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Development of a non-perennial to ephemeral fluvial system in continental fault-bounded basin – an example from the early Permian Krajanów Formation of the Intra-Sudetic Basin (NE Bohemian Massif) – reply

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First, we would like to thank Paweł Henryk Karnkowski for his interest and critical reading of our recent paper (Kowalski and Furca, 2023) and the discussion he initiated (Karnkowski, 2024). In our reply we will focus on methodological and regional issues which were critically discussed by him (Karnkowski, 2024). We group our answers based on four major topics raised in his discussion: (1) methodological issues; (2) depositional processes and Permian palaeogeography of the Intra-Sudetic Basin (ISB); (3) lithostratigraphy, geometry and tectonics of the Intra-Sudetic Basin fill; and (4) controlling factors in early Permian cyclic sedimentation: climate vs. tectonics.

METHODOLOGICAL ISSUES

An important part of Karnkowski's (2024) comments on our paper (Kowalski and Furca, 2023) concerned methodological issues and the location of the exposures studied. Alleged "*discrepancies*" in locations of the main exposures described in our text, pointed out by Karnkowski (2024) in the discussion and on his figure 1, are only a result of differences in the scale of the maps presented on our figures 2 and 11C (Kowalski and Furca, 2023, p. 4 and 20). Firstly, figure 2 presented in our paper shows the simplified (and also generalized) regional-scale geological map of the northern ISB area. It should be stressed that it is impossible on a map of the scale of figure 2 to show satisfactorily the location of small-scale exposures. Secondly, figure 11C in our paper presents the location of the exposures studied in relation to the palaeogeographic scheme as interpreted and proposed. It is also practically impossible to cartographically compare the exact location of exposures between the regional-scale map (fig. 2C; Kowalski and Furca, 2023, p. 4) and the detailed palaeogeographic map shown on figure 11C (Kowalski and Furca, 2023, p. 20). To illustrate this problem, we note that the measured diameter of each of the location points marked in our figure 2 reach ~1 km at the scale of this map. The accurate topographic location of each of the exposures studied was shown separately on our figures 6 and 7, respectively (Kowalski and Furca, 2023, p. 12–13).

Figure 1 prepared by Karnkowski (2024) shows an author's attempt of GIS-based callibration of our figure 11C (Kowalski and Furca, 2023, p. 20). This map was georectified and readjusted onto the map from our figure 2 (Kowalski and Furca, 2023, p. 4), based on the location of points (exposures) situated nearly the centre of the map, with no reference points placed in its corners. This resulted in the apparent map "deformation" shown by Karnkowski (2024) on his figure 1 which may lead to significant confusion. Hence, we cannot agree with Karnkowski (2024), who concludes that the *transport direction considerations based on field studies may need to be revised with respect to the original palaeogeographic map*. Palaeotransport directions obtained from deposits of the lowermost Krajanów Formation have been measured in the field in logged sections, and were finally shown on our figures 6, 7 and 10 (also as rose diagrams; see Kowalski and Furca, 2023, p. 12–13 and 18). Then, these directions were positioned on the interpretive palaeogeographic map (fig. 11C; Kowalski and Furca, 2023; p. 20).

Karnkowski (2024) further analysed the location of selected archival boreholes located in the eastern part of the ISB (fig. 2 in Karnkowski, 2024). We agree with Karnkowski (2024) that lithological data obtained from these boreholes may constitute an important element for regional palaeogeographic interpretation. We have also analysed archival borehole data as shown by Karnkowski (2024, his fig. 2). However, it should be emphasized that the main part of our paper concerns the analysis of the outcrop-derived data. Analysis of (mainly artificial) exposures in our study area included macroscopic recognition, description, classification and detailed characterization of lithofacies, as well as vertical logging of the rock texture and sedimentary structures. Data derived from exposures was complemented by analysis of selected borehole data, especially those described in detail by Mieczník (1989). It is important to note that the lithological profile of the Świerki IG 1 bore-

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hole was shown on figure 5 in our paper (Kowalski and Furca, 2023; p. 9) only as the reference profile which shows the lihology and main features of the Krajanów Formation in the proximal to medial parts of the eastern Permian ISB. This complete lithological profile of the Krajanów Formation was shown with reference to deposits of the overlying Słupiec, and underlying Ludwikowice, formations drilled in the eastern part of the ISB. Despite that, Karnkowski (2024) criticized this approach and argues that *it seems illogical to integrate partial surface profiles of points 1–7 (Kowalski and Furca, 2023, fig. 5) into the complete profile of the Świerki IG 1 borehole*. In a subsequent paragraph Karnkowski (2024) stated also that in our paper we could refer to the profiles of other boreholes in the study area: *For example, the Świerki IG 2 borehole is located near point 3, the Głuszyca G-8 borehole near point 1 and the Nowa Ruda GN-24 and Nowa Ruda W-4 boreholes near point 6.* Unfortunately, many of these prospective boreholes, and other boreholes shown on figure 2 by Karnkowski (2024), have not been fully cored. For example, the original description of the lower Permian Krajanów Formation penetrated by the Nowa Ruda W-4 borehole is as follows: *7.0–20.0 m: fine- and medium-grained conglomerates; 20.0–100.0 m: reddish-brown sandstones, mudstones and conglomerates; 100.0–137.0 m: light-grey and brown sandstones and conglomerates*, etc. (Bossowski, 1974). Another significant example mentioned by Karnkowski (2024) is the profile of the Świerki IG 2 borehole (Fig. 1), located close to our exposures nos. 3, 4 and 5 (Kowalski and Furca, 2023, figs 6 and 10). The problem here is that the lowermost part of the Krajanów Formation in this borehole is cut by a zone of significant, unnamed regional faulting (Krechowicz and Kisielewski, 1965; Krechowicz and Berezowska, 1968). As a consequence ~100 m of the core is strongly crushed and no lithological/sedimentological information can be obtained from its description (the core is not preserved). In this context it is important to note that this missing interval of the Krajanów Formation was analysed by Kowalski and Furca (2023) in exposures situated in the nearest proximity of the Świerki IG 2 borehole. We conclude that any palaeogeographic interpretations based on borehole data derived from the study area must be evaluated with care.

Due to the limited length of our recent paper (with its significantly different approach) and the problems noted above, we did not discuss these issues and we also did not present profiles of other prospective boreholes penetrating the Krajanów Formation in the study area. Furthermore, these incomplete data have not been omitted in our palaeogeographic analyses (which refers only to the lowermost portion of the Krajanów Formation) and will probably be the subject of separate papers in the future.

DEPOSITIONAL PROCESSES AND PERMIAN PALAEOGEOGRAPHY OF THE INTRA-SUDETIC BASIN

The early Permian ISB constituted one of the semi-enclosed, fault-bounded, internally-drained (partly endorheic?) basins developed within and around the Bohemian Massif during the terminal phases of the Variscan orogeny (Holub, 1972, 1975; Lützner, 1988; Wojewoda and Mastalerz, 1989; Opluštil et al., 1998; Turnau et al., 2002). The Permian, non-marine sedimentary-volcanogenic succession of the ISB exhibits distinct, large-scale cyclic structure and comprises three fining-upwards continental megasequences up to 700 m thick (Nemec et al., 1982; Mastalerz et al., 1993; Awdankiewicz et al., 2003), which are traditionally distinguished as the Krajanów, Słupiec and Radków formations. These formations are mainly composed of an alluvial fan and fluvial deposits in their lower to middle parts, and fluvial/deltaic to lacustrine deposits in the uppermost parts (Nemec et al., 1982; Wojewoda and Mastalerz, 1989).

In our paper (Kowalski and Furca, 2023) we interpret the fluvial depositional system which developed in the eastern part of the ISB during the early Permian, as a distributive fluvial system (DFS). Such aggradational, fan-shaped systems with a downstream distributive runoff pattern are dominated by distinct sedimentary sub-environments (Fig. 2), which resulted in variations in sedimentary architecture across the proximal to distal zones of the system (e.g., Nichols, 1987; Nichols and Fisher, 2007; Weissmann et al., 2013; Owen et al., 2015; Carraro et al., 2023). Distributive fluvial systems tend to exhibit (i) gradual downstream decrease of channel abundance as well as their depth (and resultant downstream decrease in the amalgamation of channel-fill architectural elements); (ii) a decrease in overall grain size downstream and (iii) a downstream increase in sheet-flood and floodplain (overbank) deposits (Kelly and Olsen, 1993; Cain and Mountney, 2009; Coronel et al., 2020; Priddy and Clark, 2021). In the more distal sectors of the system, fluvial deposits are interbedded with playa, aeolian and ephemeral lacustrine deposits (Picard and High, 1973; Collinson, 1996; Kiersnowski, 2013; Al-Masrahy and Mountney, 2015; Priddy and Clarke, 2020). We pointed out that such large-scale features of the fluvial system in the eastern ISB are the apparent result of dry and semi-arid climates as well as regional tectonic activity during early Permian.

Karnkowski (2024) draw attention to terms used in the title of our paper and further contends that *the term "non-perennial" is used only once* and also that *the term 'ephemeral' is used only as 'ephemeral lake' in relation to the study area "(also only once)*. We would like to point out that both of these terms ("*non-perennial*" and "*ephemeral*") have been used and described many times in our paper (Kowalski and Furca, 2023). For example we referred to this terms during description of architectural elements of the fluvial system (*The CHa elements are interpreted as a palaeochannels of a multi-storey, non-perennial to ephemeral braided fluvial system* and further *In the upper part of the succession studied, the braided style of fluvial architecture evolved laterally and gradually upwards into non-perennial to ephemeral fluvial strata*; Kowalski and Furca, 2023, p. 17) and also during characterisation of the entire fluvial system in the study area (*The early Permian (?Asselian) fluvial system in this area was dominated by non-perennial to ephemeral fluvial processes influenced strongly by semi-arid to arid climate.*; cf. Kowalski and Furca, 2023, p. 21).

We agree that the uppermost part of the Krajanów Formation may be interpreted as deposits of playa subenvironment which developed in the medial to distal sectors of a distributive fluvial system in the eastern ISB. The palaeogeographic scheme presented on our figure 11C (Kowalski and Furca, 2023, p. 20) refers only to the lowermost part of the Krajanów succession. It is important to note that Karnkowski (2024, fig. 3A) offered little documentation to support his revised palaeogeographic scheme, which is based on our palaeogeographic map [*On the basis of figure 11C (Kowalski and Furca, 2023), I created a palaeogeographic map (Fig. 3PM)*]. Also the "CS-1" cross-section proposed by Karnkowski (2024; fig. 3B) are based on our palaeogeographic map and only one borehole profile (Świerki IG 1 borehole; Miecznik 1989). However, we agree with Karnkowski (2024, fig. 3A, B) who pointed out that his maps (and our palaeogeographic map (Kowalski and Furca, 2023, fig. 11C) *represent only the lower and middle part of the Krajanów Formation profile*.

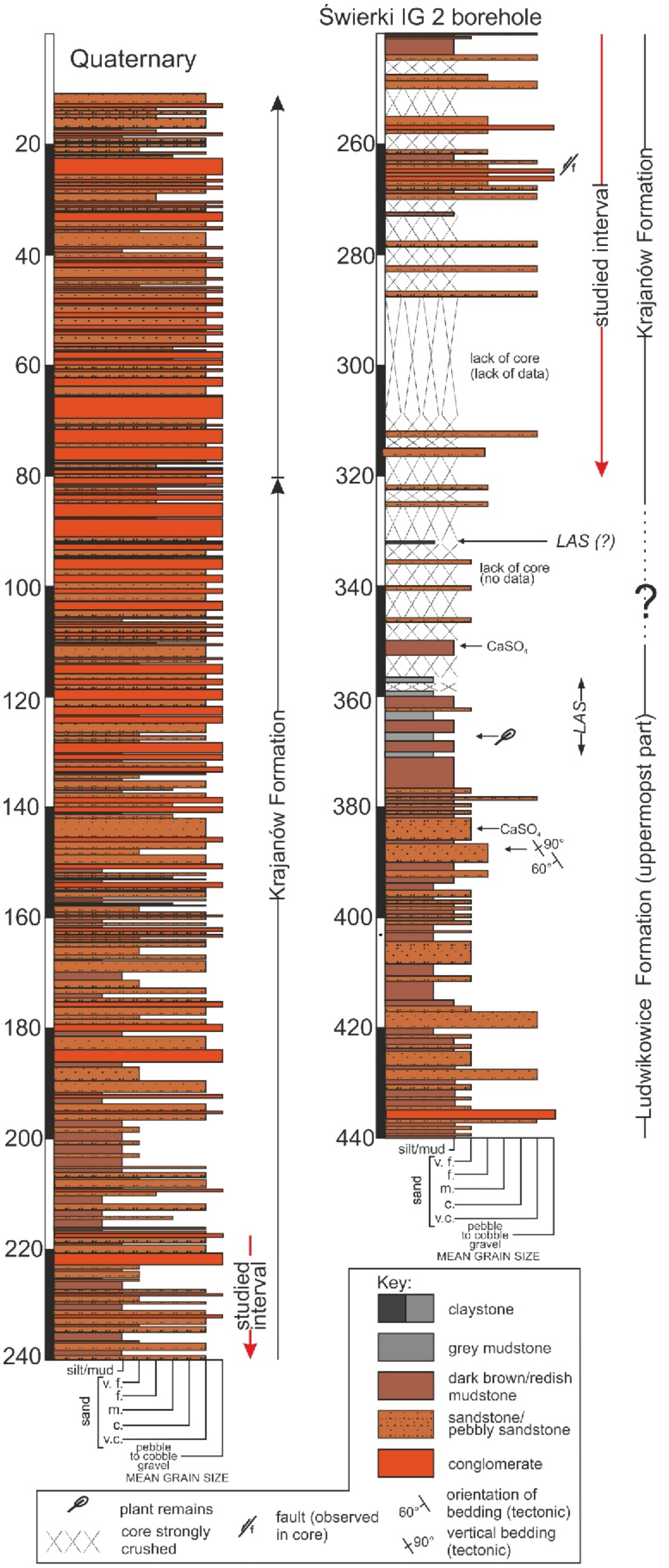

Fig. 1. Lithology and main features of the Krajanów Formation shown on an example of the Świerki IG 2 borehole located in the proximal part of the eastern Permian ISB

Note lack of data in interval of strongly crushed core in the area close to the fault zone (for location of the borehole see fig. 2 in Karnkowski, 2024)

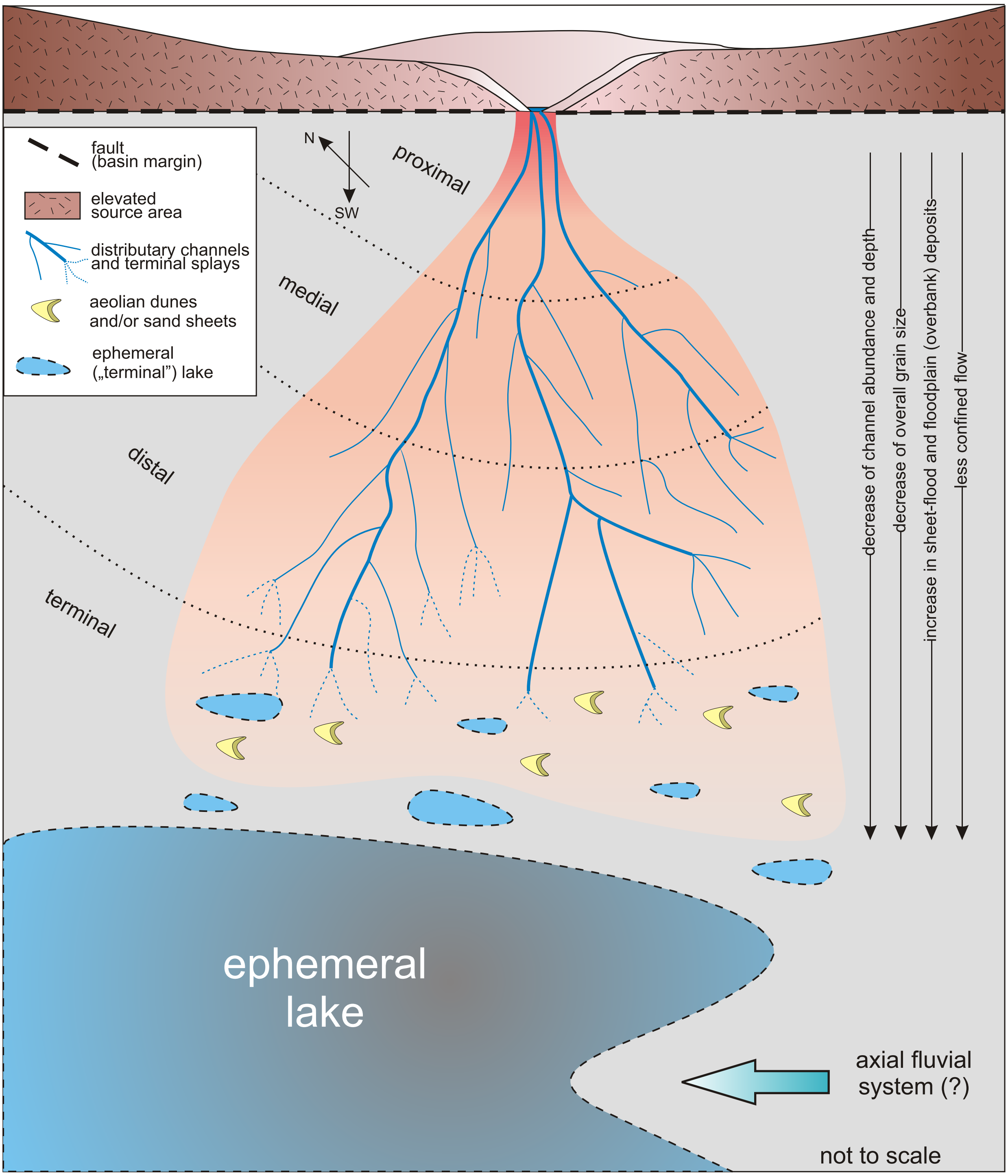

Fig. 2. Depositional model of the distributive fluvial system (DFS) with reference to the Intra-Sudetic Basin (inspired by and modified after Weissmann et al., 2013)

On the other hand we cannot totally agree with Karnkowski (2024), who further postulated that *the central part of the basin of the Krajanów Formation was occupied by lake deposits, but these were playa-type lakes filled with red clay deposits*. Firstly, many previous researchers (Don, 1961; Dziedzic, 1961; Nemec et al., 1982; Wojewoda and Mastalerz, 1989; Lorenc, 1993; Mastalerz and Nehyba, 1996; Nowak et al., 2022; Dąbek-Głowacka et al., 2024) indicated that organic-rich, black claystones and mudstones referred historically to as the Anthracosia shales (both the lower and upper ones), are interpreted as organic-rich, open-lake sediments, but not *red clay deposits*. Secondly, the statement that *the Anthracosia layers (lower and upper) have a small thickness, but a considerable lateral extension* (Karnkowski, 2024) is contradicted by many regional studies conducted by previous authors. For example, Miecznik (1989, p. 21) argued that *the second horizon of the Anthracosia shale does not constitutes a continuous lithological level, but occurs in the form of isolated lenses*. Also Nowak et al. (2022, p. 2) provided an interpretation that *the Anthracosia shales do not occur in each profile of the Pennsylvanian/Perm-*

ian sequence, so they do not form laterally continuous units, but rather occur as flat lensoidal bodies with a thickness varying from 20 to 70 m. These interpretatations, however, need further detailed sedimentological regional investigations, and should be corroborated also by borehole data.

LITHOSTRATIGRAPHY, GEOMETRY AND TECTONICS OF THE INTRA-SUDETIC BASIN FILL

In our recent paper (Kowalski and Furca, 2023), we adopted the widely used stratigraphic scheme proposed by Nemec et al. (1982) for the ISB area. The scope of our paper was not intended to discuss existing stratigraphic subdivisions, but to describe a process-based, sedimentological case study of the lowermost Krajanów Formation, investigated for the first time. In our opinion this remark also applies to Karnkowski's (2024) statement that *the term "member" is not used in the text, although it should be*.

We emphasize that the Krajanów Formation is formally not subdivided into individual lithostratigraphic members (Nemec et al., 1982). These authors stated that the Krajanów Formation *comprises the following units distinguished by earlier authors: the lydite conglomerate (Dathe, 1904), the quartzite conglomerate, the sandstone equivalent of the quartzite conglomerate, the Unisław conglomerate, the Czarny Bór conglomerate (Dziedzic, 1961), the red shales (Don, 1961) and the Upper Anthracosia Shale (Petrascheck, 1936)*. Deposits of the lowermost part of the Krajanów Formation: the so-called *lydite conglomerate* in the area between Nowa Ruda and Słupiec to the south-east, and the *quartzite conglomerate* between Nowa Ruda and Świerki to the north-west (Don, 1961) were distinguished based on the petrographic composition of gravel clasts. However, our detailed petrographic study (Kowalski and Furca, 2023, figs. 6 and 7, p. 7) did not allow for regional distinction between these two lithological, informal end-members. We agree with Karnkowski (2024) that the informal lithostratigraphic subdivisions proposed and used in the literature by various authors for the ISB area may cause confusion (Augustyniak and Grocholski, 1968; Śliwiński, 1980; Nemec et al., 1982; Miecznik, 1989; Bossowski and Ihnatowicz, 1994; Dziedzic and Teisseyre, 1990). Hence we used the lithostratigraphic scheme proposed by Nemec et al. (1982) which is the most widely applied and cited scheme in the regional literature (Aleksandrowski et al., 1986; Wojewoda and Mastalerz, 1989; Mastalerz et al., 1993; Awdankiewicz, 1999; Bossowski et al., 1995; Kurowski, 2004; Bossowski and Ihnatowicz, 2006; Biernacka, 2012; Voigt et al., 2012; Górecka-Nowak et al., 2021; Wójcik-Tabol et al., 2021; Awdankiewicz, 2022; Nowak et al., 2022; Ploch et al., 2023; Voigt et al., 2024).

Karnkowski (2024) also stated that the ISB infill *consists mainly of Carboniferous deposits, with Permian rocks constituting up to 10% of the total sedimentary succession*. The highly significant point here is that the total thickness of the ISB fill, estimated at 11,000 m (Nemec et al., 1982), is an assumed, aggregate stratal thickness, calculated by summing the thicknesses of individual lithostratigraphic units. In reality, especially in the central parts of the basin, the real thickness of the Carboniferous–Permian strata is much smaller. For example in the Dzikowiec IG 1 borehole, drilled in the central (axial) part of the Czerwieńczyce Graben (SE portion of the ISB), the total thickness of the Lower Permian succession reaches 991.0 m, while the thickness of the Upper Carboniferous succession is only 431.0 m (Bossowski, 1996). This borehole intersected the Carboniferous-basement unconformity at a depth of 1422 m.

Figure 4 included in Karnkowski (2024), is captioned *The conceptual model of lithofacies distribution and deposition of fluvial and lacustrine sediments in the Intra-Sudetic Basin during the Stephanian C-Autunian*. This figure, published also by this author much earlier (Karnkowski, 1986), was directly adopted from the publication of the North American Commission on Stratigraphic Nomenclature (NACSN, 1983, 2005; fig. 7, p. 1579), and shows both an allostratigraphic classification and lateral facies changes of alluvial and lacustrine deposits infilling a nearly symmetrical, tectonic graben. On the other hand, the ISB is considered as a strongly asymmetrical, fault-bounded basin (Nemec et al., 1982), with several individual depocentres developed during Late Carboniferous and early Permian times (Dziedzic, 1961; Wojewoda and Mastalerz, 1989). The overall basin asymmetry is reflected for instance in the bulk (logged) thickness of the Krajanów Formation in the study area (eastern termination of the ISB) where it reaches 420 m (Kowalski and Furca, 2023, fig. 5), and in the opposite (western) part of the ISB, where the coeval deposits of this formation drilled in the Lubawka IG 1 borehole are ~100 m thick (Grocholski, 1994). Such thickness relationships, reflected also in facies changes, result from strong lateral and vertical variations of the fluvial system across the opposite margins of the ISB.

Contrary to the opinion *only the outcrops around the Intra-Sudetic Synclinorium and the southern outcrops of the North Sudetic Synclinorium are accessible for field studies* (Karnkowski, 2024), the middle (central) part of the ISB exposes also the uppermost part of the uppermost lower–middle (?) Permian deposits which are assigned to the Chełmsko Śląskie Beds (Śliwiński, 1980, 1984). We emphasize that the Zechstein Sea did not reach the Intra-Sudetic area, which was elevated in relation to the North-Sudetic Synclinorium during the early and late Permian. A shallow-marine bay (lagoon?) dominated by carbonate sedimentation formed in the southernmost portion of the North-Sudetic Basin at that time (Kowalski et al., 2018). During the late early–middle(?) Permian, deposition in the ISB was terrestrial, dominated by alluvial fan and braided river environments (Dziedzic, 1961; Śliwiński, 1981, 1984; Fig. 3). The boundary between the Permian and the Triassic deposits in the middle part of the ISB area is an erosional unconformity (Śliwiński, 1981, 1984; Kowalski, 2020). If an late early to middle (?) Permian age of the Chełmsko Śląskie Beds is assumed, the minimum time gap corresponding to this unconformity would be ~20 Ma (Kowalski, 2020). This estimate implies a possible break in sedimentation in the middle part of the Intra-Sudetic area encompassing the whole late Permian. Thus, contrary to palaeogeographic scheme presented by Karnkowski (2024, fig. 6), the Wuchiapingian (~259–251 Ma) deposits are probably absent from the ISB (Śliwiński, 1984; Kowalski et al., 2018; Kowalski, 2020). However, it should be not excluded that the present-day Intra-Sudetic area constituted the source area for the North-Sudetic Basin during this time (Kowalski, 2020; Fig. 3). The middle to late Permian deposits may have been partially eroded before the Early Triassic sedimentation in the area of the ISB.

In palaeogeograpical reconstructions of the Sudetic area, special attention needs to be paid to relationships between the geometry of the basin fill and tectonics (i.e. the possible amount of lateral shortening). In our opinion, inferences about the original extent of the Permian deposits based on their current extent in the ISB are awkward. Crucial to a palaeogeographic reconstruction of the Permian ISB is the mutual relationship between its (inferred) primary boundaries and the present-day relics of basin-fill deposits preserved within a synclinorial unit, termed the Intra-Sudetic Synclinorium (Oberc, 1972; Żelaźniewicz and Aleksandrowski, 2008; Żelaźniewicz et al., 2011). The current

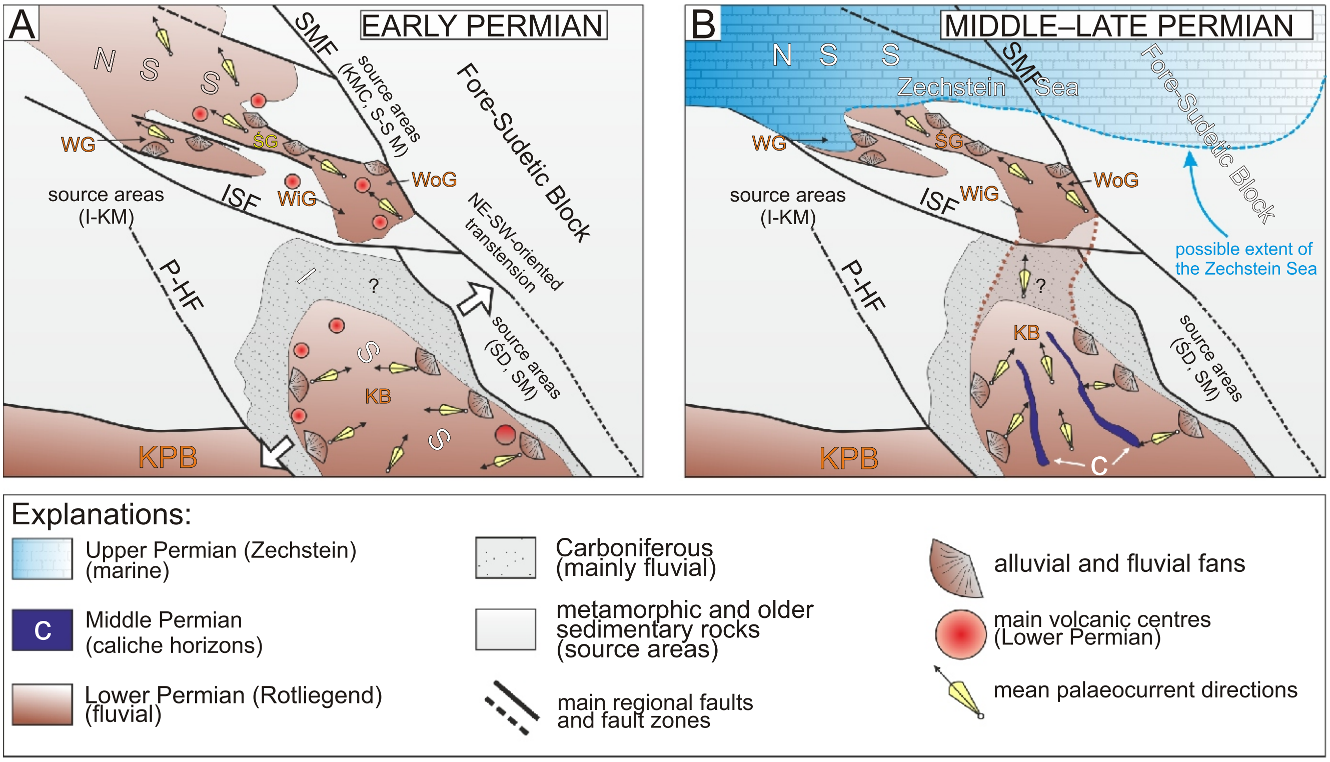

Fig. 3. Schematic palaeogeographic evolution of the marginal parts of the North-Sudetic and Intra-Sudetic basins in the early- (A) and middle–late(?) Permian (modified after Kowalski, 2020)

Note the hypothetical sediment source areas and the postulated interconnection of the Intra-Sudetic and North-Sudetic basins (brown dashed lines) during middle–late Permian. Location of the Permian volcanic centres after Awdankiewicz (1999). Letter symbols: I-KM – Izera-Karkonosze Massif; ISF – Intrasudetic Fault; KMC – Kaczawa Metamorphic Complex; KPB – Karkonosze Piedmont Basin; P-HF – Poříčí-Hronov Fault; ŚD – Świebodzice Depression; SM – Góry Sowie Massif; ŚG – Świerzawa Graben; SMF – Sudetic Marginal Fault; S-SM – Strzegom-Sobótka Massif; WG – Wleń Graben; WiG – Wierzchosławice Graben; WoG – Wolbromek Graben

tectonic structure of this unit is an apparent result of Late Cretaceous–early Paleogene compressional tectonic event (Oberc, 1972; Żelaźniewicz et al., 2011; Głuszyński and Aleksandrowski, 2022) and Neogene block movements (Oberc, 1972). These events led to inversion and significant tectonic deformation of the basin fill which was dissected mainly by NW–SE and NE–SW-trending fault systems. These processes resulted also in tectonic shortening, uplift and erosion of considerable part of the post-Variscan (lower Carboniferous–Upper Cretaceous) sedimentary cover. Thus, the present-day extent of the ISB fill is probably much smaller than originally. However, the eastern boundary fault of the Intra-Sudetic Synclinorium (Głuszyca Fault) may coincide with the eastern margin of the Permian ISB (cf. figs 2 and 11C in Kowalski and Furca, 2023), though the real extent of the Permian deposits in the Sudetic area remains unknown. Taking into account the above, it was also intentional to label our figure 11C (Kowalski and Furca, 2023) as “not to scale”.

CONTROLLING FACTORS IN EARLY PERMIAN CYCLIC SEDIMENTATION: CLIMATE VS. TECTONICS

Many authors (Nemec et al., 1982; Wojewoda and Mastalerz, 1989; Awdankiewicz et al., 2003) have emphasized that regional tectonic activity (i.e. a synsedimentary active fault system) played a crucial role in controlling accommodation space, sediment supply and fluvial architecture in the Carboniferous-Permian ISB. We agree with Karnkowski (2024), that the Permian Intra-Sudetic fluvial system was significantly influenced by the long-term climatic oscillations. However, the characteristics of the Permian sedimentary succession preserved within the ISB indicate a progressive aridification of the climate and probably its coincident warming during the early Permian (Dziedzic, 1961; Wojewoda and Mastalerz, 1989), in our paper we conclude that *the gradual change in the fluvial architecture within the Krajanów Formation can be attributed to a lateral and temporal changes in river system rather than gradual shift in regional climate*. In our opinion, in the case of the ISB, tectonic control, understood as periodic uplift of the source terrains, strongly influenced the formation of well-developed, hierarchically organized, fining-upwards megasequences. On the other hand, the volume and chemical composition of sediment load, frequency and magnitude of flow events as well as pedogenic processes have been influenced strongly by climatic factors (e.g., Mosciarello, 2017). To conclude, we consider that the Permian Intra-Sudetic fluvial system was influenced by a combination of tectonic and climatic factors, as is – in our opinion – reflected in the title and content of our recent paper (Kowalski and Furca, 2023).

CONCLUDING REMARKS

We would like to thank Paweł Henryk Karnkowski for his discussion and valuable comments. We are especially grateful for comments and remarks on the paleogeography of the Polish

Rotliegend Basin. In our recent paper (Kowalski and Furca, 2023) we have based our conclusions and palaeogeograpic interpretation on integrated sedimentological, petrographic and facies analysis. As geologists professionally involved in the renewed project of high-resolution geological mapping in the Sudetes at the scale of 1:25,000, we would also like to thank P.H. Karnkowski for emphasizing the crucial role of detailed geological maps in the recognition and construction of palaeogeographic schemes for the early Permian sedimentary basins. We hope that our current research and discussion initiated by Karnkowski (2024) contributed to better recognition of the lower Permian (?Asselian) deposits in the eastern Intra-Sudetic Basin.

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