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Bitumen/gas shows in Mesozoic intervals of deep boreholes in central Poland: implications for hydrocarbon migration and preservation potential

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This study evaluates the significance and origin of small and relatively scattered Mesozoic hydrocarbon shows in the Łódź Trough, Kujavian Swell and the Płock Trough, which have long been neglected in detail. The depiction of hydrocarbon shows on newly prepared maps and diagrams shows their link to Permian-Mesozoic geological structures and the mineralization of formation waters. Many bitumen shows in cores are observed at the Jurassic/Cretaceous boundary; the most common hydrocarbon inflows occur in the Middle-Upper Jurassic reservoir levels sampled. The Triassic-Lower Jurassic hydrocarbon occurrences are distributed more randomly, probably because of a scarcity of boreholes piercing those intervals. The majority of the observed hydrocarbon shows are related to the Mesozoic cover of salt anticlines or fault zones reaching the pre-Mesozoic basement. The presence of hydrocarbons in Mesozoic rocks overlying salt domes and elevated areas of the East European Platform characterized by low thermal maturity is interpreted as a result of their migration. The tectonic involvement of the Mesozoic strata, related to halokinetic movements and the Late Cretaceous-Early Paleogene inversion of the mid-Polish Trough, along with the documented scarcity of efficient sealing horizons and halting of the process of kerogen transformation, have likely prevented the formation of hydrocarbon accumulations. There is, however, still insufficient data on organic matter content and hydrocarbon occurrences in Triassic deposits containing potentially effective caprocks.

Key words: hydrocarbon shows in Mesozoic strata, Polish Lowlands, water mineralization, rock porosity, sealing horizons, migratory hydrocarbons.

INTRODUCTION

Deeply buried Mesozoic strata of the Polish Lowlands, located in the Łódź Trough (Synclinorium), Kujavian Swell (Anticlinorium) and the Płock (Warszawa) Trough (Synclinorium), have attracted attention from petroleum geologists as potential source rocks and a probable place of hydrocarbon accumulations. Early studies discussed the possibility of hydrocarbon migration, along fault zones, from older deposits or their generation in deeply buried Triassic and Jurassic rocks, as well as prospects for hydrocarbon accumulations in permeable Triassic, Jurassic and Lower Cretaceous rocks, sealed by impermeable layers or contacting steep Permian salt diapirs (Calikowski, 1970, 1983; Królicka, 1970, 1971; Calikowski et al., 1971; Depowski, 1980; Depowski et al., 1983; Wilczek, 1986; Sokołowski, 1990; Bachleda-Curuś et al., 1992; Bojarski and Sokołowski, 1993; Karnkowski, 1993).

A few shows of bitumens and inflows of gas or gas-cut brines/mineralized waters from Mesozoic horizons were documented from boreholes drilled in central Poland (e.g., Pożaryski, 1949; Depowski, 1980; Bojarski, 1985, 1986; Skompski, 1985b; Bojarski et al., 2008, 2012a, b; Bojarski and Sokołowski, 1990; Jaskowiak-Schoeneichowa, 1990a, b, c). Recent studies have revealed the low thermal maturity of the potentially most efficient Upper Jurassic source rocks in this area, containing significant amounts of marine, oil-prone Type II kerogen (Grotek, 2012; Więcław, 2016; Wierzbowski and Wierzbowski, 2019). Similar limitations exist in the case of the Lower Jurassic and Middle Jurassic strata, which contain early-mature, terrigenous organic matter or immature to early-mature terrigenous/aquatic organic matter, respectively (Zakrzewski et al., 2022a, b). Despite the scarcity of the data, deeply buried Triassic siliciclastic rocks of continental to marginal marine origin are considered as having low organic matter content (cf. Depowski, 1980; Górecki and Zawisza, 2011; Botor, 2023). The predominance of low to moderate water mineralization in Jurassic and Lower Cretaceous aquifers in central Poland, related to water exchange, was additionally raised as an argument against the

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formation of hydrocarbon accumulations (cf. Bojarski, 1970, 1971, 1983; Bojarski and Sokołowski, 1993; Górecki et al., 2006; Sowiżdżał et al., 2020a, b).

We note that contemporary structural and geochemical analyses of Mesozoic strata of central Poland suggest a lack of thick, effective caprocks, the presence of numerous faults, and the presumed halting of the process of kerogen transformation after the Late Cretaceous-Early Paleogene inversion of the mid-Polish Trough (Górecki and Zawisza, 2011; Botor, 2023). This limits the hydrocarbon potential of the Mesozoic rocks of the Polish Lowlands and may point to a general restriction of Mesozoic hydrocarbon shows to expected zones of hydrocarbon migration. The lack of effective caprocks also is the main structural difference between the Polish Basin and the North Sea Basin, which contains large Mesozoic hydrocarbon reservoirs (Górecki and Zawisza, 2011). On the other hand, recent modelling of hydrocarbon generation in the Polish Basin suggests significant thermal maturity and high kerogen transformation of deeply buried Triassic deposits of central Poland (Botor, 2023), which, along with high mineralization of Triassic brines (cf. Depowski, 1980; Górecki et al., 2006), raises hope for some hydrocarbon accumulations. The same may apply to the, still unexplained, possibility of the existence of Mesozoic traps for hydrocarbons migrating from older deposits.

Given the unresolved nature of relatively weak hydrocarbon manifestations in the Mesozoic strata of central Poland it is difficult to document their size and spatial range, and to deduce their source. Visualization of the hydrocarbon occurrences on a structural map showing their attachment to particular stratigraphic intervals or tectonic units may be helpful in this regard. Although many signs of hydrocarbons in boreholes from the Łódź Trough, Kujavian Swell and the Płock Trough have been reported, they are selective (e.g., Królicka, 1970, 1971; Łaszcz-Fiłakowa, 1970; Depowski, 1980; Bojarski and Sokołowski, 1993; Górecki and Zawisza, 2011) and depicted on maps of low spatial resolution (Sokołowski and Tomaszewski, 1997).

The present study aims at imaging and summarizing archival data on hydrocarbon occurrences in Mesozoic rocks in boreholes in central Poland. The data points gathered are plotted on a simplified map and geological cross-sections of the Permian-Mesozoic rock complex to show their relationship to the tectonic structures, including Permian (Zechstein) salt anticlines. The magnitude of hydrocarbon signs and their association with rocks of specific ages is discussed in order to evaluate their origin and potential importance for the Mesozoic petroleum system. The distribution of hydrocarbon signs is compared to the spatial extent of the lowermost Cretaceous evaporites and to water mineralization at the top surfaces of the Middle Triassic and the Middle Jurassic as well as to the reported total porosity of the rocks.

We note that the archival character of the data on hydrocarbon occurrences and rock porosity in central Poland, as well as the destruction of gaseous and liquid samples and many cores, which were drilled mostly over 50 years ago, precludes the conducting of new, comparative geochemical or mechanical analyses. The newly gathered data has been, instead, strictly categorized and discussed on the basis of recent knowledge of the geological architecture and tectonic evolution of the Polish Lowlands, as well as with respect to recent findings on organic matter content and its degree of thermal transformation in the Mesozoic strata.

METHODOLOGY

This study is based on archival documentation of 596 borehole sections through the Mesozoic strata of the Łódź Trough, Kujavian Swell and Płock Trough (cf. Appendix 1; Fig 1) stored in the Central Geological Database of the Polish Geological Institute – National Research Institute ("CBDG boreholes" available at http://otworywiertnicze.pgi.gov.pl) and its document repository ("CBDG archival reports" available at http://dokumenty.pgi.gov.pl/wyszukiwarka/). The data collected document observed shows of bitumens in drill cores and reported inflows of gas, gas-cut brines/waters/drilling mud or brines/waters/drilling mud with dissolved light hydrocarbon gases from intervals sampled during drilling operations. Eighteen thousand five hundred ninety-five results of measurements of total (open) rock porosity from 154 borehole sections, reported in the "CBDG boreholes" database, are additionally depicted on diagrams.

The documented composition of collected free or dissolved gases was determined by gas chromatography. The total (open) porosity of the rocks was measured using the density meter analysis, by comparison between the masses of dry and saturated samples, according the modified Blus and Malik's methodological instruction (cf. Fuliński, 1982).

The shows of bitumens in cores and results of sampling of reservoir horizons have been collated in the form of two separated datasets (Appendices 2 and 3). The bitumen shows in cores were divided, based on visibility, into two categories: (1c) – macroscopic bitumen shows and leaks in core, (2c) – bitumen shows visible under a UV luminescence lamp (Wood's lamp) or a noticeable smell of bitumens or hydrogen sulphide. The hydrocarbon inflows during sampling of reservoir horizons or self-active inflows were divided, based on gaseous hydrocarbon content, into four categories: (1s) – inflow of natural (hydrocarbon) gas, (2s) – inflow of gas-cut brine/water/drilling mud with natural (hydrocarbon) gas or liquid bitumens, (3s) – inflow of brine/water/drilling mud containing >15% of dissolved light hydrocarbon gases, (4s) – inflow of brine/water/drilling mud containing <15% of dissolved light hydrocarbon gases.

The category (4s) comprising a hydrocarbon-poor air-gas mixture (below upper flammability limit of methane) was excluded from plotting on maps and discussion as relatively insignificant. Bitumen shows in cores which may be related to documented oil spotting procedures conducted during drilling to lubricate stuck drill collars were also excluded from the list. The same applies to occurrences of gas-cut brine/water/drilling mud or brine/water/drilling mud containing >6.5% of free or dissolved hydrogen (at categories 2pz and 3pz). Although hydrogen can be of natural origin in some cases (especially when it is accompanied by helium) it can also occur as a result of the reaction of hydrogen sulphide with drill collars, steel shavings and rock debris (cf. Bjornstad et al., 1994). It is well-known that hydrogen sulphide can be, in turn, generated by anaerobic bacterial fermentation, thermal degradation or electrochemical reactions occurring in drilling fluids containing non-stabilized lignosulphates, which were widely used in the early period of drilling as inhibitors of clay mineral swelling (Chilingarian and Vorabutr, 1983). As the co-occurrence of methane fermentation of organic compounds of drilling fluid or the appearance of other products of its decomposition cannot be excluded, such hydro-

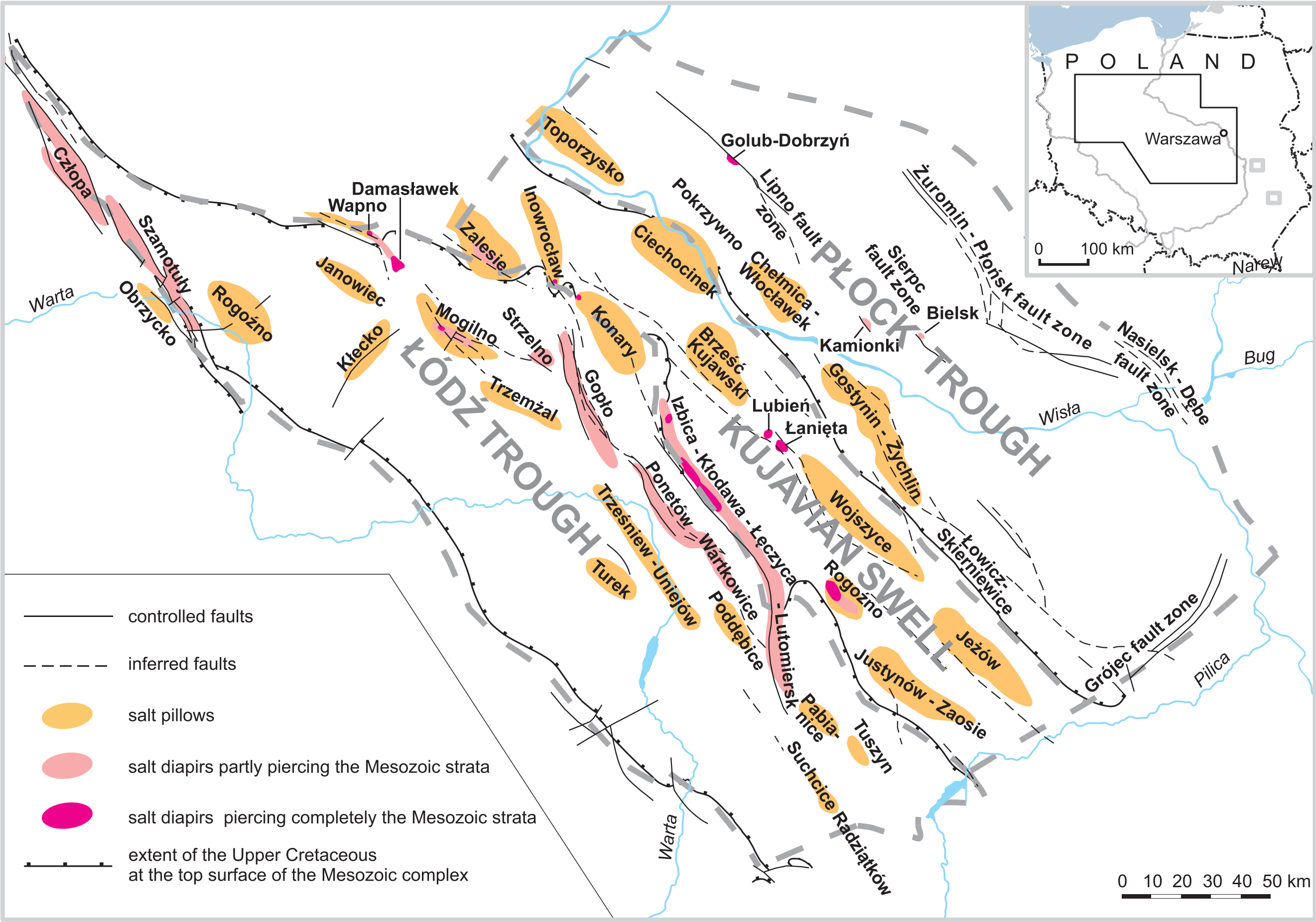

Fig. 1. Major tectonic structures of Zechstein-Mesozoic complex of central Poland (simplified map after Dadlez, 1998)

carbon occurrences should be treated with caution (cf. Leszczyński and Marek, 1990).

The intervals of hydrocarbon occurrences have been divided into series, i.e. the Lower (T1 – "Buntsandstein"), Middle (T2 – "Muschelkalk") and the Upper Triassic (T3 – "Keuper" and "Rhaetian"), the Lower (J1), Middle (J2) and the Upper Jurassic (J3) as well as the Lower (K1) and the Upper Cretaceous (K2), whose boundaries, although mostly based on lithostratigraphical data, are relatively consistent in reported chronostratigraphical divisions of various borehole sections (Fig. 2). The exceptions are relatively numerous bitumen shows in cores a narrow interval around the Jurassic/Cretaceous boundary (separately marked with the J3/K1 shortcut), which is restricted to the base of the evaporites of the Wieniec Member of the Limestone-Evaporite (Kcynia) Formation. The Wieniec Member and the overlying Skotniki Member of the Kcynia Formation, which used to be assigned to the Jurassic (cf. Marek et al., 1989; Niemczycka et al., 1997), are presently included into the Cretaceous (cf. Leszczyński, 2002; Dziadzio et al., 2004). This necessitates the verification of reported lithostratigraphical subdivisions of the borehole sections and justifies the introduction of a separate category of the Jurassic-Cretaceous boundary interval of hydrocarbon occurrences.

The location of all boreholes studied that pierce the Mesozoic strata, as well as information of observed bitumen shows in cores and inflows of gas, liquid bitumens, gas-cut brine/water/drilling mud or brine/water/drilling mud with dissolved (hydrocarbon) gases are plotted on the structural, tectonic map of the Zechstein-Mesozoic complex of the Polish Lowlands by Dadlez (1998) as well as the maps of Dembowska (1973) and Górecki et al. (2006) showing the spatial distribution of the lowermost Cretaceous evaporites and water mineralization at the top surfaces of the Middle Triassic and the Middle Jurassic series, respectively. Location of hydrocarbon occurrences is also visualized on three cross-sections (after Dziewińska et al., 2001), which cut different parts of the Kujavian Swell and adjoining areas of the Łódź and Płock troughs. In addition, data gathered on measured total porosity of the different Mesozoic series, as reported in documentation of the borehole sections, are shown on the diagrams.

RESULTS

Most of the hydrocarbon inflows and shows in borehole cores from the Mesozoic strata are spatially restricted to the sedimentary cover of deep-rooted salt structures in the north-eastern and eastern parts of the Łódź Trough, including the Mogilno, Strzelno, Gopło and the Ponętów-Wartkowice salt anticlines, as well as to a geological anticlinal structure of the Radziątków area in the south-eastern part of the Łódź Trough,

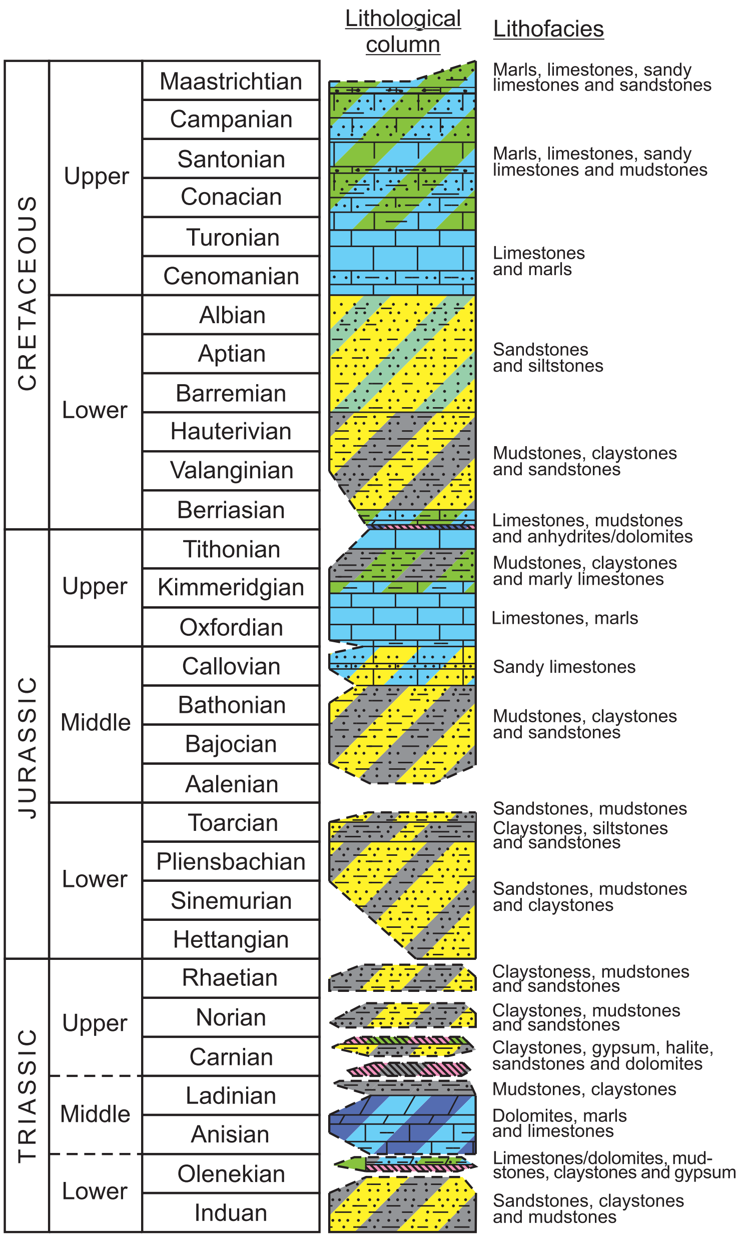

Fig. 2. Simplified lithostratigraphical log of the Mesozoic of central Poland (after Gajewska et al., 1997a, b; Szyperko-Teller et al., 1997; Krassowska et al., 1997; Leszczyński, 1997, 2012; Marek et al., 1997a, b; Pieńkowski, 2004)

The rock types are described and marked with standard lithological patterns and colour symbols

forming the prolongation of the Suchcice salt anticline (Fig. 1, Appendices 4 and 5). Other hydrocarbon occurrences in sampled horizons of the Łódź Trough, which are mostly associated with bitumen shows in cores, were reported from single boreholes drilled in the close vicinity or within the top parts of other salt domes including the northernmost part of the Trzemżal salt anticline, the southernmost parts of the Poddębice and Lutomiersk salt anticlines and the Tuszyn salt anticline (Appendices 4 and 5).

Isolated occurrences of hydrocarbons in the sampled horizons, frequently associated with bitumen shows in the cores, are documented from Mesozoic cover of salt anticlines of the Kujavian Swell including the Kłodawa-Łęczyca, Rogoźno, Justynów-Zaosie, Ciechocinek, Wojszyce and Jeżów anticlines (Appendices 4 and 5). The same applies to the northwestern, western and southwestern parts of the Płock Trough including the Toprzysko and Gostynin-Żychlin salt anticlines as well as to the (not depicted on the map) minor Pokrzywno and Łowicz-Skierniewice salt pillows close to the Kujavian Swell (Fig. 1; cf. Marek and Znosko, 1972).

Several bitumen shows in Mesozoic cores, without noticeable hydrocarbon inflows or leaks, have been reported from the central and eastern parts of the Płock Trough, which are located on the thickened basement of the East European Platform, outside the axial part of the Polish Basin (Appendices 4 and 5). Single cases of hydrocarbon inflows documented from this area (boreholes: Płońsk 1, Cieszkowo 1, Kamionki 1) may, however, be related to minor salt structures or significant tectonic fault zones.

The spatial relationship of other isolated hydrocarbon occurrences in the southeastern part of the Płock Trough (Nadarzyn IG 1) and the southwestern part of the Łódź Trough (Barczew 1, Zakrzyn IG 1) to the tectonic structure is unclear (Appendices 4 and 5). Hydrocarbon shows are also observed within deeply buried Mesozoic deposits of the eastern part of the Łódź Trough, located between salt anticlines in the Damasławek 22, Koło GT 1, Dobrów IGH 1 and Poddębice PIG 2 boreholes.

Hydrocarbon occurrences in the southermost part of the Łódź Trough, including the Radziątków anticline (Zakrzyn IG 1, Kliczków 1, Barczew 1, Bełchatów 6 and Radziątków 1, 2A, 3, 4, 5, 7 boreholes) were mostly observed in Triassic deposits (Appendices 4 and 5). Hydrocarbon occurrences in northeastern, eastern and southeastern parts of the Łódź Trough are predominantly restricted to the Middle-Upper Jurassic and the Jurassic-Cretaceous boundary intervals. From the latter horizon, located directly below the evaporites of the Wieniec Member of the Limestone-Evaporite (Kcynia) Formation or within its lower part, are reported numerous bitumen shows in cores. Bitumens were, occasionally, observed in other stratigraphical intervals in that area, such as the Upper Triassic (Trzemżal 1 and Młyny 2 boreholes), the Lower Jurassic (Damasławek 22) and the Cretaceous (Cykowo IG 1, Gopło Geo-4, Poddębice PIG 2).

Hydrocarbon occurrences in the Kujavian Swell are documented from Upper Triassic and Lower-Middle Jurassic intervals (Appendices 4 and 5), which may be related to the elevation of the Mesozoic basement of this tectonic unit. A few hydrocarbon shows have been reported from other stratigraphical intervals of the Kujavian Swell: the Lower Triassic (Buków 1, Jeżów IG 1) and the Upper Jurassic (Borów 2/C, Gawrony 6V, Głogowiec IG 1). Hydrocarbon occurrences in the northwestern, western and southwestern parts of the Płock Trough are predominantly restricted to the Middle-Upper Jurassic and the Jurassic-Cretaceous boundary intervals (Appendices 4 and 5). Exceptions are, however, quite numerous and include the Lower Triassic of Różyce IG 1, Szwejki IG 1 and Wałdowo Królewskie 1, the Upper Triassic of Sochaczew 1, the Lower Jurassic of Kamionki IG 3 and Różyce IG 1 as well as the Lower Cretaceous of Gostynin 8, Unisław 2 and Sochaczew 2. Hydrocarbon occurrences in the central-eastern parts of the Płock Trough are scattered among Triassic and Jurassic deposits. They have also been reported from Jurassic-Cretaceous boundary beds of this area. An exception is the Gradzanowo 3 borehole, where UV luminescence was observed in Lower Cretaceous rocks.

DISCUSSION

GENERAL REMARKS

The density of drilled boreholes is heterogeneous. The boreholes are commonly restricted to top parts of the sedimentary cover of large, saline anticline structures (Appendices 4 and 5). The variable depth limit of the borehole sections should also be taken into account, as many of them do not pierce Lower Jurassic and Triassic strata. The effects observed in the cores may additionally be underestimated by partial coring, albeit no selective coring of specific Mesozoic intervals can be observed in the boreholes studied.

The restriction of many bitumen/gas shows to the Jurassic-Lower Cretaceous cover of large, saline anticlinal structures or prominent tectonic zones may, nevertheless, demonstrate the presence of migratory hydrocarbons, which flowed from more deeply buried Mesozoic deposits of intervening synclines, and/or along deep-rooted fault zones constituting a pathway for fluid migration from Paleozoic deposits. This is related to the relatively low thermal maturity of the Jurassic-Lower Cretaceous deposits of central Poland (cf. Grotek, 2012; Więcław, 2016; Wierzbowski and Wierzbowski, 2019; Zakrzewski et al., 2022a, b), which particularly applies to elevated areas of the Mesozoic cover of Permian (Zechstein) salt anticlines or marginal areas of the Płock Trough, where Mesozoic rocks are not deeply buried due to their resting on the thick basement of the East European Platform.

JURASSIC/CRETACEOUS BOUNDARY INTERVAL

Poorly lithified and containing numerous sandy and sandy limestone layers, the Upper to mid-Cretaceous deposits are highly permeable (cf. Figs. 2 and 3; Krassowska et al., 1997; Leszczyński, 2012). Clayey mudstone horizons of the Lower Cretaceous Włocławek, Rogoźno and a part of the Limestone-Evaporite (Kcynia) formations of low permeability might theoretically play a role in sealing rocks but this is not consistent with the low mineralization of Cretaceous deep water aquifers (cf. Leszczyński, 2002; Górecki et al., 2006).

Special attention should be paid to evaporite deposits of the Wieniec Member of the Kcynia Formation as many bitumen shows in cores are reported from lower parts of that member or from the Purbeckian limestone-marly facies underlying the evaporite rocks (Appendix 2). The Wieniec Member, dated to the ostracod layer E, is presently included into the lowermost Beriassian (cf. Leszczyński, 2002; Dziadzio et al., 2004) but was previously assigned to the uppermost Tithonian (cf. Marek et al., 1989; Niemczycka et al., 1997). This results in discrepancies in the description of various borehole sections causing, for a long time, problems with the proper classification of this stratigraphical level of hydrocarbons shows. The observed effects in the cores seem to be more or less randomly scattered over the whole area of distribution of evaporite rocks of the Wieniec Member, including its marginal zones (Fig. 4). Interestingly, large petroleum shows/leaks and sweating of cores were observed in the Ponętów-Wartkowice anticline (borehole section: Koło GT 1, Dobrów IGH 1 and Przybyłów 1). The Jurassic-Cretaceous boundary interval was, as a rule, not tested for gas inflow but the observed shows in the cores appear to be related to residual heavier hydrocarbon fractions that may have migrated from the underlying rocks and become trapped in this horizon.

The evaporites of the Wieniec Member attain a few tens of metres in central Poland and consist of anhydrite or gypsum deposits intercalated with marls, marly clays, dolomites and limestones (Radlicz, 1967; Dembowska, 1973, 1979). Although their thickness increases towards the axial part of the Polish Basin, they are not present in many parts of the Łódź Trough and the Kujavian Swell due to Neo-Cimmerian and Laramian erosion or to lateral replacement by marly-limestone deposits (Dembowska, 1973, 1979). It should also be born in mind that the evaporites are shallowly buried (down to 500 m below sea level), if present, in the Kujavian Swell (cf. Górecki et al., 2006). Due to their moderate thickness, marly-limestone intercalation or relatively shallow burial in many parts of the Polish Lowlands, the evaporites of the Wieniec Member cannot be expected to be a widespread and effective sealing horizon that might have been involved in the mechanism of flexible propagation of deep-rooted rigid faults constituting potential migration routes of hydrocarbons from underlying deposits (cf. Górecki et al., 2006).

MIDDLE-UPPER JURASSIC

Hydrocarbon occurrences in the Upper Jurassic rocks from the top parts of the sedimentary cover of large Permian (Zechstein) saline anticlines of the Łódź Trough and western part of the Płock Trough, as well as in prominent fault zones of the Płock Trough, mostly correspond to areas of increased water mineralization of the top Middle–Upper Jurassic aquifers reported by Górecki et al. (2006) (Fig. 5). The hydrocarbon shows are usually observed in porous deep-water Oxfordian limestones of massive (biohermal) spongy-microbial type and Lower Kimmeridgian shallow-water organodetrital and oolitic limestones (Appendices 2 and 3). These rocks are generally assigned to the Spongy-limestone (I) Formation, the Oolitic (IV) Formation and coquina beds of the Limestone-marly coquina (V) Formation, distinguished according to the lithostratigraphical scheme of Dembowska (1979).

Variable total/effective porosity and permeability values of the Oxfordian-Lower Kimmeridgian horizons are documented by physical property analyses of core sections (cf. Feldman-Olszewska, 2008, 2012; Karcz, 2018; Sobień, 2019; Fig. 3). This is likely a result of the presence of poorly permeable marly limestone and marl intercalations between more permeable Upper Jurassic beds (Fig. 2). Also, the Upper Jurassic limestone deposits pass gradually into marly and mudstone/marly-claystone facies in the northwestern margin of the study area (cf. Dembowska, 1979). The Upper Jurassic strata show, consequently, low values of filtration and effective porosity coefficients; mineralization of these aquifers is low to moderate and only locally in the eastern and northeastern part of the Łódź Trough it exceeds 100 g/dm^3 (Górecki et al., 2006).

Numerous hydrocarbon shows also are observed in the Middle Jurassic of the Łódź Trough and the Płock Trough (Fig. 5). Although Middle Jurassic rocks are locally deeply buried in these regions (down to ~3500 and ~2750 m below sea level, respectively; cf. Górecki et al., 2006), the observed hydrocarbon manifestations are mostly restricted to uplifted zones of the sedimentary cover of salt anticlines (Fig. 6). In addition, Middle Jurassic hydrocarbons have been observed in four boreholes

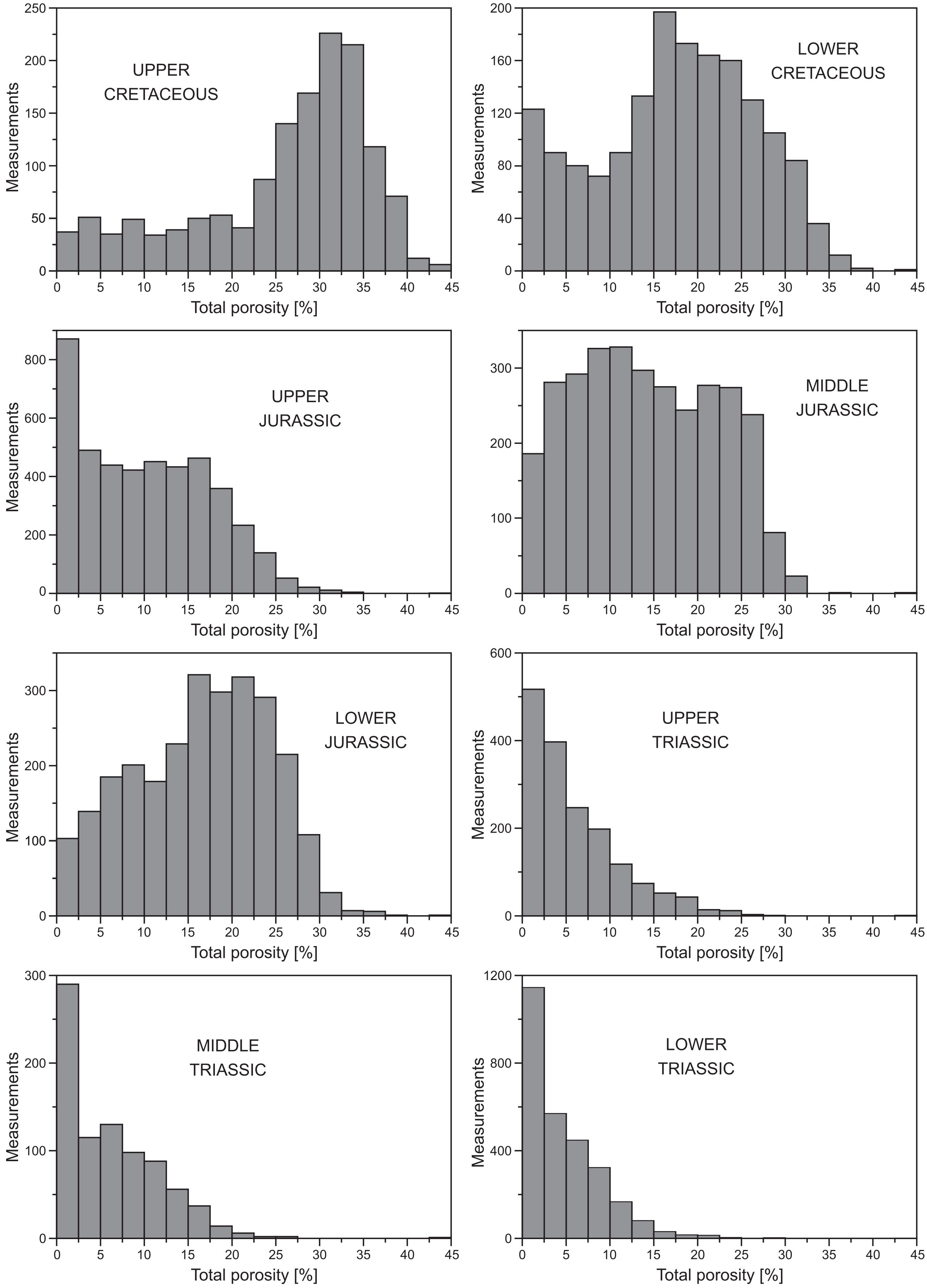

Fig. 3. Total (open) porosity of different series of the Mesozoic strata of central Poland (archival data gathered from the Central Geological Database of the Polish Geological Institute – National Research Institute)

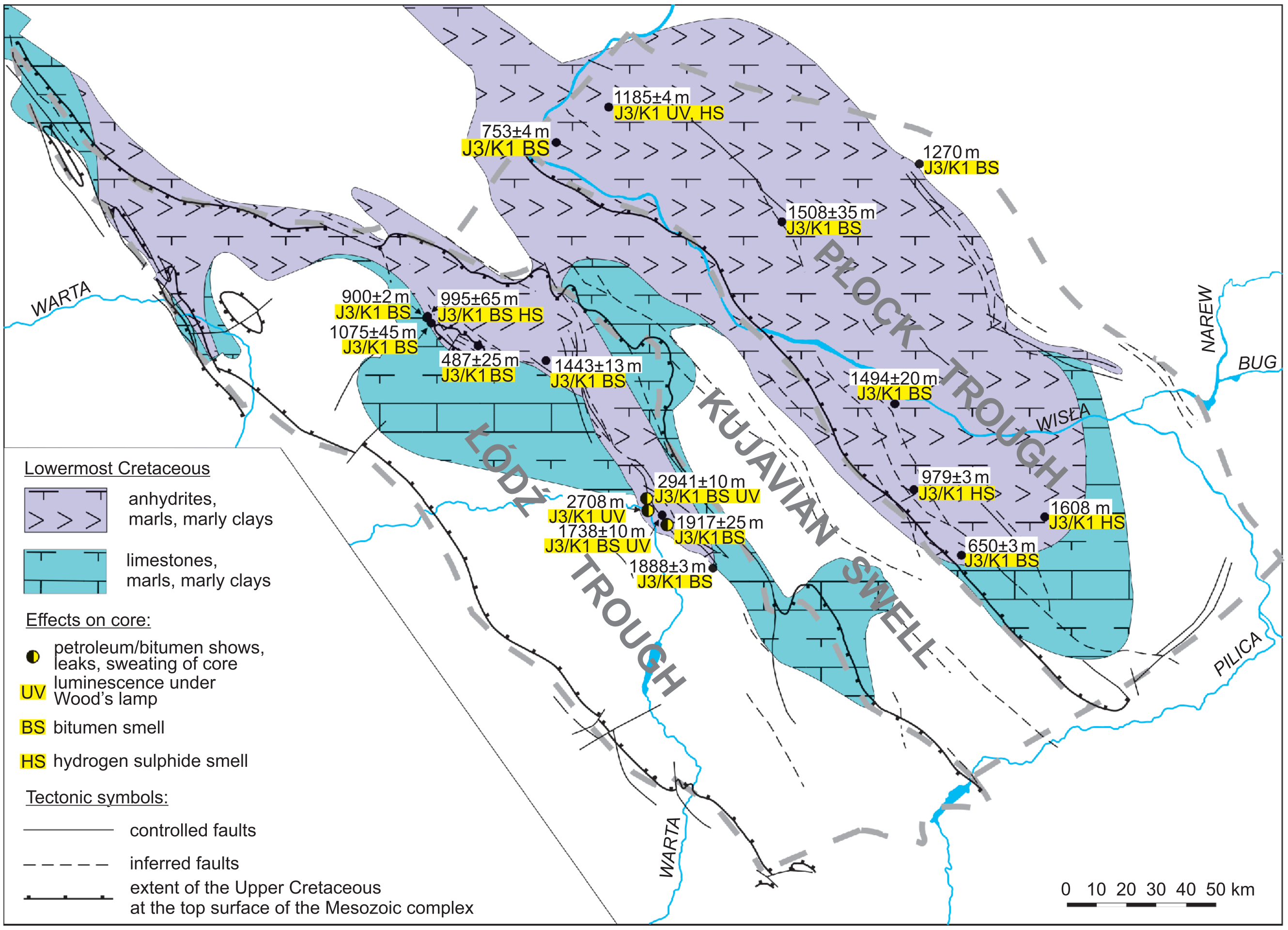

Fig. 4. Bitumen shows in cores at the Jurassic/Cretaceous boundary, their depths and the distribution of the evaporites of the Wieniec Member of the Kcynia Formation (after Dembowska, 1973, modified)

penetrating the Kujavian Swell, at various depths from 800 to 2200 m (Appendices 2 and 3).

Three major Middle Jurassic hydrothermal water aquifers (Lower Aalenian, Upper Bajocian and Lower-Middle Bathonian), are relatively poorly permeable and consist of sandstones and heterolithic beds sealed by impermeable clay layers; there are also permeable Callovian sandstone-limestone beds (cf. Fig. 2; Feldman-Olszewska, 1997; Górecki et al., 2006). This results in a scatter of total porosity values of the Middle Jurassic rocks (Fig. 3). The mineralization of Middle Jurassic waters varies from 1050 g/dm^3 in the Kujavian Swell to 100 g/dm^3 in the eastern and northeastern parts of the Łódź Trough and some western parts of the Płock Trough (Fig. 5).

The spatial links of the Middle-Upper Jurassic hydrocarbon shows to the elevated areas of the sedimentary cover of salt anticlines of the Łódź Trough and the Płock Trough and prominent tectonic zones in the eastern part of the Płock Trough, showing low thermal maturity and intermediate values of mineralization of formation waters, indicate the presence of migratory hydrocarbons. The hydrocarbons may have been derived from intervening synclines, where Middle-Upper Jurassic rocks are expected to be thermally more mature (cf. Wierzbowski and Wierzbowski, 2019; Zakrzewski et al., 2022a, b) or underlying Mesozoic or Paleozoic strata.

Reconstruction of hydrocarbon formation and migration in the Mesozoic strata of central Poland needs taking into consideration the tectonic evolution of that region. Its axial part (the so-called Mid-Polish Trough) showed an extensional character and significant subsidence during much of the Mesozoic, which resulted in the deposition of a thick Triassic-Lower Cretaceous rock succession above Permian (Zechstein) evaporites. A central part of the Polish Basin (the mid-Polish Swell including its Kujavian segment) was uplifted as a consequence of Laramian tectonic movements during the Late Turonian-Paleocene (Marek, 1988; Stephenson et al., 2003; Krzywiec, 2006, 2012; Krzywiec et al., 2017). The bottom salt tectonics and tectonic compression related to inversion of the central part of Polish Basin are, thus, the main factors determining its tectonic regime.

The salt structures started to grow in the Early Triassic – they included salt rollers located at the footwalls of rotated blocks bounded by listric faults and salt pillows (Krzywiec, 2012; Krzywiec et al., 2017). Successive Late Triassic-Jurassic salt movements resulted in the gradual growth of salt structures, and the formation of half-grabens and initial salt diapirs (Krzywiec, 2012). A prominent acceleration of salt movement took place during the Late Turonian–Paleocene inversion of the mid-Polish Trough, leading to compressional re-activation of major listric faults, folding/uplift of salt structures and the formation of major salt diapirs (Marek, 1988; Krzywiec et al., 2017). The tectonic compression resulted in the uplift and deep erosion of the mid-Polish Swell, re-activation of old transverse strike-slip fault zones, such as the Grójec fault zone, and likely

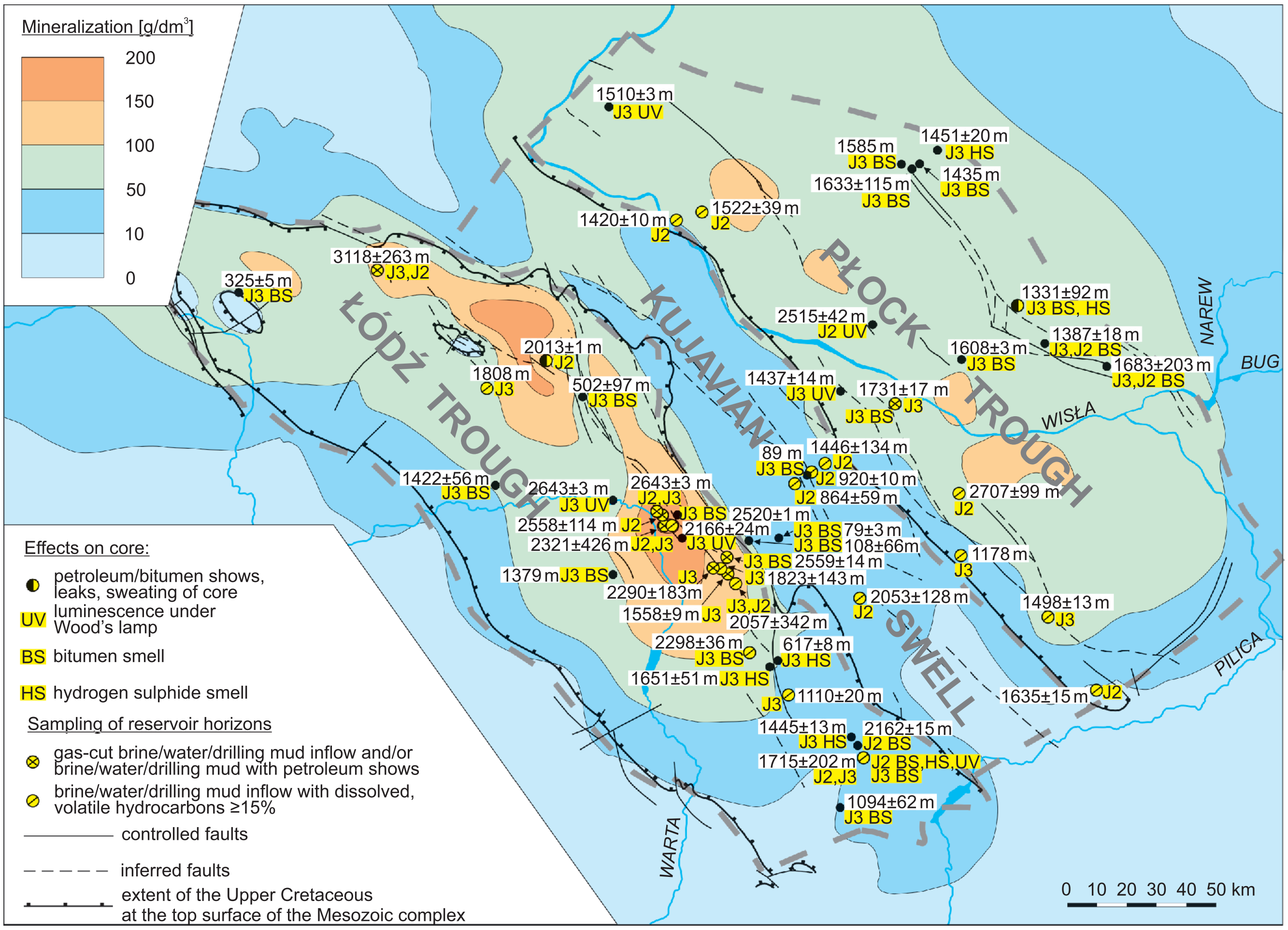

Fig. 5. Middle-Upper Jurassic hydrocarbon occurrences in cores/sampling horizons (without Jurassic/Cretaceous boundary horizons), their depths and water mineralization at the top the Middle Jurassic (after Górecki et al., 2006)

the appearance of new faults, especially within the Mesozoic cover of uplifted salt structures (cf. Krzywiec, 2002; Krzywiec et al., 2017).

Taking into account positive thermal anomalies above the salt structures due to the two to four times higher thermal conductivity of salt compared to other sedimentary rocks (Magri et al., 2008; Zhuo et al., 2015), the existence of rock fractures and faults above elevated salt pillows/diapirs and a general lack of thick sealing horizons (cf. Górecki and Zawisza, 2011) the geological architecture of the Polish Lowlands is expected to stimulate fluid circulation in the Mesozoic cover of salt anticlines. This aspect has never been studied in detail at regional scale. However, reported features of the Middle-Upper Jurassic rocks in halokinetic structures of central Poland, including the ferruginous-dolomitic mineralization of Bathonian sandstones and widespread dolomitization of Callovian-Lower Kimmeridgian carbonates in the form of veins or chimney-like bodies (Znosko, 1957; Radlicz, 1967; Teofilak-Maliszewska, 1968; Maliszewska, 1999; Franaszek and Lis-Martyniak, 1973; Urban-Łucka, 1973; Dąbrowska, 1974; Zydorowicz, 1982; Chlebowski, 1985; Skompski, 1985a; Niemczycka and Feldman-Olszewska, 2012) as well as sulphide mineralization of Oxfordian–Lower Kimmeridgian dolomite-limestone rocks tied to fault zones (Krajewski, 1957; Radlicz, 1964; Górecka, 1985) clearly points to late diagenetic fluid flow. This mineralization is not accompanied by significant amount of diagenetic gypsum, which might increase the sealing capacities of the rocks.

Diagenetic fluid circulation and rock recrystallization may have caused a loss of integrity of weak sealing horizons of the Middle-Upper Jurassic traps and explain the lack of documented hydrocarbon accumulation in coeval rocks of central Poland. The same may apply to the role of active faults. In addition, deep erosion of the mid-Polish Swell, which removed uppermost Jurassic and overlying Cretaceous rocks, significantly affected the permeability of Middle-Upper Jurassic horizons, allowing inflow of surface waters, which is reflected in the low mineralization of Jurassic aquifers in the Kujavian Swell and its marginal areas (Fig. 5). Its uplift is also thought to definitely have halted the process of kerogen transformation (Botor, 2023).

TRIASSIC–LOWER JURASSIC

Triassic-Lower Jurassic hydrocarbon signs are generally observed in the top parts of saline anticline structures or prominent fault zones in south and eastern parts of the study area (e.g., the Radziątków anticline). They are mostly decoupled from zones of the highest mineralization of coeval formation waters noted in central parts of the Łódź Trough and the Kujavian Swell (cf. Górecki et al., 2006; Fig. 7). Certain features of the

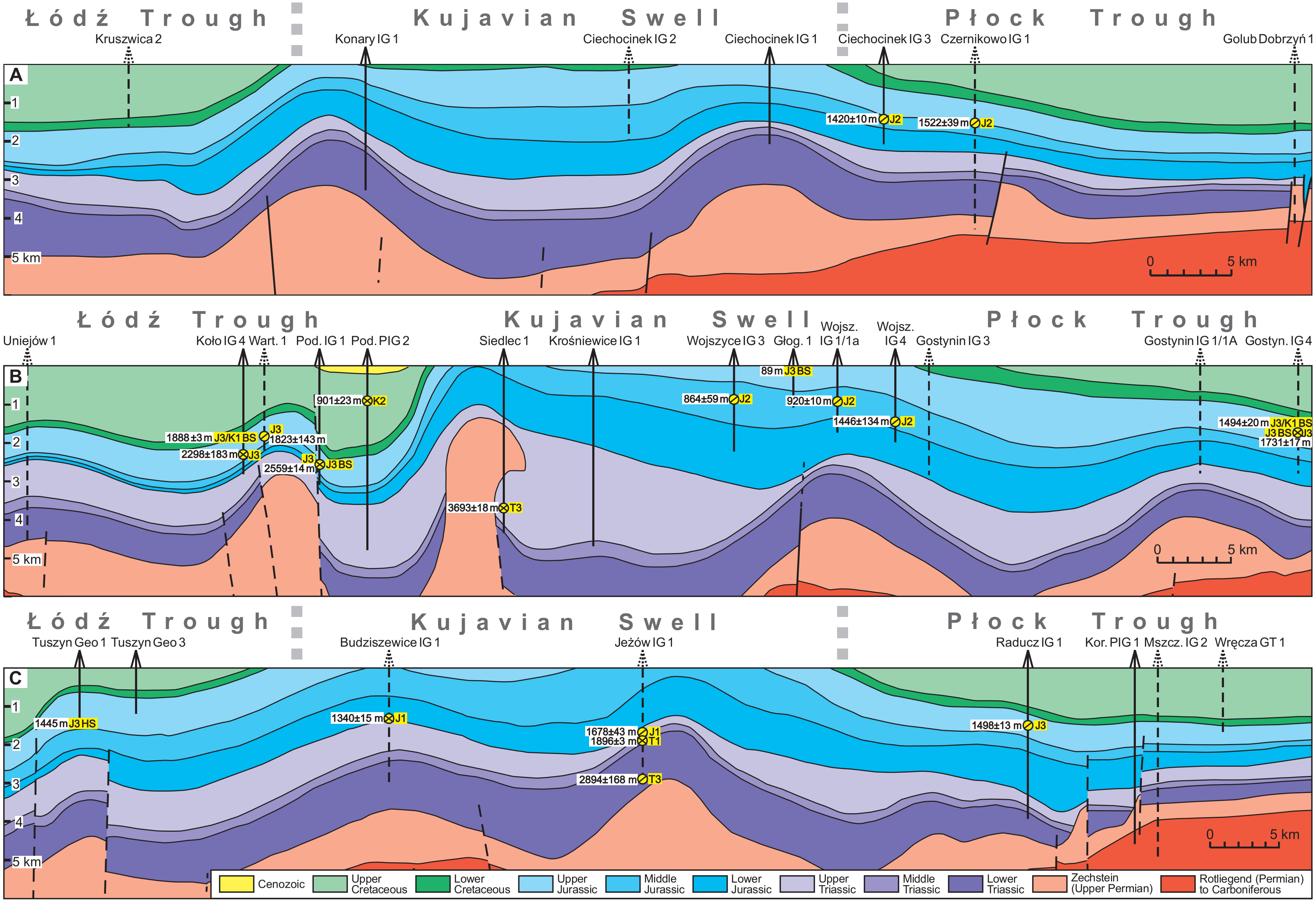

Fig. 6. Cross-sections throughout the Kujavian Swell and neighbouring areas of the Łódź and Płock troughs (after Dziewińska et al., 2001) with occurrences of hydrocarbons marked on the borehole sections

The position of cross-sections is marked on Appendix 4; borehole sections marked by solid lines are located in the cross-section plane; borehole sections marked by dashed lines are located in the proximity of the cross-section and projected onto its plane; minor faults are not depicted on the diagram as they could not have been distinguished in seismic datasets processed by Dziewińska et al. (2001); see Figure 5 for symbols of hydrocarbon shows

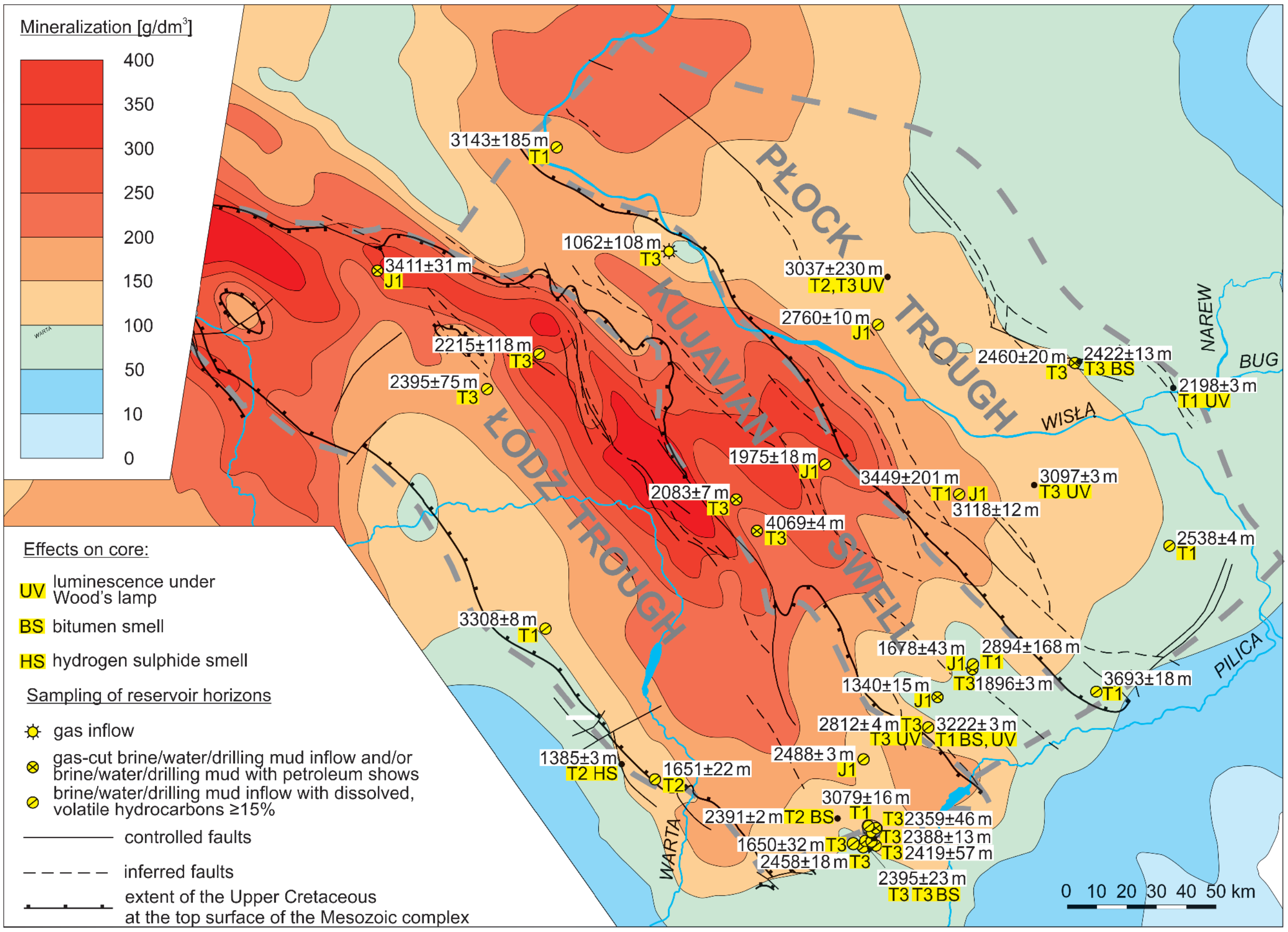

Fig. 7. Triassic-Lower Jurassic hydrocarbon occurrences in cores/sampling horizons, their depths and water mineralization at the top of the Middle Triassic (after Górecki et al., 2006)

Triassic–Lower Jurassic dataset may be related to a more random distribution of boreholes piercing that stratigraphic interval compared to the Middle–Upper Jurassic boreholes. Notably, the Triassic rocks in southernmost and easternmost parts of the study area occur at a shallower depth that in its central parts. For example, they were generally sampled at a depth of 1400 to 2500 m below sea level in the Radziątków anticline (cf. Appendix 3), whereas the top of the Triassic deposits occur <2500 m below sea level in the eastern part of the Łódź Trough and western part of the Płock Trough (Fig. 6). The top of the Middle Triassic lies usually <3000 m below sea level in the Kujavian Swell, due to the significant thickness of the Upper Triassic-Lower Jurassic deposits (cf. Górecki et al., 2006). The shallowly buried Triassic deposits were, therefore, easier accessible for borehole studies.

The thick Lower Jurassic water-bearing sandstone horizons of central Poland are sealed by impermeable mudstone-claystone beds and have good water reservoir properties (cf. Figs. 2 and 3; Górecki et al., 2006; Sowiżdżał et al., 2013, 2020a, b). Therefore, they are regarded as having locally high potential as thermal water aquifers. The efficient sealing horizons of the Triassic aquifers are Roetian (Lower Triassic) carbonate-evaporite beds and Keuper (Upper Triassic) Gypsum Beds, which consist of clayey-silty deposits with anhydrite, gypsum and halite intercalations (Fig. 2; Górecki et al., 2006). The Lower Gypsum Beds have the greatest regional extent and thickness, attaining up to a few hundred metres in the north-central part of the Łódź Trough and central part of the Kujavian Swell (Gajewska, 1978, 1988; Gajewska et al., 1997). In that area they contain 1–3 halite seams of total thickness of 40 to 143 m (Czapowski and Thomassi-Morawiec, 2016). The Lower Gypsum does not show, however, complete lithological development and evaporite intercalations are gradually lost towards the east, eventually disappearing in the area of the Płock Trough (Gajewska, 1978, 1988; Gajewska et al., 1997). A similar situation is observed in the Upper Gypsum Beds, whose uppermost part consisting of grey claystones with top anhydrites is not preserved east of the Łódź Trough (Gajewska, 1978). The Roetian carbonate-evaporite deposits occur southwest of the Mid-Polish Swell and in its central part only (Szyperko-Teller et al., 1997). The presence of Triassic evaporite-clayey beds, which may form sealing horizons, is reflected in low values of total porosity of many rocks of this system. The porosity of intervening or underlying sandstone layers of the Upper Triassic (Keuper) and the Lower Triassic (Buntsandstein) is, however, not high, which limits their reservoir properties (cf. Fig. 3; Górecki et al., 2006).

The relatively small amounts of Lower Jurassic rocks of very low porosity, which may act as sealing horizons, probably did not favour hydrocarbon accumulations (Fig. 3). The low porosity of the Triassic siliciclastic rocks, the presumed low organic matter content of these strata and expected completion of kerogen transformation after Late Cretaceous-Early Paleogene inversion of the mid-Polish Swell (cf. Botor, 2023) should also be treated as factors limiting the possibility of hydrocarbon accumulations. Some Triassic hydrocarbon accumulations might, however, be associated with minor, deeply buried and poorly tectonically transformed anticlinal structures. The same applies to wedged Triassic or Jurassic deposits contacting elevated Permian (Zechstein) salt diapirs outside their top areas, which may act as curtain caprocks.

CONCLUSIONS

Published data on Mesozoic bitumen shows in cores and on hydrocarbon inflows from sampled horizons of the central part of the Polish Lowlands, comprising areas of the Łódź Trough, Kujavian Swell and Płock Trough, have been collated in the form of tables with the categorized significance of the shows. Detailed maps and diagrams presenting the location of hydrocarbon occurrences against the background of geological structures, the extent of the Jurassic/Cretaceous boundary evaporites, and water mineralization of the Middle Triassic and Middle Jurassic intervals, have been constructed based on the data assembled. Our study additionally provides a summary of data on rock porosity of different series of the Mesozoic rocks and a critical review of published information on the geochemical and structural evolution of the study area.

The data obtained show a spatial link of the majority of hydrocarbon occurrences to the topmost part of the sedimentary cover of elevated salt anticlines. The bases of Jurassic/Cretaceous evaporites and Middle-Upper Jurassic carbonate rocks are the most important intervals of concentrations of hydrocarbon signs in cores and sampled horizons, respectively. Due to the low thermal maturity of kerogen in coeval strata, both sorts of hydrocarbons are regarded as migratory. They might have been derived from adjoining synclines and/or have been transported by fault systems from underlying rocks.

A lack of documented Mesozoic hydrocarbon accumulations in central Poland where there are observed signs of hydrocarbons is interpreted as a result of the variable porosity of the Mesozoic deposits, devoid of thick sealing horizons, the tectonic involvement of the Mesozoic succession, which was deformed by salt movements, and Late Cretaceous-Early Paleogene uplift of the mid-Polish Swell. The appearance of fault systems and fluid circulation, particularly in the cover of salt anticlines may have led to a decrease in the moderate sealing capacities of Mesozoic strata. It is also documented that the tectonic inversion stopped the process of Mesozoic kerogen transformation.

Detailed information on hydrocarbon occurrences and the organic matter content of the Lower Jurassic, and especially of Triassic rocks in many areas of the Polish Lowlands, is still lacking. The existence of some hydrocarbon accumulations in Triassic strata cannot be yet excluded taking into account higher water mineralization and the enhanced integrity of Roetian and Keuper claystone-evaporite beds, which may form sealing horizons. The reservoir properties of Triassic sandy beds are, however, limited due to their low to moderate porosity.

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