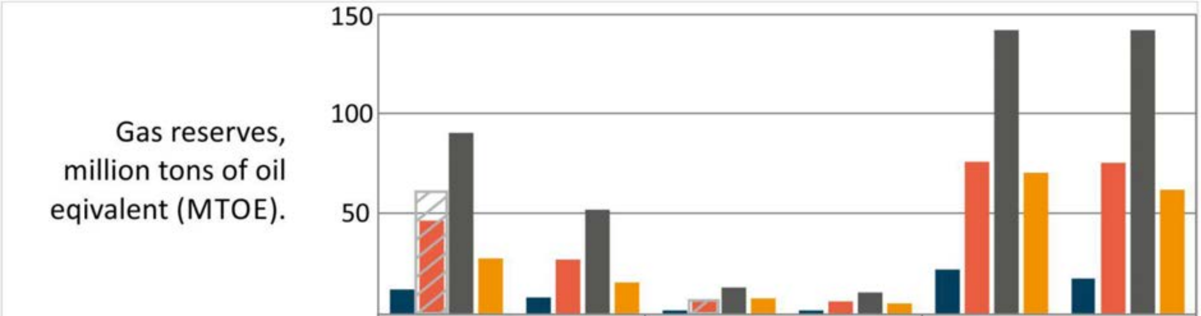


Figure 17—Range of density anomalies associated with gas reservoirs of the displaced blocks of diapir's overburden

Basing on the linear functional relationship between the porosity, fluid density, and rock density, we created the 3D models of porosity and gas saturation. The latter were used to estimate hydrocarbon resources in place using volumetric integration within identified prospects (later referred to as volumetric method). Monte Carlo simulation was used to obtain alternative estimates. Volumes of initial HC in place by Arsirii et al. (1999) for known HC accumulations besides the salt dome were used as a reference data to calibrate volumetric calculations.

Volumetric method and P50 estimate by Monte Carlo gave us similar numbers, showing that deep prospects of the studied area (assumable associated with the displaced salt blocks of salt overburden) may have total reserves exceeding 150 million tons of oil equivalent (MTOE) (Fig. 18).



	South-western flank of the salt dome		South-eastern flank of the salt dome		New prospects	
	Accumulations in production	Deep targets	Accumulations in production	Deep targets	I	II
Q10 (P90), MTOE	12	7	2	1	22	17
Q50 (P50), MTOE	47	27	6	6	76	75
Q90 (P10), MTOE	91	51	13	11	142	142
Estimation by heterogeneous volumetric method, MTOE	27	15	7	5	71	62
Initial recoverable reserves under production (Arsiriy Yu.O. , 1998), MTOE	61		7			

Figure 18—Expected reserves of the identified deep prospects

Probability of success (POS)

Geological

Analysis of play elements above allows defining probability of success for the prospects in the displaced blocks as a function of trapping mechanism, reservoir, and seal quality while skipping source rocks as a parameter. High probability of seals and reservoirs to be present is substantiated above. In our opinion, the trapping mechanism is a major risk as we have several trapping scenarios, and hitting a high-angle- dip reservoir is a challenging task itself.

Geophysical

Comparative analysis of the prospects (low-density zones) by the results of 3D gravity inversion at 24 licenses within the DDB, the Carpathian oil & gas bearing region and the Black sea offshore with well testing results of 80 wells (164 well tests in depth interval down to 6276 m) shows that the probability of success for gas reservoir is 82%.

Conclusions

The proposed model of the displaced blocks of salt overburden gives a simple explanation of the complex alteration of different-aged Carboniferous sediments near the salt wall. The formation mechanism of this model is simpler than the case of differential vertical extrusion of relatively small different-aged blocks by salt. From a geomechanical point of view, 2.3-2.6 km thick breakthrough of salt caused by its reactivation is more probable than over 8 km thick breakthrough resulting from Permian activation in alternative models (Stovba et al. 1999, cited from (Nochvay et al. 2000)). The model also meets the problem of space for such a big salt diapir to intrude.

Speculating about geological consequences, we may assume that the model might also explain some other geological features of the DDB such as reverse faults of the Northern flank, facial zoning in Permian (the nature of productive "apron" facies), and in the lower part of Upper Carboniferous, promising for big lithological HC accumulations, etc.. However, these questions need further research.

In the context of oil and gas exploration if the proposed model of the displaced blocks of diapir's overburden is confirmed by drilling, it will open new direction for deep hydrocarbon exploration around multiple salt diapirs in the deep axial part of the DDB (Fig. 18).

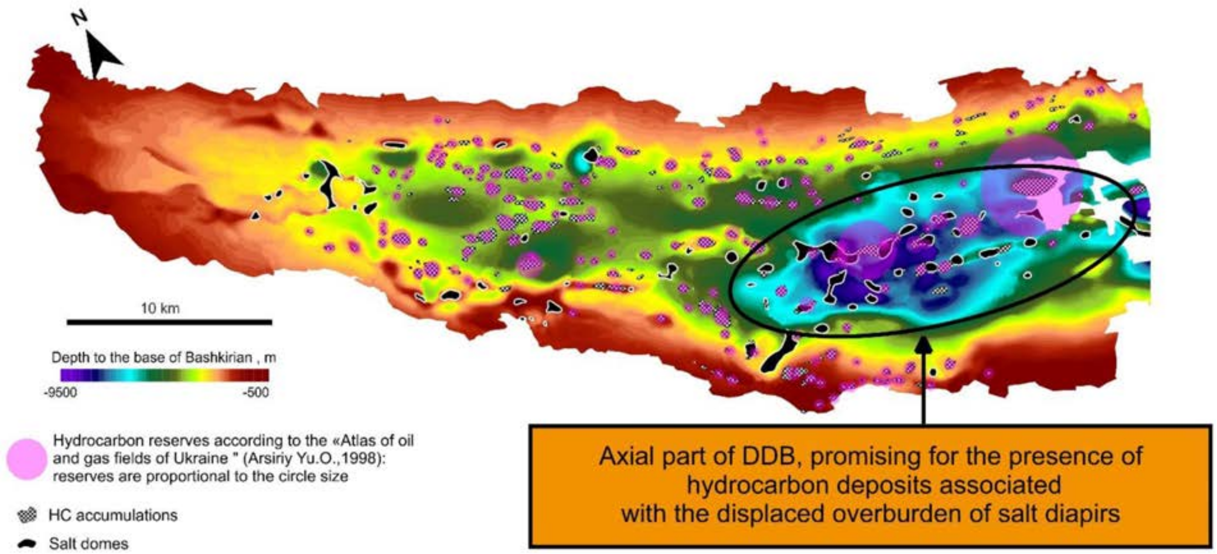


Figure 19

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