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HYDROCARBON PROSPECTS IN THE DNIEPR-DONETS BASIN, UKRAINE, AND THE UKRAINIAN CARPATHIANS: AN OVERVIEW

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Abstract: This paper provides a brief overview of geology and petroleum geology of the Dniepr-Donets Basin (DDB) and the Ukrainian Carpathians. Selected examples reveal the significant undiscovered hydrocarbon potential of these provinces and show that it is due to the presence of a large number of promising but poorly explored hydrocarbon accumulations and traps. It is also shown that revision of the existing geological models of many known fields will significantly increase reserve estimates for these fields. This will permit an increase in the annual hydrocarbon production at each of the underexplored fields in a short period of time. The authors also show that the revision of geological models is needed for many structural traps. They failed to detect hydrocarbons, owing to 'dry' wells or wells that were not even tested, despite logging data, indicating the presence of hydrocarbon-bearing reservoirs. This will make it possible to bring into operation previously missed productive formations. Special attention is paid to predicting new hydrocarbon fields in underexplored areas of the Ukrainian Carpathians. Very important further research in the DDB should involve the revision of geological models of both productive and unproductive structural traps, associated with salt tectonics at depths penetrated by wells. As well, it should include exploration for new structural traps near salt stems and beneath the overhangs of salt diapirs, where they may be much more numerous than currently thought and larger in size. The implementation of the exploration and geological research discussed in this paper will ensure that Ukraine's hydrocarbon resources will meet domestic demand for oil and gas and also become an important source of petroleum for Europe.

Key words: Oil and gas exploration, hydrocarbon resources, structural traps, reservoirs, salt tectonics.

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INTRODUCTION

Ukraine is one of the largest countries in Europe, covering about 603,500 km^2 onshore and 117,000 km^2 offshore (Fig. 1). The country has three main hydrocarbon producing regions: the Dniepr-Donets Basin (east), the Carpathian Mountains and their foredeep basin (west), and the southern region, which includes the northern part of the Black Sea, the western part of the Sea of Azov and the Crimean Peninsula (south; Fig. 1).

Despite a long history of exploration, these three major hydrocarbon-producing regions remain prolific and prospective. Two other hydrocarbon areas – the Volyn-Podolia (Lviv) Basin (west) and the Pre-Dobrogea Depression (southwest) – are much less explored and do not have significant proven reserves. About 475 conventional hydrocarbon fields have been discovered in Ukraine during its 150-year exploration history (Korpan *et al.*, 2021; Anonymous 2,

Fig. 1. Tectonic map of Ukraine simplified and slightly generalised from Kruglov *et al.* (2007). Some details for the DDB are added from Stovba *et al.* (1996). The location of hydrocarbon fields (red areas) is from Popadyuk *et al.* (2005a, b) and Korpan *et al.* (2021). The tectonic units of the Ukrainian sectors of the Black Sea and Azov Sea are not shown. The inset physical map shows Ukraine and neighbouring countries. Abbreviations: Az – Azov Sea; EEP – East European Platform; CCU – Central Crimean Uplift; CFD – Carpathian Foredeep; CM – Crimean Mountains; DDB – Dniepr-Donets Basin; DF – Donbas Foldbelt; Gga – Georgia; IT – Indolian Trough; Mld – Moldova; NCT – Northern Crimean Trough; ND – Northern Dobrogea (Lower Prutian Bulge); PDD – Pre-Dobrogea Depression; TCD – Transcarpathian Depression; VGZ – Vyhoriat-Huyn Volcanic Chain; VM – Voronezh Massif; 1 – Southern rift shoulder of the DDB; 2 – Dnipro Graben; 3 – Northern rift shoulder of the DDB.

2022; Anonymous 1, 2023). Oil and gas exploration in Ukraine is mainly focused on conventional resources, although the potential of unconventional resources has been studied since the 1990s (Law *et al.*, 1998; Prigarina *et al.*, 2003; Popova *et al.*, 2018). The peak of production in the country was reached in the 1970s (68 x 10^9 m^3 [2.4 Tcf] of natural gas per year, 14 x 10^6 tons [105 MMbbl] of oil per year; Anonymous 3, 2021), when the annual gas production was nearly four times greater and the annual oil production was nine times greater than it is at present. As a result, the present annual production of gas meets only 2/3 of the country's current needs.

Given the current energy needs not only of Ukraine but also of Europe, the question of Ukraine's hydrocarbon potential and its contribution to energy security in the future is becoming critical. According to official figures, Ukraine ranks second in Europe after Norway in terms of proven remaining natural gas reserves (11 x 10^{11} m^3 [38.8 Tcf], Anonymous 4, 2023) with annual production of 20 x 10^9 m^3 [0.7 Tcf] in 2020 and fourth in terms of oil reserves (85 x 10^6 tons [636 MMbbl]) with annual production of 17 x 10^5 tons [12.7 MMbbl] in 2020 (Anonymous 1, 2023). These figures only describe conventional reserves. In fact, exploration activity in Ukraine has been irregular and inconsistent and the country may hold significant undiscovered resources, in addition to proven reserves.

In this paper, the authors provide a brief overview of the geology and petroleum geology of the Dniepr-Donets Basin (DDB) and the Ukrainian Carpathians. They argue that significant undiscovered hydrocarbon potential exists in these provinces, each of which has a large number of promising but poorly explored hydrocarbon accumulations and traps. It will be shown that revision of the existing geological models of many known fields may increase significantly the reserves of these fields. This, in turn, will make it possible within a short period of time to bring into operation either previously undetected productive formations or to increase significantly the productive areas of known fields. Special attention is paid in this article to predicting new hydrocarbon traps in the area of salt tectonics of the DDB and especially near salt diapirs with salt overhangs. It is expected that as a result of implementation of the exploration and geological research discussed in this paper, Ukraine's hydrocarbon resources will not only meet the domestic demand for oil and gas, but also will become gas supplies and an important source of crude oil for Europe. The authors also believe that a better understanding of the current status of truly depleted hydrocarbon fields will help to address the possible use of at least some of them as safe carbon dioxide storage facilities (e.g., Hannis *et al*., 2017; Cao *et al*., 2020), which is important for achieving net-zero carbon emissions in Europe.

THE DNIEPR-DONETS BASIN

Geological setting and tectonic evolution

The DDB is the principal hydrocarbon-producing province in Ukraine, accounting for 90% of the country's production from 275 hydrocarbon fields (Anonymous 2, 2022; Figs 1, 2). It is the deepest sedimentary basin in Europe, with up to 19 km of sediment fill and developed as an intracratonic rift system in the Late Devonian (Stovba *et al.*, 1996; Stephenson and Stovba, 2012). The sedimentary succession of the basin can be subdivided into pre-, syn-, and post-rift series, corresponding to pre-late Frasnian (D_{2-3}), late Frasnian-Famennian (D_3), and post-Devonian units, respectively (Fig. 3). The sediment thickness increases from ca. 2–6 km in the NW to as much as 19 km near the Donbas Foldbelt (Fig. 4).

The oldest sediments in the DDB are the Middle Devonian to middle Frasnian, so-called "undersalt", pre-rift sediments. These were deposited in platformal terrestrial and shallow-marine environments and comprise sandstones, siltstones, clays, and carbonates, with an average thickness of 300–400 m (Chirvinskaya and Sollogub, 1980; Eisenverg, 1988; Ulmishek *et al.*, 1994). Thickness variations of the pre-rift succession are independent of the modern basement relief (Fig. 4). The sequence is preserved only locally on the rift shoulders.

Although modified by post-rift tectonics and especially salt movements (Stovba *et al.*, 1996; Stovba and Stephenson, 2003 and references therein), the basic architecture of the DDB is preserved from the time of the Late Devonian rifting stage (Fig. 4). The main marginal faults, as well as numerous smaller faults of variable polarity, were activated during the initial rifting stages of the DDB and these divide the basement and overlying pre-rift Devonian sediments into small blocks, 2–5 km wide. The rift margins are characterised regionally, either by pervasive faults, exhibiting displacements from hundreds of metres to 2–4 km, or by sets of less developed faults, displaying various displacements. Most syn-rift fault displacement appears to be confined to the main marginal faults (labelled 1 and 4 in Fig. 4) and two or more subparallel faults (labelled 2 and 3). High and laterally variable syn-rift subsidence was accompanied by the development of grabens and half-grabens (Stovba *et al.*, 1996). The Upper Devonian syn-rift sequence, which was deposited mainly in a shallow-marine environment and contains significant quantities of salt, reaches a maximum present-day thickness of about 4 km (Fig. 4).

The syn-rift phase was terminated by the end of the Devonian (Fig. 3) and, in general, the Carboniferous and younger post-rift sedimentary fill of the DDB overlies the syn-rift sequence and has the configuration of a broad syncline, centred on the rift axis, overlapping the rift shoulders, and increasing in thickness towards the southeast (Fig. 4).

The DDB was affected during its Carboniferous and Permian evolution by a series of post-rift extensional reactivations (Stovba *et al.*, 1996; Stovba and Stephenson, 2003). These occurred at the end of the early Visean, during the mid-Serpukhovian, and during latest Carboniferous–earliest Permian times (Fig. 3). The latter event was

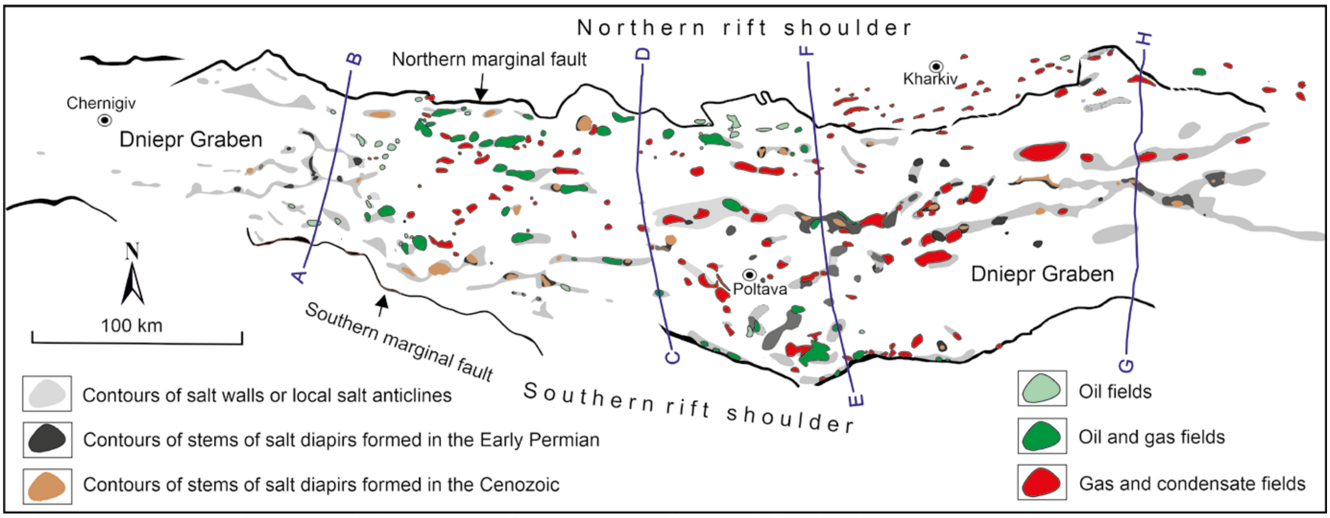

Fig. 2. A simplified map of the Dniepr-Donets Basin, showing the distribution of the main concordant (grey) and discordant (black and brown) salt structures, based on seismic and well data (modified from Stovba *et al.*, 1996; Stovba and Stephenson, 2003). Hydrocarbon fields are also shown (see legend). The fields to the north of the Donbas Foldbelt are not shown on the map. In the axial zone, concordant salt bodies are inferred to correlate with anticlinal structures, seen in seismic data, and are along strike of known salt diapirs. Black lines across the basin are lines of structural cross-sections shown in Figure 4.

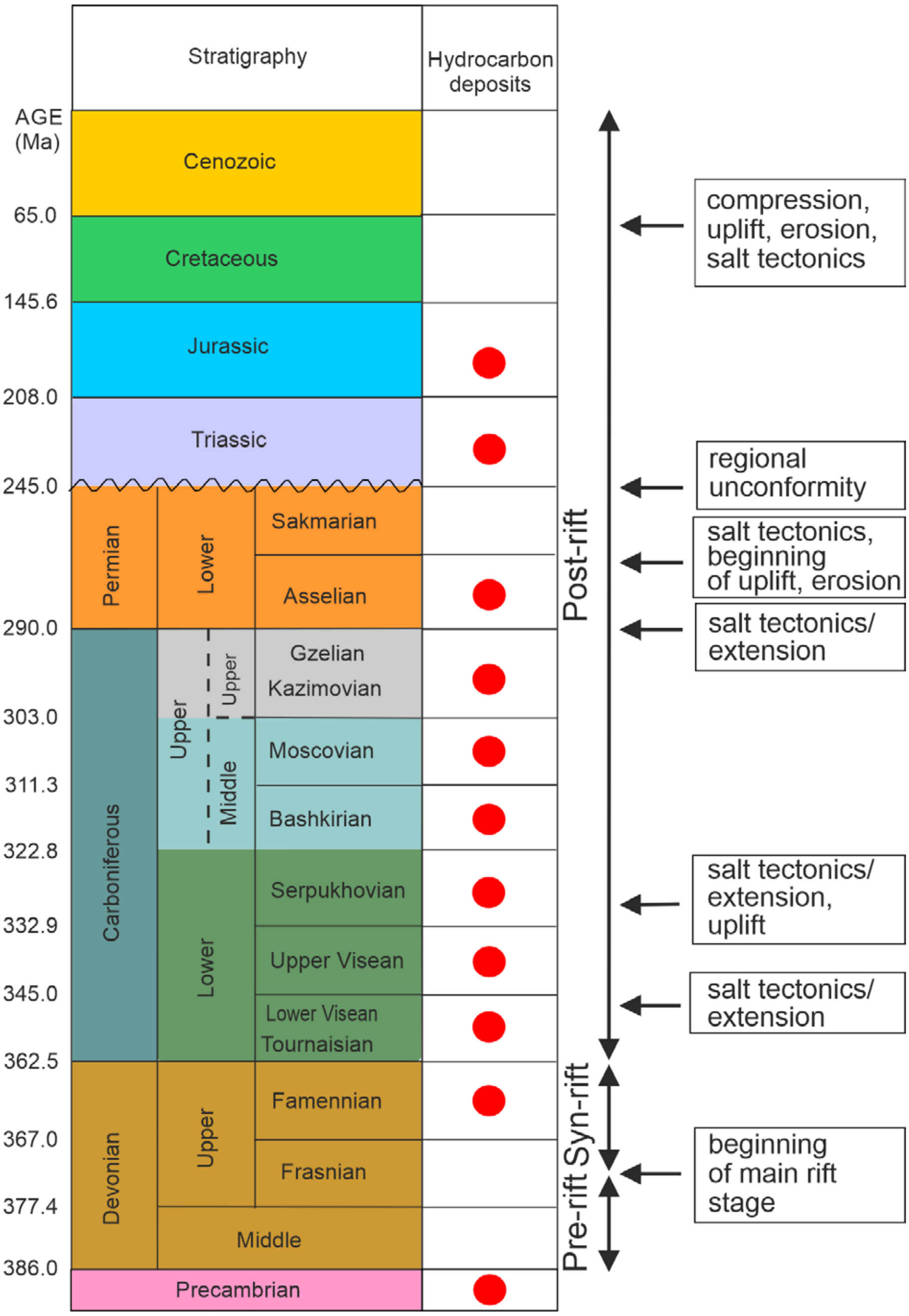

Fig. 3. Summary chrono-stratigraphic column for the Dniepr-Donets Basin showing the distribution of hydrocarbon fields in the sedimentary section (Arsiriy *et al.*, 1989) and the main tectonic phases of the basin evolution (Stovba *et al.,* 1996; Stephenson and Stovba, 2012). The subdivision of the upper Carboniferous into separate middle and upper units corresponds to common usage in Ukrainian literature. Note, that there are only the lower Permian (Asselian and Sakmarian) sediments in the Dniepr-Donets Basin.

associated with major uplift of the southern rift shoulder and erosion of pre-Triassic rocks (e.g., Stovba and Stephenson, 1999). A long period of non-sedimentation throughout the basin continued during the late Permian to the beginning of the Triassic (Eisenverg, 1988). The subsequent post-rift subsidence phase from Triassic to late Cretaceous is interrupted by the tectonic inversion of the DDB (with thrust and fold development) that occurred during the latest Cretaceous–early Paleogene (Stovba and Stephenson, 1999; Saintot *et al.*, 2003). All tectonic events described above increased in intensity towards the southeast, being minor to not observed in the north-western DDB (Stovba and Stephenson, 2003).

The Carboniferous succession is represented by mainly continental deposits in the north-western part of the DDB (Ulmishek *et al.*, 1994; Dvorjanin *et al.*, 1996; Izart *et al.*, 1996). Elsewhere in the DDB, it is characterised by continuous rhythmic sedimentation and comprises mainly siliciclastic rocks (with some clastic-carbonate sequences), deposited in shallow-marine and lagoonal environments (e.g., van Hinsbergen *et al.*, 2015). There is little variation in the position of the basin depocentre (Fig. 4). Only in the axial part of the south-eastern DDB, where the lower Carboniferous includes marine carbonates, did the depth of deposition exceed 200 m. For instance, Figure 5 shows four

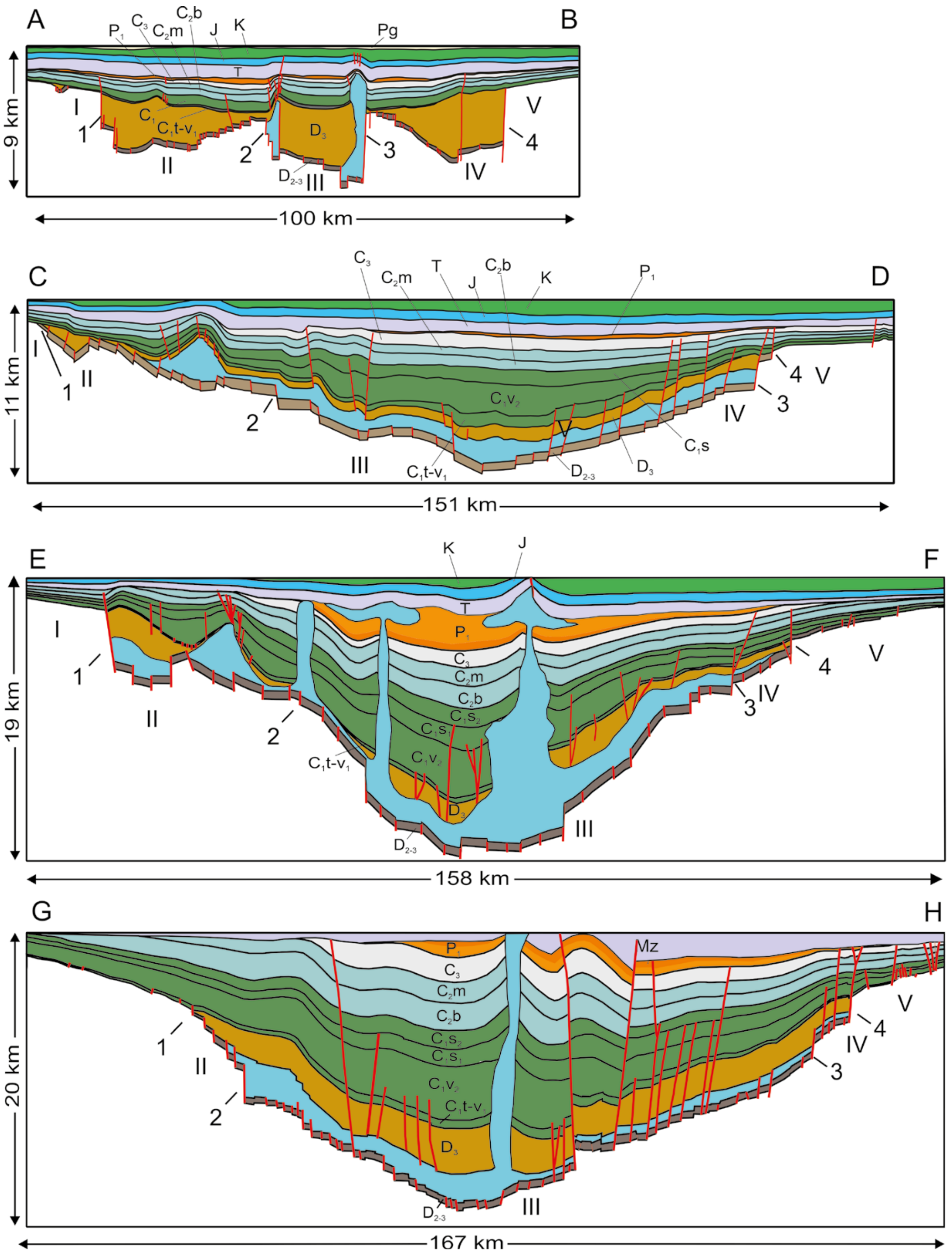

Fig. 4. Structural cross-sections through the Dniepr-Donets Basin, based on depth-converted versions of interpreted regional seismic reflection profiles (from Stovba *et al.*, 1996; Stovba and Stephenson, 1999). For locations, see Figure 2. Blue areas without stratigraphic labelling represent bodies of the Devonian salt. The Late Devonian rift infill represent brown layers. The rift has a generally symmetric structure and is subdivided into an axial, deepest part (III) and adjacent southern and northern "pre-flank" zones (II and IV), separated from the axial zone either by large displacement faults or by a system of obliquely dipping blocks, separated by faults with moderate throw (labelled 2 and 3). The pre-flank (pre-marginal) zones are separated from the southern and northern rift shoulders (I and V) mainly by regionally extensive, large amplitude boundary faults (labelled 1 and 4). Abbreviations: $D_{2\text{-}3}$ – Middle–Upper Devonian pre-rift; D_3 – Upper Devonian syn-rift; C_1 – lower Carboniferous (t – Tournaisian, v – Visean, v_1 – lower Visean, v_2 – upper Visean, s – Serpukhovian, s_1 – lower Serpukhovian, s_2 – upper Serpukhovian); C_2 – middle Carboniferous (b – Bashkirian, m – Moscovian); C_3 – upper Carboniferous (Kasimovian and Gzelian); P_1 – lower Permian; Mz – Mesozoic; T – Triassic; J – Jurassic; K – Cretaceous; Pg – Paleogene.

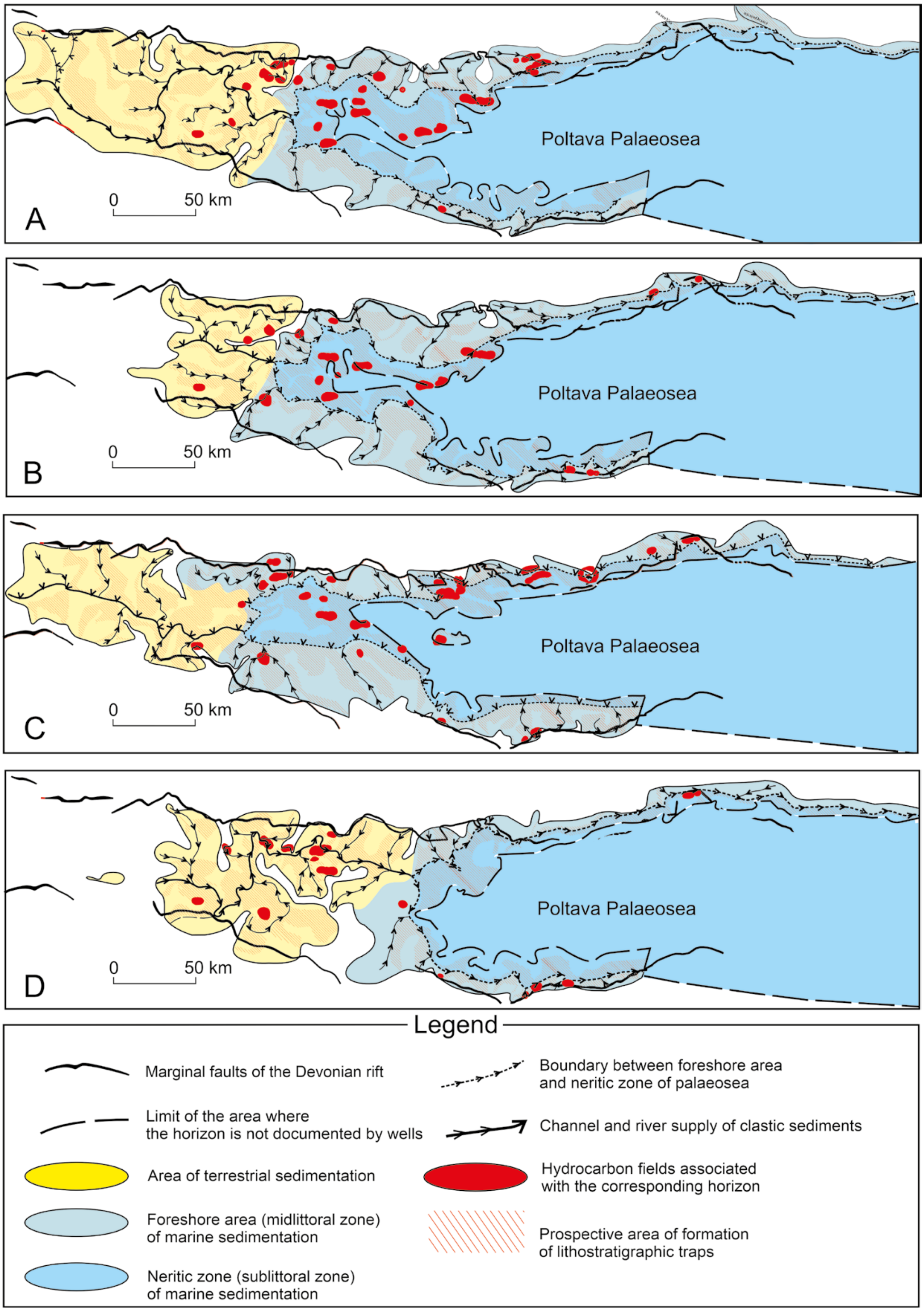

Fig. 5. Palaeogeographic reconstructions for 4 of 45 successive productive horizons (A–D) of the lower Carboniferous sequence (modified from Samoylyuk *et al*., 2003). Locations of the horizons in the sedimentary section are shown in Figure 6. The distribution of hydrocarbon fields, discovered in each productive horizon, is also shown on the maps. The reconstruction is based on detailed interpretation of well-logging data from about 1,000 wells and other available geological information. Seals, consisting mainly of clays, overlap each horizon and were formed during the periods of maximum transgression of the Poltava Palaeosea. Changes in the coastline from the southeast to the northwest and in the area of terrestrial sedimentation during the maximum regressions of the palaeosea are clearly visible.

of 45 palaeogeographic maps constructed on the basis of well-log data and available geological-geophysical information (Dvorjanin *et al.*, 1996; Samoylyuk *et al.*, 2003) and covering the early Carboniferous time span. These maps demonstrate the main features of the Carboniferous succession and distribution of sedimentary units containing hydrocarbon fields. The palaeogeographic maps reveal that early Carboniferous sedimentary fill is associated with a multifold cyclicity of sea-level, characterised by repeated transgressions and regressions on a scale of about 50 m (Fig. 6; Dvorjanin *et al.*, 1996; Samoylyuk *et al.*, 2003). Rapid changes in palaeogeographic setting along the DDB axis created 45 pairs of high-quality reservoirs and seals in the Tournaisian-Serpukhovian sequence. More than a hundred hydrocarbon fields have been discovered in this sequence of the DDB (Fig. 7), where lower Carboniferous sediments lie at depths of less than 6.5 km.

The most important hydrocarbon-bearing strata in the DDB are the lowermost Permian (Kartamysh series of Asselian age) and upper Carboniferous (Gzelian and Kasimovuan) sediments. These consist of monotonous sand-shale series, containing rare interbeds of limestones and coals that, like the entire upper and middle Carboniferous sequence reflect predominantly coastal-continental facies. The middle part of the Permian sequence represents the regional high-quality seal for many hydrocarbon fields, discovered in the central and south-eastern parts of the axial zone of the DDB (Fig. 7). The sequence comprises five to seven layers of rock salt, separated by clastics and carbonates, and includes numerous beds of gypsum, anhydrite and dolomite. The thicknesses of salt layers and the percent volume of them, increase upwards in the section (Eisenverg, 1988). The uppermost Permian (Sakmarian) sediments comprise a single salt layer, most likely consisting of redeposited Devonian salt, dissolved from diapirs piercing the depositional surface (e.g., Chyrvinska and Sollogub, 1980).

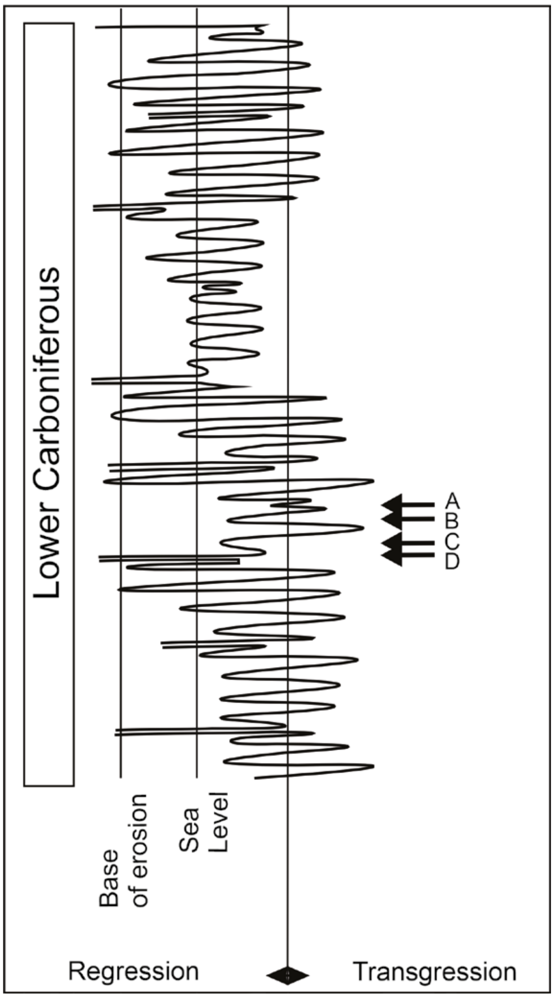

Fig. 6. The curve of relative sea level during the early Carboniferous in the DDB (simplified after Samoylyuk *et al.*, 1993, 2003 and Dvorjanin *et al.*, 1996). Locations of productive horizons (A–D) in the sedimentary section shown in Figure 5.

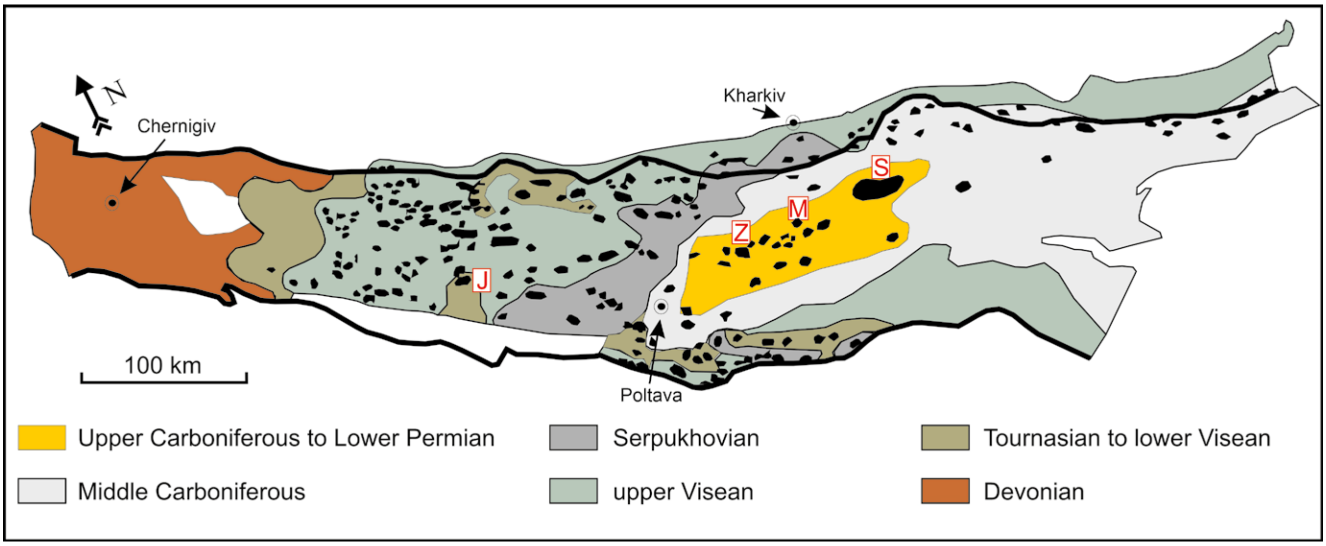

Fig. 7. The distribution of hydrocarbon fields in the DDB (oil, gas-condensate, and gas fields shown in black), in relation to the age of the dominant productive formations. Fields referred to in the text are indicated as such: S – Shebelynka; M – Melykhivka; Z – Zakhidno-Krestyshche; J – Jablunivka (slightly modified after Kabyshev *et al.*, 1998).

The general absence of upper Carboniferous and Permian sediments in the north-westernmost part of the DDB (Profile A–B in Fig. 4) can be explained by a decrease in the rate of post-rift subsidence within a platform-wide regime of relative sea-level fall. Elsewhere within the DDB, the basin margins, particularly the southern one, were exposed at the beginning of the Permian, while the axial part of the basin continued to subside (Fig. 4). Extensive erosion occurred with progressively older sediments subcropping beneath the erosion surface in the direction of the Ukrainian Shield. Locally, more than 2 km of Carboniferous rocks were eroded at this time and during the ensuing dormant phase, which lasted until the Triassic (Stovba *et al.*, 1996; Kabyshev *et al.*, 1998; Stovba and Stephenson, 1999).

Sedimentation resumed in the DDB in the Triassic, a time of tectonic quiescence, rising sea level and continuation of post-rift subsidence. Most of the Mesozoic succession, comprising both marine and continental sediments section, occurs throughout the area, overlying the rift axis as well as its flanks (Fig. 4). Exceptions are the Upper Triassic and Lower Jurassic units, which occur only in the south-eastern part of the DDB, and the Upper Cretaceous marls and chalks, which were eroded from large parts of the southern flank. The Mesozoic sequence is up to 2,000 m thick in the central part of the DDB (Fig. 4). The Cenozoic section of the DDB unconformably overlies the Upper Cretaceous and older series and reaches a maximum thickness of 500 m in the northwest DDB (Eisenverg, 1988).

Salt tectonics were active during the entire history of the DDB from Late Devonian rifting to the Cenozoic. Hundreds of concordant (pillows and anticlines) and discordant (diapirs) salt structures formed during this time (Figs 2, 4). Post-rift salt movements were triggered by the tectonic events mentioned above. The intensity of tectonic reactivation in the DDB increases to the south-east towards the DF (Stovba and Stephenson, 1999) and the number of salt structures displaying growth during all periods of tectonic reactivation also increases in this direction. Periods of halokinesis were followed by periods of passive, post-rift, thermal subsidence (van Wees *et al.*, 1996; Stovba *et al.*, 2003), during which diapirism ceased and up to several kilometres of overlying sediments could have been deposited before the next regional tectonic event triggered renewed salt movement (Chyrvinska and Sollogub, 1980; Stovba *et al.*, 1996).

Hydrocarbon resources

The published estimate, made at the beginning of 2019, of produced and remaining reserves in established fields of the DDB is 278 x 10^6 tons [2,1 Tbbl] of oil, 114 x 10^6 tons [853 MMbll] of gas-condensate and 2414 x 10^9 m^3 [85.2 Tcf] gas (Anonymous 2, 2022). The annual production in 2019 came to some 1.2 x 10^6 tons [9 MMbbl] of oil, 0.75 x 10^6 tons [5.6 MMbbl] of gas-condensate and 19 x 10^9 m^3 [0.7 Tcf] of gas (Anonymous 1, 2023), but this meets only a fraction of the total hydrocarbon requirements of Ukraine.

The official conventional remaining reserves of the DDB are 53 x 10^6 tons [397 MMbbl] of oil and 764 x 10^6 m^3 [27 Tcf] of gas (Anonymous 1, 2023). However, most productive hydrocarbon fields in the DDB are considered to be in their final stages of production. The DDB also has significant potential for unconventional resources. The preliminary assessment of unconventional prospective resources, such as tight gas in the south-easternmost part of the DDB, is from 189 x 10^9 m^3 [6,7 Tcf] (Anonymous 3, 2021) to 8 x 10^{12} m^3 [282,4 Tcf] (Law *et al.*, 1998; Prygarina *et al.*, 2003). Eastern Ukraine is also the main coal-mining area and is considered to have up to 4 x 10^{12} m^3 [141 Tcf] of coal-bed methane (Mykhailov *et al.*, 2014).

Petroleum system and trap types

The first oil discovery in the DDB was made in 1939. Since then, exploration activity was focused mainly on the upper 4–5 km of the basin, although many wells, especially in recent years, have penetrated up to 6.7 km, where significant gas fields were discovered (e.g., Golub *et al.*, 2018a). Most gas production (85%) in the basin is from fields in the south-eastern part of the basin; the oil fields are mainly in the north-west (Fig. 2).

Most of 293 oil, condensate and gas fields are in the Carboniferous to Permian post-rift series (Fig. 7). These accumulations are associated with structural traps that were formed in Carboniferous–Permian clastic sediments, owing to active salt tectonics. The most significant fields are Shebelynka, Zakhidno-Krestyshche, Melykhivka and Jablunivka (see Fig. 7 for locations). About 20% of the gas reserves of the DDB are in the Shebelynka gas field (Fig. 8), with remaining reserves of 102 x 10^9 m^3 [3,6 Tcf], the largest field in the basin, discovered in 1950 and still producing some 3 x 10^9 m^3 [0.1 Tcf] annually (Anonymous 1, 2023). Fourteen types of traps, associated with salt structures and containing hydrocarbon accumulations, have been recognised in the DDB (Varychev *et al.*, 1981). The main types of traps, containing the largest hydrocarbon fields in the DDB, are shown in Figures 8–13.

Figure 14 demonstrates the main types of structural traps within the northern margin of the DDB, where Devonian salt is absent and a number of hydrocarbon fields have been discovered (Fig. 2), including in Precambrian basement and Carboniferous sequences. The structural traps within the northern margin formed during phases of post-rift active tectonics in the DDB.

The Devonian syn-rift series contains only a small part of the total reserves of the DDB. Additional small oil and gas accumulations are stored in the Precambrian basement and in Triassic and Jurassic reservoirs. Areas in the south-eastern DDB that were strongly affected by compressional tectonic reactivation contain only minor hydrocarbon reserves.

The main oil and gas source rocks of the DDB are marine Tournaisian to lower Visean, upper Visean and Serpukhovian shales, with an average TOC content of 1.5–2.3% and maximum values of up to 5-6% (Kabyshev *et al.*, 1998). According to other sources, the TOC can be as high as 16% in oil-prone Serpukhovian black shales in the north-western DDB (Sachsenhofer *et al.*, 2010) and 10–15% in the northern margin of the south-eastern part of the DDB (Stovba *et al.*, 2012). Lower Carboniferous source rocks, consisting mainly of land-plant derived humic and marine

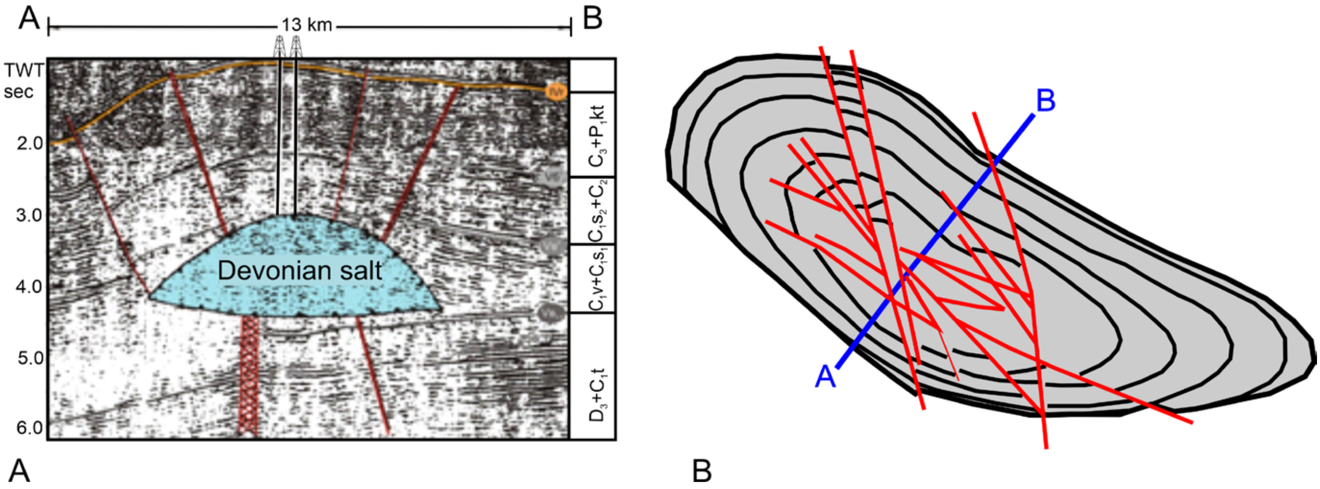

Fig. 8. Interpreted seismic section (A; from Kivshik *et al*., 1991) and gas contour area at the top of the lower Permian productive strata (B; modified from Ivanyuta, 1999), characterisation of the basic structure of the Shebelynka giant gas and condensate field. Hydrocarbon accumulations are confined to the upper Carboniferous–lower Permian sediments. The area of the gas-bearing contour is about 300 km^2 and the height of the hydrocarbon deposits is about 1180 m. The Devonian salt underlying the upper Serpukhovian sediments has been penetrated by several deep wells. In the middle of Serpukhovian time, early Carboniferous, the stem of the Devonian salt diapir pierced the palaeosurface, and the outpouring of Devonian salt created a salt overhang (tongue) of the diapir. The diapir stem has not yet been mapped, owing to poor quality of seismic data or is outside the section shown in (A). It is also possible that the stem had been originally narrow and was completely compressed as a result of regional compression during the Late Cretaceous–early Paleogene time. Stratigraphic sequence abbreviations are the same as in Figure 4.

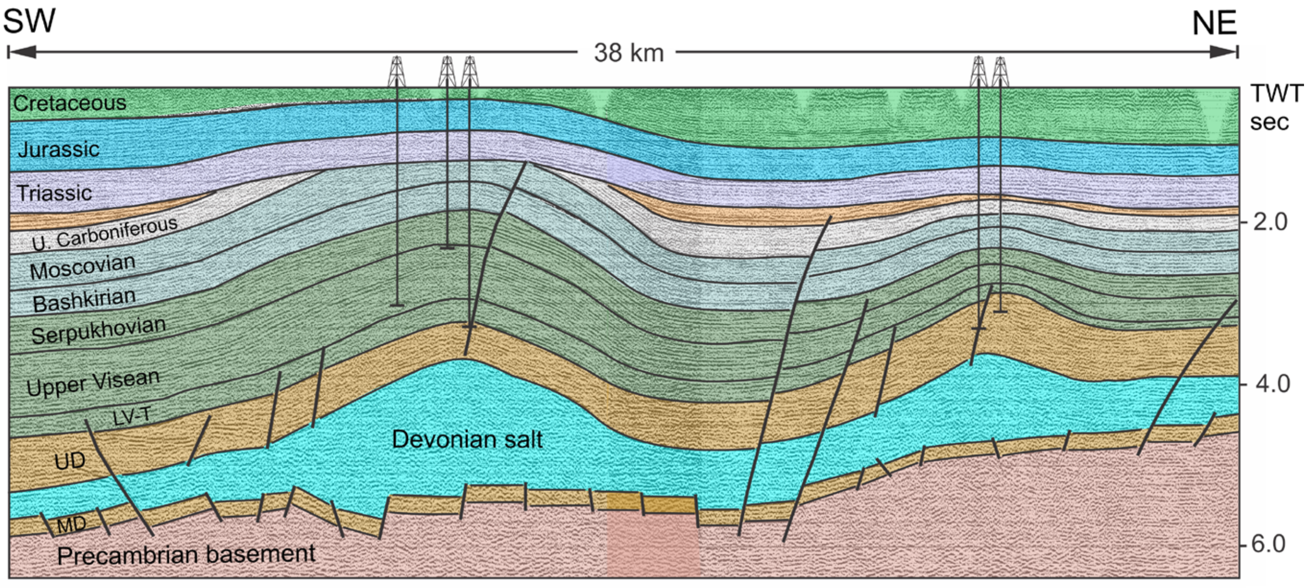

Fig. 9. An interpreted seismic section, showing two typical salt anticlines formed mainly at the end of Carboniferous and in early Permian with renewed growth in latest Cretaceous–early Paleogene time. Large gas pools were discovered in the lower and upper Visean sediments. Predominance of viscous-like deformations in the post-rift sedimentary succession in prevalent basin areas having a thick Devonian salt series. The beginning of salt flow in cores of structures coincided with the late Carboniferous regional extensional event (Stovba and Stephenson, 2003), and the duration of growth of structures was much longer than the time of tectonic extension. Additional growth of the anticlines at the end of Mesozoic was due to regional compression of the Dniepr-Donets Basin. LV-T – lower Visean – Tournaisian; MD – Middle Devonian; UD – Upper Devonian.

kerogen matter, occur in the gas window in the south-eastern part of the DDB (Arsiriy *et al*., 1989; Kabyshev *et al*., 1998). The lower Carboniferous sequence in the north-western part of the basin lies partly in the gas window, the rest being in the oil window.

Middle Carboniferous strata, comprising coals and shales, are ubiquitous, have a TOC content, consisting mainly of humic material in the range of 0.6–0.9%, and entered the gas window in the basin centre and the oil window along the basin flanks (Arsiriy *et al*., 1989; Kabyshev *et al*., 1998).

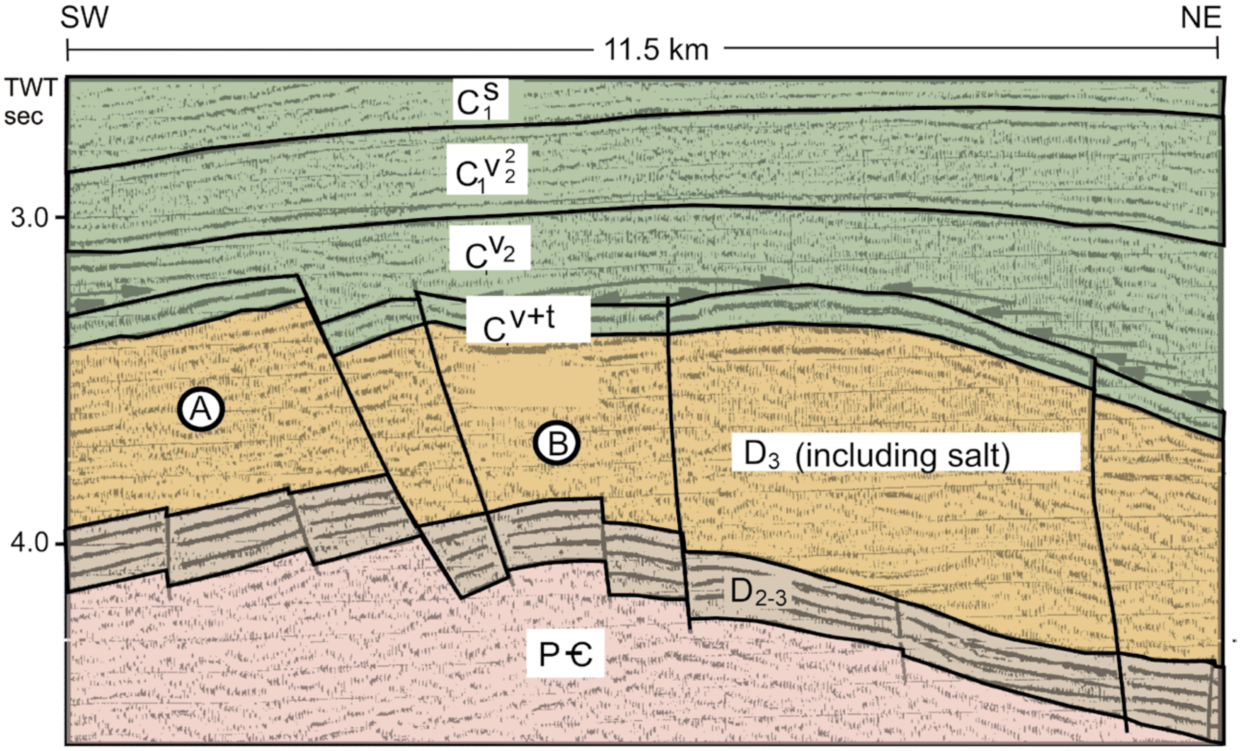

Fig. 10. Seismic sections (located in Fig. 2), showing block rotation and extensional faulting involving basement at the end of the early Visean with the continuation of salt structure formation at the beginning of the late Visean. Lithostratigraphic traps formed at the beginning of the late Visean on the limb of the growing anticlinal fold (labelled B) and on the footwall (labelled A) of a normal fault as a result of syn-tectonic pinching out of sedimentary layers (black arrows). Abbreviations are the same as in Figure 4.

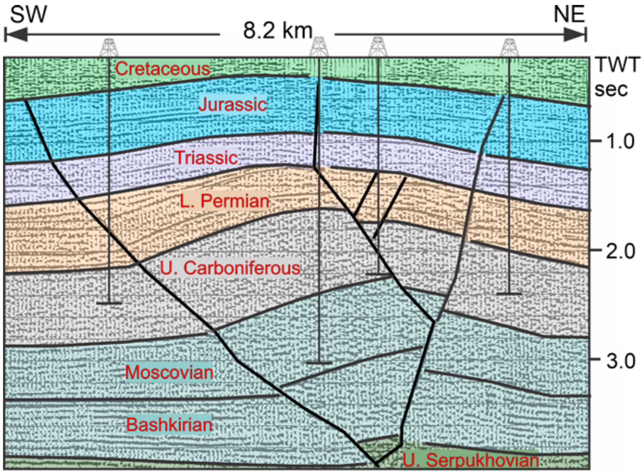

Fig. 11. An interpreted seismic section, showing a typical high-amplitude anticlinal fold that formed, owing to the tectonic and salt movements at the end of the Carboniferous to early Permian with renewed growth in the Late Cretaceous–early Cenozoic. The structure is located on an extended salt wall between salt diapirs consisting of Devonian salt and having overhangs at the level of Permian sequence like diapirs shown in Figure 4 (section E–F). A large gas field was discovered in the uppermost Carboniferous–the lowermost Permian sandy sediments. The Permian chemogenic deposits, including Permian salt layers over the whole productive area, as well as the Devonian salt of a diapir overhang at the periphery of the structure, serve as good quality seals for gas pools.

In the south-eastern part of the basin, near the transition to the DF, lower Serpukhovian and middle Carboniferous coals are oil-prone and gas condensate-prone, respectively, and gas in this area may be sourced from the latter (Sachsenhofer *et al.*, 2010).

The late Carboniferous and early Permian sediments of the axial part of the DDB contain coal and shales with TOC of 0.2–1.1% that have reached conditions for oil and gas generation only in the deepest, south-eastern part of the DDB. Mesozoic source rocks are absent and are immature for the generation of hydrocarbons (Arsiriy *et al.*, 1989; Kabyshev *et al.*, 1998).

“Primary” hydrocarbon fields of the DDB, meaning those associated with short lateral and vertical migration distances and having closely associated source rocks, occur in a variety of structural (Figs 9, 10, 14; fault blocks, anticlines), stratigraphic (Devonian reefs, sand pinch-outs) and combined traps that developed during and shortly after the deposition of the reservoir strata and sealing lithologies (Figs 10, 14). They include small Devonian-hosted reservoirs and stacked reservoir/seal pairs (2–6 levels), occurring in the cyclical lower Carboniferous series (Kabyshev *et al.*, 1998). “Secondary” fields, those associated with a greater degree of vertical migration of hydrocarbons from deeper levels, including those from destroyed ‘primary’ occurrences that had existed at deeper levels, are trapped in structures, related to the diapiric ascent of Devonian salt, which occurred in conjunction with post-rift tectonic movements (cf. Stovba and Stephenson, 2003). Salt diapirs, associated with

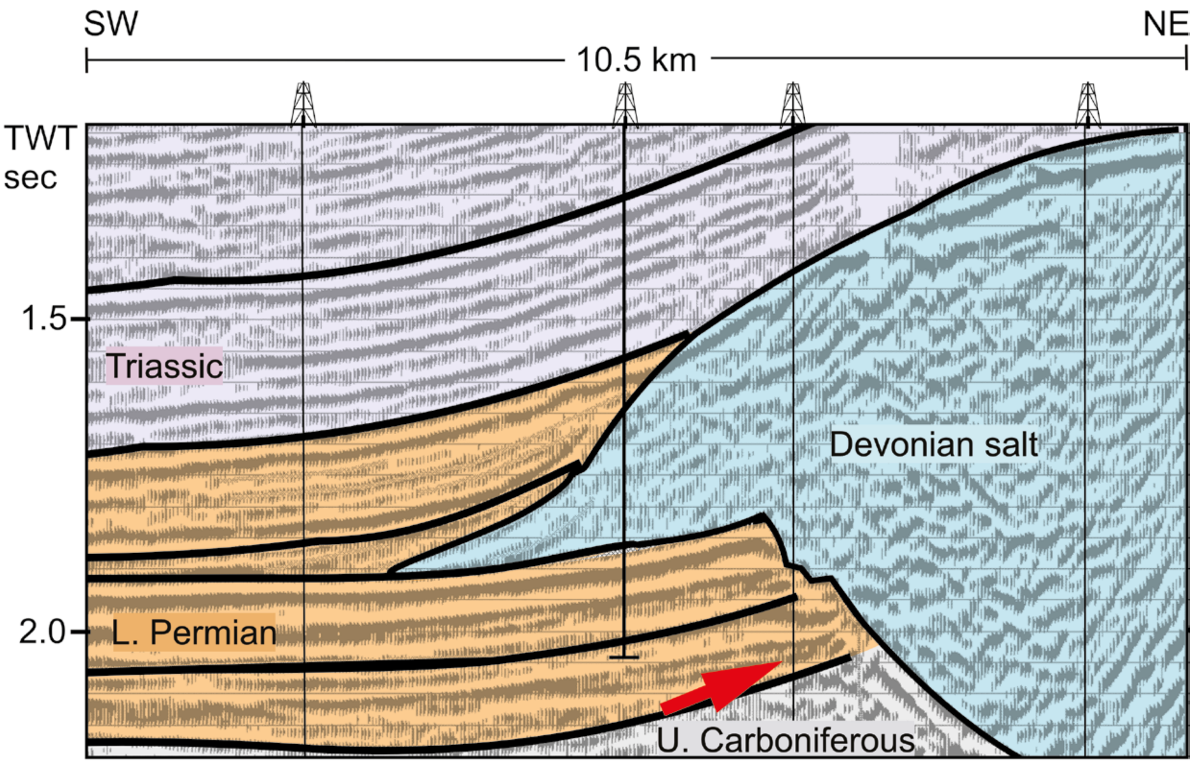

Fig. 12. An interpreted seismic section showing Devonian salt extruded onto the surface in the early Permian and covered progressively by younger lower Permian units. The growth of the concordant salt structure over the salt diapir was very slow during the Mesozoic. Significant growth of the salt anticline occurred by intrusion of Devonian salt into the existing salt overhang during the regional compressional event at latest Cretaceous–earliest Paleogene times. Large gas fields were discovered in the vicinity of the salt diapir in the lowermost Permian sandy sediments. The productive interval of the lowermost part of the lower Permian sequence is shown with a red arrow. The Devonian extruded salt together with lower Permian salt layers on the continuation of Devonian salt tongues created a regional seal for gas accumulations in the lower Permian succession.

hydrocarbon reservoirs in the prolific upper Carboniferous to lower Permian series, are broken by faults that have facilitated migration from below (Figs 8, 11–13). Most of these traps finally developed during Mesozoic time and are characterised by large hydrocarbon reserves (Kabyshev *et al.*, 1998). Mesozoic-hosted reservoirs contain oil and gas that has migrated from older formations through gaps in the regional Permian salt seal. Sealing conditions, in general, are most favourable in the middle parts of the DDB, but deteriorate towards the shallower, north-western parts of the basin, where shales are sandier, and towards its deeper south-eastern parts, where shales are more brittle, owing to their greater degree of diagenesis.

Potential for increased hydrocarbon production

Several exploration concepts are typically recommended in the DDB for the discovery of large new fields of conventional hydrocarbons (Chirvinskaya and Sollogub, 1980;

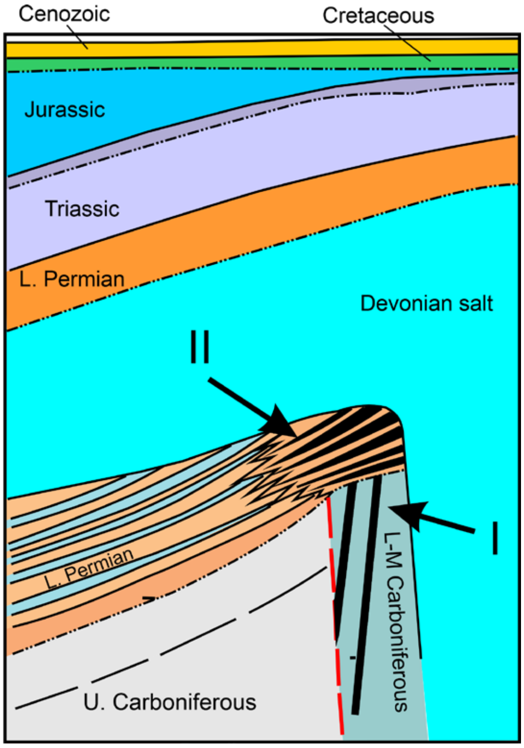

Fig. 13. Geological section, showing layers of redeposited sedimentary rocks (labelled II) originally contained in Devonian salt layers or captured by the salt during its extrusion to the palaeosurface and deposited near the diapir stem as a result of salt dissolution during early Permian (adopted from Kolomyec *et al.*, 1984). The beds of redeposited rocks overlie the highly tilted at an angle of 80° and uplifted (a few km) block of lower and middle (L–M) Carboniferous (labelled I). Large gas and condensate fields were discovered in high-quality reservoirs formed in the redeposited sediments and the tectonic block beneath the Devonian salt overhang. Productive layers are shown in bold black lines.

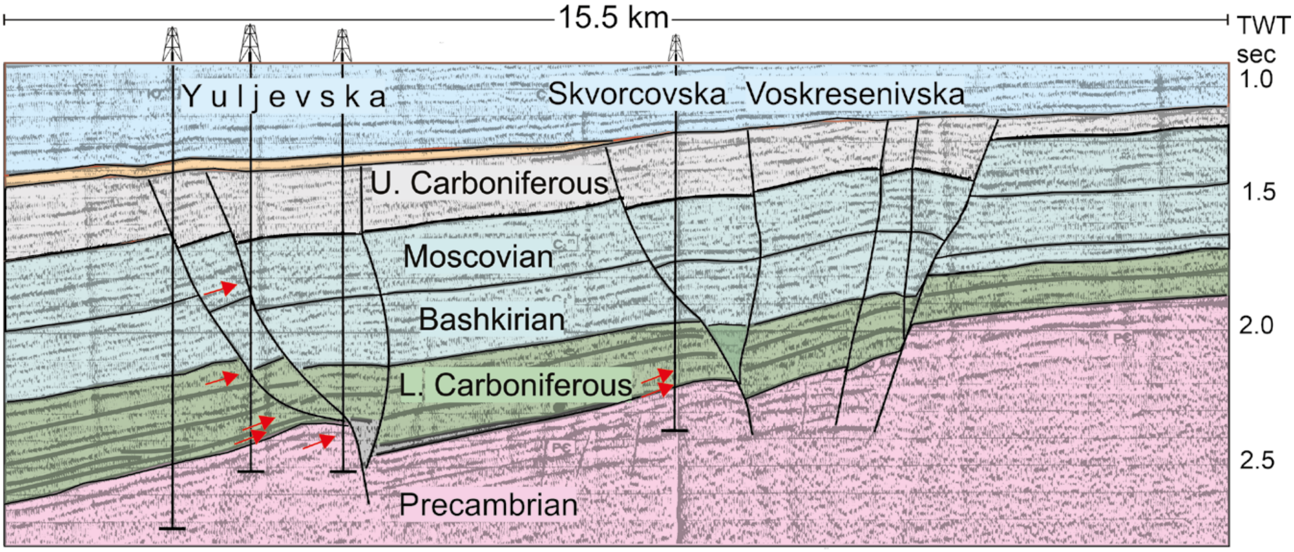

Fig. 14. An interpreted seismic section, showing typical hydrocarbon traps within the northern rift shoulder of the Dniepr-Donets Basin, where the Devonian salt is absent (modified from Stovba and Stephenson, 2003). Hydrocarbon deposits associate with small anticlines and tectonic blocks formed due to extensional events in the middle of Serpukhovian, early Carboniferous and at the end of Carboniferous to the beginning of the Permian. Hydrocarbon fields in the area crossed by the seismic line are discovered in the crystalline basement and lower and middle Carboniferous sediments in the area of Yuljevska and Skvorcovska low-amplitude structures. Approximate locations of productive reservoirs are shown with red arrows.

Varychev *et al.*, 1981; Arsiriy *et al.*, 1989; Vysochansky, 1991; Kivshik *et al.*, 1993; Kabyshev *et al.*, 1998, 2001; Samoylyuk *et al.*, 2003; Roslyi, 2006, 2012; Kryvosheyev *et al.*, 2007, 2018; Lukin, 2014; Golub, 2018a; Lukin *et al.*, 2018, 2020; Samchuk, 2022). These include: (a) searching for gas at great depths (more than 6 km) on undrilled anticlines and beneath known hydrocarbon occurrences, mainly associated with large anticlines, such as those shown in Figures 8, 9, and 11; (b) the mapping of lithostratigraphic traps (Fig. 5) in the southern and northern pre-flank zones of the Dniepr graben (labelled II and IV in Fig. 4) and on the slopes of anticlinal folds in sediments, deposited during the syn-tectonic growth of these anticlines (Fig. 10); and (c) searching for tectonic blocks and remnants of anticlines, which are bounded by salt stems and sealed (overlapped) by salt diapir overhangs and Permian salt strata, similar to the traps shown in Figures 12 and 13, respectively.

Great depths. With the introduction of modern drilling and 3D seismic technologies, significant progress has been made over the past few years in discovering several highly productive (2–5 x 10^5 m^3/d [7–17.7 MMcf] per well) gas fields at depths of up to 6.7 km from reservoirs with relatively high porosity and permeability (e.g., Roslyi, 2012; Lukin, 2014; Golub *et al.*, 2018a; Lukin *et al.*, 2020). Despite high capital expenditures, it is still expected that this direction of exploration activity will increase hydrocarbon production significantly in the coming years.

Stratigraphic traps. Several hydrocarbon fields or more in the DDB probably are entirely associated with stratigraphic traps in the lower Carboniferous sequence (Ivanyuta *et al.*, 1998; Kryvosheyev *et al.*, 2007, 2018; Lukin *et al.*, 2018, 2020). Available palaeogeographic reconstructions show that opportunities to search for stratigraphic traps exist over extensive areas of the DDB. For example, Figure 5 shows four of more than 40 palaeogeographic maps of lower Carboniferous productive strata. These maps highlight wide areas of possible stratigraphic traps. Nevertheless, exploration for such traps remains high-risk because of the lack of reliable geological and geophysical data and convincing criteria for the presence of hydrocarbon accumulations in them, even with high-quality 3D seismic and drilling data. Therefore, most likely, this very promising direction of hydrocarbon exploration will not make a significant contribution to hydrocarbon production for a long time to come.

Tectonic blocks (structural traps) near the walls of salt diapirs. Many researchers consider that the most promising strategy for the discovery of new hydrocarbon fields is associated with isolated tectonic blocks, formed during the growth of salt diapirs (Kolomyec *et al.*, 1984; Vysochansky, 1991; Kabyshev *et al.*, 2001; Lizanets and Nekrasov, 2002; Stovba and Stephenson, 2003; Samchuk, 2022). Indeed, as noted above, some hydrocarbon fields near the walls of salt diapirs are associated with inclined (up to 60–90°) tectonic blocks (e.g., Fig. 13). However, hydrocarbon fields have not been found near many salt diapirs, even though most of them are located in areas with numerous hydrocarbon occurrences, associated with salt structures (Fig. 2). Furthermore, the size of the inclined tectonic blocks, and consequently of discovered hydrocarbon fields, is very small, compared to the entire near-diapiric area, where these tectonic blocks have been mapped.

It is currently unclear whether the known size, structure and location of hydrocarbon fields near the walls of salt diapirs are a consequence of the formation of these diapirs or whether many more hydrocarbon traps could have formed in the vicinity of salt diapirs but have not been discovered simply because of the lack of data from modern drilling, and seismic and gravimetric studies. An additional cause of uncertainty may be the lack of precise knowledge of the formation of salt diapirs and the deformation of the associated sedimentary strata, given the composition and thickness of the salt layers and their sedimentary overburden, as well as changes in these parameters with time. Indeed, as Stovba and Stephenson (2003) showed, although the growth of all salt diapirs and sediment deformation during salt movement to the palaeosurface to form hydrocarbon traps were subject to factors linked to DDB evolution, each salt diapir has its own growth characteristics, which depend on its location in the basin and the local, geological environment. Various examples of possible traps formed beneath salt overhangs, near salt stems and above salt diapirs are shown in Figures 12, 13, and 15–17.

The first stage of salt diapir formation, shown in Figure 15, occurred in the Serpukhovian (early Carboniferous), when Devonian salt broke through its sedimentary cover and formed a salt stem and its overhang. This diapir was then overlain by horizontally bedded Carboniferous sediments, with a total thickness of about 6 km. The resumption of salt diapir growth at the Carboniferous-Permian boundary began with the formation of a large anticline. The core of this anticline is a salt pillow, formed by Devonian salt, intruded from the parent Devonian layer to the level of the upper Serpukhovian deposits. During this growth, the top of the anticline was subjected to strong erosion until the Devonian salt broke through the sediments and began to flow out to the bottom of the early Permian basin. Simultaneously with the extrusion of Devonian salt, early Permian saline and other chemogenic sediments accumulated in the basin.

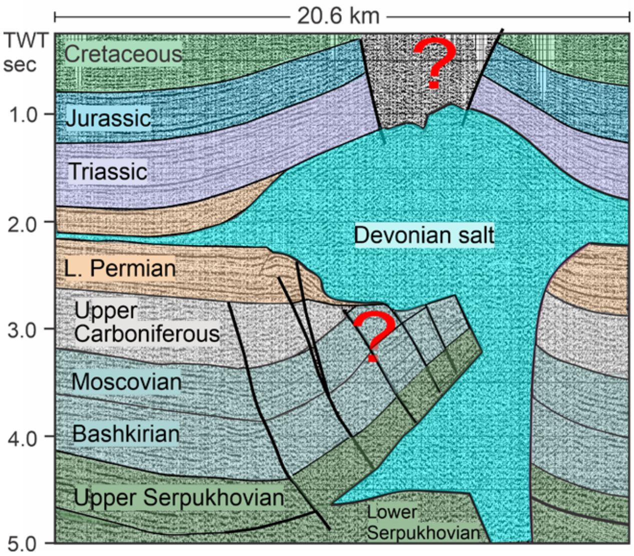

Fig. 15. An interpreted seismic section, showing a salt diapir with overhangs that was formed episodically in the middle of Serpukhovian, early Carboniferous, at the end of Carboniferous to the beginning of Permian and at the end of Mesozoic to the beginning of Paleogene. Red question marks indicate areas with poor seismic image.

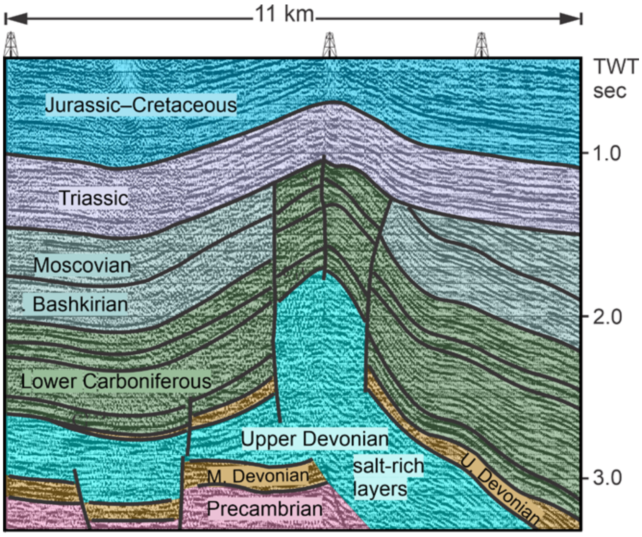

Fig. 16. A salt diapir that grew by pushing up the block of the Carboniferous sediments at the top of salt stem (from Stovba and Stephenson, 2023). The sedimentary block is isolated from the rest of the anticline by faults. The growth of the diapir ended before the Triassic because of the low rate of salt inflow to the diapir from the parent salt layer. The block that was broken from the main Carboniferous sedimentary layer had been uplifted by 1 km before the growth of the diapir ceased until the next phase of salt movements at the end of the Cretaceous.

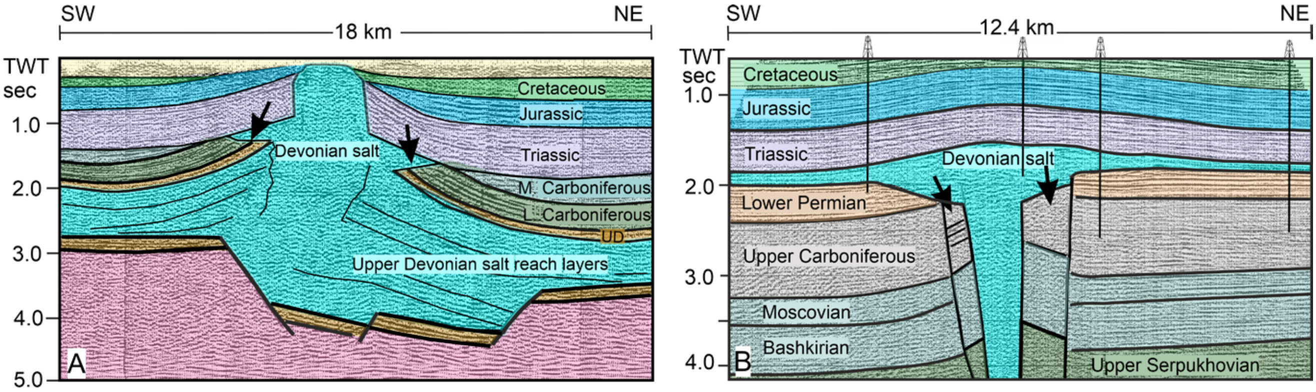

Fig. 17. Interpreted seismic sections (A, B), showing possible undiscovered traps (indicated with black arrows) beneath salt overhangs. UD – Upper Devonian.

The extrusion of Devonian salt virtually ceased by the beginning of the Triassic when the sedimentary cover began to form over the Devonian salt. In the Mesozoic, the intrusion of Devonian salt into the diapir overhang continued slowly and an extensive, but low-amplitude anticline was formed above the salt diapir. Regional compression at the end of the Cretaceous and beginning of the Paleogene promoted more rapid growth of the salt dome (pillow) under the Mesozoic sediments, linked to salt injection into the overhang of the diapir from its stem and simultaneous erosion of Cretaceous sediments at the top of the anticline.

Some seismic and well data reveal that there are salt diapirs, which evolved through the stage of salt-pillow formation by the breaking loose of a column of strata from the surrounding sedimentary succession on the head of a salt plug. This can be seen for the early Permian growth of a salt structure, shown in Figure 16. At the end of the Carboniferous, the sedimentary block above the stem of the salt diapir (Fig. 16) was separated from the rest of the anticline by faults. The block that was broken from the main Carboniferous unit had been uplifted by 1 km, until the growth of the diapir ended before the Triassic. Shear zones could have developed during the last stage of active piercing of the overburden by salt at the end of Carboniferous to early Permian. The growth of the salt diapir stopped because of the low rate of salt inflow from the parent salt layer. Regional compression of the DDB caused the resumption of the salt movements at the end of the Cretaceous without any brittle deformation in the Mesozoic sequence.

The examples in Figures 13 and 15 show that, although the formation of salt diapirs in the DDB went through a salt pillow stage, with the formation of a pronounced anticline in the sedimentary cover overlying the Devonian salt and intense erosion of the arch of this anticline, rupture deformations in the sedimentary cover and the formation of tectonic blocks before the salt was brought through to the surface also played a very important role. The vertical displacement of tectonic blocks under the influence of moving Devonian salt could reach more than 1 km (Figs 13, 16). Figure 17 provides additional examples of possible traps near the walls and beneath the overhangs of salt diapirs that developed in much the same way as the diapir shown in Figure 15; an exception is the diapir shown in Figure 17A, which grew further at the end of the Cretaceous, when it pierced the Mesozoic cover.

The difficulties in obtaining detailed seismic information on the structure of the sedimentary cover near the walls of salt diapirs can be clearly demonstrated by 2D seismic profiles, acquired in the 1990s and shown in Figures 15, 16, and 17B. Here, the structure of the sedimentary cover under the salt overhangs is poorly represented by the 2D seismic image. Nevertheless, the above examples demonstrate that exploration of hydrocarbon traps under salt diapir overhangs, such as those proven (Figs 12, 13), is a realistic way to discover new hydrocarbon fields near salt diapirs at depths of less than 6 km. It is important to note that exploration and/or stratigraphic dry wells have been drilled near almost all of the diapirs. However, these wells were drilled in many cases beyond the limits of possible hydrocarbon traps, as shown, for example, in Figure 17B. This means that the drilling of many salt diapirs should be continued, even if unsuccessful wells were drilled there during earlier exploration campaigns.

The results of existing exploration are clearly not enough to answer one of the key questions: was the formation of steeply inclined (up to 90°) tectonic blocks near the stems of salt diapirs a common consequence of the growth of many diapirs, especially those that have salt overhangs at the level of the Permian sediments (Figs 15–17). Numerical modelling of the formation of salt diapirs in the geological conditions of the DDB has provided a reasonable explanation of the mechanisms, responsible for the uplift of sedimentary blocks to the palaeosurface, as well as for the rotation of these blocks (Stovba *et al.*, 2000; Vengrovich, 2010; Vengrovich and Stovba, 2019). In addition, the modelling indicates that highly tilted blocks, which are excellent hydrocarbon traps, could have formed near many salt diapirs, and their sizes could be significantly larger than those already known in the DDB (Vengrovich and Stovba, 2019).

Underexplored anticline structures and hydrocarbon fields. It is widely believed that almost all anticlinal traps in the DDB, which formed as a result of tectonic movements and halokinesis, are adequately defined by exploratory drilling. Therefore, there is a low expectation of the discovery of large oil and gas occurrences in the sedimentary strata of these anticlines at the depths penetrated by wells. However, this conclusion is contradicted by the discovery in the early 2000s of a large gas-condensate field in the Kobzyv structure, where more than ten “dry” wells had been drilled previously (e.g., Roslyi, 2006). This and other similar cases led the authors to pay special attention to the revision of the results of exploration drilling and existing geological models for a number of large anticlinal folds located both within the anticlinal belts broken by diapirs and single salt structures in the south-eastern part of the DDB. These include anticlines unsuccessfully explored by several dry wells and anticlines, where gas accumulations have been discovered and are being developed. The results of these studies for just two anticlinal folds are summarized below.

Figure 18 shows a large anticline with an area of about 150 km^2 and with an amplitude of about 1,000 m. The structure was explored in the mid-twentieth century, using more than 60 shallow structural mapping wells, with depths ranging from 160 to 1,200 m. Then, over the next thirty years, six deep exploratory and stratigraphic wells were drilled within the crest of the fold (Fig. 18). The age of the oldest sedimentary rocks uncovered by the boreholes is late Serpukhovian (early Carboniferous). Two wells also penetrated Devonian salt. One well penetrated Devonian salt beneath Bashkirian sediments of the middle Carboniferous, and the other borehole penetrated the salt beneath the upper Serpukhovian sediments of the lower Carboniferous. This indicates that the anticline was formed over a salt diapir, which, like many others in the DDB (see Fig. 8 and the middle part of section E–F in Fig. 4), broke through its sedimentary cover in the late Serpukhovian time and stopped growing by the middle Carboniferous.

The resumption of tectonic activity and halokinesis in the late Carboniferous and late Mesozoic led to the formation of the anticline above the diapir stem. Existing 2D

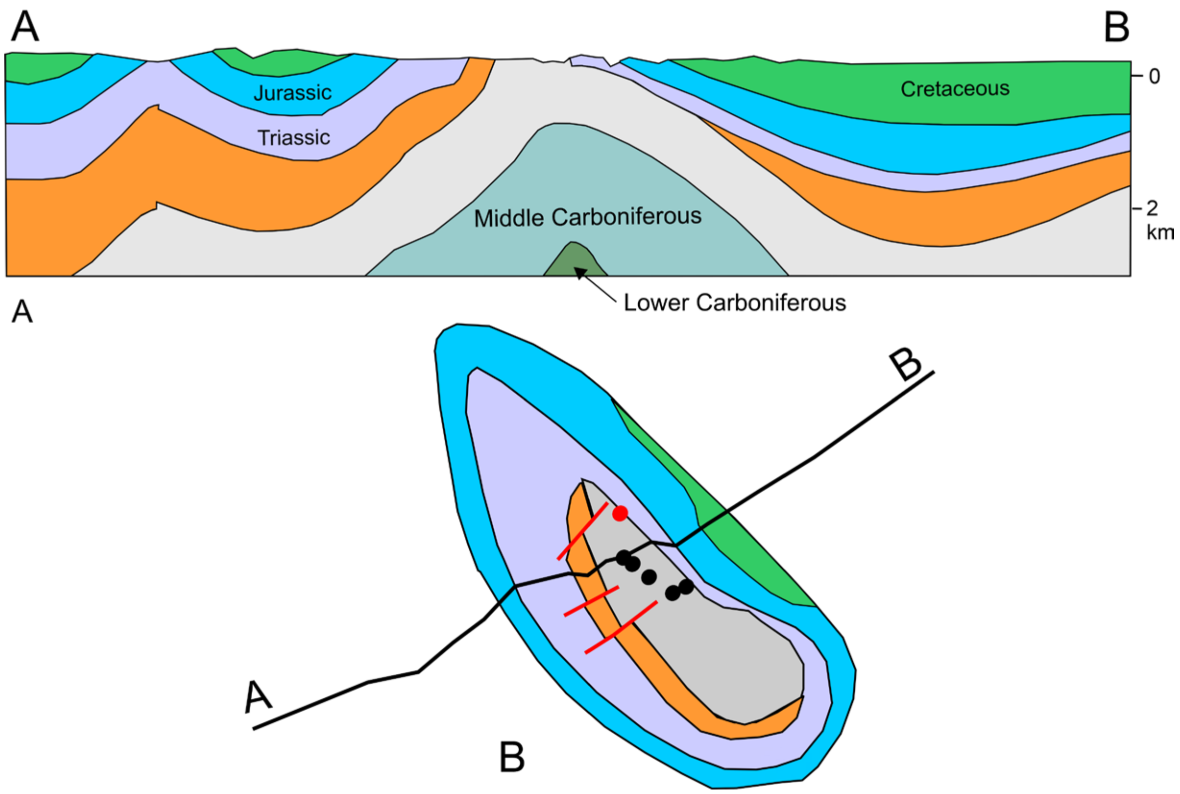

Fig. 18. Geological section (A) and geological map (B), characterising the structure of an underexplored anticline in the south-eastern part of the DDB. The red circle is the location of well characterised in Figure 22. Locations of other wells are shown in black circles.

seismic profiles are insufficient to explore fully the structure of this anticline. Although detailed geological mapping, using numerous shallow structural and deep exploration stratigraphic wells, indicates that the topography of the Carboniferous and younger sedimentary strata above the Devonian salt body is fairly well studied (Fig. 18), the available data do not allow definition of the shape of the salt diapir and the presence of its overhang at the level of the upper Serpukhovian strata.

The drilling of shallow and deep wells recorded numerous oil and gas shows from upper Carboniferous deposits, which lay at depths of more than 2 km before the final formation of the anticline at the end of the Mesozoic. One of the structural mapping wells even gave a small gas inflow from a depth of 189 m. This is evidence of an active petroleum system. Unfortunately, of the six exploration and stratigraphic deep wells, only two were subsequently tested for prospective intervals. Only one interval of the lower Carboniferous formation showed a small gas flow from one of the two wells tested.

The reasons why four wells remained untested are unknown. Most likely, it was due to some technical problems in these wells. Judging by the analysis of a large number of well reports, such problems occurred frequently in the DDB during the last century. Thus, previous prospecting efforts were unsuccessful, as none of the six deep wells yielded commercial hydrocarbons. However, reinterpretation of the available logging data shows that there are at least three potentially productive intervals in the Carboniferous strata. For example, the reinterpreted well-logging data unambiguously indicate the presence of reservoir rocks in the middle Carboniferous strata (Fig. 19). The thickness of these reservoir rocks is 19 m and their porosity varies from 7 to 12.5%, which is comparable to the parameters of reservoirs in the nearby gas fields. The reservoir rocks in the well were not tested, but according to the results of re-interpretation, very low spontaneous potential values clearly indicate the presence of gas in these reservoirs rocks with a high degree of probability (Fig. 19).

The results of re-interpretation of well-log data and other geological and technological information clearly demonstrate that the anticline structure shown in Figure 18 was underexplored. The total prospective resources, preliminarily estimated for two reservoirs in the middle Carboniferous succession and one in the lower Carboniferous sequence at depths of less than 3 km, could reach 50 x 10^9 m^3 [1.8 Tcf] of gas. This estimate is based on the size of the potential productive area, a reservoir thickness of 15 to 40 m for each of the three reservoirs, and an average porosity of 10%, assuming that these parameters are maintained throughout the anticlinal structure.

The second illustrative example of the potential effectiveness of revising existing geological models of structural hydrocarbon traps concerns a gas condensate field, located in the area of salt-dome structures, extending to the Shebelynka supergiant gas condensate field. According to available data (Fig. 20), the area of the anticlinal fold, where gas field has been discovered in upper Carboniferous and lower Permian strata, is about 70 km^2, and its amplitude varies from 400 to 1,100 m depending on the stratigraphic level. Nearly

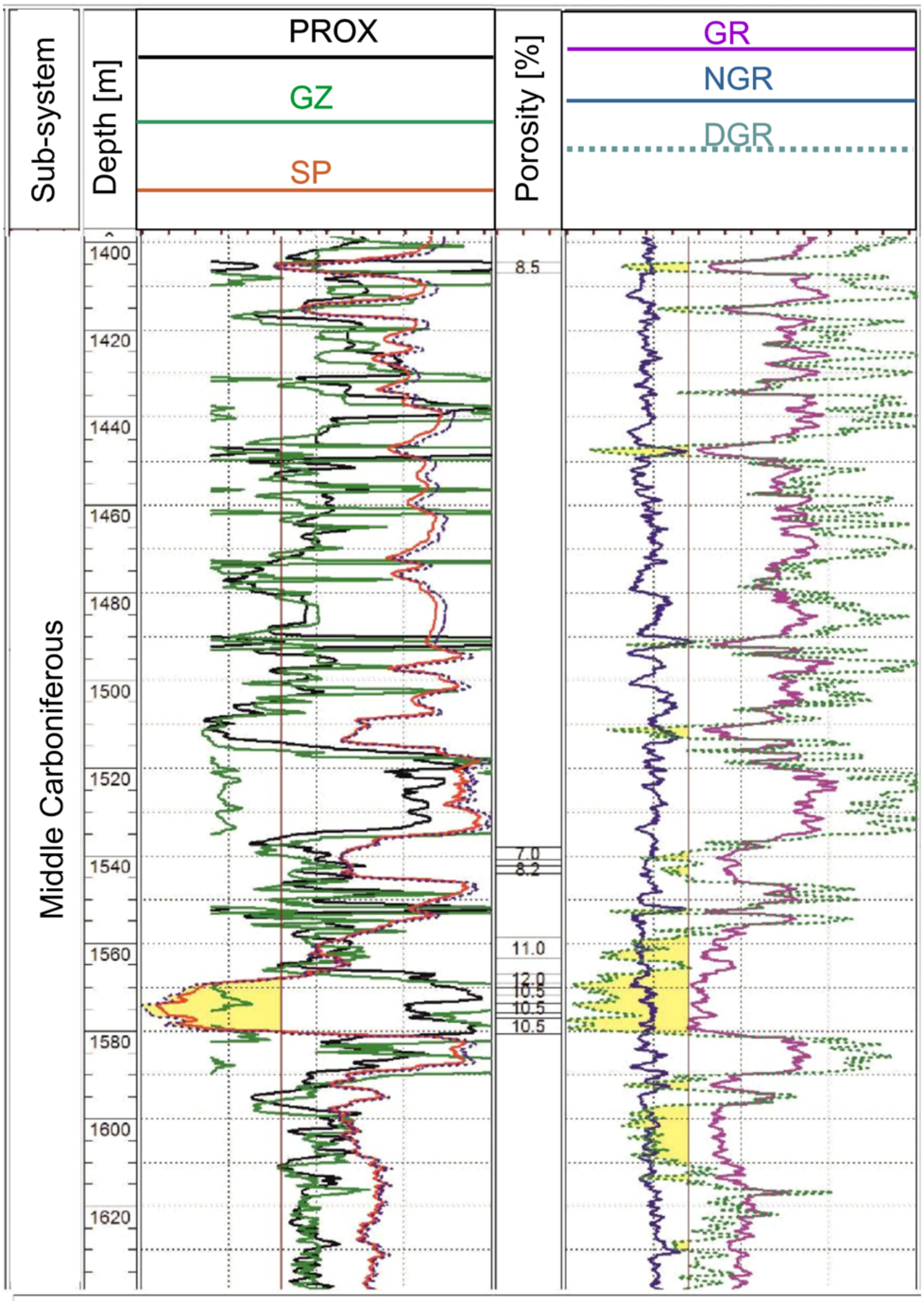

Fig. 19. The re-interpreted logging data for the well located at the top of the anticline structure shown with a red circle in Figure 18. The possible productive interval in the middle Carboniferous sequence is shown with yellow colour. The porosity of sand rocks is between 7.0 and 12.5% that is comparable to other gas deposits discovered at the same sequence in the neighbouring areas. Abbreviations: SP – spontaneous potential; PROX – micro resistivity; GZ – resistivity; GR – gamma ray; NGR – neutron gamma ray; DGR – dual gamma ray.

30 wells have been drilled within the anticline, including structural mapping, exploration, and appraisal wells.

The deepest wells penetrated the lower and middle Carboniferous sediments, but most wells were terminated in the upper Carboniferous sequence. Commercial gas flow was obtained from the lower Permian reservoirs, with maximum daily rates of more than 80 x 10^3 m^3 [2.8 MMcf] and from the upper Carboniferous sediments – > 100 x 10^3 m^3 [3.5 MMcf]. The presence of gas in the middle Carboniferous sediments was also confirmed by tests in several wells, but the flow rate was rather low (up to 1,500 m^3/day [53 Mcf/day]). The lower Carboniferous reservoirs were tested only in one well, but no gas inflows were obtained. However, increased gas content was recorded at a depth of > 5,000 m.

Despite the high gas flow rates obtained from several wells, the total cumulative recoverable gas resources are quite small at just a few billion cubic metres. The existing assessment was based on a summary of well drilling and reservoir testing results. To explain the lack of flow from potentially productive intervals in “dry” wells, the conclusion was made that in some wells, it was because of a sharp deterioration in reservoir properties, caused by lithological changes in the reservoir rocks; in other wells, there had been the destruction of gas occurrences, due to post-sedimentary deformations, including the formation of faults and fractures. Below, using only two wells as an example, the authors show that this conclusion is incorrect and is not based on diagnostic geological and geophysical data.

In order to estimate independently the hydrocarbon resources of the anticline, the available well-logging data for two wells were processed and reinterpreted (the well locations are shown in Fig. 20A). A high gas flow rate (> 100 x 10^3 m^3/day [3.5 MMcf]) was obtained from Formation 2 in well 1 (Fig. 20B). However, in the same well, the highly promising interval of Formation 1, potentially productive according to logging data and having even better petrophysical parameters in comparison with the productive reservoir, was not tested at all. In well 2, the same two potentially productive intervals with very similar petrophysical parameters were not even tested (Fig. 20B). According to well-logging data, the untested reservoirs are gas-saturated and could produce high gas flow rates. The productive area of the lower reservoir could be at least six times larger

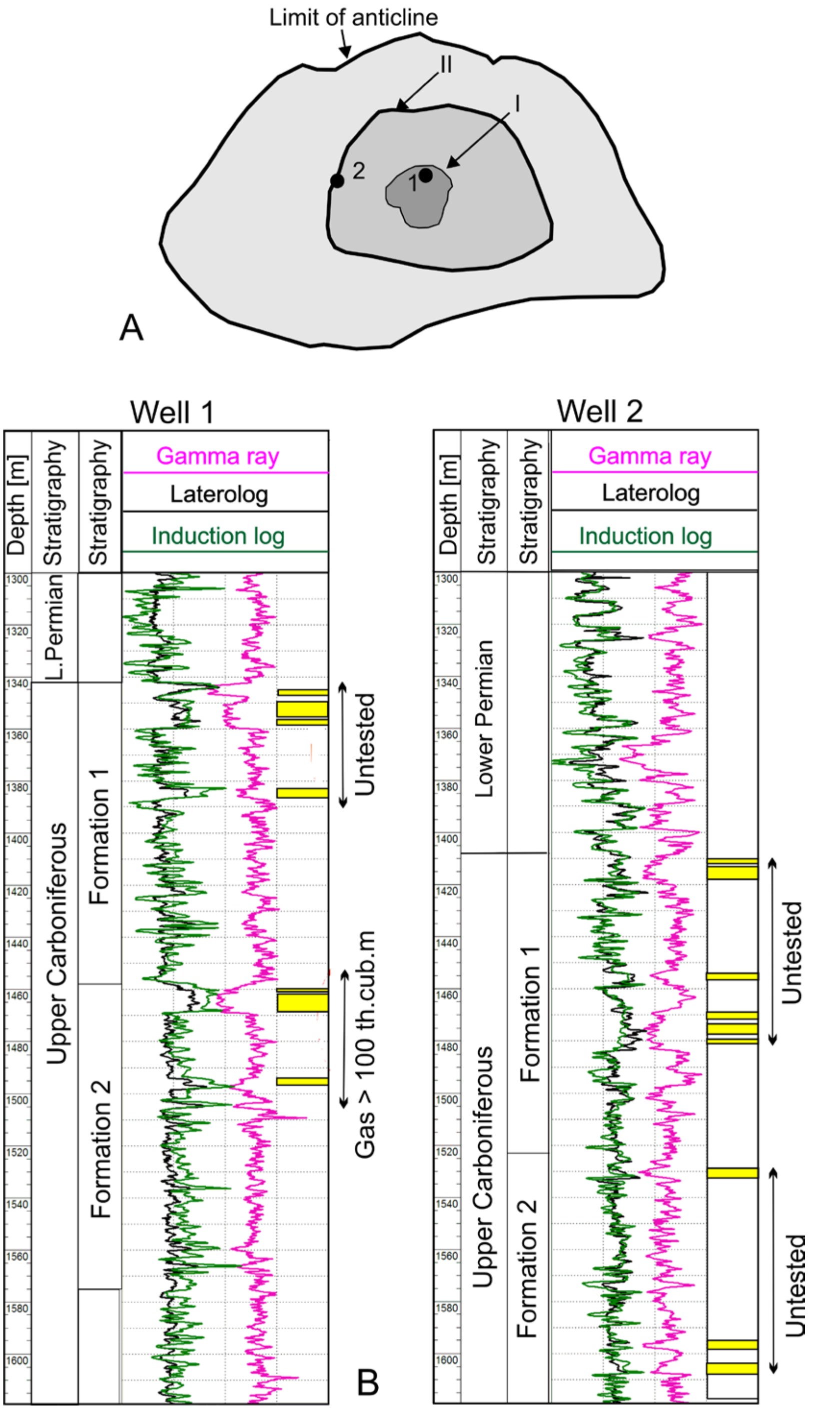

Fig. 20. Simplified map, showing limits of the anticline and hydrocarbon deposits (A) and logging data of wells 1 and 2, drilled within the field (B). I – limit of the area of gas field in the event of the Formation 2 in well 1 being the only productive unit; II – minimal limit of the area of gas accumulation, if the Formation 2 is also productive in well 2. Other explanations are in the text.

(compare contours 1 and 2 in Fig. 20A). An equally large area of productivity may exist for gas accumulations, contained in Formation 1. Preliminary estimates of prospective gas resources, contained in formations 1 and 2 of the upper Carboniferous indicate that these resources may be at least twelve times the official estimate. Taking into account all potential reservoirs, the total prospective resources of the field are some 60 x 10^6 m^3 [2.1 Tcf] and could be even much more if the potentially productive area is wider than area II, shown in Figure 20A. Thus, the hydrocarbon field is clearly insufficiently explored, and the gas resources, contained at depths of less than five kilometres, are significantly underestimated.

These two simple examples indicate that other anticlinal traps, despite negative drilling results, may also be considered understudied and of great interest for further exploration. In addition, there are gas fields in the DDB that can also be considered unexplored and could contain much larger hydrocarbon resources than currently estimated. This offers good potential for further exploration, which could lead to a significant increase in hydrocarbon production from relatively shallow depths (<5 km) in 2–5 years – the time required to re-enter existing wells and to build additional production facilities, assuming the effective revision of the existing geological models of anticlinal traps and existing hydrocarbon fields.

UKRAINIAN CARPATHIANS AND THEIR FOREDEEP BASIN

Geological setting

The Ukrainian Carpathians and their foreland are a part of the North Carpathian Petroleum Province (Pawlewicz, 2006), composed of the fold-and-thrust belt and the foredeep basin trending from NW to SE in western Ukraine (Fig. 1). This province includes the Bylche-Volytsia unit of the Carpathian Foredeep, which is its main gas-producing zone, and the Boryslav-Pokuttya zone of the Outer Carpathians, which produces mainly oil and condensate (Fig. 21). Detailed information about the stratigraphy, tectonics, evolution, and hydrocarbon resources of the Bylche-Volytsia and Boryslav-Pokuttya zones can be found in key papers published by AAPG in 2005 (Oszczypko *et al.*, 2005; Popadyuk *et al.*, 2005a, b; Ślączka *et al.*, 2005; Sozański *et al.*, 2005). Therefore, only the basic geological information about this region is provided below.

The Outer Carpathians region is a flysch belt, made up of a stack of nappes and thrust sheets (e.g., Krzywiec, 2018; Fig. 22). Two of the nappes, namely Boryslav-Pokuttya and Skyba, which together constitute the Boryslav-Pokuttya zone (Figs 21, 22), contain the majority of the oil and condensate fields, discovered in western Ukraine. The Boryslav-Pokuttya Nappe is the most north-eastern nappe and the outermost tectonic unit of the Ukrainian Carpathians; it comprises a complex set of superimposed thrust-sheets, consisting of Cretaceous to Lower Miocene flysch strata, overlain by molasse (Koltun *et al.*, 1998; Popadyuk *et al.*, 2005a; Ślączka *et al.*, 2005). Most fields were discovered in the sedimentary succession of this nappe (Popadyuk *et al.*, 2005a). It is overlapped by the Skyba (Skole) Nappe (Fig. 21), which is the more internal structural unit of the Flysch Carpathians (Popadyuk *et al.*, 2005a) and consists of an Upper Cretaceous to Paleogene succession (Ślączka *et al.*, 2005; Fig. 22). Most of the Miocene sediments and, in part, the Paleogene–Cretaceous rocks were eroded within the unit.

The Carpathian Foredeep (Figs 21, 22) contains a thick Miocene molasse unit that is underlain by the basement of the East European Platform (Oszczypko *et al.*, 2005; Popadyuk *et al.*, 2005b). The foredeep includes its outer (Bylche-Volytsia unit) and inner (Sambir unit) parts. Most gas fields in western Ukraine are discovered within the Bylche-Volytsia zone (Fig. 21). The Bylche-Volytsia unit of the Outer Carpathian Foredeep is filled with the Middle Miocene (Badenian and Sarmatian) marine and evaporite deposits, which range from a few hundred metres in thickness in the northern marginal part to as much as 5,000 m in the south-eastern part. The Bylche-Volytsia zone is an autochthon, which was formed on the south-western margin of the East European Platform, at the final stage of the formation of the Carpathian foredeep basin, beginning in the Middle Miocene. The Miocene sedimentary cover of the Bylche-Volytsia zone is weakly dislocated and superimposed on Paleozoic and Meso–Neoproterozoic rocks, which are overlapped by Jurassic and/or Cretaceous sediments (Fig. 22).

Hydrocarbon resources

The Ukrainian Carpathians represent one of the oldest producing provinces in the world (Koltun *et al.*, 1998; Fedyshyn, 1999; Hnylko and Vaschenko, 2004; Sozański *et al.*, 2005; Pawlewicz, 2006; Radkovets *et al.*, 2016; Craig *et al.*, 2018; Krzywiec, 2018). Current estimates of the oil reserves of the Ukrainian Carpathians and their foredeep basin amount to 30.1 x 10^6 tons [225.4 MMbbl], and oil production is carried out at 55 hydrocarbon fields (Anonymous 2, 2022). The gas reserves of the Ukrainian Carpathians and their foredeep basin amount to some 97 x 10^9 m^3 [3,4 Tcf] (Anonymous 2, 2022), and production takes place at 139 fields. In 2020, the annual production in the western Ukraine came to some 546 x 10^3 tons [4,1 MMbbl] of oil and 1.4 x 10^9 m^3 [0,5 Tcf] of gas (Korpan *et al.*, 2021).

Exploration activity

Active exploration in the Carpathians began in the mid-1800s, followed by discovery of 115 oil and gas fields. In 1861, one of the world's first oil rigs was constructed there (Sozański *et al.*, 2005; Krzywiec, 2018). By 1909, the area was producing 5% of the world's oil, or about 40,000 barrels per day, and had more than 12,000 rigs (Sozański *et al.*, 2005; Craig *et al.*, 2018; Krzywiec, 2018). The oil and gas industry boomed in the region, when the Boryslav Oil Field (1893) and the Dashava Gas Field (1920), Europe's largest at that time, were put into commercial production. Most of the oil discoveries in the region had been made by the 1990s and only a few minor oil fields were discovered in the past 30 years. Such a significant decline in exploration activity

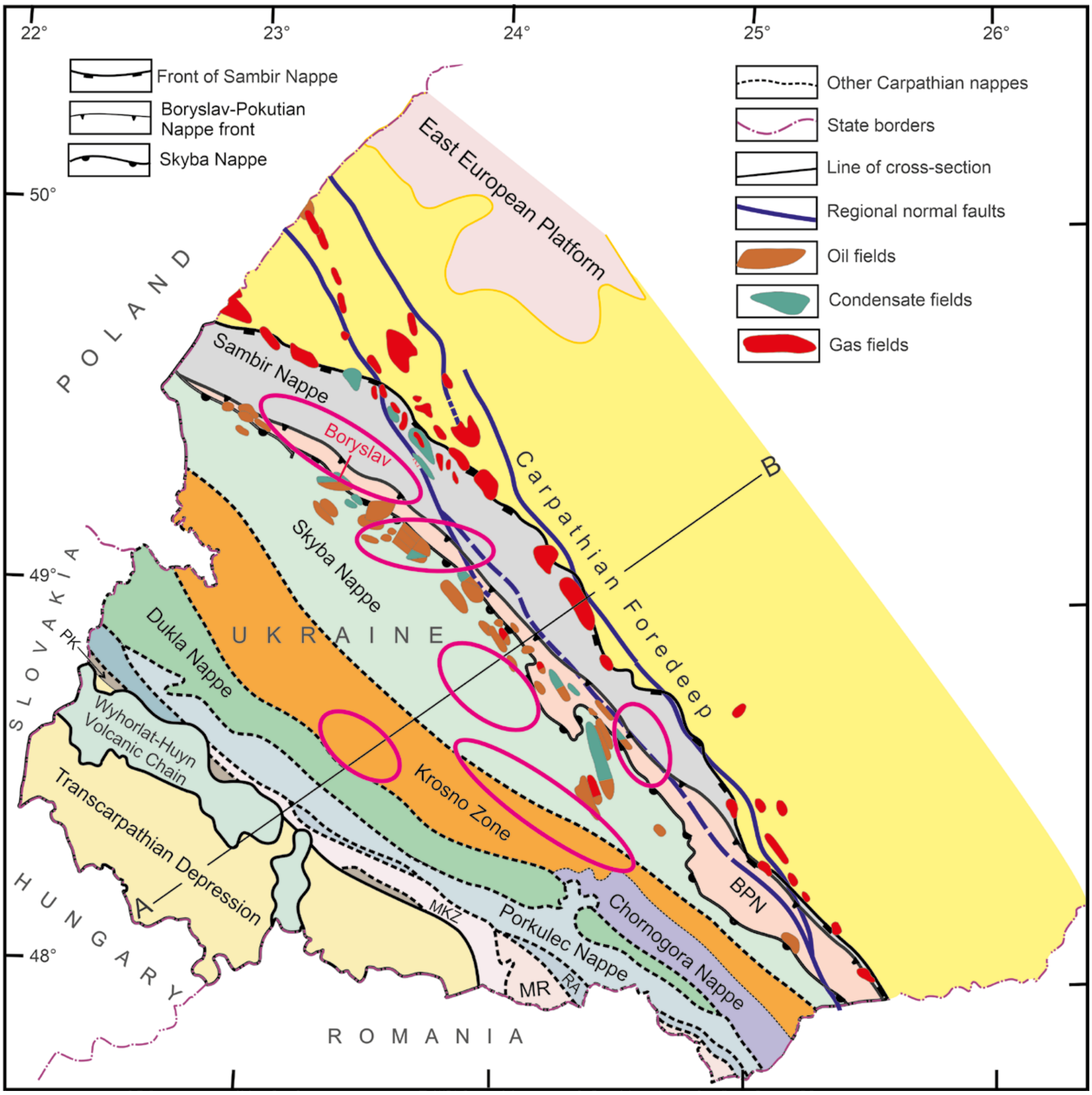

Fig. 21. Tectonic map of the Ukrainian Carpathians (simplified after Ślączka *et al*., 2006), showing locations of the HC fields (after Popadyuk *et al*., 2005a, b). Red circles show six areas that are prospective for the discovery of new hydrocarbon fields. Abbreviations: BPN – Boryslav-Pokuttya Nappe; MKZ – Marmarosz Klippen Zone; MR – Marmarosz Massif; PK – Pieniny Klippen Belt; RA – Rachiv Nappe. Boryslav oil field cross-section (Fig. 23) is shown as a short red line.

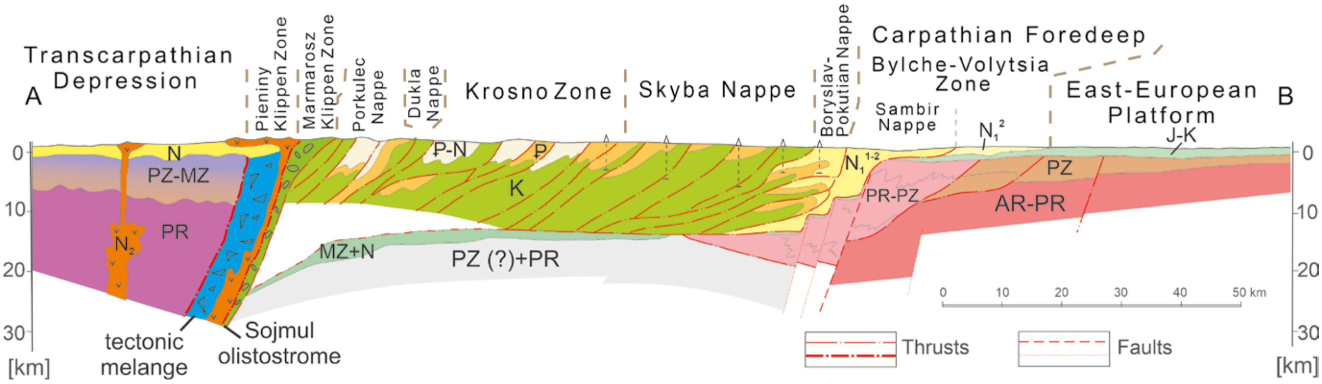

Fig. 22. Ukrainian Carpathians, cross-section A–B (simplified from Kruglov *et al*., 2007). The location of the cross-section is shown in Figure 20. Abbreviations: AR – Archean; J – Jurassic; K – Cretaceous; MZ – Mesozoic; N – Neogene; N_2 – Late Neogene andesite-basalts; N_1^2 – Middle Miocene; $N_1^{1\text{-}2}$ – Early–Middle Miocene; P – Paleogene; PZ – Paleozoic; PR – Proterozoic.

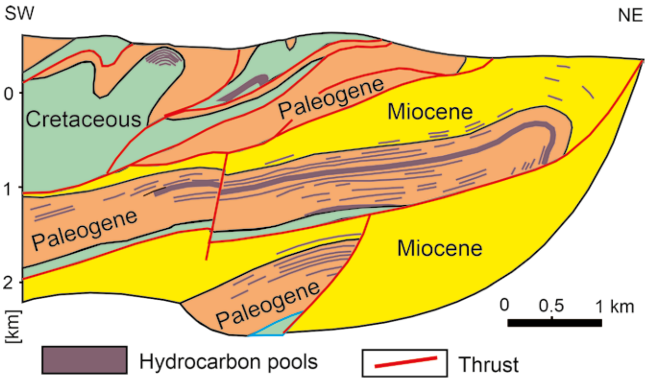

Fig. 23. Boryslav Oil Field cross-section (modified from Fedyshyn, 1999). The location of the field is shown in Figure 21.

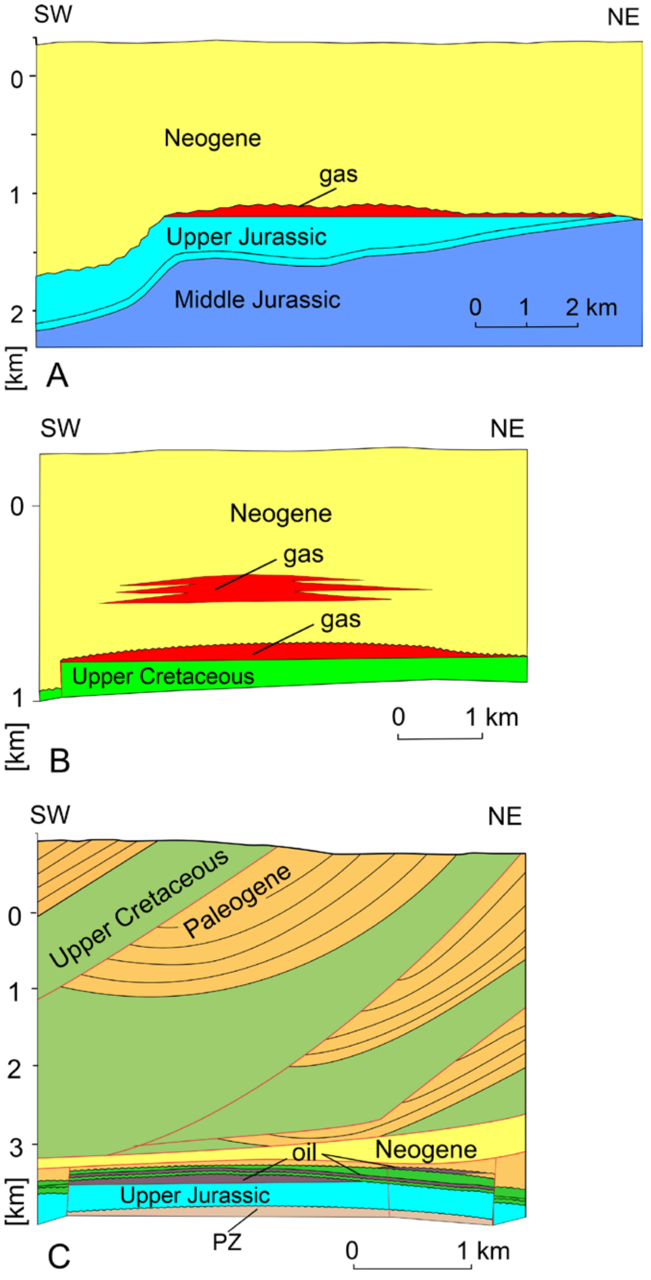

Fig. 24. Simplified geological sections of typical gas fields, discovered in the Bylche-Volytsia zone (A–C; modified from Fedyshyn, 1999). PZ – Paleozoic.

in the region was related mainly to a lack of funding for exploration and production over recent years.

Almost the entire sedimentary succession (Jurassic, Cretaceous, Miocene) of the Carpathian Foredeep and the upper nappes of the Outer Carpathians contain numerous productive reservoir horizons in different formations (Popadyuk *et al.*, 2005a, b). Most oil and condensate accumulations were discovered in the Boryslav-Pokuttya Nappe of the Carpathians at depths of 3–4 km. Only a few relatively small fields were discovered in the Skyba Nappe at depths of less than 2 km (Fig. 21). In all the fields of the Boryslav-Pokuttya Zone, hydrocarbon accumulations are located in structural or combined structural-stratigraphic traps, formed before the Pliocene in the Upper Cretaceous–Paleogene strata, but the predominant traps are confined to anticlines, bounded by detachments. The gas fields, discovered in the Bylche-Volytsia zone, mainly occur in three main types of trap in the Upper Jurassic, Cretaceous and Miocene: (i) stratigraphic trapping beneath and above unconformities; (ii) thrust-related trapping along the frontal Sambyr thrust; and (iii) normal-fault-related trapping, associated with the regional fault, which created low-amplitude anticlinal rollover structures (Fedyshyn, 1999; Popadyuk *et al.*, 2005b).

Only the uppermost part of the Ukrainian Carpathians (up to a depth of about 3–4 km) has been drilled intensely. Most discoveries have stacked productive horizons (Figs 23, 24), which makes drilling each new well more profitable, if one approaches both brownfields and green fields properly, in terms of the accurate construction of their geological model and production technology. A good example of a field with multilevel positions of hydrocarbon accumulations is the Boryslav Oil and Gas Field (Fig. 23). Twenty-two oil and gas pools have been discovered so far (Fedyshyn, 1999). By 2002, the cumulative production at the field had reached about $32x10^6$ tons [240 MMbbl] of oil and $0,11x10^9$ m^3 [4 Bcf] of gas. However, its reserves of oil are three times more and of gas 15 times more (Fedyshyn, 1999). The main reason for such a slow pace of production is the lack of modern production technologies. This field, like almost all others in the region, has been developed by a natural driving mechanism with the depletion of formation pressure. It seems that by applying modern methods of secondary and tertiary recovery, it may be possible to mobilize a significant portion of the remaining reserves in the region, as has been done in hydrocarbon fields elsewhere in the world (e.g., Walsh and Lake, 2003).

Prospective areas

The main way to increase the resource base of the Ukrainian Carpathians remains the discovery of new hydrocarbon fields in the poorly explored areas and at greater depths than those of known oil and gas occurrences. For instance, six new promising areas (red ellipses in Fig. 21) were identified by SPK-GEO LLC (Popadyuk *et al.*, 2015), as a result of the integrated interpretation of existing well data, seismic interpretations and other relevant geological information from different parts of the Ukrainian Carpathians. Each promising area contains at least one anticlinal fold with probable stacked oil and/or gas pools at different stratigraphic levels in the Paleogene and Cretaceous strata. The depths of hydrocarbon pools in the prospective areas range from 500 to 2,000 m, and in several areas the maximum depths are between 3,000 and 7,000 m. The prospective resources of each area range from 3 to 20 x 10^6 tons [22.5–150 MMbbl] of oil equivalent, and the annual production at each area in 5–6 years after the start of drilling could reach 100 x 10^3 tons [0,75 MMbbl] of oil equivalent and more (Popadyuk *et al.*, 2015).

There are five of the six promising areas mentioned above (Fig. 21), where new fields could be discovered at depths of less than 2,000 m. One example of an unexplored anticlinal fold in the Skyba Nappe is shown in Figure 25. The anticlinal fold has two crests in the Upper Cretaceous–Eocene strata, its total dimensions are 8.9 km x 1.1 km, and its amplitude is about 600 m. More than 20 wells were drilled within the fold and in its vicinity. The shallow Paleogene sedimentary section in the area was poorly logged, never tested and no core was taken. However, one of the first wells yielded hydrocarbon inflows from Cretaceous sediments, and another well gave direct indications of the presence of oil and gas in the same sequence of this nappe. However, these positive results did not attract much attention because the main target of all wells was to discover large hydrocarbon accumulations in the deep strata of the Boryslav-Pokuttya Nappe underlying the Skyba Nappe. However, on the basis of the re-interpretation of well data and surface geology, it is possible to predict with a high probability of success at least two oil fields and their limits in the Paleogene strata at depths of less than 1 km (Fig. 25). The assessment shows that the prospective oil resources of the anticline may range from 1.3 to 5.3 x 10^6 tons [10–40 MMbbl]. In addition, the presence of gas pools in deeper horizons is supported by the well data. However, the contour of the gas field and its resources at deeper horizons (> 1 km) has not yet been determined because of a lack of geological and seismic data.

Importantly, there is an analogue for the prospect – the Shydnytca Oil Field (Fig. 26). Indeed, the prospect shown in Figure 25 is located in the same structural setting at roughly the same depth and has a geological structure similar to that of the Shydnytca Oil Field. The reserves of the Shydnytca Field are 4.1 x 10^6 tons [30.7 MMbbl] of oil and these reserves are concentrated in a small area of only 5 km^2 (Fedyshin, 1999). The first well ('Magdalena') with a daily oil rate of 1.1 ton [8.35 bbl] was drilled about 150 years ago. One of the other wells ('Jacob'), drilled in the late 19th century, yielded some 500 tons [3.75 Mbbl] of oil per day (Fedyshin, 1999). In total, by 1994, 259 out of 1,171 wells produced oil. Daily oil rates from each well during the period of maximum production ranged from 1 to 200 tons [7.5–1500 bbl] from an oil field less than 450 m deep. In total, the field had produced approximately 3.8 x 10^6 tons [28.5 MMbbl] of crude oil by 2019. According to official information, the recoverable reserves of the field are completely exhausted, and it is partly abandoned. However,

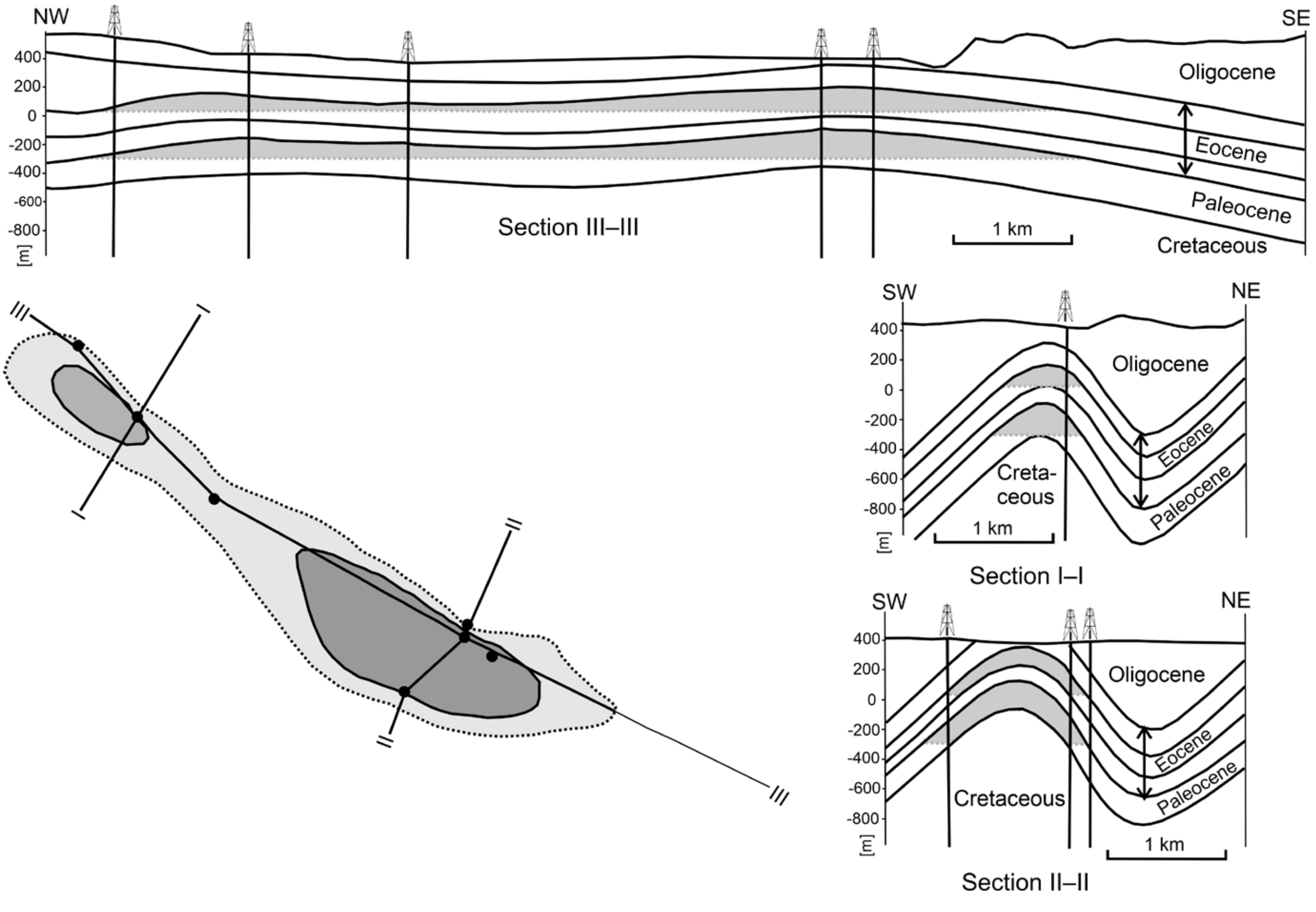

Fig. 25. Simplified structural map and geological sections, characterizing a shallow prospect in the Outer Carpathians.

the presence of the Shydnytca Oil Field supports the concept of discovering a hydrocarbon field in the anticlinal fold, shown in Figure 25.

Only a few gas fields were discovered in the Boryslav-Pokuttya Nappe. However, despite many uncertainties, the regional geological data reveal there is the potential to discover gas fields in three of the six prospective areas, shown in Figure 21 (Popadyuk *et al*., 2015). Figure 27 shows anticlines, predicted on the basis of regional investigations. These anticlines are bounded by major thrusts that are located at depths of 5 to 7 km in one of these three areas. These anticlines may contain large, stacked HC accumulations at different stratigraphic levels within the Paleogene. The anticlines were formed mainly in the frontal part of the Boryslav-Pokuttya Nappe and their area can reach several tens of square kilometres. Some fields could be discovered beneath the existing oil fields, as seen in the central part of the section, shown in Figure 27. In the case of gas, each field could contain up to 10 x 10^9 m^3 [0.35 Tcf] and much more, depending on the sizes of the traps and the quality of reservoirs at great depths (Popadyuk *et al*., 2015). However, the number of wells > 5 km deep in this part of the Borislavsko-Pokutta Nappe is currently insufficient to draw a definitive conclusion on the quality of reservoirs at such great depths. Additionally, owing to the very poor quality of seismic data across the entire sedimentary section of the Carpathians, it is currently impossible to obtain accurate information on the actual size of prospective traps. In order to make significant progress in the discovery of new fields in the Ukrainian Carpathians, a new series of 2D seismic profiles and 3D seismic surveys should be acquired in the identified areas of interest, using modern approaches to the acquisition of seismic data in mountains. Only on the basis of a comprehensive interpretation of new seismic surveys, reprocessed legacy seismic data, existing well data and other geological information, will it be possible to confirm the existence of HC traps in the deep horizons of the conjunction zone of the Boryslav-Pokuttya Nappe and Carpathian Foredeep, where deep prospects are expected.

General problems of hydrocarbon development in the Ukrainian Carpathian region. Despite the opportunities described above for a sharp increase in oil and

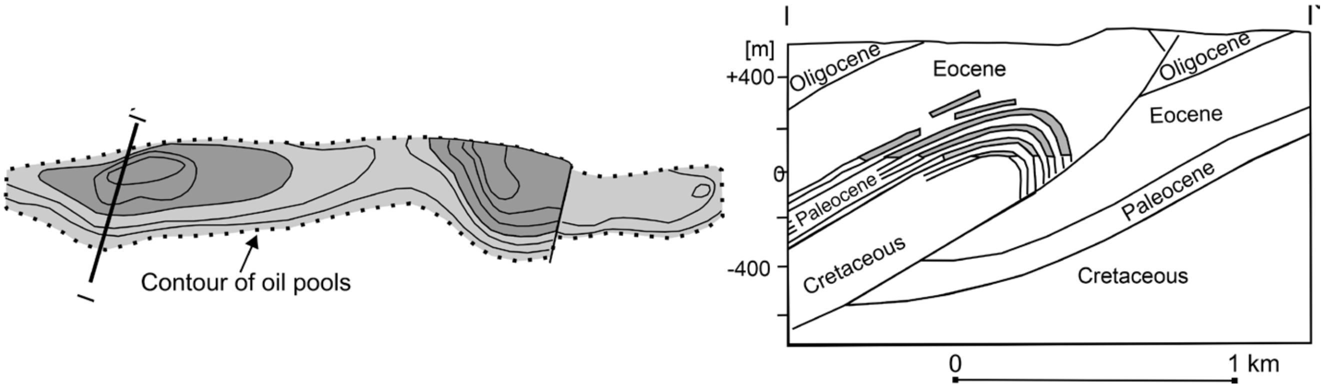

Fig. 26. Skhidnytsa oil field: simplified structural map, the top of the Paleocene and a geological section along line I–I` (adopted from Fedyshyn, 1999).

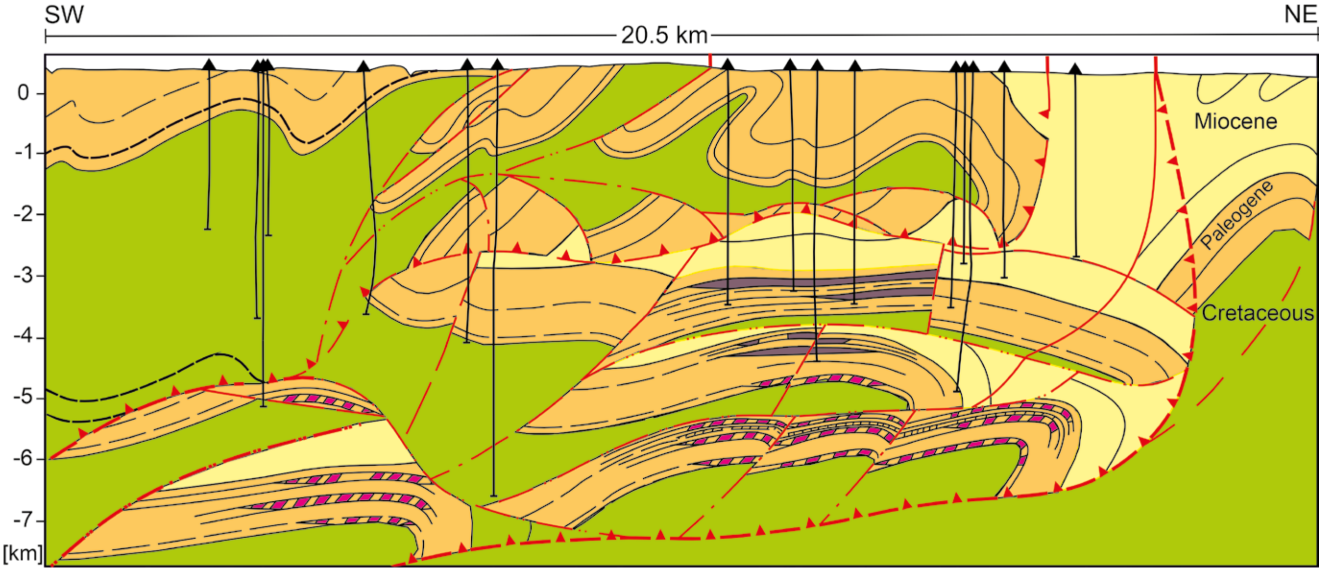

Fig. 27. Geological section (from Kuzovenko *et al*., 1990), showing predicted hydrocarbon prospects at great depths (from Popadyuk *et al*., 2015). The explored hydrocarbon accumulations at shallow depths are shown with plum-coloured polygons; predicted gas pools at great depths are shown with cross-hatched purple polygons.

gas production, due to new discoveries in the Ukrainian Carpathians, there are also good chances of significantly increasing production from already exploited fields in two ways, namely by cleaning the bottom-hole parts of productive formations and revising geological models of hydrocarbon fields with the subsequent drilling of new wells or the reconstruction of existing wells.

Cleaning of the bottom-hole part of productive formations. One of the significant problems that greatly affects the efficiency of the development of Ukrainian fields and the assessment of their true reserves is the clogging (contamination) of oil and gas reservoirs in the bottomhole zone of wells (e.g., Golub *et al.*, 2018b). As a result of reservoir contamination during drilling, potentially highly productive intervals of the section after testing turn out to be of low production rate or even dry, despite the fact that their petrophysical characteristics practically do not differ from those in neighbouring productive wells. The application of modern chemicals for the treatment of reservoirs in bottomhole zones can significantly increase production, as shown in Figure 28 for one of the oil- producing wells.

Revision of the geological models of hydrocarbon fields. Another potentially effective approach for a significant increase in hydrocarbon production from the Ukrainian Carpathians fields is the refinement (comprehensive revision) of their geological models with a critical review of all geological and operational (technological) data accumulated over the entire period of their exploration and operation. For many fields, a detailed revision of their geological models either was never carried out at all, or such a revision is not accompanied by the comprehensive interpretation of all available data. An example, demonstrating the effectiveness of building updated geological models, is shown in Figure 29. According to the existing geological model, the anticlinal fold is divided by transverse tectonic faults into three blocks and only one of these blocks is associated with a commercial hydrocarbon occurrence (Fig. 29A). More than 60 wells were drilled within the field, which made it possible, using only a part of them and in the absence of high-quality seismic data, to significantly change the understanding of its geological structure.

According to the new (substantially refined) model (Fig. 29B), the structure of the anticlinal fold containing hydrocarbons is much simpler than in the existing model (Fig. 29A). This refined model is consistent with the drilling results and other data, documented in well reports (Fig. 29A). There are no faults crossing the strike of the fold axis in the new model. Hydrocarbon production occurs in an area that is approximately half the area of the predicted new contour of the field. In the course of a critical review of the well data, it was found that the low flow rates of some wells, especially in the apical part of the fold, are not caused by changes in the petrophysical parameters of reservoir rocks, but mainly by deep clogging of the productive interval in the bottomhole zone of the wells. Calculations show that if the new field model is confirmed as a result of additional

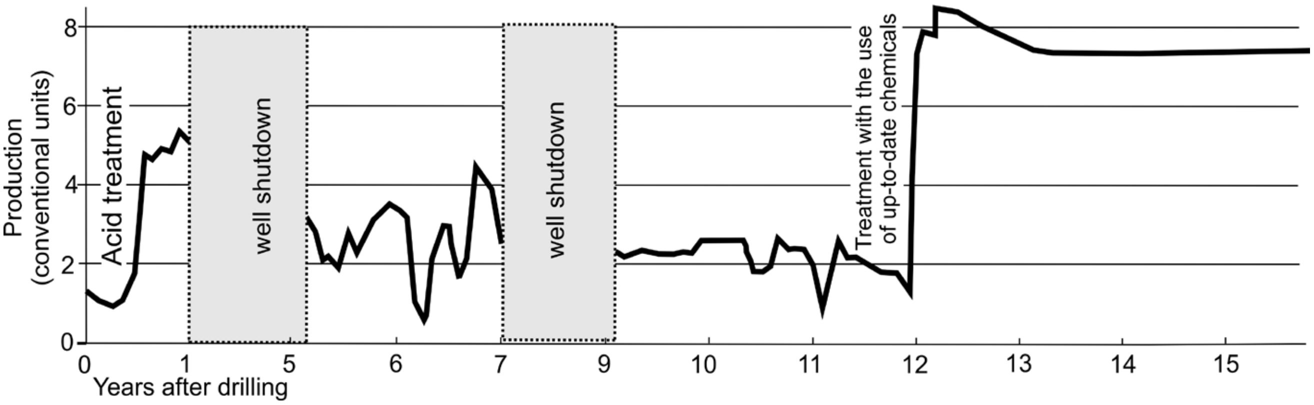

Fig. 28. An example of the successful use of an environmentally friendly chemical composite for a significant increase in the oil production rate (from Popadyuk *et al.*, 2015).

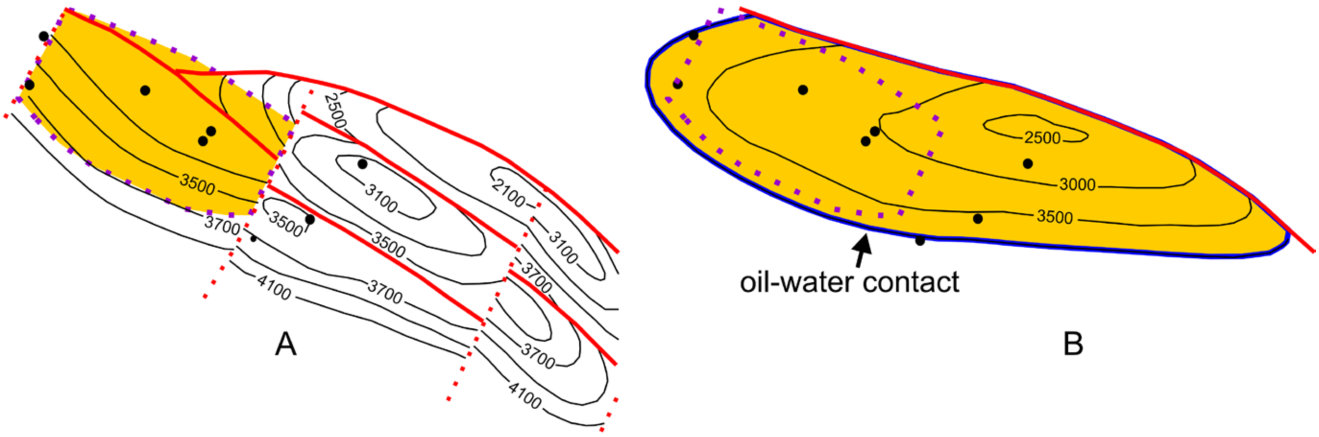

Fig. 29. An example of an old (A) and revised (B) geological model of a productive oil field in the Ukrainian Carpathians.

exploration, the estimate of the field's reserves could at least double (Popadyuk *et al*., 2015).

DISCUSSION AND CONCLUSIONS

Even the few examples described above refute the widely held opinion that most anticlinal traps in the Dniepr-Donets Basin and the Ukrainian Carpathians are well explored and, therefore, the discovery of new, large hydrocarbon accumulations at relatively shallow depths (< 5 km) penetrated by wells is unlikely. A review of the geological models of randomly selected hydrocarbon fields located in these two regions shows that they are underexplored and that each may contain more resources than is currently estimated. This means that numerous brownfields require, at a minimum, a thorough revision of relevant geological models and, if necessary, additional exploration. This would sharply increase hydrocarbon production from each of the underexplored fields in a relatively short time. The authors also show that the revision of geological models is necessary for many structural traps that have failed to detect hydrocarbons, owing to 'dry' wells or wells that were not even tested despite logging data, which indicated the presence of hydrocarbon-bearing reservoirs.

A critical issue in the revision of existing geological models should be an understanding of whether the negative test results of potentially productive reservoirs reflect actual geological settings, or were due to drilling and testing deficiencies that may have resulted in the deep plugging of reservoirs by drilling fluids. Analyses of many well reports indicate that the plugging of potentially hydrocarbon-bearing formations in the near-wellbore zone is the primary cause of negative drilling results for many wells in both the DBB and the Ukrainian Carpathians.

Continued exploration in the DDB is required to find gas accumulations beneath known hydrocarbon fields at depths of > 5–6 km and in lithological traps on the slopes of the DDB. Other very important concepts for further research in this sedimentary basin should be (a) the revision of geological models of productive and unproductive structural traps, associated with salt tectonics at depths penetrated by wells (< 6 km), and (b) exploration for new structural traps, including steeply dipping blocks, near salt stems and beneath the overhangs of salt diapirs, where they are much more numerous than currently thought and may be larger in size. It is expected that, if successful, these two areas of geological research and exploration in the DDB will allow a rapid increase in gas production.

The present results show that the structure of the sedimentary strata under many salt diapir overhangs in the DDB is not well understood, even though a number of productive and/or dry wells have been drilled near the diapirs. Although the formation of all salt diapirs in the DDB was subject to the general features of the basin's evolution, each diapir has its own additional features of formation, which depend on local geological factors. Lack of knowledge regarding these features is one of the main problems in mapping new hydrocarbon traps in the vicinity of salt diapirs. The use of 3D seismic exploration is the major method that allows more detailed imaging of the vicinity of diapirs in the DDB. Currently, detailed gravimetric surveys often are performed in conjunction with 3D seismic surveys (e.g., Petrovskiy *et al.*, 2011). Without denying the effectiveness of such seismic and gravimetric studies, it should be noted that even they are not always able to solve the geological problems set before them.

In the Ukrainian Carpathians, six underexplored areas have been identified that have potential for the discovery of new oil and gas accumulations, both shallow (< 2 km) and deep (3–7 km), with the potential recoverable resources in each area from 3 to 20 x 10^6 tons [22.5–150 MMbbl] or more of oil equivalent. The discovery of new fields in six areas and revision of the geological models of mature fields could sharply increase total production in the Ukrainian Carpathians.

Finally, the authors note that in the coming decades, despite its ambitious goals for achieving carbon net zero in line with international norms, Ukraine will remain dependent on oil and gas as a critical source of energy and for the chemical and manufacturing industries. This is especially relevant, in connection with the need for rapid recovery and further growth of this country's economy after repelling the illegal aggression by Russia. Therefore, in conditions of general deficit and high cost of energy on the world market, it is vital for Ukraine to increase its own production of hydrocarbons. Currently, the general direction of development of the European energy complex is the production of energy from renewable sources. Nevertheless, European countries will also continue to need hydrocarbons for many years to come. In the event of a sharp increase in gas production, allowing the fulfilment of domestic demand in Ukraine, opportunities will open up for European countries to import alternative and cheap Ukrainian gas.

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