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Geotectonic setting of Permian polymetallic deposits in the Polish Basin

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The Polish Basin is located between the Precambrian East-European Platform and the Cadomian Bohemian and Małopolska massifs. The basement of this Permian-Mesozoic basin comprises mainly Variscides and epi-Caledonian Paleozoic rocks. In the proximal (NE) part of the basin, the Mid-Polish Trough is distinguished. In the distal (SW) part, the thickness of the Permian-Mesozoic succession is much smaller than in the Polish Trough. Palaeorift zones were active from the Permian to the end of the Jurassic in the distal part of this basin. The Kupferschiefer mineral system indicates a palaeorift zone and smaller hot spots as sources of supply of metalliferous brines. The relatively small thickness of the Rotliegend sandstones and their good permeability and porosity properties created very favourable routes for the migration of metal-bearing brines. The entire Kupferschiefer polymetallic reservoir is regionally sealed by anhydrites and salts of the Werra cyclothem. This was inclined constantly from Permian times onwards to the north, favouring the migration of polymetallic brines from rift zones to geochemical reservoir traps. Mineral system analysis of the polymetallic Kupferschiefer deposits shows that the geotectonic setting of this zone relates only to the distal part of the Polish asymmetric rift basin.

Key words: geotectonics, mineral system concept, continental rift system, Kupferschiefer, polymetallic deposits, Polish Basin.

INTRODUCTION

The greatest achievement of Polish geology after the Second World War is the in-depth exploration of the Polish Lowlands. Scoping work began in 1945, but it was not until the adoption of the geological survey program in the first half of the 1950s that systematic and extensive exploration took place. One of the priorities was the search for copper deposits, which began first in the previously known deposit areas (the Holy Cross Mts. and North-Sudetic Basin, on the southern side of the Fore-Sudetic Block), where the former German copper mines Konrad and Lena were known (Piestrzyński, 2007). The geologist who conducted the search was Jan Wyżykowski of the (Polish) Geological Institute in Warsaw. He designed, supervised and documented new boreholes in the North-Sudetic Basin in the mid-1950s. At the same time, petroleum exploration was carried out on the northern side of the Fore-Sudetic Block. In 1956, in the drilling of the Wschowa-1 borehole, prof. Adam Tokarski, who was the chief geologist in the Polish National Petroleum Company, found macroscopically visible rich mineralization in the copper-bearing shale and submitted the relevant samples for analysis to the Geological Institute in Warsaw. Laboratory results confirmed a high content of copper minerals. On this basis, Jan Wyżykowski located two boreholes in the immediate vicinity of the Fore-Sudetic Block, on its northern side. The results of both boreholes confirmed the high-grade mineralization of the Kupferschiefer. And so, in 1957, the largest deposits of copper and silver in Europe were discovered, located in the Lubin-Sieroszowice region (Wyżykowski, 1958). A long period of deposit characterization and new exploration work began, which enabled the formulation of regional patterns of the mineralization in SW Poland (Rydzewski, 1969, 1978, 1996; Wyżykowski, 1971; Preidl et al., 1971; Piestrzyński and Sawłowicz, 1999; Banaszak and Leszczyński, 2007; Oszczepalski, 2007; Speczik et al., 2021).

Regionally, the Lower Silesian Permian polymetallic deposits belong to the same province as the deposits of southern Germany (e.g., Mansfeld, Richelsdorf). They are stratigraphically related to the level of the Zechstein shale (Kupferschiefer). Also, the adjoining formations (Zechstein Basal Limestone and Weissliegend sandstone) and adjacent ones (Zechstein Limestone) are mineralized. Rich copper mineralization occurs only in the south-western part of the Polish Basin and in the southern part of the East German Basin (Fig. 1). However, the German deposits are much smaller than the Polish ones. In this paper we refer only to the geotectonic setting of the Permian polymetallic deposits in the area of the Fore-Sudetic Monocline and the position of these deposits in relation to the rest of the Polish Basin.

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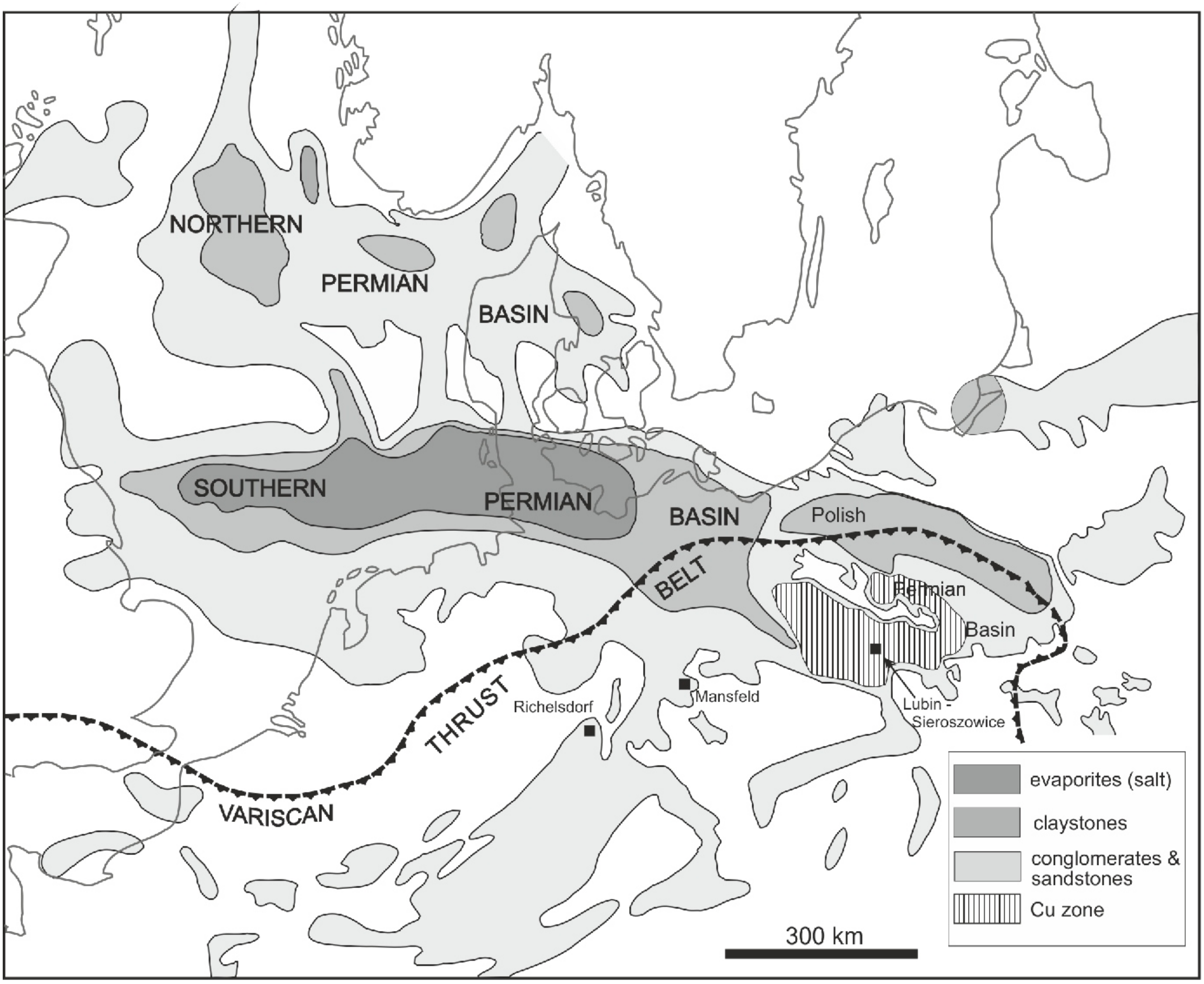

Fig. 1. Cu-Ag zone in the Polish Permian Basin* within the Rotliegend basins in Central and Western Europe (main sources: Karnkowski, 1987, 1999; Gast et al., 2010; Oszczepalski and Rydzewski, 1997, 2007; Oszczepalski and Speczik, 2014)

* Polish Basin is designated by the extent of the Rotliegend deposits

Today we know that the rich mineralization is not only attached to the zone on the northern side of the Fore-Sudetic Block, but extends almost to the entire area of the Fore-Sudetic Monocline, up to the Poznań region. A main assumption is the existence of a great palaeogeothermal anomaly in the Permian-Jurassic period, characterized by the heat flow values attributed to rift zones (Karnkowski, 1999). On the basis of this and other premises, Karnkowski (1999) proposed a rift model for the Polish asymmetrical basin.

The first geologist who noticed this asymmetry of the Polish Basin was Olewicz (1959). Karnkowski (1991: 449), on the other hand, was the first to conclude that *in the area of the Fore-Sudetic Monocline and Western Pomerania, there are premises for the adoption idea of a continental rift, which was marked in the Lower Permian period by a deep burial of basement, followed by the phenomenon of great volcanism*. This statement came from a petroleum geologist not in the mainstream of academic studies, and so rarely quoted in the relevant bibliography. However, it reflected petroleum geologists being directly involved in exploration, with experience of drilling, seismic images, petrological and geochemical analyses, etc.

A new conceptual model concerning the genesis of polymetallic brines for the mineralization of the Rotliegend-Zechstein zone in the southern Fore-Sudetic Monocline (Blundell et al., 2003) was based on the stratigraphic, sedimentological, palaeogeographic, tectonic and palaeogeothermic studies of Karnkowski (1999). The model cited proposes that the polymetallic solutions were sourced from a palaeogeothermal anomaly zone located in Wielkopolska. The mechanism proposed is based on the pulsatory injection of hot brines from the deep crust substrate into the clastic deposits of the Rotliegend (mainly sandstones of alluvial-fluvial and aeolian origin), and then the migration of these brines towards structurally higher areas, i.e. mainly to the Lubin-Głogów copper region (LGOM). Repeated, cyclical tectonic impulses during the development of the Polish rift basin opened and tightened normal faults (and numerous related fractures) by pumping polymetallic brines from the rift zones, which, having already entered the clastic deposits of the Rotliegend, migrated towards the Kupferschiefer with strongly reducing properties. Above the Kupferschiefer zone (T1+Ca1), across the entire Polish Basin, there are anhydrites and Zechstein salts, which prevented the dispersion of concentrated mineralization in the Rotliegend-Zechstein boundary zone. The onset of the appearance of polymetallic brines may be associated with the volcanic episode in the Rotliegend, that is, even with the age of 290 Ma (Sawłowicz, 1990). However, it was only with the regional sealing by Zechstein evaporites of the migration of metallic brines (250 Ma; Kucha and Pawlikowski, 1986) that permanent mineralization was initiated (Sawłowicz, 1993). This process was completed only at the end of the Jurassic when the area of the Fore-Sudetic Monocline was elevated and largely eroded. The present ranges of Permian, Triassic and Jurassic deposits are very similar to the structural pattern in the Lower Cretaceous (Dadlez, 2006).

The Polish Permian polymetallic deposits are sediment-hosted stratiform copper deposits, located in the transition zone of the Rotliegend and Zechstein successions (Oszczepalski, 1999). The main metals are copper and silver, and in significant amounts also zinc, lead, gold, platinum, palladium, molybdenum, cobalt, nickel, selenium and rhenium (Oszczepalski and Chmielewski, 2015). In recent years, prospects for the occurrence of Cu-Ag, Au, Pt, Pd and other metals have been explored, not only in the vicinity of already documented deposits, but throughout the Polish Basin, and metalogenic maps (Oszczepalski and Rydzewski, 1997) have been significantly supplemented (Oszczepalski and Rydzewski, 2007; Speczik et al., 2007, 2013, 2014, 2022; Bachowski et al., 2011; Oszczepalski et al., 2011, 2012, 2019; Oszczepalski and Speczik, 2011a, b, 2014; Mikulski et al., 2015; Zientek et al., 2015; Oszczepalski and Chmielewski, 2015; Sztromwasser et al., 2015; Zieliński and Speczik, 2017; Zieliński and Wierchowiec, 2018). Ranges of ore mineralization occurrence and resource estimates in prospective areas have been revised (Piestrzyński and Sawłowicz, 1999; Oszczepalski and Speczik, 2009, 2014; Mikulski et al., 2015; Oszczepalski and Chmielewski, 2015). From the regional point of view, the results from areas where the Zechstein bottom lies deeper were of most interest, notably the central and northern Fore-Sudetic Monocline with huge hypothetical (due to the mineralization lying below 2000 metres depth) copper and silver resources (Oszczepalski and Chmielewski, 2015; Oszczepalski et al., 2019; Speczik et al., 2022). These high polymetallic concentrations in Rotliegend-Zechstein formations in deeper zones of the Fore-Sudetic Monocline prompted our interest in the geotectonic system of Cu-Ag-Au-Pt-Pd mineralization in the Polish Basin. The results obtained so far have been showed on prospective maps of Cu-Ag, Au, Pt and Pb mineralization (e.g., Oszczepalski and Chmielewski, 2015), helping construct Figure 2 of this paper.

THE ORE-DEPOSIT ASPECT

The Polish Basin is most often regarded as an area of sedimentary deposition in the Polish Lowlands. The post-war exploration program was launched more or less with this image in mind. This diagnosis provided much data from drilling and seismic surveys, enabling the construction of maps of individual systems and formations (Dadlez, 1998). The analysis of these maps clearly shows the outline of the Polish Basin in the Permian, but the occurrence of Mesozoic deposits often blurs the original framework of the basin, not to mention the presently incomplete profiles due to pre- and post-Cretaceous erosion (Dadlez, 1998). The volcanic episode in Rotliegend time can be considered as the beginning of this basin's formation (Karnkowski, 1999); therefore, the Permian framework of this basin seems most appropriate for geotectonic considerations. The best base maps for our analysis are the palaeogeographic maps of the end of the Rotliegend (Pokorski, 1988,1989; Karnkowski, 1994, 1999) which provide the wider background of the European basins (Fig. 1).

In this context, the Polish Basin, along with the German Basin, is part of the great European basin (Southern Permian Basin; Doornebal and Stevenson, 2010). To the north there is the northern European basin, separated by the Ringkøbing-Fynn high. This combination of the Polish and German basins suggests many analogies between the two areas. However, the differences between them are significant. In the Polish Basin, in contrast to the German Basin, there are no evaporites in the Rotliegend. The Polish Basin is located largely on continental crust consolidated during the Variscan and the German Basin is in the Variscan foreland (except for the easternmost part called the North-East German Basin). Indeed, as far as the vicinity of Berlin, we observe links between the north-western part of the Permian Basin in Poland and northeastern Germany. A remarkable palaeotectonic structure that plays a fundamental role in the palaeogeography and palaeotectonics of the Rotliegend in Poland is the Wolsztyn Ridge, which has practically no equivalent in the German Basin (Kiersnowski et al., 2010). When tracing the occurrence of the copper-bearing zone in the Polish Basin, it can be immediately noticed that it is strongly conditioned by the existence of the Wolsztyn Ridge. The main area of this zone is located between the southern edge of the basin and the Wolsztyn Ridge. But, on the north-eastern side of it, solid mineralization of Cu-Ag and platinum metals has also been documented (Fig. 2). The western range of this zone slightly extends beyond the Odra line and does not continue into Germany (Fig. 1).

Today the Legnica-Głogów Copper District (LGOM) ore field, exploited for Cu-Ag in Poland, is located near the edge of the Fore-Sudetic Block. This may suggest its activity in the Permian. Between today's North-Sudetic Trough and the LGOM area up to the Wolsztyn Ridge, there was free hydraulic contact beneath a seal of Zechstein evaporites. The scale of this free hydraulic area is 300 x150 km, that is ~45,000 km^2. Such a large area already requires a geotectonic explanation, regarding the genesis of the Polish Basin and its polymetallic mineralization. Two deposit areas in Germany (Mansfeld and Richelsdorf) marked on Figure 1 show that these and other similar German deposits occur in different tectonic and sedimentary conditions (these are usually small and occur in the marginal zones of small local sedimentary basins). However, they show some features comparable to Polish Cu-Ag deposits (in mineral zonation and attachment also to the Kupferschiefer copper-bearing zone).

The recognition of Cu-Ag, Pb-Zn, and platinum minerals in the Polish Basin is described in many publications (Oszczepalski and Rydzewski, 1997, 2007; Speczik et al., 2014; Oszczepalski et al., 2017and references therein). A simplified, synthetic approach to analysing the distribution of metals in the distal part of the Polish basin is shown in Figure 2. The copper-bearing zone is located around the Wolsztyn Ridge. The highest, industrial concentrations of Cu-Ag are in the vicinity of the Fore-Sudetic Block (mainly due to the economic depth of exploitation). Similar or even higher concentrations have also been documented in other areas, including on the northern slope of the Wolsztyn Ridge. In addition to copper and silver, there are concentrations of zinc, lead and platinum (Au, Pt, Pd). Their location indicates an area of occurrence similar to that of the base metals. The area of the Fore-Sudetic Block, currently devoid of Permo-Mesozoic sedimentary cover, originally formed the total area of ore mineralization from the North-Sudetic Basin area to the LGOM ore-deposit region. Figure 2 shows these elements together

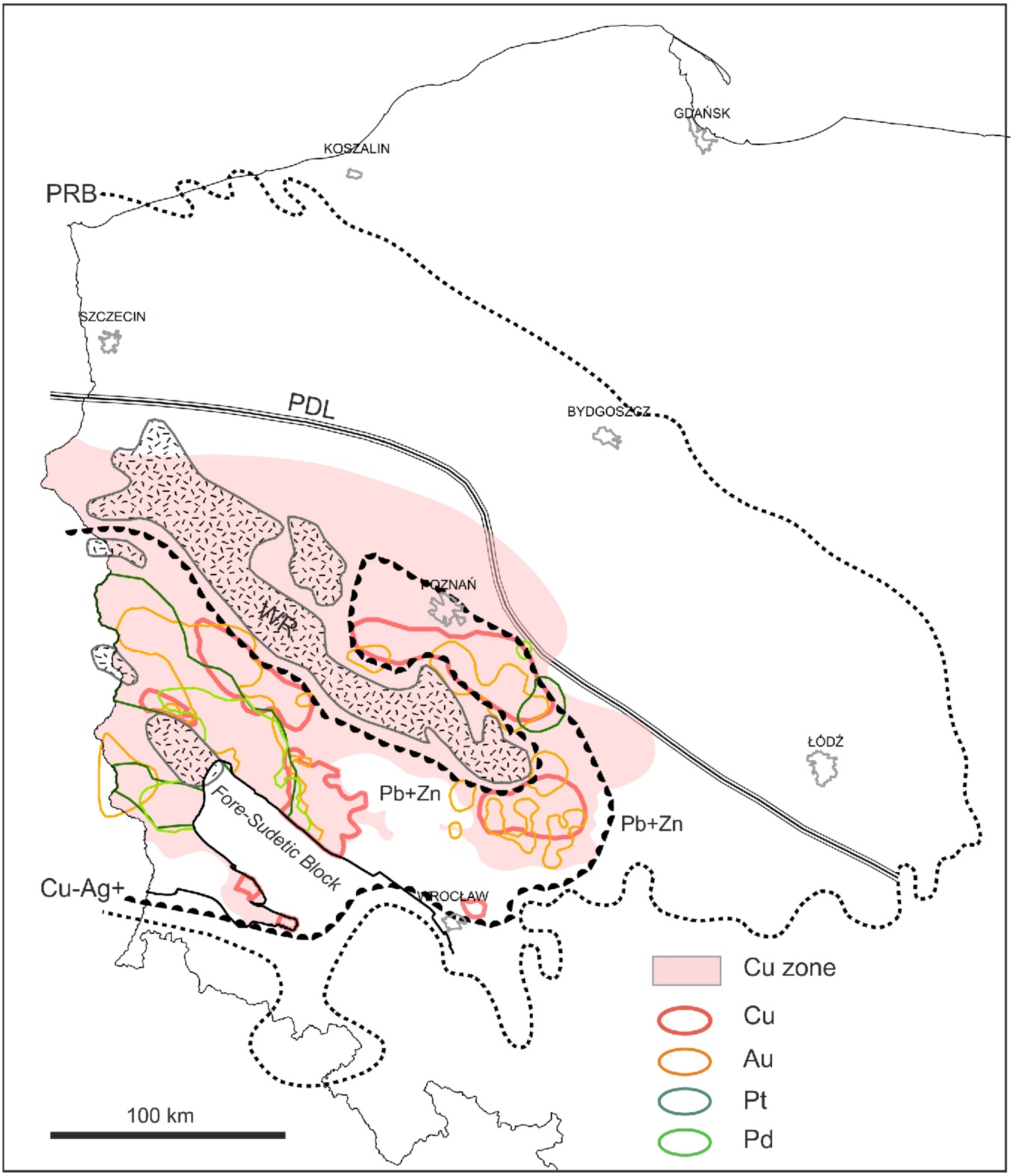

Fig. 2. Distribution of metals in the distal part of the Polish Basin (main sources: Oszczepalski and Rydzewski, 1997, 2007; Speczik et al., 2007, 2013, 2014, 2022; Oszczepalski et al., 2011, 2012; Oszczepalski and Speczik, 2011a, b, 2014; Zientek et al., 2015; Oszczepalski and Chmielewski, 2015)

Cu zone – copper zone, Cu – main areas of copper surface density above 25 kg/m^2, Au-Pt – prospective areas for gold, palladium and platinum; Pb+Zn – lead-zinc zone, Cu-Ag+ – main area of polymetallic mineralization in the transition zone between the Rotliegend and Zechstein. PDL – boundary between proximal and distal parts of the Polish Basin, PRB – Polish Rotliegend Basin (extent of deposits before Cenozoic erosion), WR – Wolsztyn Ridge

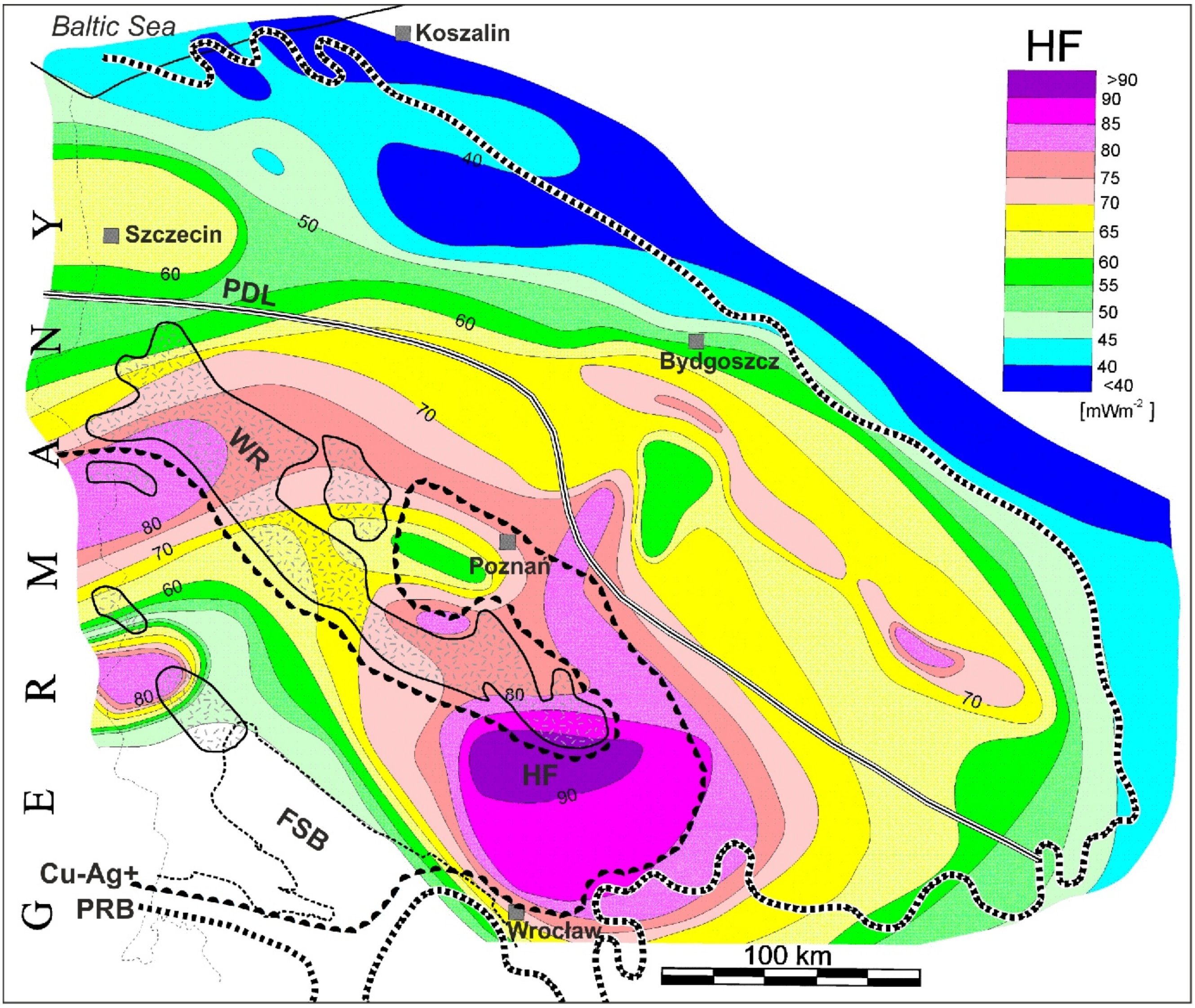

Fig. 3. Map of the average heat flow values in the Polish Basin during Late Rotliegend to Late Jurassic time (after Karnkowski, 1999)

Cu-Ag+ main area of polymetallic mineralization in the transition zone between the Rotliegend and Zechstein deposits, PDL – boundary between proximal and distal parts of the Polish Basin, PRB – Polish Rotliegend Basin (extent of deposits before Cenozoic erosion), WR – Wolsztyn Ridge, HF – heat flow anomaly, FSB – Fore-Sudetic Block

with the inferred original extent of the Polish Rotliegend Basin and the demarcation line between the distal and proximal parts of the Polish Basin. The copper mineralization zone is located in the distal zone of the basin, which was an area of variable heat flow from the Permian period to present day. The main palaeogeothermal change probably took place at the end of the Jurassic period (Karnkowski, 1999). The second element that marks the line separating the distal and proximal parts of the basin is a significant difference in the magnitude of the tectonic subsidence in the Permian and Mesozoic in the central and western parts of the basin (Karnkowski, 1999). The distribution of polymetallic mineralization (Fig. 2), however, requires reference to additional elements in order to better illustrate the tectonic context of this regional mineralogical pattern.

GEOLOGICAL ASPECTS

The hot brines which led to the formation of huge polymetallic resources in the transition zone of the Rotliegend and Zechstein successions in the distal part of the Polish Basin must have had a very large source of supply and prolonged activity. Their possible derivation from a rift zone (Karnkowski, 1999), indicated already by Blundell et al. (2003), has received much support (Pieczonka and Piestrzyński, 2000; Michalik and Sawłowicz, 2001; Speczik et al., 2007; Borg et al., 2012; Alderton et al., 2016; Mikulski and Stein, 2017; Oszczepalski et al., 2017). Attention has focused on the largest palaeogeothermal anomaly, located in the Wielkopolska area (HF). Variation in the heat flow in the Permian-Jurassic interval in the Polish Basin (Fig. 3) shows, however, that it is worth considering a wider range of palaeogeothermal zones (in a "hot corridor" on the northern side of the Wolsztyn Ridge). In particular, this concerns their widening on the northern side of the Wolsztyn Ridge and the small anomaly at the border zone with Germany (Fig. 3). This distribution is much larger than previously assumed. However, its extent is better able to explain the occurrence of rich mineralization on the northern side of the Wolsztyn Ridge without the need to change the direction of brine migration. Throughout the Permian-Jurassic interval, these mainly migrated to the southwest. Concentration may have taken place in the northern Wielkopolska region (north of the Wolsz-

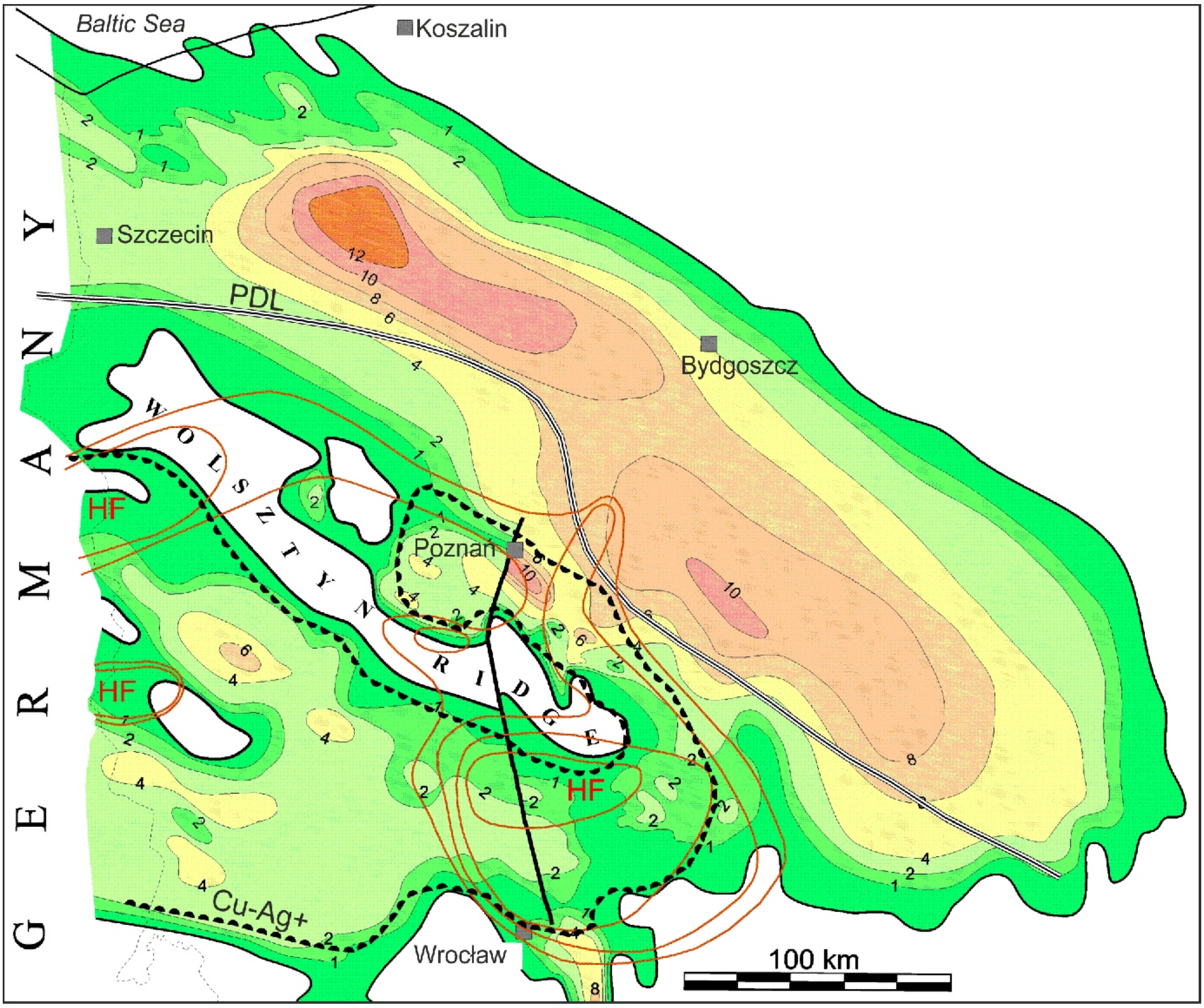

Fig. 4. Restored isopach map (in 100-metre intervals) of the Wielkopolska Subgroup (Upper Rotliegend) in the Polish Basin (Karnkowski, 1999) together with heat flow values during Late Rotliegend to Late Jurassic times (cf. Fig. 3)

HF – heat flow anomalies with values >75 mWm^{-2}, other abbreviations as in previous figures

tyn Ridge) and in the LGOM area at the same time. The Wolsztyn Ridge, which was not overlain by permeable Rotliegend deposits beneath the Zechstein evaporites, was a barrier to brine migration to the south-west. Also, apart from the northern distal part of the Polish Basin, there was no other area with such high heat flow values then (Fig. 3).

The hot polymetallic brines migrating from the deep basement finally reached the clastic, permeable deposits of the Rotliegend. Analysis of the Wielkopolska Subgroup (upper part of the Rotliegend) thickness distribution (Fig. 4) on the background of a map of palaeogeothermal anomalies clearly shows the possibilities of brine migration. Zones with high heat flow input are covered by a relatively thin unit of sandstone (>200 m-thick). This relatively small thickness of the migration zone resulted in its concentration in the levels with the best porosity and permeability parameters. Thus, migration was not dispersed in space and was taking place towards structurally higher surfaces. The distribution of sedimentary facies (fluvial and aeolian; mostly parallel to the Wolsztyn Ridge), and hence of the basic petrophysical parameters were similar.

In the proximal parts of the Polish Rotliegend Basin, the thickness of the clastic deposits was much greater and exceeded 1000 m. The asymmetry of the Polish Basin, which was expressed already during sedimentation of the Rotliegend, was a very significant factor in the distribution of the sandstone thickness around the Wolsztyn Ridge. These geotectonic conditions are therefore also visible in the burial history during late Rotliegend time, which resulted in the creation of favourable migration zones for polymetallic brines.

The sandstones noted above are of aeolian and alluvial-fluvial origin, while in the uppermost contact zone with Zechstein deposits some are of marine origin (Błaszczyk, 1981; Karnkowski, 1986). Figure 5 shows the palaeogeography of the Rotliegend and distribution of sedimentary environments of the Wielkopolska Subgroup. In the proximal part of the basin, a playa environment dominated and in the distal part, mainly fluvial and aeolian sandstones were deposited. The reason for this lithological distribution was primarily subsidence, which was greater in the proximal than in the distal part. Areas of greater burial allowed retention of a lake environment (playa), and ar-

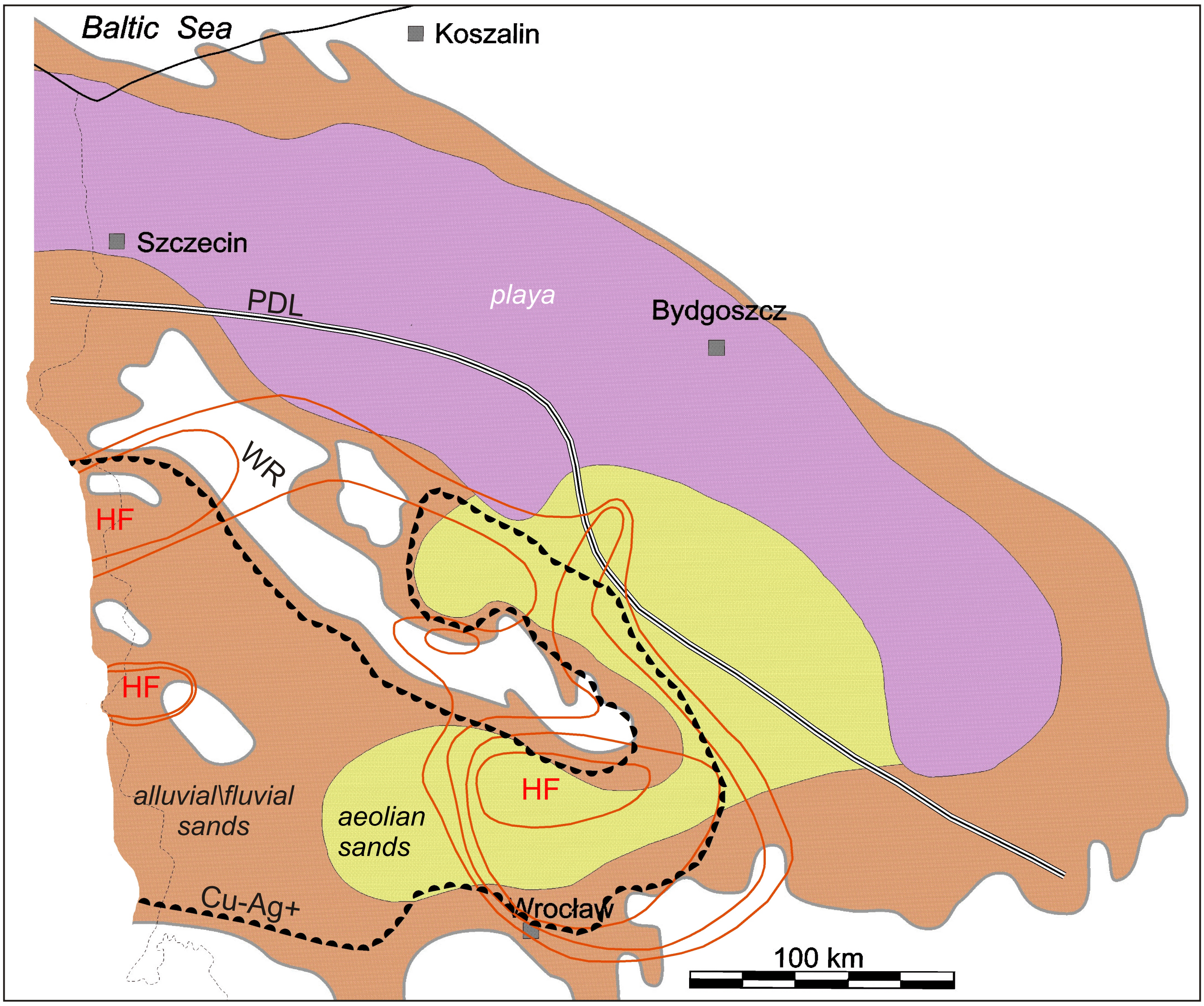

Fig. 5. Palaeogeographic map of the Polish Basin in Rotliegend time (mainly after Karnkowski, 1999), showing also heat flow values during the Late Rotliegend to Late Jurassic interval (cf. Fig. 3)

Abbreviations as in previous figures

eas with less subsidence were transition zones and source areas for Wielkopolska Subgroup clastic deposits (Karnkowski, 1987, 1994). These fluvial-aeolian environments over a large area are associated with palaeogeothermal anomalies (cf. Fig. 5). This is not the case everywhere and, for example, the northwestern edge of the Wolsztyn Ridge consists mainly of conglomerates and alluvial sandstones with significant clay and silt content. These compositions have very low values of porosity and permeability, and the polymetallic brines could not migrate through them (Poszytek, 2014). This analysis shows that the distribution of Rotliegend lithofacies was also geotectonically determined.

The evidence provided above show that the polymetallic brines reached the top zone of the Rotliegend relatively easily and continued to move towards structurally higher zones. Detailed analyses of changes in structural patterns during the Permian and Mesozoic periods for this region have been made (Karnkowski, 1980a, b). The top surface of the Rotliegend was tilted almost all the time to the north or north-east (Fig. 6). Thus, the brines mostly migated to the south-west and south. An analysis of top Rotliegend surface at the end of the Jurassic (Fig. 6), performed for the entire Polish Basin, coroborates earlier research (Karnkowski, 1980a, b). This map was prepared for other purposes and its use in analysis of migration of polymetallic brines in the Rotliegend uppermost zone includes puzzling features. The shortest path from the main palaeogeothermal anomaly (main HF, Fig. 5) to the structurally highest area runs exactly through the LGOM deposit zone (Fig. 6). Migration on the northern side of the Wolsztyn Ridge also took place mainly to the south-west but did not cross this structure. On the southern side of the Ridge, hydrothermal solutions may also have been supplied by a small palaeogeothermal centre located in the Polish-German border region. Due to the smaller size and worse petrophysical conditions of these Rotliegend deposits to enable the migration of brines, the scale of this phenomenon was probably much smaller compared to the main palaeogeothermal anomaly in the Wielkopolska area.

GEOTECTONIC ASPECTS

The sub-Cenozoic geological structure was already well known in the mid-1950s, because drilling to 200-300 metres depth was sufficient to map it out. The intense development of geological research that took place in 1950–1996 contributed

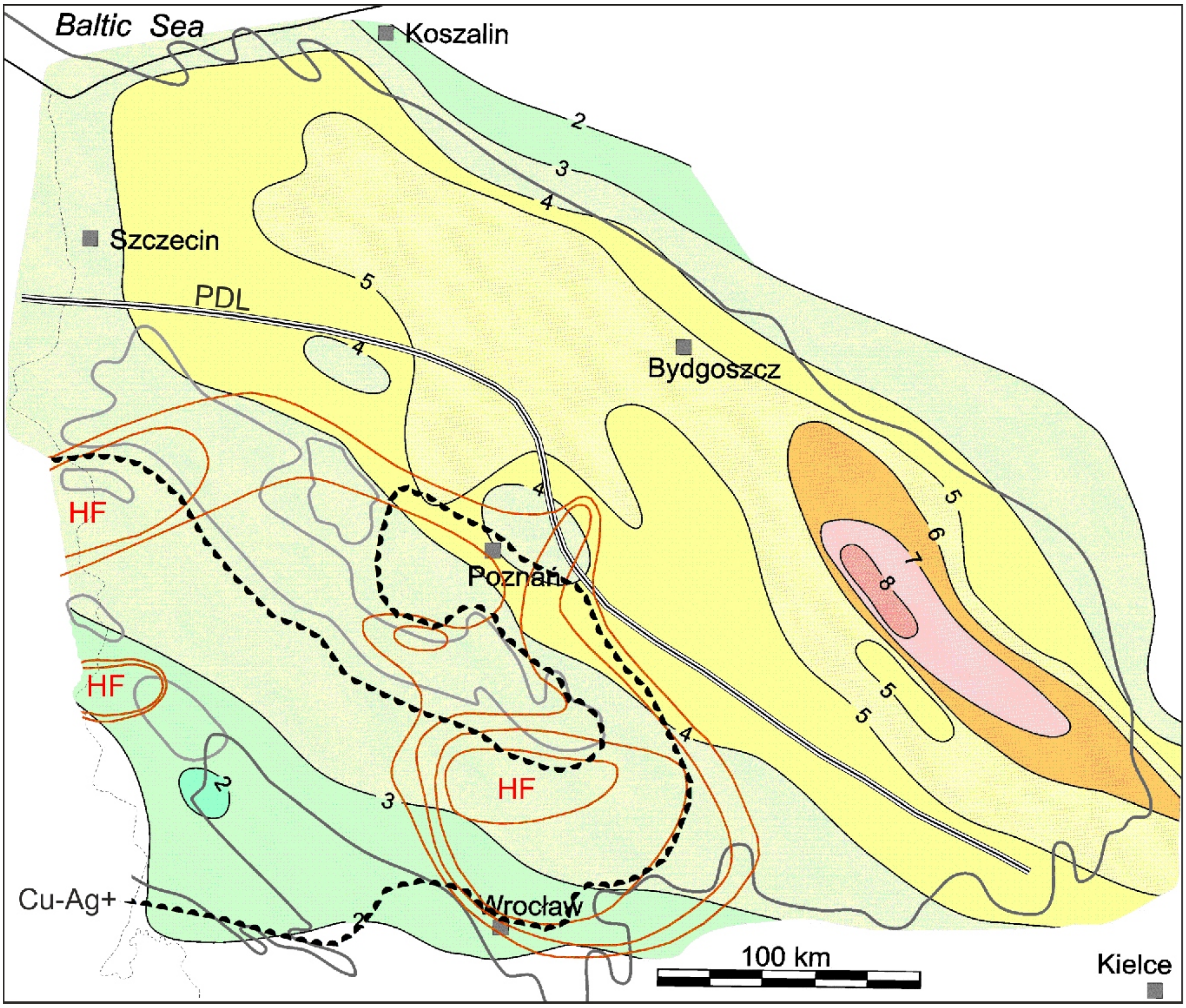

Fig. 6. Top of the Rotliegend deposits at the end of Jurassic time in the Polish Basin (after Karnkowski, 1999) together with heat flow values during the Late Rotliegend to Late Jurassic interval (cf. Fig. 3); abbreviations as in previous figures; note the 2 km depth anomaly (SW corner of map) and 8 km depth anomaly marking the potential directions of brine migration

significantly to knowledge of the deep structure of the Polish Lowlands (Pożaryski, 1956, 1957a, b, 1963, 1964, 1969, 1974, 1979; Znosko, 1998; P. Karnkowski, 1979, 1993; Pożaryski and Dembowski, 1983; Pożaryski and Karnkowski, 1992; Dadlez et al., 1994; Karnkowski, 2008; Dadlez, 1997, 1998, 2006; Van Wees et al., 2007; Narkiewicz and Dadlez, 2008; Żelaźniewicz et al., 2011).This is also demonstrated by the "Geological Atlas of Poland: Geological Maps of Horizontal Shear" edited by Kotański (1997).

The influence of palaeogeothermal, palaeotectonic and sedimentary factors on the distribution of polymetallic mineralization zones in the Permian formations of the Polish Basin indicates the distribution of this phenomenon in relation to the distal part of this basin (cf. Figs. 3-6), which outlines the extent of Rotliegend deposits (Fig. 7). Obviously, this single line (Rotliegend extent) is not the exact boundary of the Polish Basin, which varied in its extent depending on the scale of marine transgressions or the magnitude of subsidence in adjacent areas. Despite these influences, the north-eastern boundary of the basin generally corresponds to the extent of the basement consolidated in the Precambrian, while the southern boundary is almost E-W and lies in the Variscides. The Caledonian consolidation area is present only in the proximal part (Fig. 7). An important element is the limitation of the basin to the south-east by the Małopolska Massif with a Cadomian consolidation age (Karnkowski, 1999; Żelaźniewicz et al., 2020). The Permian polymetallic zone is particularly linked to the area located south of the Wolsztyn Ridge, i.e. the basement with a Variscan consolidation age.

Some of the tectonic maps of Poland made to date have taken the age of basement consolidation into account (e.g., Dadlez and Jaroszewski, 1994; Znosko, 1998). Such a visualization of tectonic pattern is understandable because of the stacked structure of the crust, i.e. the influence of the substrate on the genesis and development of large regional units results from the assumption that the youngest orogenic event that affects a given section of the Earth's crust provides the conditions for a wide array of dynamic and metamorphic processes. Within these settings, geological structures with specific (coherent) characteristics affecting all subsequent geological phenomena develop only in a platform regime. The map of the provinces of the consolidated substrates provided here (Fig. 7) is a slightly

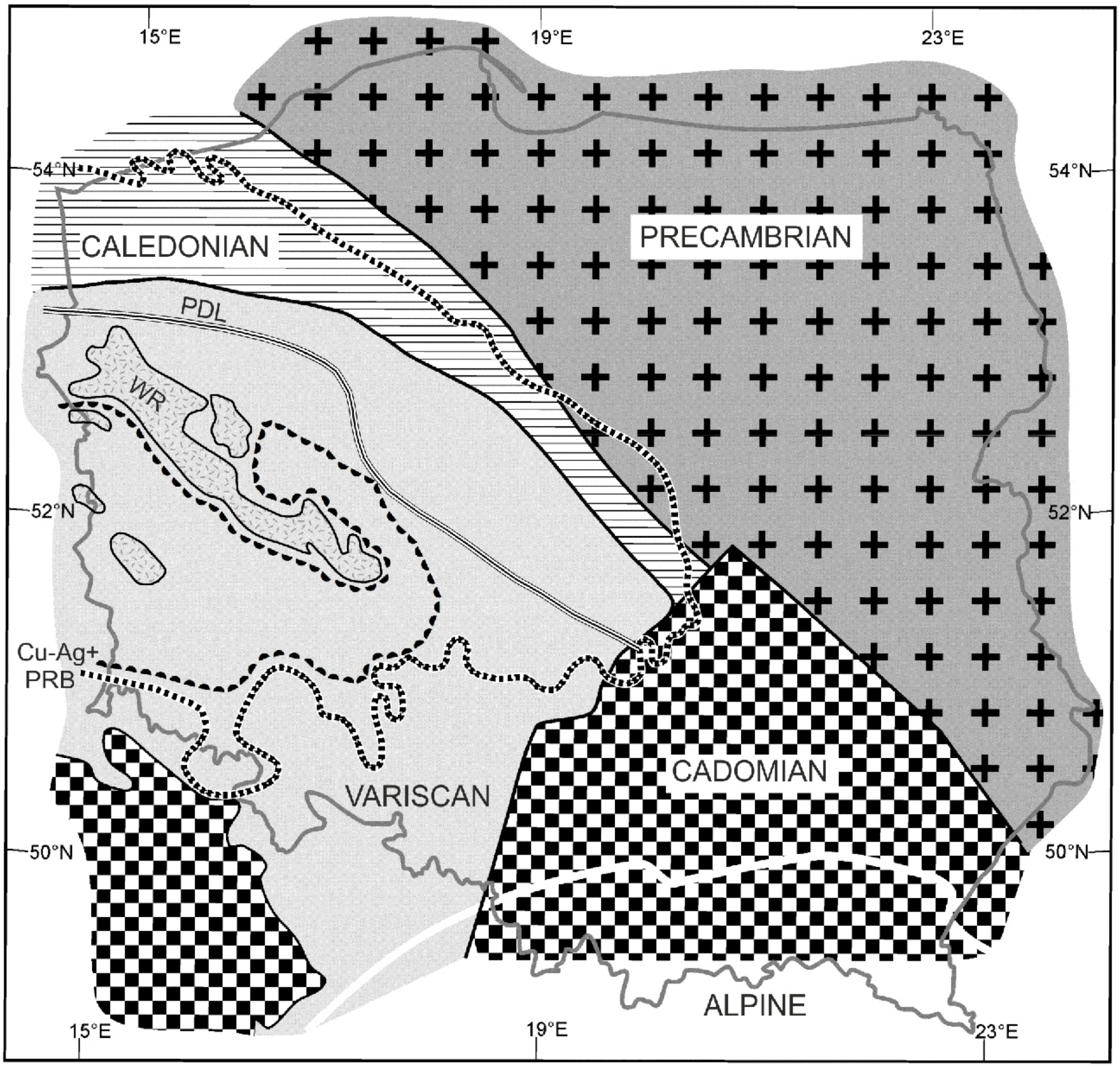

Fig. 7. Extent of the Polish Rotliegend Basin and main area of polymetallic mineralization in the transition zone between Rotliegend and Zechstein deposits on a background of the basement provinces of Poland

Abbreviations as in previous figures

modified version of the map previously published by Karnkowski (1999). What clearly distinguishes this map from the maps of Dadlez and Jaroszewski (1994) and Znosko (1998) is the distinction in the Małopolska region of a province of Cadomian consolidation (650–550 Ma) rather than Caledonian consolidation. Also, in central Poland, the Caledonides cover a smaller area than indicated on earlier maps (Znosko, 1965, 1986; Dadlez et al., 1994). The main geotectonic units of basement consolidation exactly match the distribution of the contemporary geothermal field in Poland (Majorowicz, 2021).

In the Polish geological literature over the past several decades, the most common location of the Polish Basin is referenced to the Mid-Polish Anticlinorium, which extends to southern Poland, to the Carpathians, and even to Dobruja (Świdrowska et al., 2008). These ideas were initiated in the 1950s as geological research into the Polish Lowlands commenced. Pożaryski (1956) proposed a division of the Polish Lowlands into the Kujawy–Pomerania Swell and the troughs surrounding it: This area, with increased Permo-Mesozoic subsidence in the Polish Lowlands along the Polish part of the East European Craton, was originally distinguished as the Danish-Polish Furrow by Pożaryski (1957a, b). It was considered to be a geosyncline extending from Denmark to the Carpathians (Fig. 8), and even to the Carpathian-Tethyan area. This view met with strong opposition from Wdowiarz (1983). In the 1970s, introduced the term Mid-Polish Trough, and then the taphrogenic term aulacogen (Pożaryski and Brochwicz-Lewiński, 1979; Fig. 8). In south-eastern Poland, this problem was discussed in particular by Głazek (1993; Kutek and Głazek, 1972; Głazek and Kutek, 1976), who fully shared the views of Pożaryski (1963, 1964, 1969) concerning a symmetrical Polish Basin, the central part of which was the Mid-Polish Furrow. Kutek (1989), however, developed his views in 1994, believing that the Mid-Polish Furrow in the Małopolska section was rifted

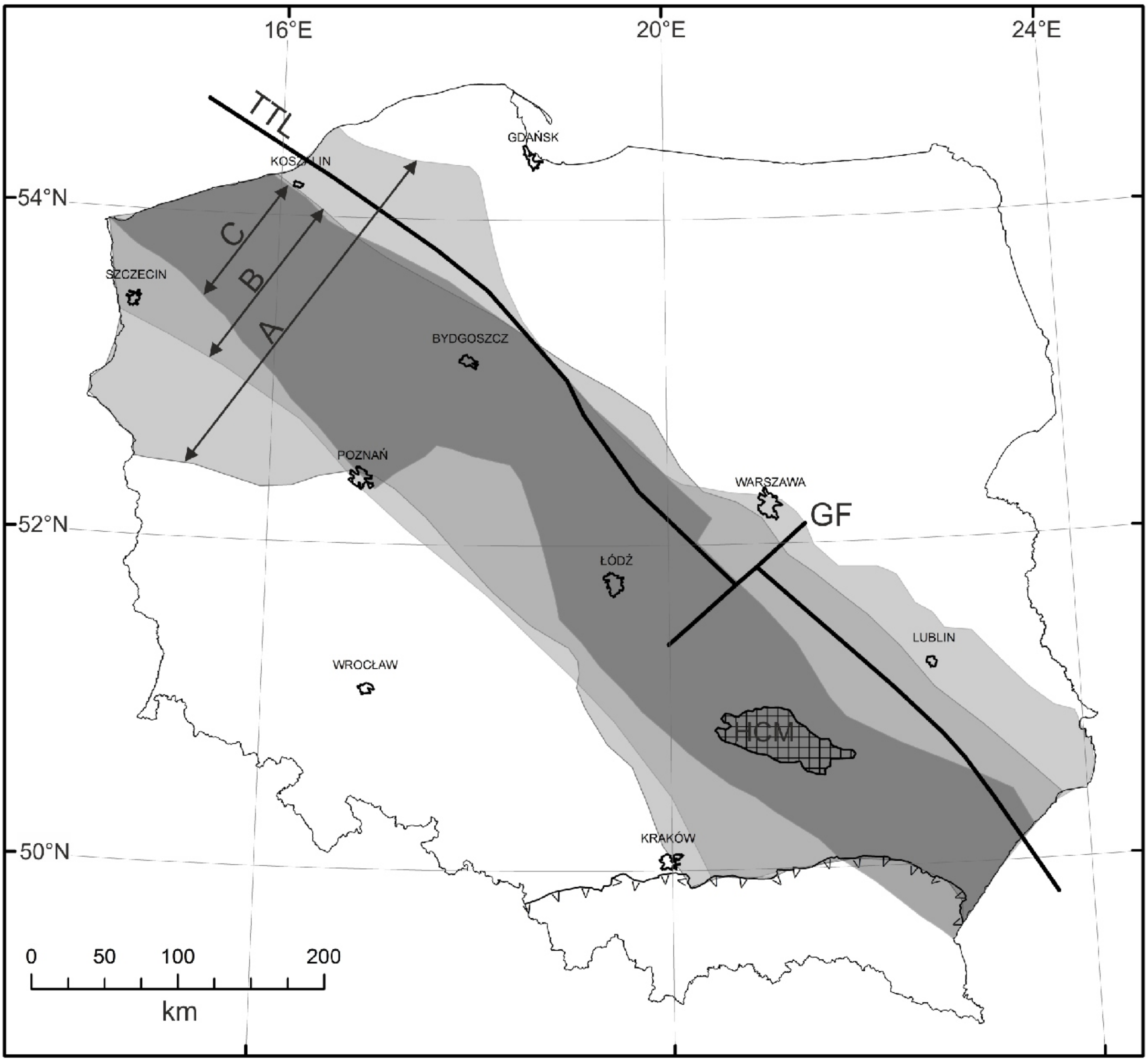

Fig. 8. Extent of the main subsidence area of the Mesozoic depocentre in Poland distinguished by Pożaryski as: A – peri-cratonic basin (1953–1970), B – furrow (1970–1978), C – aulacogen (1978–2008)

TTL – Teisseyre-Tornquist Line, HCM – Holy Cross Mts, GF – Grójec Fault

asymmetrically and genetically linked to the Carpathian rift system. Kutek (1994) considered the Holy Cross Mountains as a link between the Małopolska-Carpathian and Pomeranian-Kujawy parts of the rift. Kutek (1994) derived his concept of rift from the studies on southeastern Poland and wanted it to be spatially extended to the north-west, and temporally from the Permian, and not from the Jurassic, as he believed was the case in SE Poland (Kutek, 1996a, b, c).

In the 1980s and 1990s, much exploration work was carried out in the Mesozoic formations of the Carpathian Foredeep. Thanks to the efforts of many geologists, it was possible to significantly change the stratigraphic ranges of some lithostratigraphic units. It turned out that the thickness of the Upper Jurassic deposits is two to three times smaller than originally assumed (Dziadzio et al., 2004; Gliniak et al., 2005; Matyja, 2009; Urbaniec, 2021). Given this new data, the existence of the mid-Polish Furrow in southeastern Poland (Kutek and Głazek, 1972; Pożaryski and Brochwicz-Lewiński, 1979; Kutek, 1994; Hakenberg and Świdrowska, 1997; Świdrowska et al., 2008) was not supported by the evidence. Wdowiarz (1983) had raised these doubts much earlier. Also, studies on the Upper Cretaceous deposits, e.g., by Walaszczyk and Remin (2015), began to support the earlier views of Krasowska (1997) concerning the existence of an elevation (island) in the Holy Cross Mountains at the end of the Mesozoic. The results of these studies are incompatible with the concept of Kutek and Głazek (1972) regarding the existence of an extension of the Mid-Polish Trough in southern Poland, and do not support the existence of a rift (Kutek, 1994) in this area. Also testing the correctness of the model envisaged by Kutek

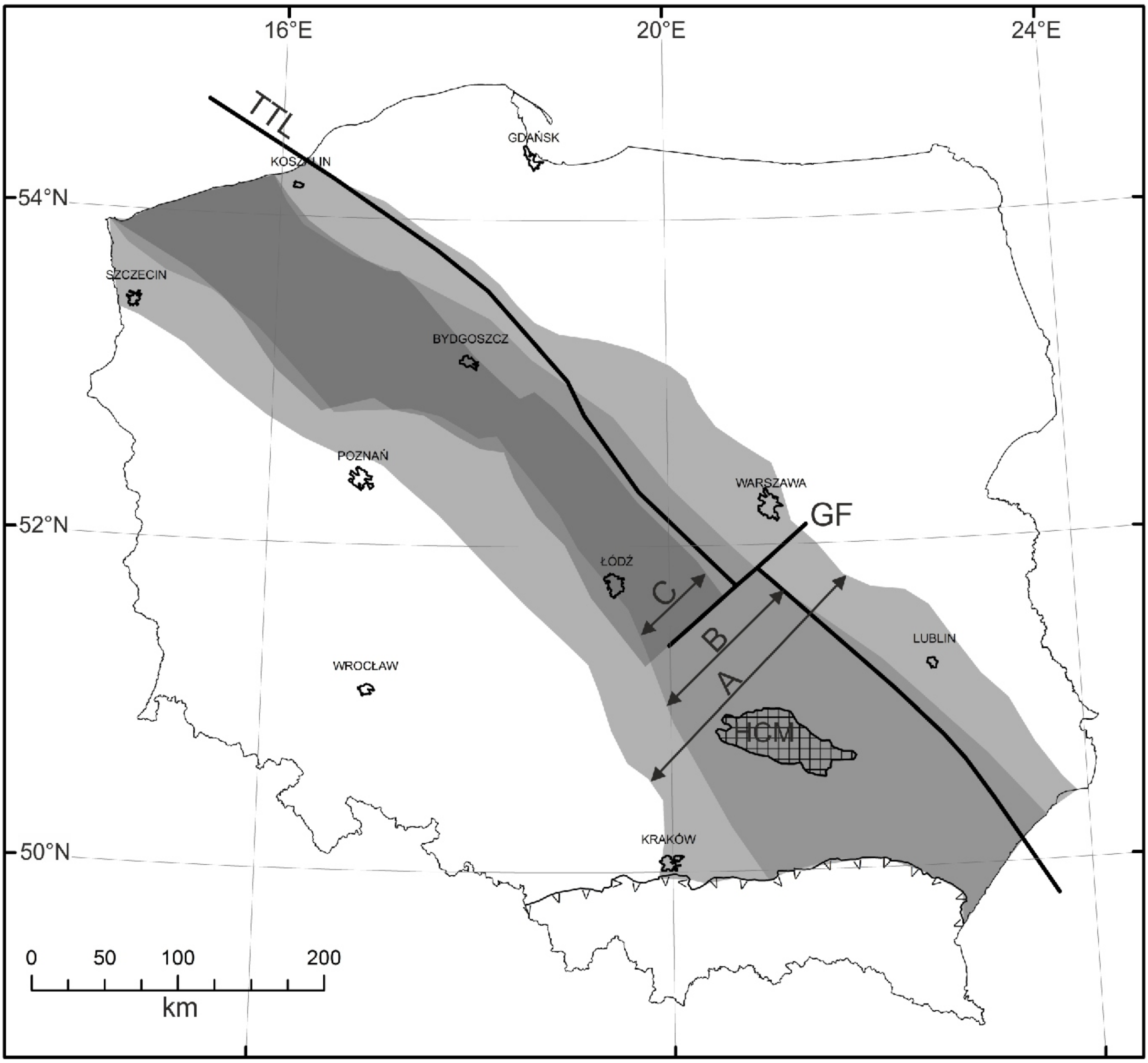

Fig. 9. Extent of the main subsidence area of the Mesozoic depocentre in Poland (Mid-Polish Trough) distinguished by Dadlez: A — (1970–2002), B – (2003), C – (2006)

Other abbreviations as in previous figures

(1994, 1996a, b) is palaeogeothermal research in the area of the Małopolska Massif. Lewandowski (1982) believed that the sedimentary thickness established by Kutek and Głazek (1972) over the Paleozoic basement of at least 4,000 m was overestimated. Taking into account the contemporary geothermal gradient, the temperature at the bottom of the Permian-Mesozoic succession should be 110°C. At this temperature, hematite minerals should undergo magnetization in all pre-Cretaceous rocks. However, such a phenomenon is not observed (Lewandowski, 1982). Therefore, it can be explained by assuming a smaller thickness of Mesozoic overburden or a lower heat flow in the Holy Cross Mountains area at the end of the Mesozoic. Lewandowski (1982) estimated that the maximum palaeotemperature of the Permian deposits did not exceed 70°C, because higher temperatures would destroy the Cretaceous rocks' magnetic polarity. In this situation, Lewandowski (1982) suggested that the maximum thickness of the Mesozoic succession could not exceed 2500 m, or the geothermal gradient was not higher than 18°C/1 km. Obeservations of other geologists of the colour of Carboniferous conodonts in the western region of the Holy Cross Mountains indicated that temperatures were not higher than 50°C (Jurkiewicz and Szczerba, 1976; Belka, 1990; Marynowski, 1997, 1999; Szczepanik, 2002; Malec, 2002a, b; Marynowski et al., 2002; Narkiewicz, 2002, 2007; Narkiewicz et al., 2010). Narkiewicz et al. (2010) rejected the concept of Kutek and Głazek (1972) because of the impossibility of such a large thickness (4000 m) of Mesozoic deposits. Importantly, Narkiewicz et al. (2010) corroborated the earlier observations of Lewandowski (1982). Therefore, the model of Kutek (1994) cannot be extrapolated farther to the north-west or back in geological time as far as the Permian. The Małopolska Massif of Cadomian age consolidation (Żelaźniewicz et al., 2020) was the northern slope of the Tethys in the Permo-Mesozoic.

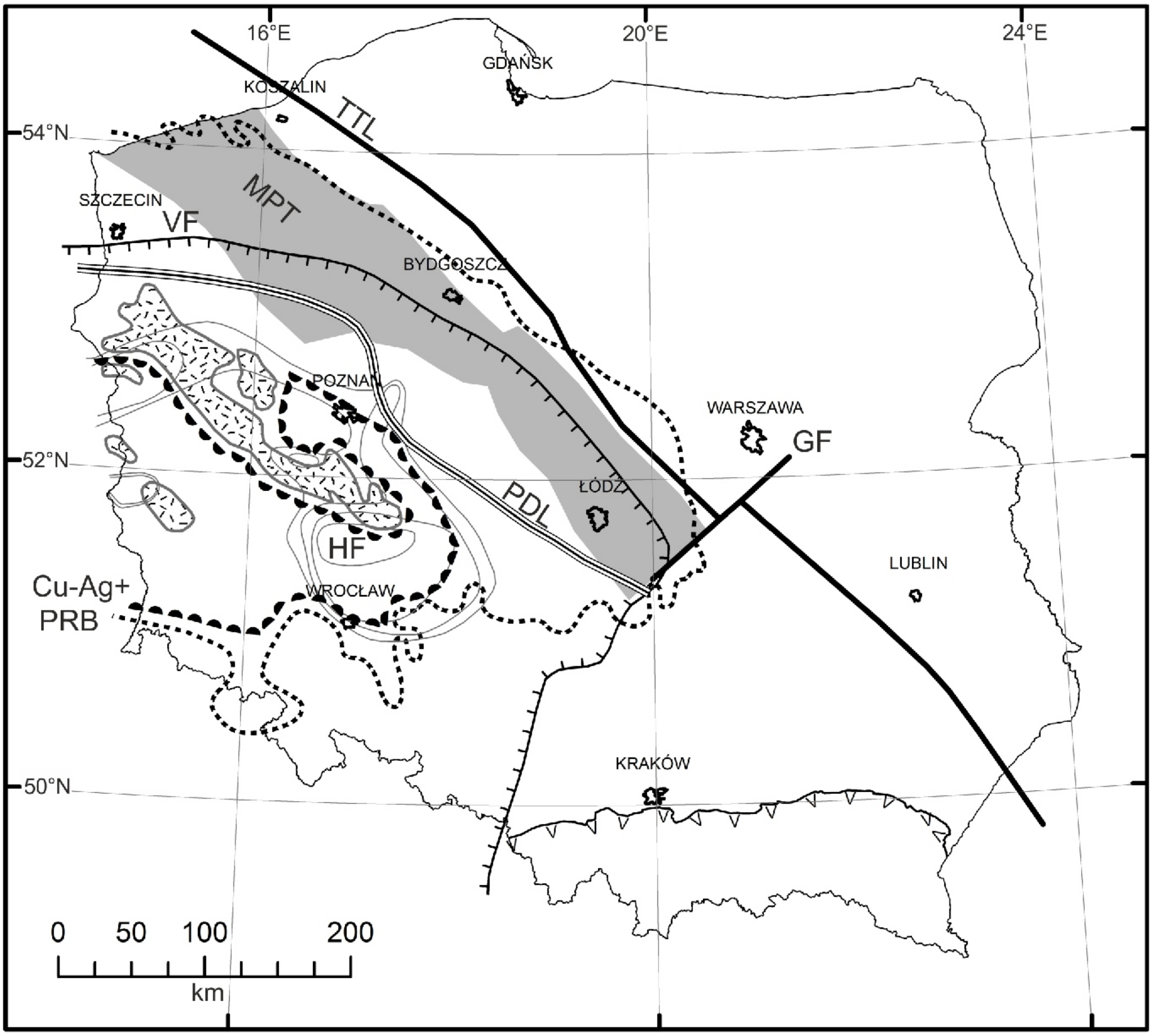

Fig. 10. The main elements of the Polish Basin on the background of Permian polymetallic mineralization: MP – Mid-Polish Trough (*sensu* Dadlez, 2006) in a proximal part of the Polish Basin

VF – Variscan Front; other abbreviations as in previous figures

The geotectonic distinctiveness of the Małopolska Massif in relation to the areas to the north (Polish Lowlands) suggests that the term the Polish Basin should be used only for the area located north-west of the Grójec fault, i. e. the proximal and distal parts of the Polish Basin *sensu* Karnkowski (1999).

The concept of a mid-Polish rift by Kutek (1994) was also contested by Dadlez et al. (1998) and Stephenson et al. (2003). Dadlez's views on the location and position of the mid-Polish Trough in 1970–2002 were almost identical to Pożaryski's views (1963, 1964, 1969, 1974; Fig. 9). However, Dadlez (1997, 1998) divided the Trough into three parts: Pomerania, Kujawy and Małopolska. At the same time, he opined that the Małopolska segment differs significantly from the Pomerania–Kujawy segment, both in its crystalline and sedimentary rocks. In later years, Dadlez (2003, 2006) strongly moderated his opinion on this issue (see Fig. 9), reduced the lateral extent of the Trough (Dadlez, 2003), and finally limited it to a narrow Pomerania–Kujawy segment (Dadlez, 2006). At the same time, Świdrowska et al. (2008) developed a detailed characterization of the sedimentary and tectonic evolution of the southwestern edge of the East European Craton (from Małopolska to Dobruja in Romania) from the Permian to the present day.

Our overview of the geotectonic position of the Polish Basin shows mainly its relationship with the area of Variscan consolidation (Fig. 7). The position of the Polish Trough in the Polish Basin (*sensu* Dadlez, 2006) should be understood as the proximal part of this basin (Fig. 10). The main area of Permian polymetallic mineralisation in the Polish Basin was genetically related to its rift zone (maximum values of heat flow in Permian-Jurassic time), but the final concentrations of copper, silver, zinc, lead and platinum minerals was also conditioned by the migration of hydrothermal solutions from the rift zones to "reservoir rocks", that is, the uppermost part of the Rotliegend and lowest Zechstein successions (Fig. 10). The timing of these concentrations has been corroborated by many studies (Oszczepalski, 1999; Michalik and Sawłowicz, 2001; Speczik et al., 2007; Alderton et al., 2016; Mikulski and Stein, 2017). They point out that the mineralization took place in several stages from the deposition of cupriferous shale, for at least 100 My, up to the Cretaceous period. Such a statement corresponds well with inferences regarding the rifting period in the Polish Basin (Karnkowski, 1999) and indicates the multi-stage nature of this process (Blundell et al., 2003). On the other hand, it can be seen that the rift mechanism, which tectogenetically drove the development of the basin, resulted in the formation of its framework in closely in accord with the age of basement consolidation of the basin.The sedimentary development directly necessary for the formation of the Permian polymetallic mineralization (as regards thickness, lithofacies and structural patterns) was also largely controlled by the tectonic factors needed for brine migration. We explore this issue in more detail below.

The various geological processes noted above, which contributed to the formation of the Permian polymetallic deposits, have their original determinants in the geotectonic nature of the Polish Basin. The location of rift zones, their long-term activity and their influence on the sedimentation, subsidence, diagenesis and thermal maturation of the deposits directly involved in the formation of polymetallic deposits have become more clearly understood as research has progressed. The copper deposits of the Polish Basin demonstrate the synergistic effects involved in geological processes. As a rule, geotectonics is a primary and long-lasting factor.

DISCUSSION

The synthetic compilations of geological data concerning Permian polymetallic deposits described above show the location of various geotectonic elements within the Polish Basin in relation to base and precious metal mineralisation zones (Figs. 2–10). From the beginning of the exploration and exploitation of copper deposits in Lower Silesia, concepts of the genesis of these deposits have developed. The first of these referred to the crystallization of sulphides in estuarine deposits (Brongersma-Sanders, 1966; Harańczyk, 1972; Konstantynowicz, 1973; Tomaszewski, 1986; Sawłowicz, 1990, 1993). In the second stage of research, diagenetic models dominated: both early (Rentzsch, 1974; Mayer and Piestrzyński, 1985; Haynes and Bloom, 1987a, b; Brown, 1997) and late diagenetic models (Jowett et al., 1987a, b; Püttmann et al., 1988; Vaughan et al., 1989; Bechtel et al., 2002).

In the context of these models and of current research , it is useful to recall Oszczepalski's (1999) statement that *The Kupferschiefer mineralization resulted from upward and laterally flowing fuids which oxidized originally pyritiferous organic matter-rich sediments to form hematitic Rote Fäule areas, and which emplaced base and noble metals into reduced sediments. The Rote Fäule may be a guide to favoured areas for both the Cu-Ag and new Au-Pt-Pd Kupferschiefer-type deposits*. Alderton et al. (2016) corroborated that observation and adopted a model involving the deposition of precious metals and the oxidation of the existing copper ore deposit.

Opinions on the sedimentary-hydrothermal origin of the metals appeared parallel with sedimentary-only models. It was inferred that the metals may have come from igneous deposits located beneath the Fore-Sudetic Monocline at a depth of 15 km, with tectonic processes being responsible for the delivery of mineralized solutions to the Permian deposits (Ekiert, 1960; Wyżykowski, 1971).

These composite models showed the complexity of the genesis of the Lower Silesian Permian polymetallic deposits, which requires a holistic approach to understanding metallogeny, particularly of the metal sources of the Kupferschiefer ores. Indeed, this research direction has become very active (Vaughan et al., 1989; Blundell et al., 2003; Hitzman et al., 2005, 2010; Kucha, 2014). Borg et al. (2012) stressed the need to organise future research as a fully integrated approach to the European dimension of the metallogenic systems that have been triggered and driven by major crustal tectonic and magmatic events in continental-scale processes, to form regional metallogenic districts.

The present paper attempts to answer that challenge. Terms such as "igneous solutions beneath the Fore-Sudetic Monocline" or "Variscan crystalline high area" appearing in previous papers were intended to encourage characterization of the deep basement of the Lower Silesia region. Similarly, here we focus on geotectonic analysis of various elements in the Polish Basin, which began to form at the beginning of the Permian (Rotliegend) up to end of Jurassic time. In the Late Jurassic and Early Cretaceous, the distal area of the Polish Basin was significantly elevated, leading significant erosion of Mesozoic strata. There was another sedimentation episode in the Middle Cretaceous related to a large-scale global transgressive event. As the Cretaceous gave way to the Paleogene, another phase of tectonic inversion of the Polish Basin took place. These two major episodes of tectonic movement correspond well with the main metallogenic stages that have produced economically viable ore bodies (Borg et al., 2012).

The development of the Mesozoic sedimentary cover in Poland, particularly the thickness pattern of these deposits, was for many years the main clue concerning the symmetry of the Polish Basin (Figs. 8 and 9). Much geological data from deep boreholes and geophysical surveys enabled good understanding of the Permian deposits representing the first stage of Polish Basin development (Figs. 4 and 5). These data also made it possible to undertake geological modeling of the thermal history of the Polish Basin (Fig. 3) and to propose a coherent model of the Polish Basin as an asymmetrical rift basin (Karnkowski, 1999). In this view, the Polish Trough (*sensu* Dadlez, 2006) is recognized as the proximal part of the basin, the distal part being located to the west of the Trough i.e. in the Lower Silesia and partly in the Wielkopolska region. The ore mineralization of Permian deposits in the Polish Basin is related only to its distal part (Fig. 10).

It is now necessary to analyze the Permian metallic mineralization pattern in the Polish Basin by means of a fully integrated approach. Modern procedure to the exploration of mineral resources is based on a "mineral system concept" (McCuaig and Hronsky, 2014; Hagemann et al., 2016). Its nomenclature references the methodology used in oil exploration by the petroleum industry since the 1970s (Magoon and Beaumont, 1991), where three basic elements are considered in the formation of deposits: source rock, migration and trap. This is, of course, a great simplification, the purpose of which is to show that the methodology of a "mineral system" is similar, where the term "source" covers the issues of the origin of metals; migration is related to analysis of pathways and the word traps is understood as areas of metal deposition. All these processes take place in geological time and space, and the recognition of patterns of mineralization requires the analysis of much geological, geophysical and geochemical data. It is necessary to understand the evolution of mineral processes in their geotectonic and geodynamic context.

The understanding of mineral deposits has evolved from hand samples to determining concentration levels in favorable host rocks and analysing the structural processes controlling the influx of fluids and metasomatic processes (Conolly, 1936; McKinstry, 1941, 1955; Korzhinskii, 1968; Kirkham, 1989). This led to a holistic understanding of mineralization processes in their broad geodynamic and geotectonic setting (Groves et al., 2005; Kerrich et al., 2005; Goldfarb et al., 2010; Leach et al., 2010; Cawood and Hawkesworth, 2013; O'Neill et al., 2013; McCuaig and Hronsky, 2014). Such a complete approach to studying mineral deposits also results from the use of an ever wider spectrum of research methods, particularly involving geophysical and deep drilling techniques. Data from such studies make it possible to better combine detailed stratigraphic, sedimentological, geochemical, tectonic and cartographic studies into one data set in order to develop a coherent model of the development of mineralization in time and space (Groves et al., 2005; Kerrich et al., 2005; Goldfarb et al., 2010; Leach et al., 2010; McCuaig and Hronsky, 2014; Hagemann et al., 2016).

Good examples of such methodology in this paper include the synthetic analysis of heat flow distribution during the Permian-Jurassic times, especially its maximum values with regard to source areas (Fig. 3) and in relation to the thickness distribution of clastic deposits (bedrock migration, Fig. 4), and the analysis of the facies sedimentary pattern of sub-Kupferschiefer strata (Fig. 5). And, analysis was made of the position of the top surface of Jurassic strata at the end of the Jurassic time in relation to the distribution of heat flow then, to help determine the directions of flow of mineral brines with respect to thermal and hydraulic differences (Fig. 6).

Reference here is made to the term "mineral system" originally defined by Wyborn et al. (1994), and modified many times (cf. Knox-Robinson and Wyborn, 1997; Lord et al., 2001; Price and Stoker, 2002; Kreuzer et al., 2008, 2010; McCuaig et al., 2010; Murphy et al., 2011; McCuaig and Hronsky, 2014; Hagemann et al., 2016). Each time, however, complex, synthetic observations helped develop broad, regional conclusions serving optimal exploration geology (O'Driscoll, 1986; Woodall, 1994).

Each system, which consists of many interdependent elements, must be analyzed through the prism of the critical values of these elements, because the final evaluation of the mineral system is the product of the values of its individual elements. It is enough for only one element to have a negative (zero) value, and the final result will also be negative (zero). That is why so much importance should be attached to a detailed analysis of the critical elements of the mineral system in a broad regional and temporal aspect. The main elements are: 1) *Favourable whole lithosphere architecture* (e.g., Chernicoff et al., 2002; Crafford and Grauch, 2002; Murphy et al., 2008); 2) *Transient favourable geodynamics* (i.e. time of favourable deposit formation processes; 3) *Fertility* – understood as the tendency for a particular geological region to be systematically better endowed than otherwise geologic environments (McCuaig and Hronsky, 2014; Hagemann et al., 2016); and 4) *Preservation of primary depositional zone* (McCuaig and Kerrich, 1998).

The concept of "mineral system" described here must therefore be well-established in time and space in relation to adjacent geotectonic elements. The relation of the distal part of the Polish Basin to other geotectonic elements of this basin and elements in the neighbouring regions discussed in this paper (Figs. 2–10) clearly indicates a critical role of the rift zone of the asymmetrical Polish Basin as a place where all the elements of the mineral system existed, leading to the accumulation and preservation of the polymetallic Permian deposits.

CONCLUSIONS

1. Consideration of the origins of mineral deposits and the patterns of their occurrence are currently carried out in the "mineral system" methodology, which refers directly to practices of petroleum exploration. In this context, it is natural to analyze the origin of the ore deposits in their regional and geotectonic aspect.

2. The temporal and spatial relationships between the various elements of the mineral system described in this paper build a coherent model of the origin of Permian polymetallic deposits in the distal part of the Polish Basin. Within this, many previous concepts can be included in a broader regional and geotectonic context.

3. The Polish geological archives still contain much data that have not yet been studied in detail as regards Permian polymetallic mineralization. Their analysis with further exploration work is needed in order to better understand the deposit formation processes and to discover and document new mineral resources.

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