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Geological and geophysical studies for assessing the energy potential of land-sea transition zones of the Azov-Black sea region

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The article is devoted to integrated geological and geophysical investigations of land-sea transition zones of the Azov-Black Sea region (the Western Black Sea area and the Kerch Bay-Azov Sea). These zones, which are strategically important for hydrocarbon exploration, cover more than 30,000 km^2 and are extremely challenging for the application of conventional seismic exploration methods. This is primarily due to specific physical-geographical conditions and technological limitations. Such studies are critically important for reducing the risk of «dry» drilling and attracting investment, as well as for addressing engineering and safety issues in the context of post-war reconstruction.

A detailed analysis of two key areas the Western Black Sea area and the Kerch Peninsula is presented. In the Western Black Sea area, the most promising zone extends from Lake Sasyk to Lake Alibey, with a forecast estimate of undiscovered resources of 20—30 thousand tonnes of oil equivalent (TOE) per 1 km^2, associated with Paleozoic (Silurian, Devonian, Carboniferous) and Mesozoic deposits. The Kerch area is also among the most promising regions (20—30 thousand TOE per 1 km^2), where hydrocarbon potential has been proven in Neogene (Tortonian) and Oligocene deposits and is also expected in older complexes (Cretaceous and Jurassic).

In the transition zones of the northeastern part of the Kerch Peninsula (Kerch Bay-Azov Sea), exploration seismic surveys using the 2D CMP (CDP) method were conducted by the State Enterprise «Ukrgeophysica» during 2009—2011. Five seismic profiles with a total length of 43.64 km were acquired; they cross anticlinal structures including the Velykotarkhansky and Baksynsky mud volcanoes. The obtained migrated time sections allowed for a detailed reconstruction of the geological structure of the transition zone and the internal structure of mud volcanoes, confirming their genetic relationship with anticlinal folds.

Seismic methods, particularly the 3D seismic surveying, represent the only effective tool for identifying and delineating prospective structures in transition zones. Comprehensive geophysical investigation of these areas is critically important not only for realizing Ukraine's energy potential but also for engineering geophysics (mapping weak soils, designing landslide protection structures) and seismic microzonation. These studies provide a scientific basis for the sustainable development of transport infrastructure and for ensuring the safety of coastal territories.

Key words: land-sea transition zone, seismic exploration, mineral exploration, energy potential, shallow and deep geological structure.

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Relevance of the Study. The land-sea transition zones of the Azov-Black Sea region (the Western Black Sea area and the Kerch Bay-Azov Sea) represent strategically important territories in terms of expanding Ukraine's domestic mineral and raw material base. These zones are characterized by significant but insufficiently studied hydrocarbon potential, complex geological structure, and specific physical-geographical conditions, which substantially complicate the application of standard seismic exploration techniques. Given the need to reduce geological risks associated with «dry» drilling, enhance the investment attractiveness of oil and gas projects, and ensure engineering and geological safety of coastal areas, integrated geological and geophysical studies of transition zones are of particular relevance.

Aim of the Study. The aim of this study is to assess the geological structure and energy (hydrocarbon) potential of land-sea transition zones of the Azov-Black Sea region, using the Western Black Sea area and the Kerch Bay-Azov Sea as case studies. This is achieved through the integration of geological and geophysical data, refinement of the structural-tectonic models of the studied territories, and identification of the most promising areas for further exploration and appraisal.

Research Methods. A complex of methods was applied, including the analysis and synthesis of archival and published geological materials, as well as the interpretation of geological and geophysical data. Methods of comparative analysis of the prospectivity of oil and gas-bearing complexes and predictive assessment of resource potential were used. The integration of results obtained by different methods ensured a comprehensive evaluation of the studied territories.

Results of the Study. In recent years, land-sea transition zones have attracted considerable interest from oil and gas companies due to the discovery of large hydrocarbon fields in coastal areas of various countries, such as the deltas of the Mississippi, Colorado, Tigris, and Euphrates rivers, Prudhoe Bay, Lakes Maracaibo and Samotlor, the Baltic Syneclise, and the California coast of North America, among others [Galloway et al., 2000; Mann et al., 2006; Hein, 2013; Miao et al., 2022].

Transition zones include shallow lagoons, surf zones, and marine areas with depths insufficient for the operation of towed streamer systems. Accordingly, large areas of southern Ukraine fall within transition zones. These include onshore territories and parts of the Azov and Black Seas, the mouths of the Danube, Dnipro, and Southern Buh rivers, as well as lakes Yalpuh, Kotlabukh, Sivash, and others, within which seismic exploration has practically not been conducted.

In transition zones, seismic surveys can only be conducted using specialized equipment and instrumentation, as technologies currently employed in conventional land and marine surveys are not suitable for such conditions.

The analysis of geological and geophysical information obtained in adjacent areas indicates high prospects for hydrocarbon exploration in the transition zones of southern Ukraine [Atlas ..., 1998; Gozhyk et al., 2006]. This is supported by their tectonic setting, structural forms capable of hosting hydrocarbon traps, reservoir and seal rocks, source and prospective petroleum-bearing formations, and the potential for hydrocarbon generation and migration.

Transition zones represent some of the most challenging areas for geophysical exploration due to their specific physical-geographical conditions. In addition, technogenic obstacles such as submerged forested areas, buildings and structures, fishing nets, and other anthropogenic objects further complicate surveys. These factors prevent the use of standard equipment and necessitate the application of specialized seismic systems based on autonomous seismic stations, which are widely used worldwide for surveys in transition zones. Such three-component seismic stations have also been developed at the S.I. Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine [Gryn, Verbytskyi, 2019; Gryn et al., 2019].

Transition Zones of the Azov-Black Sea Region. In Ukraine, four areas with structures within transition zones have been identified:

the Western Black Sea area, the Crimean Plain, the Kerch Peninsula, and the Northern Black Sea region (Fig. 1). These four areas were identified by V. H. Bondarchuk [Bondarchuk, 1959], who developed the concept of transition (peripheral) zones between platform and folded structures in his fundamental works. According to his regionalization, these territories are considered elements of a single structural belt covering southern Ukraine.

This article focuses the geological prospects of structures in the Western Black Sea area and the northern part of the Kerch Peninsula. The first area is currently safe for conducting geophysical exploration aimed at hydrocarbon discovery, while the second area is one where seismic surveys were carried out by the State Enterprise «Ukrgeophysica» [Morozova, 2016] in the land-sea transition zone. The acquired seismic data are important for understanding the geological structure of the area in relation to its hydrocarbon potential.

Western Black Sea Area. Within the land-sea transition zones of the Western Black Sea area, three distinct sectors can be identified, characterized by different geological structures, degrees of exploration, and hydrocarbon prospectivity.

The *first sector* covers the area from the mouth (delta) of the Danube River and the Black Sea coast to Lake Sasyk. Tectonically, it is located within the Danube tectonic plate and the Tatarbunary (Kamensky) rift-related trough and is characterized by a relatively simple geological structure and seismic-geological conditions. The main hydrocarbon-prospective deposits containing reservoirs and seals are developed within two lithodynamic complexes of Jurassic and Triassic age. Older and deeper complexes may also be considered potentially hydrocarbon-bearing.

Hydrocarbon occurrence within the Jurassic complex has been directly proven in the transition zone, where oil shows were recorded in well No. 6 near the city of Izmail. The hydrocarbon potential of the Triassic complex has been confirmed by the discovery of several hydrocarbon fields in Romania and Bulgaria [Georgiev, Botoucharov, 2003; Chemberski, Pene, 2010; Chemberski, Botoucharov, 2013].

Within this sector, Triassic and Middle Jurassic deposits, and possibly Silurian and Cambrian strata predicted at great depths, may be considered as potential source rocks.

The inventory of identified structures includes five onshore objects mapped by Jurassic and Triassic reflecting horizons [Fund…, 2020]. The relatively small number of identified structures is explained by the poor degree of exploration of this territory, both onshore and offshore. According to data from UkrDGRI, the State Enterprise «Ukrgeophysi-

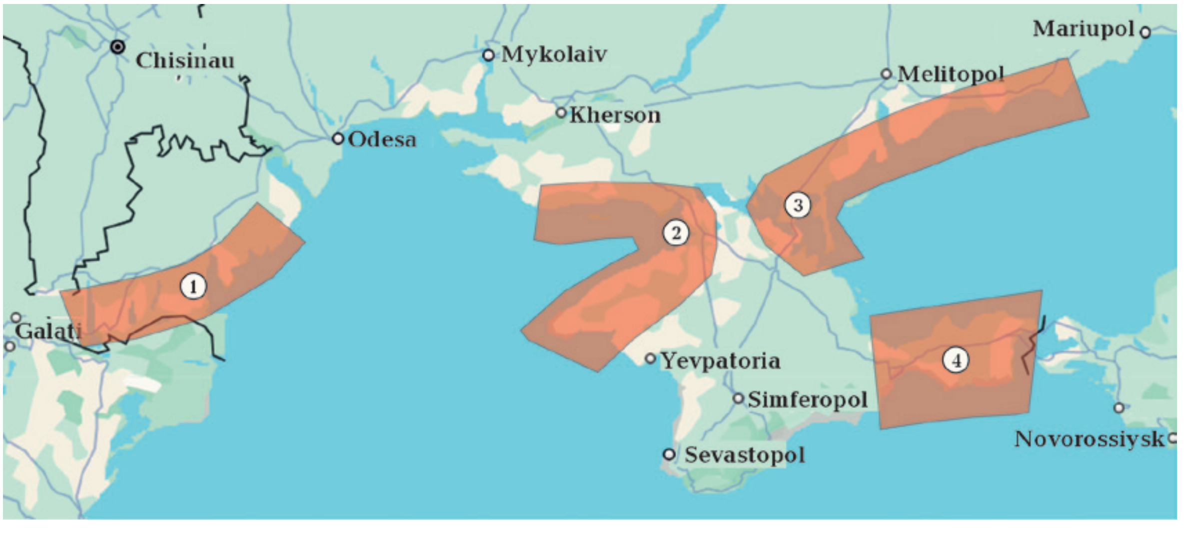

Fig. 1. Location of land-sea transition zones within the territory of Ukraine: 1 — Western Black Sea area, 2 — Crimean Plain, 3 — Northern Black Sea area, 4 — Kerch Peninsula.

ca» and other sources, the forecast density of undiscovered resources is estimated at 10—20 thousand tonnes of oil equivalent (TOE) per 1 km^2 [Naumenko et al., 2019; Fund…, 2020; Hryhorchuk et al., 2024].

The *second sector* extends from Lake Sasyk to Lake Alibey. Tectonically, it is associated with the Biloliski block of the Pre-Dobruja foredeep. Deep seismic-geological conditions are classified as complex, while near-surface conditions are considered simple. Onshore drilling has confirmed the presence of reservoirs and proven hydrocarbon potential in the Upper-Middle Devonian and Lower Carboniferous deposits [Kolodii, 2006; Hnidets et al., 2024]. Reservoir rocks are also present in the Lower Devonian, Silurian, and Triassic-Jurassic complexes. Potential source rocks include the Silurian, Cambrian, Triassic, and Middle Jurassic deposits.

The inventory of identified structures in this sector includes nine onshore objects [Fund…, 2020]. Seismic exploration coverage is highly uneven: relatively good onshore and sparse offshore, while the water areas of Sasyk, Alibey, and Shagany lakes have not been studied at all.

The main prospects for hydrocarbon exploration (onshore) in the area between Sasyk and Alibey are associated with Paleozoic deposits (Silurian, Devonian, Carboniferous). Other structural-lithological levels are either of low prospectivity onshore or have uncertain potential in the offshore areas of the Black Sea and the lakes [Mykhailov et al., 2014]. The «Atlas of Oil and Gas Fields of Ukraine» indicates that this sector is the most promising within the Western Black Sea area, with a forecast density of undiscovered resources of 20—30 thousand TOE per 1 km^2 [Atlas …, 1998].

The *third sector* covers the area from Lake Alibey to the Dniester Estuary. Tectonically, it is associated with the Dniester syncline of the western segment of the South Ukrainian monocline. The geological structure is characterized by a monoclinal uplift toward the northwest and the absence of anticlinal structures. In addition, the main hydrocarbon-prospective complexes and source rocks occur at shallow depths (up to 1—3 km). All these factors significantly reduce the prospects of this sector. In terms of undiscovered resource density, this area belongs to category 8 (less than 5 thousand TOE per 1 km^2) [Mykhailov et al., 2014].

Thus, within the Western Black Sea area, the highest hydrocarbon prospects are associated with Paleozoic deposits in the sector between Sasyk and Alibey lakes, as well as with Mesozoic deposits near the Danube mouth and delta and Lake Sasyk. In total, 18 prospective structures have been identified in this area [Fund …, 2020].

Kerch Peninsula. The land-sea transition zones of the Kerch Peninsula are located within the central graben and the southern flank of the Indolo-Kuban Rift, which is superimposed on the eastern plunge of the Crimean fold-and-thrust belt. These tectonic elements are characterized by a complex geological structure, variable lithofacies composition of deposits, and differing hydrocarbon prospects [Atlas…, 1998].

The degree of geological and geophysical exploration of different parts of the transition zones is uneven. The onshore part of the peninsula is the best studied, where detailed exploration seismic CMP (CDP) grids of varying fold have been acquired over different periods. The coastal zone of the Azov and Black Seas, 2—4 km wide, has not been investigated by seismic methods.

The coastal territory of the Kerch Bay has been studied by a sparse seismic profile grid, while the offshore area has not been studied at all. Within the onshore southern coast of the Kerch Peninsula, CMP seismic surveys were conducted using an exploration-detailed profile grid, except for coastal areas (Cape Opuk, Cape Chauda, etc.). The coastal offshore zone of the Black Sea, up to 4—5 km wide, remains practically unexplored.

In the immediate vicinity of the transition zones, numerous wells of various depths and purposes (parametric, exploration, and production) have been drilled, providing data on reservoir distribution and hydrocarbon prospectivity. In the transition zones of the northern Kerch Peninsula and the Kerch Bay, reservoirs and seals are developed in the Neogene and Oligocene (Maykop Series) deposits [Vernigorova, Ryabokon, 2018]. Older deposits have not been penetrated by drilling due to their great burial depths (4,500—5,000 m).

Within the Oligocene deposits, reservoirs are identified at two stratigraphic levels: at the base of the Planorbellian stage (basal unit) and in the upper part of the Upper Kerleut. Lower Planorbellian reservoirs are represented by siltstone-sandstone packages with thicknesses of up to several tens of meters. The regional seal is formed by clayey deposits of the Lower and Middle Maykop. Hydrocarbon potential of these deposits has not been proven directly within the transition zones; however, several hydrocarbon fields (Povorotne, Prydorozhne, North Kazantyp, etc.) have been discovered in the lower part of the Maykop Series in adjacent areas.

Within the Neogene petroleum system, the Tortonian and Meotian deposits are of exploration interest. Their hydrocarbon potential has been proven in fields of the Azov Sea (East Kazantyp, North Bulhanak, etc.) and onshore (Aktashske, Semenivske, Voikivske, etc.) [Vernyhorova, 2014]. Source rocks for all lithodynamic complexes are represented by the Maykop Series, the Kum Horizon, Lower Cretaceous, Jurassic, and possibly Triassic deposits.

Based on the reflecting horizons associated with petroleum systems, approximately 20 prospective objects of various types have been mapped within this part of the territory, including eight discovered oil and gas fields. More than ten objects located onshore extend offshore but remain unexplored due to the absence of seismic surveys in the coastal waters of the Azov Sea and Kerch Bay.

Within the transition zones of the southern Kerch Peninsula, the presence of reservoirs and seals is predicted in Jurassic, Cretaceous, Paleocene-Eocene, and Oligocene deposits, whose hydrocarbon potential has been proven in adjacent areas (Moshkarivska, Fontanivska, etc.). In Jurassic deposits, reservoirs are represented by fractured Upper Jurassic limestones, with Lower Cretaceous clay deposits acting as seals. The hydrocarbon potential of Jurassic deposits has been confirmed by drilling in the Moshkarivska, Vidnenska, and other areas [Gozhyk et al., 2006].

At the same time, the proximity of this zone to the southern flank of the Indolo-Kuban Trough and the similarity of geological structures allow the prediction of reservoir development and hydrocarbon saturation in Oligocene, Paleocene, Cretaceous, and Jurassic deposits. Within the transition zones of the southern Kerch Peninsula, 13 prospective objects have been identified and three fields have been discovered. Most of these objects remain unexplored both onshore and offshore due to the lack of seismic surveys in coastal zones. Existing structural interpretations for various horizons are sketchy and do not allow for the preparation of objects for deep drilling.

Overall, the transition zones of the Kerch Peninsula are among the most promising areas for hydrocarbon exploration in the southern region of Ukraine. According to some estimates, this territory belongs to prospectivity category 5, with a density of undiscovered resources of 20—30 thousand TOE per 1 km^2 [Fund…, 2020; Mykhailov et al., 2014].

CMP Seismic Surveys in the Transition Zones of the Northern Kerch Peninsula. In the northeastern part of the Kerch Peninsula, 2D CMP seismic exploration surveys were conducted by the State Enterprise «Ukrgeophysica» to refine the geological structure of the Karam, Buras, Bondarenkivska, and Yurkivska structures of the Indolo-Kuban Trough and to investigate geological features of the land-Azov Sea transition zone within Neogene and Paleogene deposits [Morozova, 2016]. During 2009—2011, the Crimean Geophysical Expedition «Krymgeophysica» acquired five seismic profiles (Fig. 2) with a total length of 43.64 km, using SV-10-180 vibratory seismic sources and the «Progress T-155» seismic recording system. Field data were recorded in 60-channel (onshore) and 120-channel (offshore) configurations.

The lengths of the conducted seismic surveys are summarized in Table.

Hydrocarbon Potential of the Northern Part of the Kerch Peninsula. The hydrocarbon

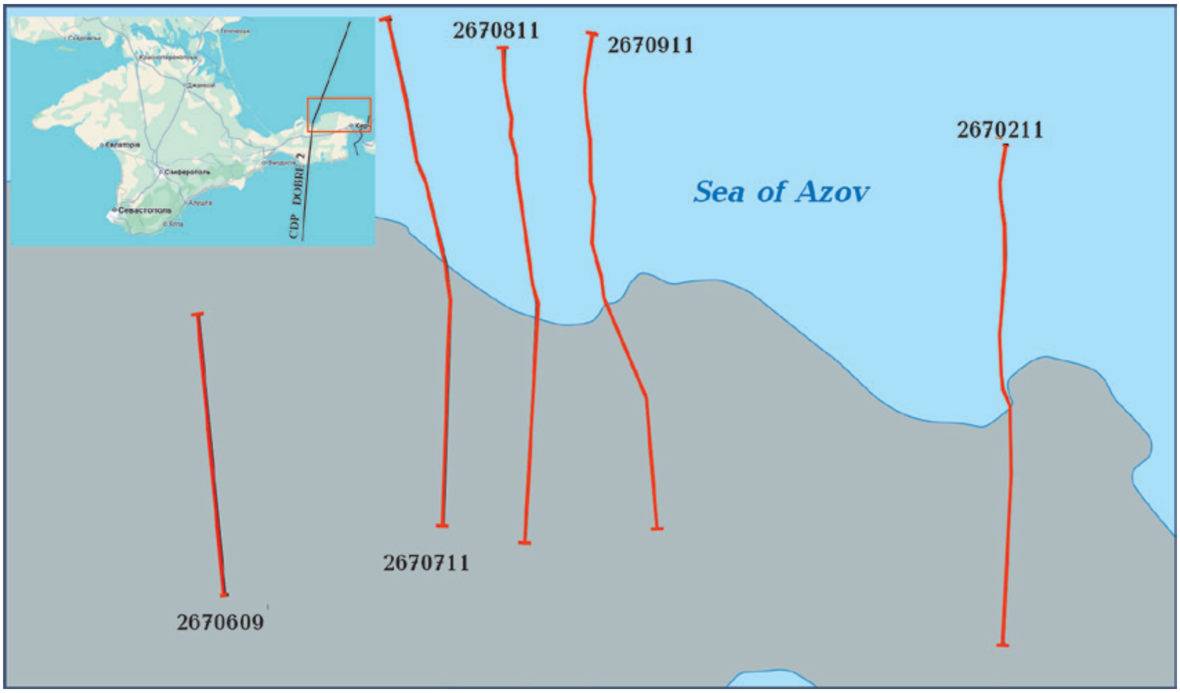

Fig. 2. Location of the processed CDP seismic lines and the CDP DOBRE-2 regional profile traversing the Kerch Peninsula.

A summary of the acquired seismic data

Number	Profile ID	Length, km
1	2670609	7.41
2	2670911	8.975
3	2671211	8.825
4	2671711	9.40
5	2671811	9.025
Total	—	43.64

prospects of the study area are primarily associated with terrigenous-carbonate deposits of the Tortonian Stage (Neogene).

Upper Cretaceous-Paleocene Complex. Deposits of this complex have not been directly tested within the study area. During the drilling of the Bulganatska-1 well, gas shows in the drilling mud were observed at depths of 4485—4500 m, 4573—4585 m, and 4847—4952 m (Paleocene-Upper Cretaceous).

In the Bondarenkivska-1 and Malbabchytska-1 wells, elevated gas readings were recorded in Paleocene deposits at depths of 3609—3620 m and 4469—4528 m, respectively [Atlas…, 1998].

Reservoir rocks are represented by fractured marls and limestones, while seals are composed of argillites.

Oligocene Complex. From the Planorbellian Horizon in the Bondarenkivska area, formation water was produced at a rate of 3.1 m^3/day with dissolved combustible gas. Reservoirs are represented by sandstones of the basal unit, while seals consist of clay deposits.

Neogene Complex. Within the onshore areas, several hydrocarbon fields have been discovered in deposits of this age, including Borzivske and Voikivske, while within the offshore shelf areas fields such as North Kerch and North Bulganak have been identified.

The highest hydrocarbon inflows were obtained during testing of Tortonian deposits. Inflows and oil and gas shows of varying intensity were recorded from the Koroliovskyi and Batisyphon horizons.

Lower Miocene. In wells drilled within the Malobabchytska, Bondarenkivska, and other areas, inflows of formation water with dissolved gas were obtained from Lower Miocene deposits.

Middle Miocene deposits have been investigated by deep drilling across most of the study area (Borzivska, Baherivska, Voikivska areas, among others). In the Borzivska area, a gas accumulation was discovered in the Konkian Stage, while an oil accumulation with a gas cap was identified in the Chokrakian Stage. In well No. 21, testing yielded oil and gas inflows from the 502—509 m interval at rates of 15 m^3/day of oil and 10.6 thousand m^3/day of gas through a 4.1 mm choke. In well No. 23, gas inflow from the 418—419.2 m interval reached 7 thousand m^3/day through a 5.1 mm choke.

In the Voikivska area, oil inflows with a rate of 4.2 m^3/day under natural flow conditions were recorded from Chokrakian deposits (interval 86.5—88 m). From the Karaganian Horizon in well No. 18 (interval 100.0—112.0 m), the initial oil rate reached 15.5 m^3/day through a 20 mm choke.

In the Yurkivska area, degassing of drilling mud was observed during structural drilling.

In the Malobabchytska area, minor oil inflows were obtained from Chokrakian deposits during coring operations [Atlas…, 1998].

Within the offshore shelf of the Azov Sea, in the North Bulganak area, well No. 1 produced combustible gas from Tortonian deposits (interval 1079—1091 m) at a rate of 259.6 thousand m^3/day through a 15.8 mm choke. In the North Kerch area, well No. 1 produced free-flowing combustible gas from Tortonian deposits at a rate of 69.9 thousand m^3/day.

Reservoir rocks include porous and fractured marls, sandy-silty and organogenic-detrital limestones, sandstones (Chokrakian), and thin interbeds of fine-grained sands (Konkian). Seals are represented by clay deposits.

Upper Miocene. Sarmatian deposits are represented by a relatively homogeneous clay sequence that contains almost no reservoirs. Minor gas inflows were recorded during drilling in the Malobabchytska area.

Thus, the results of well testing within the study area have practically confirmed the hydrocarbon potential of Middle Miocene (Tortonian) deposits.

Mud Volcanism in the Transition Zone of the Northern Kerch Peninsula. One of the characteristic features of land-sea transition zones is mud volcanism, which is associated with surface emissions of various gases, including hydrocarbon-bearing gases. Numerous publications in international scientific literature emphasize the importance of mud volcanism for understanding deep geodynamic processes and its relationship with hydrocarbon-bearing geological structures. One of the most recent studies [Napoli et al., 2025] presents a comprehensive inventory of submarine mud volcanoes in transition zones, accounting for their spatial distribution and characteristics. Such databases are compiled based on detailed regional studies of mud volcanism, for example, in Japan and Taiwan [Tanaka et al., 2020], northern Colombia [Dill, Kaufhold, 2018], Azerbaijan [Komatsu, Feyzullayev, 2024], and other regions.

Numerous scientific publications have been devoted to the study of Ukrainian, and particularly Black Sea, mud volcanoes [Shnyukov et al., 2006, 2010; Shnyukov, Kobolev, 2018]. In the Kerch shelf area and along the continental slope of the Black Sea, E.F. Shnyukov and his colleagues identified 41 gas flares and two mud volcanoes during the 65th cruise of the research vessel «Professor Vodyanitsky». The monograph [Shnyukov, Yanko-Hombach, 2020] notes that mud volcanoes can be used as indicators in the exploration for gas hydrates and other mineral resources in the Black Sea region. This work presents new data on driving forces, mechanisms, origin, geological and geomorphological features of mud volcanoes, as well as new information on the composition of solid, gaseous, and liquid components of the erupted material.

Submarine mud volcanoes in the Azov Sea are mainly concentrated in its southern part and are particularly active in the region adjacent to the Kerch Strait. They are located above the South Azov Fault, a tectonically active zone where gases (primarily methane) accumulate within folded sedimentary strata.

Along the coast of the Kerch Peninsula [Nesterovskyi et al., 2021], several onshore mud volcanoes occur that belong to the same geological zone as the submarine ones. The most well-known are the Bulganak mud volcanoes, located near the village of Bondarenkove in the eastern part of the Kerch Peninsula.

Periodic occurrences of oil have been observed in the gryphon waters of the Bulganak, Tobechytskyi, Malotarkhanskyi, Dzhautepe, Yenikale, Novoselytskyi, and other mud volcanoes [Nesterovskyi et al., 2021]. Other studies have shown that mud volcanoes may act as marine sources of methane (CH_4) and the greenhouse gas CO_2 [Menapace et al., 2017; Mazzini, Etiope, 2017].

According to estimates by Shnyukov et al. [2006], mud volcanoes of the Kerch Peninsula during their active phase emit approximately 1500—2000 m^3 of gas per day, and about 520 m^3/day during passive stages. Over the entire period of mud volcanic activity (approximately 30 million years), the total volume of emitted gases is estimated at 17—20 trillion m^3.

Monitoring observations of gryphon gases on the Kerch Peninsula during 2007—2013 revealed that methane is the dominant gas for all volcanoes and individual gryphons. The highest methane concentrations, up to 96 %, were recorded in gryphons of the Bulganak mud volcano (Andrusov and Tyshchenko gryphons) and at the Soldatska Slobidka mud volcano [Nesterovskyi et al., 2021].

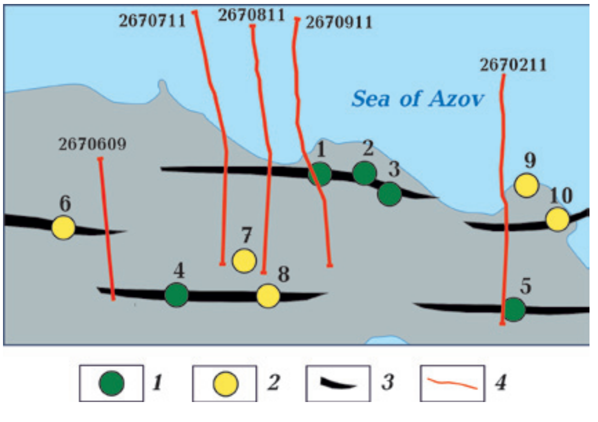

Fig. 3. Map showing anticlines and mud volcanoes in the northeastern transitional zone of the Kerch Peninsula (after Nesterovskyi et al., 2021; Shnyukov et al., 2006 modified): *1* — mud volcanoes with subsided synclines; *2* — depressed synclines; *3* — anticlines; *4* — seismic profiles. Mud volcanoes with subsided synclines: 1 — Velykotarkhanskyi, 2 — Malotarkhanskyi, 3 — Bulhanatskyi, 4 — Burasivskyi, 5 — Baksynskyi. Depressed synclines: 6 — Chokratska, 7 — Kezen, 8 — Malobabchytska, 9 — Osovynska, 10 — Borzivska.

Results of Seismic Surveys Conducted by the State Enterprise «Ukrgeophysica». CMP seismic profiles acquired in the northeastern part of the Kerch Peninsula intersect a number of geological structures that host mud volcanoes. All profiles cross anticlinal folds, while profiles 2670911 and 2671211 directly intersect the Velykotarkhansky and Baksynsky mud volcanoes. The locations of seismic profiles and mud volcanoes are shown in Fig. 3.

Migrated time sections of CMP seismic data from the land-sea transition zone are presented in Figs. 4—8 [Morozova, 2016, modified]. The in-phase axes of reflected waves from high-impedance horizons provide a detailed reconstruction of the spatial geological structure of the transition zone and the internal structure of the mud volcanoes. In the upper parts of the figures, the sea is marked by a blue line and land by a brown line to facilitate identification of the transition zone. Areas on the seismic sections corresponding to mud volcanoes or associated geological structures are highlighted in red.

On all migrated seismic sections, the locations of the mud-volcanic zones are distinctly expressed in the wavefield patterns, fully corresponding to the geological structure of the northeastern Kerch Peninsula.

Deep Structure of Transition Zones Based on Regional Profiles. In 2007, seismic surveys were carried out along the regional CDP profile DOBRE-2 [Sydorenko et al., 2017], which crosses the northeastern part of the Black Sea, the Kerch Peninsula, and the Azov Sea, and coincides with the wide-angle reflection/refraction (WARR) profile DOBRE-2 [Pashkevich et al., 2018]. These profiles made it possible to reconstruct the deep geological structure and tectonic evolution of the region, as well as to assess the hydrocarbon potential of the northern part of the Kerch Peninsula, which directly adjoins the Indolo-Kuban Trough and is characterized by the presence of mud volcanoes.

The CDP DOBRE-2 profile clearly demonstrates that sedimentary rocks in this area

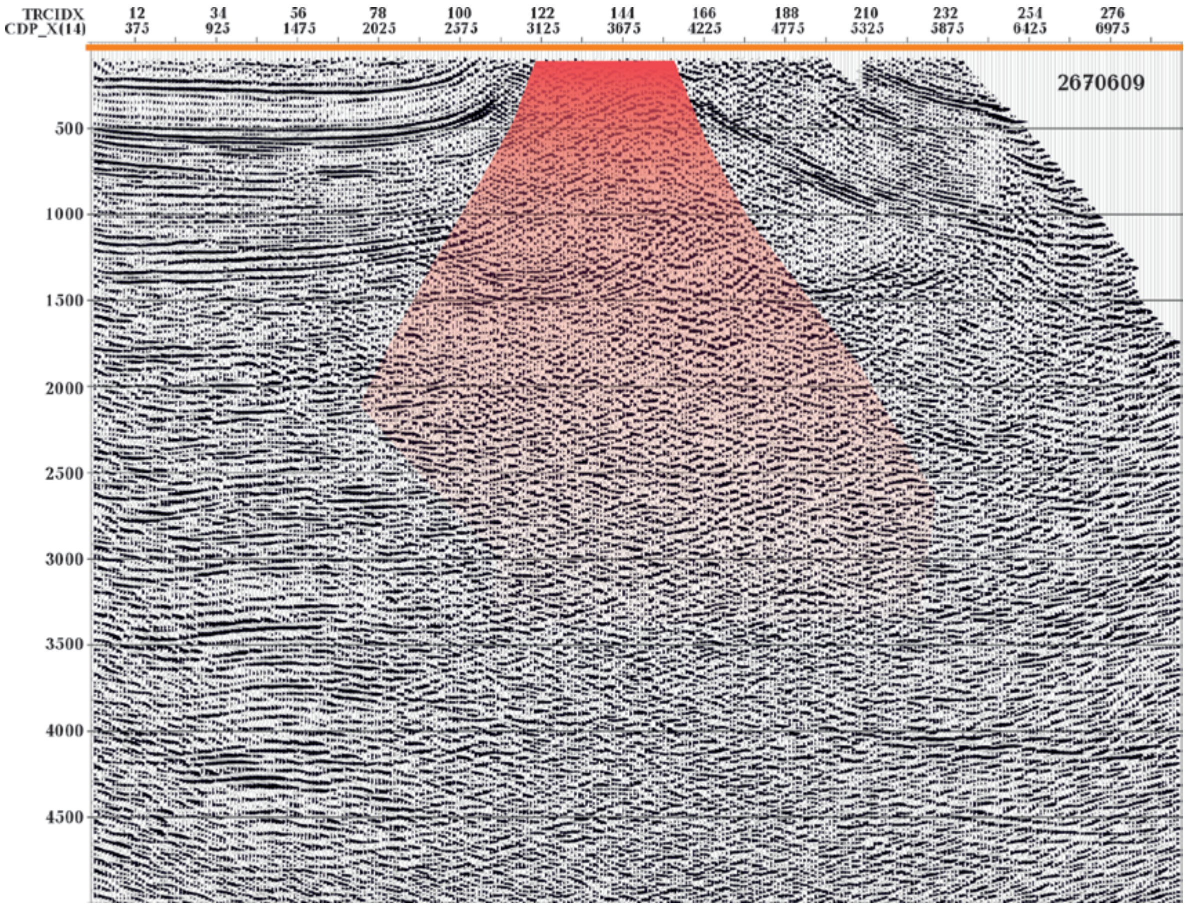

Fig. 4. Migrated time section along profile 2670609 [Morozova, 2016, modified].

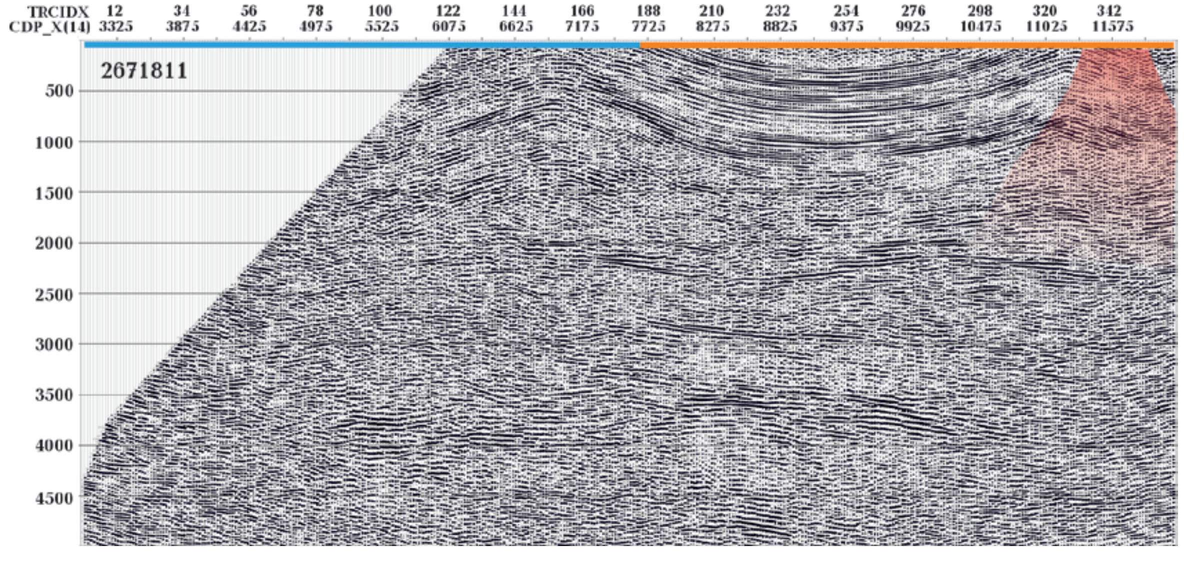

Fig. 5. Migrated time section along profile 2670711 [Morozova, 2016, modified].

subside to depths of approximately 10—12 km. They are composed predominantly of deposits of the Maykop Series (Oligocene-Lower Miocene), whose thickness exceeds 3—5 km, a factor of critical importance for hydrocarbon generation and accumulation.

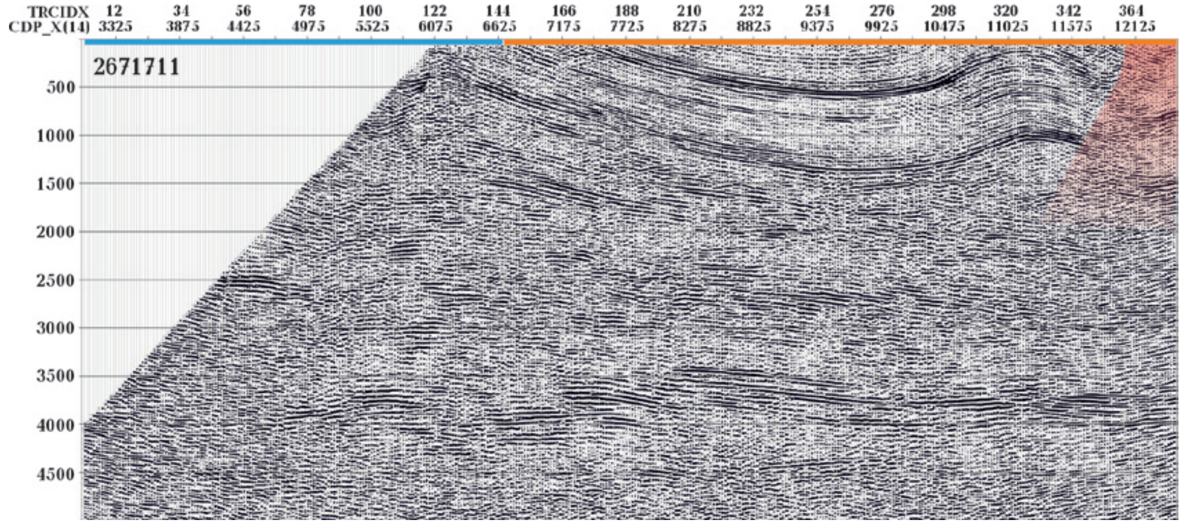

Fig. 6. Migrated time section along profile 2670811 [Morozova, 2016, modified].

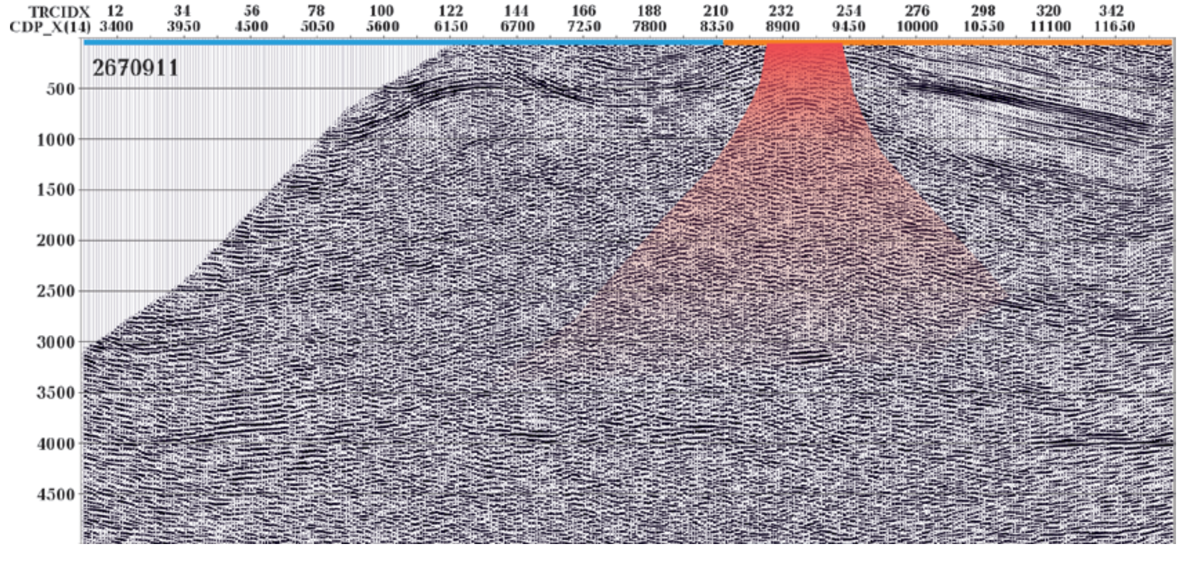

Fig. 7. Migrated time section along profile 2670911[Morozova, 2016, modified].

Seismic data indicate the lateral pinch-out of sandy units within the Maykop Series toward the Azov Sea, which may suggest the presence of lithological traps for oil and gas. In the northern part of the profile, gentle uplifts (anticlinal folds) are identified; unlike the disrupted structures in the southern sector, these uplifts are more coherent and capable of hosting large gas accumulations.

Seismic data also reveal zones of reduced density and numerous faults that cut through the entire thickness of the Maykop deposits (Oligocene—Lower Miocene). In the northern sector and the adjacent waters of the Azov Sea, the CDP DOBRE-2 profile identifies deep, near-vertical faults that penetrate down to the lower crust. These faults serve as migration pathways along which hydrocarbons and associated gases ascend from depths of 8—10 km toward the surface (Fig. 9).

This structural configuration explains the mechanism of mud volcanism on the Kerch Peninsula: high formation pressures in deep-seated horizons are released along these fault zones, transporting breccia and gas to the surface. The enormous sedimentary load

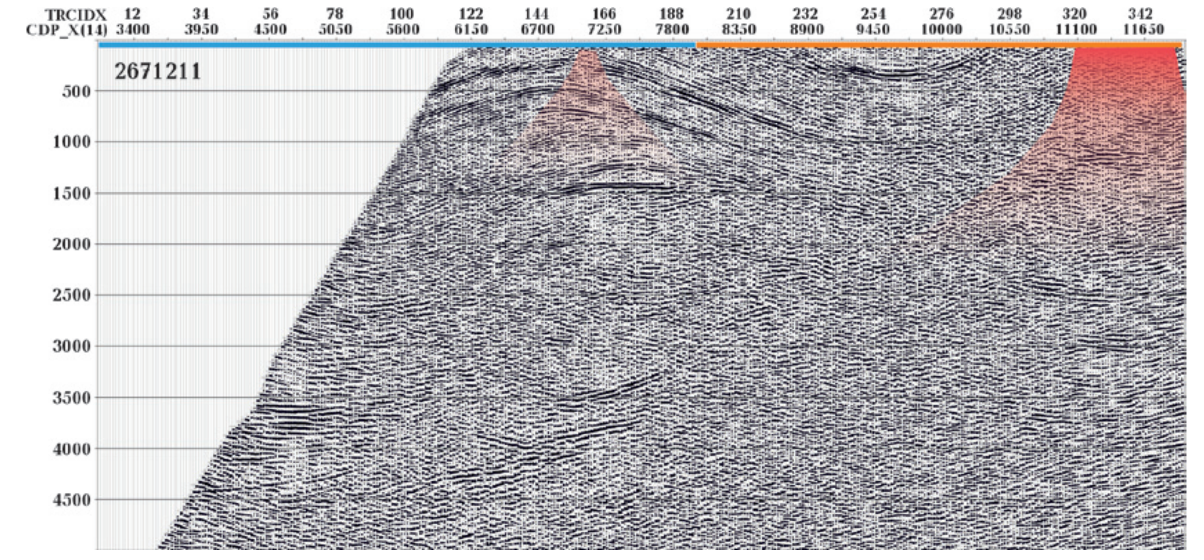

Fig. 8. Migrated time section along profile 2670211[Morozova, 2016, modified].

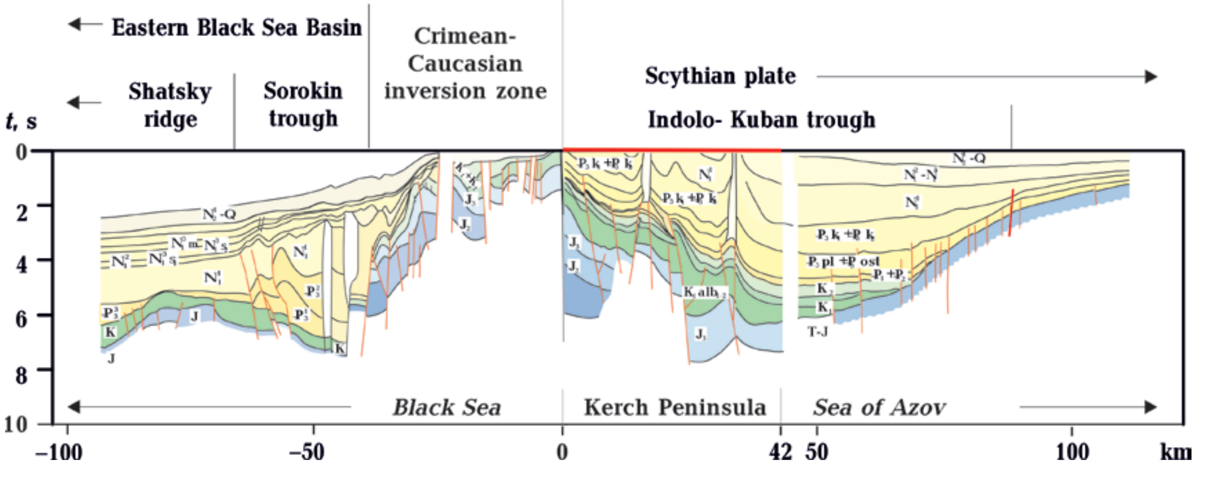

Fig. 9. Geological structure of the transitional zones Black Sea—Kerch Peninsula—Azov Sea.

within the Indolo-Kuban Trough effectively «squeezes» the plastic Maykop clays upward, resulting in the formation of mud volcanoes, such as those observed near the village of Bondarenkove.

Hydrocarbon-Prospective Objects and Mud Volcanism. As a result of correlating the spatial distribution of anticlinal structures and mud volcanoes within the transition zone of the northeastern part of the Kerch Peninsula (see Fig. 3) with the corresponding fragment of the Map of the Inventory of Hydrocarbon-Prospective Objects of the Southern Oil and Gas Province of Ukraine [Fund…, 2020], a schematic model was constructed that clearly demonstrates a strong spatial relationship between mud volcanism and hydrocarbon-bearing structures (Fig. 10).

Most mud volcanoes are located directly along, or in close proximity to, the axial zones of anticlines. This spatial association provides additional evidence supporting the use of mud volcanism indicators in the exploration for deep-seated oil and gas accumulations.

Anticlinal structures associated with deep degassing include the Velykotarkhansky, Malotarkhansky, and Bulganak mud volcanoes, which are aligned along a single trend

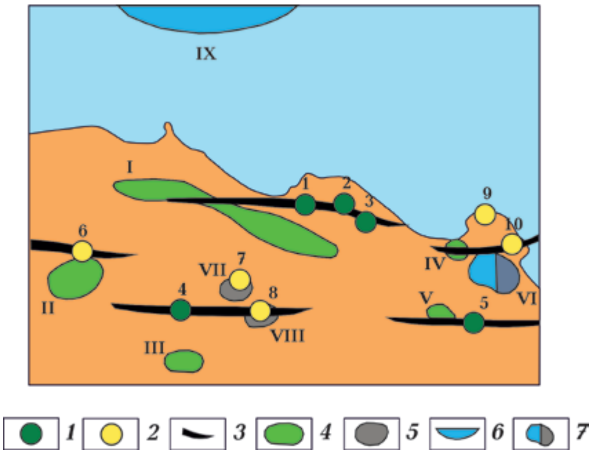

Fig. 10. Schematic correlation between the spatial distribution of hydrocarbon-prospective structures and fields and manifestations of mud volcanism (based on [Atlas…, 1998; Shnyukov et al., 2006; Nesterovskyi et al., 2021]): *1* — mud volcanoes associated with depressed synclines; *2* — depressed synclines; *3* — anticlinal folds; *4* — hydrocarbon-prospective structures; *5* — oil fields; *6* — gas field; *7* — oil and gas field. Hydrocarbon-prospective structures: I — Bondarenkivska; II — Buraska; III — Michurynska; IV — Yurkivska; V — Hlazivska. Fields (oil, gas, oil and gas): VI — Borzivske; VII, VIII — Voikivske; XI — North Bulganak.

together with the Bondarenkivska prospective structure. This alignment may indicate a unified uplift zone. Farther north, within the Azov Sea, the North Bulganak field is located, confirming the productivity of this structural trend. The Burasky mud volcano is situated in close proximity to the Buraska prospective structure, while the Baksynsky mud volcano is associated with the Hlazivska structure. This represents a classic example of mud volcanoes being positioned above deep-seated fluid migration pathways that channel hydrocarbons, mineralized waters, and mud breccia toward the surface.

Depressed synclines, such as the Kezenska and Malobabchytska structures, surround the Voikivske field. To the east, the Borzivske field is closely associated with the Borzivska depressed syncline and the Yurkivska structure. This area may represent one of the most promising zones for offshore hydrocarbon development, as these structures extend into the offshore domain.

Thus, it can be concluded that areas characterized by the simultaneous occurrence of three factors — an anticlinal flexure, the presence of an active mud volcano, and an associated depressed structure — are also highly prospective. Each of the identified objects (highlighted in green; structures I—V) shown in Fig. 10 requires more detailed investigation with respect to its hydrocarbon potential.

Conclusions and Prospects for Further Research. The investigation of sea-land transition zones in the Black Sea and Azov Sea regions using geophysical methods is critically important for the economy of Ukraine, as these methods represent the most effective tools for assessing geological structure and subsurface energy (hydrocarbon) potential. Detailed studies of transition zones are essential for addressing a wide range of key engineering, energy, and safety-related challenges.

Seismic surveys are the only effective means of constructing detailed three-dimensional models of hydrocarbon fields. Studies of transition zones enable the identification and delineation of prospective geological structures (traps) located both offshore (on the shelf) and onshore. The availability of high-quality seismic data from such zones significantly reduces the risk of «dry» drilling. In offshore oil and gas exploration, where drilling and field development costs are extremely high, seismic exploration is a prerequisite for attracting investment.

This paper presents an analysis of the energy potential and hydrocarbon exploration prospects within the transition zones of the Western Black Sea region and the Kerch Peninsula. Available geological and geophysical data were analyzed and summarized. At the current stage of exploration, the most promising areas in terms of hydrocarbon potential are considered to be the transition zones of the Kerch Peninsula, the Sivash Lagoon, the Arabat Spit, and the Western Black Sea region from the Danube River delta to Lake Alibey. In addition, the relationship between hydrocarbon occurrences and mud volcanism within the transition zones of the Kerch Peninsula and adjacent areas was examined.

The presence of mud volcanoes in coastal zones is not only an indicator of potential hydrocarbon accumulations but also a potential hazard to infrastructure. Therefore, in addition to mineral exploration objectives, transition zones must be investigated to address engineering geophysics problems. In particular, high-resolution seismic surveys and seismic-acoustic profiling can be applied to:

- assess soil bearing capacity beneath the foundations of piers, breakwaters, shipyards, and grain terminals;
- map weak soil layers (e.g., silts or water-saturated sands) that may cause settlement or deformation of structures;
- design dredging operations to ensure safe water depths in port areas.

Seismic methods applied in transition zones allow for accurate mapping of slip surfaces and identification of water-saturated zones within coastal slopes. These data form the basis for designing effective landslide mitigation measures (piles, counterforts, drainage systems). Given that the Black Sea region is seismically active (the Vrancea zone), seismic microzonation is required to determine realistic seismic loads on coastal structures, which is critical for ensuring their earthquake resistance.

Future research should focus on the development of an updated geological exploration program for transition zones (land-sea interface) within the Ukrainian sector of the Azov-Black Sea region, addressing both oil and gas exploration and engineering geology objectives.

The seismic investigation of sea-land transition zones is not only a scientific task but also an economic and security necessity for Ukraine, as it provides the foundation for sustainable development of transport infrastructure, realization of domestic energy potential, and protection of coastal territories.

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Геологічні та геофізичні дослідження з метою оцінки енергетичного потенціалу перехідних зон (суходіл-море) Азово-Чорноморського регіону

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Стаття присвячена комплексним геолого-геофізичним дослідженням перехідних зон (море—суша) Азово-Чорноморського регіону (Західне Причорномор'я та Керченська затока — Азовське море), що охоплюють понад 30 000 км^2. Ці стратегічно важливі для пошуку вуглеводнів зони надзвичайно складні для виконання стандартних сейсморозвідувальних робіт, що пов'язано з фізико-географічними умовами та технологічними можливостями досліджень, які мають вирішальне значення для зниження ризику «сухого» буріння та залучення інвестицій, а також необхідні для вирішення інженерних питань і питань безпеки у контексті післявоєнної відбудови.

Наведено детальний аналіз двох ключових площ — Західного Причорномор'я та Керченського півострова. У Західному Причорномор'ї найперспективнішою є ділянка від оз. Сасик до оз. Алібей з прогнозною оцінкою нерозвіданих запасів 20—30 тис. т у.п. на 1 км^2, пов'язаних з палеозойськими (силур, девон, карбон) і мезозойськими відкладами. Керченська площа є також однією з найбільш перспективних (20—30 тис. т у.п. на 1 км^2). Її нафтогазоносність доведена у відкладах неогену (тортон) та олігоцену, а також прогнозується у більш давніх комплексах (крейда, юра).

У перехідних зонах північно-східної частини Керченського півострова (Керченська затока—Азовське море) ДГП «Укргеофізика» було виконано пошукові сейсморозвідувальні роботи МСГТ 2D (2009—2011 рр.). Досліджено п'ять профілів загальною довжиною 43,64 км, які перетинають антиклінальні структури, зокрема Великотарханський та Баксинський грязьові вулкани. Отримані міграційні часові розрізи дали змогу детально відтворити геологічну будову перехідної зони та структуру грязьових вулканів, підтвердивши їх зв'язок з антиклінальними складками.

Сейсмічні методи (особливо 3D сейсморозвідка) є єдиним ефективним інструментом для виявлення та оконтурення перспективних структур у перехідних зонах. Комплексне геофізичне вивчення цих ділянок є критично важливим не лише для реалізації енергетичного потенціалу України, а й для інженерної геофізики (картування слабких ґрунтів, проєктування протизсувних споруд) і сейсмічного мікрорайонування, забезпечуючи основу для стійкої розбудови транспортної інфраструктури та безпеки прибережних територій.

Ключові слова: перехідна зона (море—суша), сейсморозвідка, пошуки корисних копалин, енергетичний потенціал, приповерхнева та глибинна будова.