TRIASSIC PALAEOGEOGRAPHY OF NE BOHEMIAN MASSIF BASED ON SEDIMENTOLOGICAL RECORD IN THE WLEŃ GRABEN AND THE KRZESZÓW BRACHYSYNCLINE (SW POLAND)

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Abstract: This paper presents a new sedimentological and palaeogeographic interpretation of the Early to Middle(?) Triassic continental deposits in the Wleń Graben and the Krzeszów Brachysyncline (Sudetes, SW Poland). These two tectonic subunits, located in the peripheral segments of the North Sudetic and Intra-Sudetic synclinoriums, respectively, represent the crucial elements for deciphering the post-Variscan palaeogeographic evolution of the NE termination of the Bohemian Massif. Sedimentological studies and facies analysis show that the Early Triassic siliciclastic deposition in both areas was dominated by fluvial sedimentation of the typical Buntsandstein facies within a gently sloping alluvial plain, locally followed by ephemeral lake environments in the late Early or Middle(?) Triassic. The lithofacies and the measured palaeocurrent directions indicate that the area was drained by braided streams flowing towards the northwest and north. Individual fluvial channels had depths not exceeding 1 m and widths of up to a few metres. Overbank deposits are poorly preserved due to the lateral shifting of channels. Based on available borehole data, an analysis of isopach maps was performed for the first time in the study areas. The study areas are presently separated by crystalline units devoid of sedimentary rocks, but the analysis indicate that they might have been in constant or periodical connection during the Triassic. It is concluded that the present-day extent of Triassic deposits is a result of the primary basin configuration combined with the Middle Triassic to Late Cretaceous erosion and post-Cretaceous tectonic uplift. The paper summarizes the present state of research on the continental Triassic preserved in the terminal parts of the North Sudetic and Intra-Sudetic synclinoriums, presents the first detailed sedimentological logs, and proposes new palaeogeographic interpretation. New findings include bioturbation structures, such as plant-root traces or tunnels formed by invertebrates and possible tetrapod footprints, which shed new light on the sedimentological interpretation of the continental Mesozoic deposits in the NE part of the Bohemian Massif.

Key words: fluvial sedimentation, Buntsandstein, Polish Buntsandstein Basin, Triassic Germanic Basin, epi-Variscan cover, Bohemian Massif.

INTRODUCTION

The terminal phases of the Variscan orogeny formed numerous, fault-controlled extensional and transtensional continental sedimentary basins within and around the Bohemian Massif (BM) in Central Europe (e.g., Holub, 1976, Malkovsky, 1987; Lützner, 1988; Coward *et al.*, 1995). Development of the North Sudetic Basin and Intra-Sudetic Basin, situated within the Sudetic Block (SW Poland) at the NE periphery of the BM, commenced in the middle to late Carboniferous, probably in the Viséan (ca. 336 Ma;

cf. Nemec *et al.*, 1982; Turnau *et al.*, 2002). These two long-lived basins formed as narrow intramontane troughs (Augustyniak and Grocholski, 1968; Teisseyre, 1966, 1971; Wojewoda and Mastalerz, 1989; Mastalerz and Raczyński, 1993), their further multi-stage evolution involved repetitive accumulation of terrestrial and marine deposits until the Late Cretaceous. In this time span, the two basins often constituted semi-enclosed segments of a wider depositional area. In the Early Triassic, the study areas were situated in

the southernmost part of the so-called Polish Buntsandstein Basin – the eastern part of the Triassic Germanic Basin (Fig. 1; cf. Szyperko-Teller and Moryc, 1988; Feist-Burkhardt *et al.*, 2008; Bachmann *et al.*, 2010). The Bohemian Massif was one of the source areas surrounding this basin from the south (Mroczkowski and Mader, 1985; Prouza *et al.*, 1985; Uličný, 2004). The topography of the Triassic Germanic Basin is commonly considered to have been partly inherited from the late Permian basin configuration (see review in Feist-Burkhardt *et al.*, 2008). The marine Late Cretaceous North Sudetic Basin, which formed as a southeastern extension of the East Brandenburg Basin (Musstow, 1968; Voigt *et al.*, 2008), was supposedly connected – at least temporarily – by narrow straits with the adjacent Intra-Sudetic Basin and further with the large Bohemian Basin (Scupin, 1910; Milewicz, 1985, 1997; Partsch, 1986; Leszczyński, 2018). However, the hypothetical straits are unpreserved and, thus far, only the sedimentological evidence from the North Sudetic Coniacian (Leszczyński and Nemec, 2019) seems to support this palaeogeographic notion. The sedimentation pattern in the Sudetic basins was strongly controlled by

regional tectonics and by the repetitive uplift, erosion and denudation of the framing crystalline massifs (see reviews in Uličný, 2004; Uličný *et al.*, 2009; Żelaźniewicz *et al.*, 2011). The routes of clastic input and tectonic development in these areas are still a matter of debate (cf. Wojewoda, 2016, 2019).

It has been widely considered that the present-day shape, spatial trend and extent of these Sudetic synclinoriums, despite their multistage tectonic evolution, correspond to the depocentres and poorly preserved margins of the primary sedimentary basins (e.g., Dziedzic, 1961; Teisseyre, 1966; Ostromęcki, 1973; Milewicz, 1985, 1997; Mroczkowski and Mader, 1985; Wojewoda and Mastalerz, 1989; Mastalerz, 1990; Mastalerz and Nehyba, 1997; Raczyński, 1997; Uličný, 2001; Wojewoda, 2011, 2019; Leszczyński, 2018; Leszczyński and Nemec, 2019). However, it remains highly uncertain if the Sudetic basins were interconnected through most of their Carboniferous to Cretaceous history or were possibly parts of a larger sedimentary basin, particularly in the Triassic. Unlike in marine basins, the facies gradients in terrestrial basins are a poor indicator of basin margins
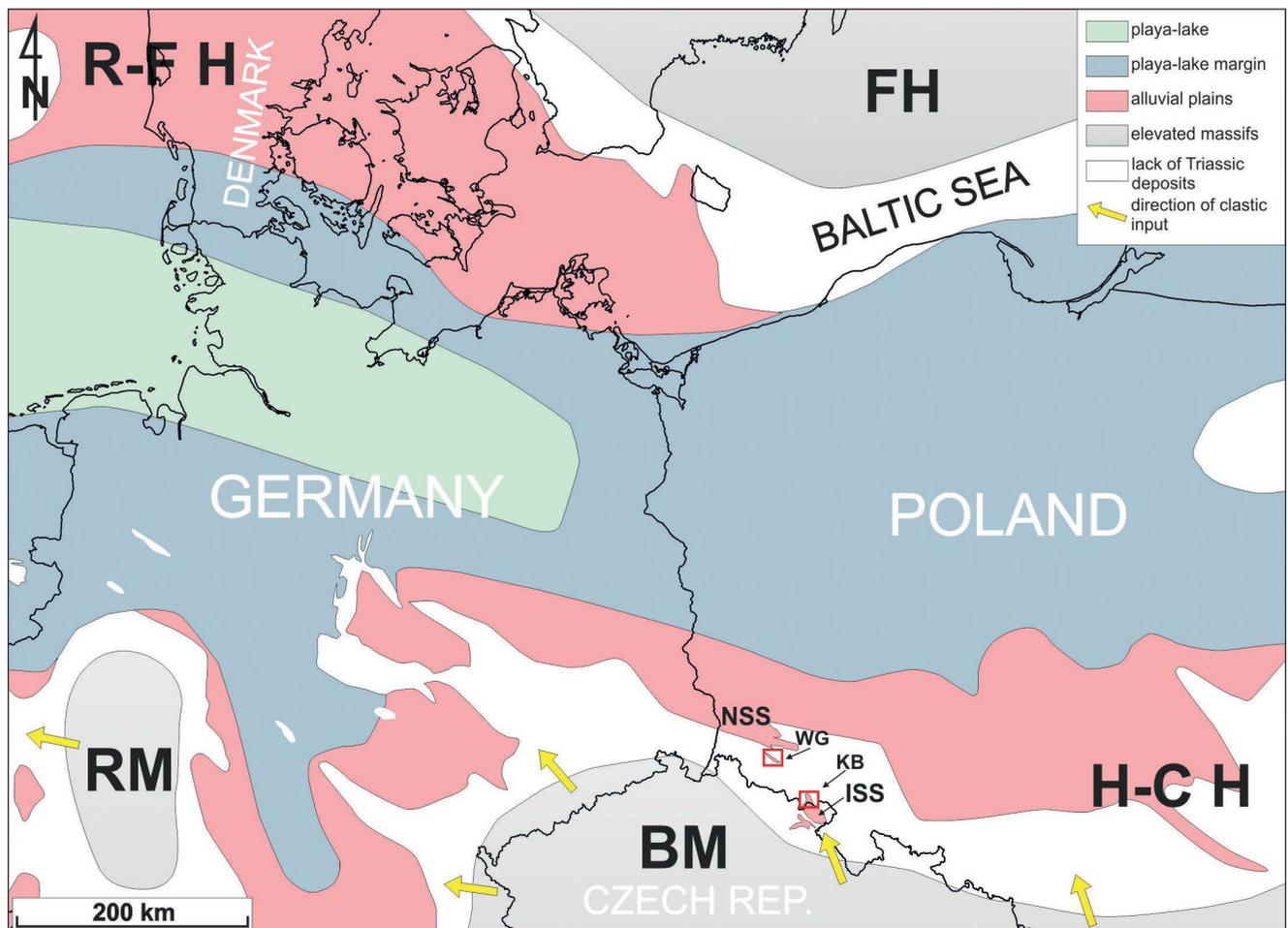

Fig. 1. Generalized facies map and extent of the Lower Triassic (Buntsandstein) in the eastern part of the Triassic Germanic Basin (modified from Feist-Burkhardt *et al.*, 2008; Bachmann *et al.*, 2010). Letter symbols: BM – Bohemian Massif; FH – Fennoscandian High; H-CH – Holy-Cross Mountains High; ISS – Intra-Sudetic Synclinorium; KB – Krzeszów Brachysyncline; NSS – North Sudetic Synclinorium; R-F H – Ringkøbing-Fyn High; RM – Rhenish Massif; WG – Wleń Graben. Note the location of the present study areas (marked with red squares) relative to the elevated part of the Bohemian Massif (source area), with the inferred directions of clastic sediment supply in the Early Triassic (yellow arrows).

and the key criterion are accumulated sediment thicknesses (e.g., Einsele, 1992; Allen and Allen, 2013).

The North Sudetic (NSS) and Intra-Sudetic (ISS) synclinoriums developed due to large-scale regional folding and faulting of the sedimentary-volcanic basin-fill rocks mainly between the end of Cretaceous and the Neogene (see reviews in Malkovsky, 1987; Żelaźniewicz *et al.*, 2011). They are fault-bounded, large-scale synclinorial structures trending NW–SE, containing a slightly deformed and relatively well-preserved Upper Carboniferous to Upper Cretaceous discontinuous volcano-sedimentary succession. The main

synclinorial structures consist of a series of minor, adjoining, fault-controlled synclines, grabens, half-grabens and horsts separated by regional fault systems trending NW–SE and NE–SW (Fig. 2; see Wojewoda and Mastalerz, 1989; Cymerman, 2004). Crucial to a palaeogeographic reconstruction of these Sudetic areas is the mutual relationship between the primary boundaries of sedimentary basins and the present-day relics of basin-fill deposits preserved within the tectonic synclinoriums.

Particularly important in this respect are basinal outliers peripheral to the ISS and NSS, such as the Wleń Graben
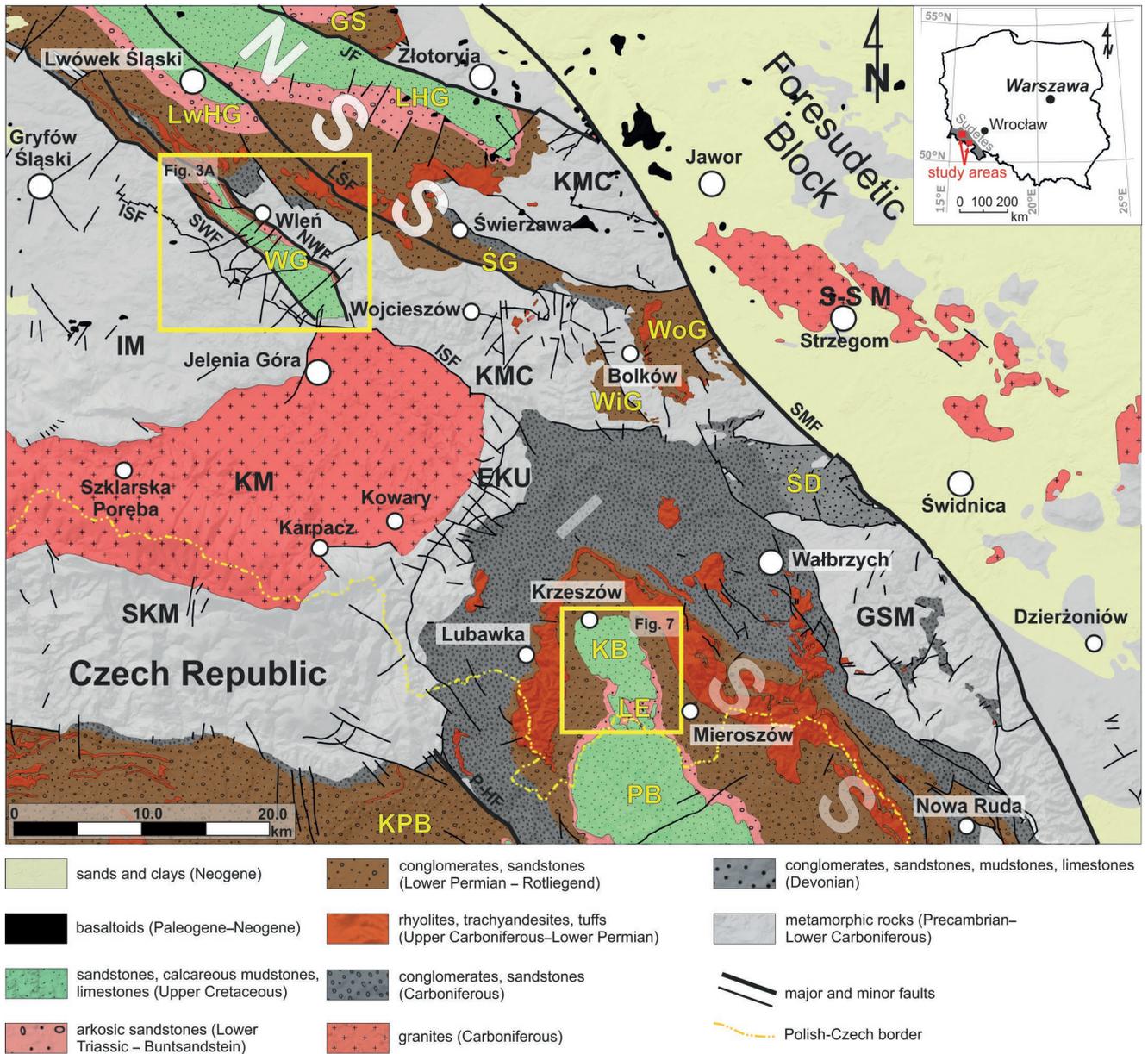

Fig. 2. Simplified geological map of the marginal parts of the North Sudetic Synclinorium (NSS) and Intra-Sudetic Synclinorium (ISS) with location of detailed geological maps presented in Figures 3A and 7 (yellow squares). Letter symbols: GS – Grodziec Syncline; KPB – Karkonosze Piedmont Basin; LHG – Leszczyna Half-Graben; LwHG – Lwówek Śląski Half-Graben; WoG – Wolbromek Graben; ŚD – Świebodzice Depression; ŚG – Świerzawa Graben; WiG – Wierzchosławice Graben; WG – Wleń Graben; EKU – Eastern Karkonosze Unit; GSM – Góry Sowie Massif; IM – Izera Massif; KM – Karkonosze Massif; KMC – Kaczawa Metamorphic Complex; SKM – South Karkonosze Metamorphic Unit; S-SM – Strzegom-Sobótka Massif; IF – Intrasudetic Fault; JF – Jerzmanice Fault; LŚF – Lwówek-Świerzawa Fault; NWF – Northern Wleń Fault; SWF – Southern Wleń Fault; P-HF – Poříčí-Hronov Fault; SMF – Sudetic Marginal Fault. Map superimposed over an SRTM DEM with a resolution of 30 m. Geological map based on Sawicki (1995) and Cymerman (2004).

(WG) and the Krzeszów Brachysyncline (KB) (Fig. 2), as the sedimentary successions therein may potentially shed crucial light on the palaeogeographic and tectonic relation. This issue has been little investigated and is addressed by the present study. The outliers are separated by crystalline basement horst devoid of a post-Variscan sedimentary cover, but their Lower Triassic successions show much similarity and have a considerable thickness.

Regional geological studies of the Lower Triassic (Buntsandstein) in the KB and WG reach back to the early 20th century (Scupin, 1916, 1931, 1933; Petrascheck, 1933). More detailed studies of these deposits were conducted before the mid-1980s (Scupin, 1933; Milewicz, 1968; Mroczkowski, 1969, 1972, 1977; Lorenc and Mroczkowski, 1978; Mroczkowski and Mader, 1985; Prouza et al., 1985) and were limited to the lithological characteristics and general stratigraphic architecture of the local successions. Detailed sedimentological logs, modern facies analysis and isopach maps were lacking. The available geological maps show differences in the extent and stratigraphic range of Triassic deposits, with the main discrepancies pertaining to the southern part of the WG (cf. Zimmermann, 1932; Szałamacha, 1977; Gorczyca-Skała, 1977) and the middle sector of the KB (cf. Berg and Dathe, 1940; Grocholski, 1971). The regional discrepancies and uncertainties can now be resolved to large extent based on outcrops and the numerous boreholes drilled in the more recent years (Fig. 3; Wojtkowiak et al., 2009; SPDPSH, 2019).

The principal objective of this paper is to provide an improved understanding of the Triassic palaeogeography and depositional history in the WG outlier of the NSS and the KB termination of the ISS (Fig. 2), as compared to the previous studies (Scupin, 1933; Milewicz, 1968; Mroczkowski, 1969, 1972, 1977; Gorczyca-Skała, 1977; Mroczkowski and Mader, 1985; Prouza et al., 1985). The present study began with a detailed geological remapping of the two areas and employed modern sedimentological methods and facies analysis. The study of outcrops in these areas was for the first time supplemented with borehole data, which became available only after the aforementioned publications. The focus was on palaeotransport directions and isopach maps, with a consideration of the sediment provenance. On the account that the Mesozoic pattern of sedimentation was likely influenced by the inherited Late Palaeozoic structure and topography, the Sudetic Permian basin configuration is also reviewed as a background at the present state of regional knowledge.
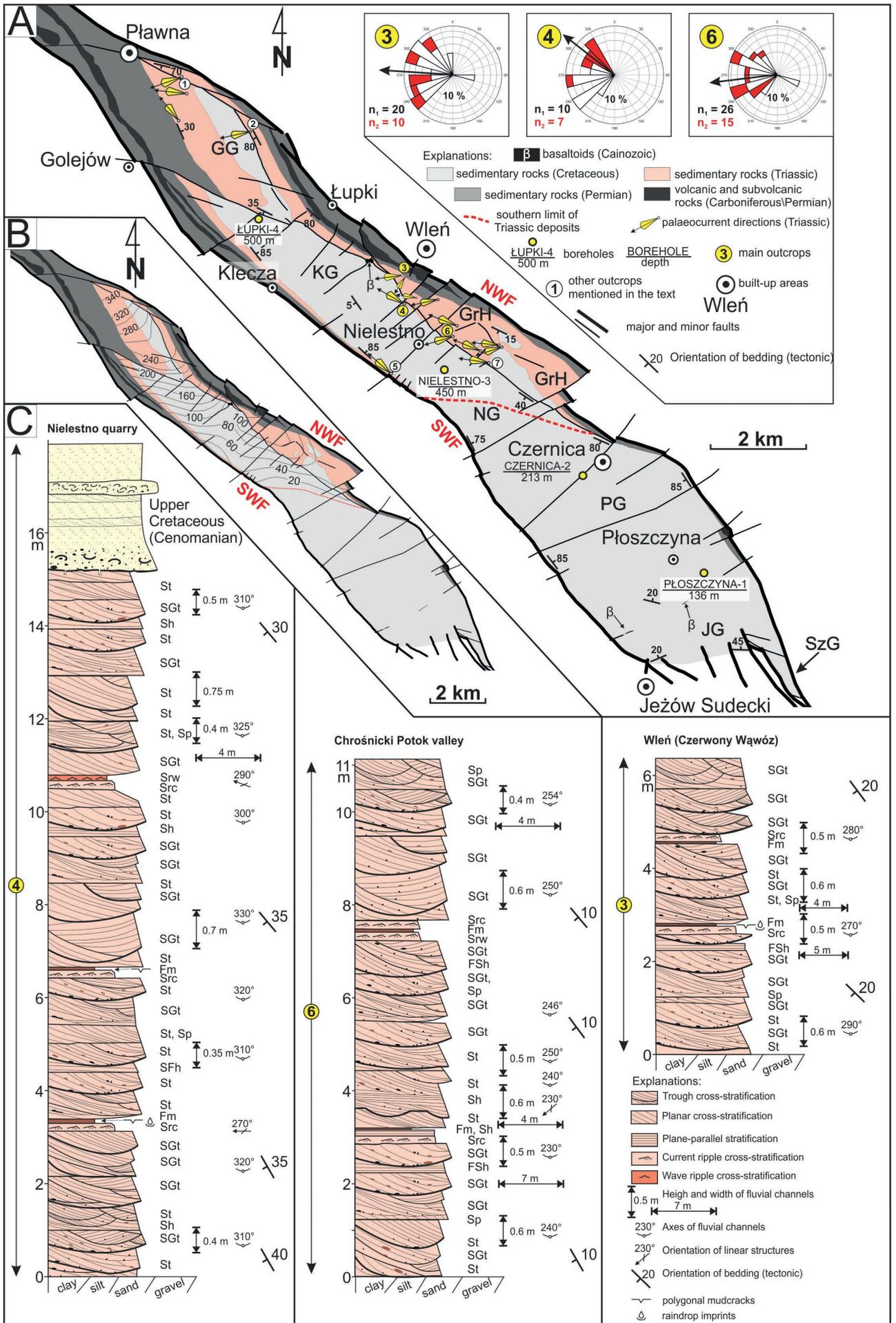
GEOLOGICAL BACKGROUND AND PREVIOUS WORK

The WG and KB (Fig. 2) are minor tectonic subunits of the NSS and ISS, respectively, with a partially preserved Triassic continental sedimentary succession. The Triassic deposits cover unconformably a faulted and lithologically varied bedrock composed of the Early Permian (Rotliegend) and Late Permian (Zechstein) deposits. The two areas are ca. 40 km from each other and are separated by crystalline basement rocks of the Karkonosze Granitic Massif (KM), Eastern Karkonosze Metamorphic Unit (EKU) and Kaczawa Metamorphic Complex (KMC) (Fig. 2).

The WG (Fig. 3A), as a structural outlier of the NSS, is one of the best-developed tectonic troughs in the Sudetic region. This subunit is ca. 17.5 km long and up to 3.5 km wide, bounded by steep normal and reverse faults trending NW–SE (Kolb, 1936; Milewicz, 1959; Gorczyca-Skała, 1977; Gierwielaniec, 1998). The basement and elevated flanks of the WG are composed of metamorphic rocks assigned to the KMC (also referred to in the literature as the Kaczawa Complex, Kaczawa Metamorphic Unit or Kaczawa Greenstone-and-Slate Fold Belt; cf. Baranowski et al., 1990). The sedimentary succession in the WG includes the Late Carboniferous to Early Permian (Rotliegend) terrigenous clastic deposits, Late Permian (Zechstein) marine deposits, Early Triassic (Buntsandstein) terrigenous deposits and a Late Cretaceous marine cover.

The undifferentiated Upper Carboniferous and Lower Permian of the Świerzawa Formation (Milewicz, 1965, 1985) crop out in the northern and central parts of the WG (Fig. 3A, B) and consist mainly of poorly sorted conglomerates and sandstones interpreted as alluvial-fan and braided-river deposits (Kowalski et al., 2018a). The inferred Rotliegend succession, up to 1300 m thick (cf. Milewicz, 1965), includes shallow sub-volcanic bodies, lava flows and dykes comprising trachyandesites, trachybasalts and rhyolitoids. This "Lower Permian Volcanic Complex" (sensu Milewicz, 1965; Kozłowski and Parachoniak, 1967) reaches a maximum thickness of 300 m in the vicinity of Wleń to ca. 500 m near Pławna (Fig. 3A). The volcanic complex is overlain by the Rotliegend sandstones and conglomerates of fluvial origin with calcrete-type cementation, known as the Bolesławiec Formation (Raczyński, 1997; Raczyński et al., 1998; Śliwiński et al., 2003). The Rotliegend succession is discordantly covered by the marine Upper Permian (Scupin, 1931; Eisentraut, 1939; Milewicz, 1966; Kowalski et al.,

Fig. 3. Extent, thickness and sedimentological features of the Lower Triassic (Buntsandstein) in the Wleń Graben. **A.** Detailed geological map of the WG (made by the present author) with the marked extent and southern limit of the Buntsandstein and the location of boreholes. The measured mean transport directions are indicated in the map for each locality. The inset rose diagrams (upper right corner) show the measured orientation of cross-stratification (white rose) and channel axes (red rose) with their mean directions (black arrow) for selected localities. Letter symbols: NWF – Northern Wleń Fault; SWF – Southern Wleń Fault; GG – Golejów Graben; GrH – Grodowa Horst; JG – Jeżów Sudecki Graben; KG – Klecza Graben; NG – Nielestno Graben; PG – Płoszczyna Graben; SzG – Szybowisko Graben. **B.** Isopach map of the Lower Triassic (Buntsandstein) in the WG. **C.** Synthetic sedimentological logs from selected outcrops (localities 3, 4, 6) in the WG, with indicated sedimentary facies (letter code as in Table 1 and in the text) and other observed features.

2018a). It includes the Platy Dolomite (< 15 m thick) of the Zechstein cyclothem PZ3 (Kowalski *et al.*, 2018a), grading upwards into fine-grained sandstones and mudstones of the Permo–Triassic Transitional Terrigenous Series (PZt of Peryt, 1978) – interpreted as deposits of a muddy coastal plain formed by the Zechstein Sea regression. The bulk thickness of the PZ3 and PZt deposits in the WG reaches 10 to 30 m.

The PZt series passes upwards, nearly concordantly, into the clastic deposits assigned to the Lower Triassic (i.e. Buntsandstein; Scupin, 1933; Milewicz, 1968; Mroczkowski, 1969). They constitute a monotonous series of pink and red arkosic sandstones and sandy conglomerates of the Radłówka Formation (Milewicz, 1985), considered to represent mainly fluvial sedimentation (Mroczkowski, 1969, 1972; Mroczkowski and Mader, 1985). The maximum thickness of the Buntsandstein deposits in the northern part of the WG, in the Łupki-4 borehole, is 190 m (SPDPSH, 2019), whereas their maximum thickness there calculated by cartographic methods is nearly 340 m. The deposits thin out towards the SE, reaching only a few metres near Klecza and Czernica (Fig. 3B), and virtually lacking in the southern part of the WG.

In the northern part of the WG, the Triassic succession is unconformably overlain by the Upper Cretaceous marine sandstones and calcareous mudstones (Scupin, 1913) of the Rakowice Formation (Milewicz, 1997). In the southern part of the WG, these Cretaceous rocks lie directly on the Lower Permian (Rotliegend) or Cambrian to Lower Carboniferous metamorphic rocks (near Płoszczyna and Czernica and in the Płoszczyna-1 borehole; SPDPSH, 2019). The most complete Cretaceous marine succession (upper Cenomanian to lower Coniacian) is preserved in the central, axial part of the WG. The sedimentary and volcanic rocks in the WG are cut by Palaeogene and probably Neogene basaltoid veins (Milewicz and Frąckiewicz, 1988; Badura *et al.*, 2006). Quaternary unconsolidated deposits in the WG are no more than 20 m thick (Milewicz and Frąckiewicz, 1983, 1988), and have not been considered in the mapping survey of the present study.

The Krzeszów Brachysyncline (KB) is a northern extension of the ISS (Figs 2 and 7), with the Permian (Rotliegend) to Lower Triassic (Buntsandstein) terrestrial deposits overlain discordantly by the Upper Cretaceous (upper Cenomanian to upper Turonian/Coniacian?) marine sandstones and calcareous mudstones (Jerzykiewicz, 1971). These sedimentary rocks form a large brachysynclinal fold trending NW–SE in the axial part of the ISS (Jerzykiewicz, 1969; 1971). To the south, the so-called Łączna Elevation (LE), trending WNW–ESE (Kowalski, 2017), separates the KB from the adjacent Police Brachysyncline (PB), similarly trending NW–SE (Fig. 2). For the purpose of palaeogeographic reconstructions in the present study, the KB and LE areas are considered and referred to jointly as the Krzeszów Brachysyncline (KB).

The oldest, Rotliegend deposits occur in the peripheral parts of the KB and consist of coarse-grained conglomerates and sandstones with calcareous intercalations interpreted as caliche and travertine horizons (Śliwiński, 1980, 1981, 1984). They were earlier regarded as Zechstein

marine deposits (cf. Berg and Dathe, 1940; Lorenc and Mroczkowski, 1978; Łapot, 1982), but are presently interpreted as alluvial-fan and braided-river deposits of the Chełmsko Śląskie Beds (Śliwiński, 1980, 1981, 1984). These deposits, with a maximum thickness of 45 m, are discordantly overlain by the Buntsandstein with maximum thickness of ca. 150 m, known as the Bohdašin Formation (Tásler, 1964) in the Czech part of the ISS. The Buntsandstein succession is composed of coarse-grained, pinkish to white arkosic sandstones with subordinate conglomerate intercalations, interpreted as braided-river deposits (Mroczkowski, 1977; Mroczkowski and Mader, 1985; Prouza *et al.*, 1985). The Bohdašin Formation is exposed in the middle to southern marginal parts of the KB and in the central part of the LE (Jerzykiewicz, 1971; Don *et al.*, 1981). The arkosic sandstones grade upwards into a unit of strongly kaolinized and weakly lithified, undated "Kaolinitic Sandstones", ca. 10–15 m thick, with coaly mudstone intercalations known from the Góra Świętej Anny east of Krzeszów. The Bohdašin Formation and the Kaolinitic Sandstones lack palaeontological documentation, and their age is inferred to be Early to Middle(?) Triassic based on lithological similarities with the NSS (Mroczkowski, 1969, 1972, 1977; Kowalski, 2017), although they were also regarded as middle Cenomanian (Jerzykiewicz, 1971). The Kaolinitic Sandstones in the ISS were interpreted earlier as shallow-marine (Wojewoda *et al.*, 2016), lacustrine (Prouza *et al.*, 1985) or even aeolian deposits (Uličný, 2004).

In the southern to middle part of the KB, the Triassic rocks are overlain by fossiliferous Cretaceous marine clastic deposits, reaching a total thickness of up to 350 m (Jerzykiewicz, 1971). In the northern part of the KB, devoid of Triassic deposits, the Cretaceous strata rest directly on the Rotliegend bedrock (cf. Berg and Dathe, 1940). The Cretaceous succession, late Cenomanian to early Coniacian(?) in age, consists of sandstones with a minor admixture of conglomerates, calcareous and siliceous mudstones (gaizes), as well as calcareous claystones with thin limestone intercalations (Jerzykiewicz, 1971). The Triassic and Cretaceous deposits of the KB constitute the northernmost preserved Mesozoic sedimentary cover of the ISS (Fig. 2).

METHODS

Standard field and laboratory methods were used. The first part of the study included a geological mapping survey at the scale of 1 : 10 000. Detailed cartographic work was conducted in 2015–2020 with surface observations in natural and artificial outcrops such as tors, abandoned quarries and road-cut sections. Special attention was given to the accurate localization of documentation sites by using precise GPS receivers with the precision of position determination from 1 to 3 m. The mapped area was ca. 55 km² in the WG and 60 km² in the KB. The resulting new geological maps are presented in this article and partly in the author's earlier publications (Kowalski, 2017; Kowalski *et al.*, 2018b). Geological maps were made with the application of LiDAR-based Digital Elevation Models (DEMs) with a resolution of 1 × 1 m, acquired by airborne laser scanning

(ALS) conducted in Poland in 2011-2014 within the frame of project ISOK (IT System of the Country's Protection against Extreme Hazard). The DEMs were used to determine regional geological boundaries with the use of GIS software: Global Mapper v. 12.0 and Microdem Software v. 2015.8 (developed by Peter Guth). In addition, borehole profiles with documented Triassic deposits were analysed in the WG (2 boreholes) and KB (8 boreholes). The geological mapping survey with borehole data was aimed at a revision of the existing geological maps and precise reconstruction of the geometry, thickness and isopach maps of the Triassic deposits in the study areas.

Sedimentological lithofacies analysis of the Triassic deposits was then conducted in 155 selected exposures, grouped herein into 18 representative sites. The distinction and coding of lithofacies followed the Miall (1985) scheme, slightly modified by Zieliński & Pisarska-Jamroży (2012). The main lithofacies (Tab. 1) served for the interpretation of depositional processes and palaeoenvironment reconstruction. Special attention was given to the nature of bed contacts,

Table 1

Main lithofacies distinguished in the Lower to Middle(?) Triassic exposed
in the Wleń Graben and the Krzeszów Brachysyncline.

Facies associations	Facies	Textural characteristics	Sedimentary structures and other features	Interpreted origin
Gravelly lithofacies association	GSm, SGm	Conglomerates interbedded with sandstones. Sub- and well-rounded pebbles, locally scattered in coarse sand. Rare muddy intraclasts. Poor sorting.	Continuous and discontinuous gravel sheets resting on erosional surfaces. Crude stratification, common imbrication and pebble lineation. Erosional solemarks: flutes, grooves, obstacle scour marks.	Relic deposits of strong, erosive water flow and sediment bypass, interpreted as channel-floor lag.
Sandy lithofacies association	St, SGt	Medium to very coarse sand. Local concentration of sub- and well-rounded pebbles.	Trough cross-stratification, pseudoimbrication of scattered pebbles resting on bedform lee side.	Migration of sinuous-crested, linguoid or crescentic 3D dunes, probably forming mid-channel bars or their core parts.
	Sp, SGp	Medium to very coarse sand. Local concentration of sub- and well-rounded pebbles.	Planar cross-stratification, pseudoimbrication of scattered pebbles resting on bedform lee side.	Migration of straight-crested, 2D dunes accreted to mid-channel bars or acting as transverse/oblique unit bars.
	Sh, SGh	Fine to medium sand with cattered granules.	Planar, parallel or nearly parallel stratification.	Plane-bed transport in the upper flow regime, including sheet floods in inter-channel areas.
	Src	Fine to medium sand, well sorted.	Current ripple cross-lamination; undulatory and linguoid ripple forms.	Transport by unidirectional current in the lowermost part of lower flow regime.
	Srw	Fine to medium sand, well to very well sorted.	Wave ripple cross-lamination; symmetrical and locally bifurcated ripple forms. Rippled surfaces with mud cracks and raindrop pits.	Deposition by the action of waves in floodplain ponds or ephemeral lakes, some possibly of "terminal" type for fluvial drainage.
Muddy lithofacies association	Fm	Mud with silt and fine sand intercalations; locally coaly (in KB area).	Massive, with polygonal mud cracks, raindrop imprints, possible tetrapod footprints(?), rare plant-root traces.	Deposition from suspension in floodplain ponds or ephemeral lakes.
	FSh	Interlaminated mud, silt and fine sand.	Thin lamination, small current or wave ripples.	As above, with influence of weak waves and/or river suspension plumes.
	Fb	Mixed mud and silt to fine sand.	Massive, locally recognizably heavily bioturbated.	Deposition from suspension in floodplain ephemeral ponds/lakes with intense bioturbation.

their cross-cutting relationships, lateral boundaries as well as changes in sediment composition and grain size, particularly on regional scale. The widths and depths of palaeo-channels were measured, as were also the mean and maximum particle sizes of gravelly deposits. Photomosaics and sketches were made for the largest exposures. Directional palaeocurrent data, based on cross-stratification and palaeo-channel axes, were corrected for tectonic tilt and plotted as cumulative rose diagrams. The directions of individual palaeochannel axes are shown in the sedimentological logs compiled for selected exposures. For selected main lithological varieties, thin-sections were made and analysed with the use of a Nikon Eclipse LV100N POL polarizing microscope.

STUDY RESULTS

The Triassic deposits in the WG and KB are exposed mainly in the marginal parts of these tectonic subunits, and are covered by Cretaceous rocks in the interior. In the mapped areas, the outcrops of Triassic rocks cover 6.45 km^2 (WG) and 12.85 km^2 (KB). The unexposed Buntsandstein beneath Cretaceous deposits occurs over an area of 9.83 km^2 in the WG and an area of 22.25 km^2 in the KB.

Lower Triassic in the Wleń Graben

Spatial extent and stratigraphy

The Lower Triassic, known as the Radłówka Formation (Milewicz, 1985), occurs almost throughout the WG main structure, except for its southernmost part (Fig. 3A). The succession crops out within belts trending NW–SE, parallel or subparallel to the graben-bounding Southern Wleń Fault (SWF) and Northern Wleń Fault (NWF) (nomenclature after Gorczyca-Skała, 1977). Close to these bounding faults, the Triassic strata are tectonically disturbed and tilted to nearly 90º (see Fig. 3A). The best exposures are in the central parts of the Wleń Graben, in the Bóbr river valley near Nielestno (localities 4 and 5) and within the so-called Grodowa Horst (GrH; localities 3, 6 and 7).

Triassic deposits are lacking towards the south, in the Płoszczyna (PG), Jeżów Sudecki (JG) and Szybowisko (SzG) grabens (Fig. 3A), where the Cretaceous overlies directly the Rotliegend succession of the NSS or the metamorphic basement of the KMC (Fig. 2).

Lithology and petrography

The Buntsandstein succession in the WG is monotonous and consists typically of moderately- to poorly-sorted, weakly cemented, red-brownish, through pink to yellowish-grey, medium- to coarse-grained sandstones, with a small contribution of conglomeratic interbeds (cf. Figs 3C, 4). In the central part of the WG, thin (up to 2 cm) intercalations of reddish to brown mudstones and claystones occur. The sandstones are arkosic to lithic arenites and subordinately quartz wackes. Subrounded to subangular quartz grains, 0.3 to 0.7 mm in size and with a wavy or mosaic light extinction, predominate in the grain framework, with an admixture of strongly kaolinized, white feldspars showing automorphic or hypautomorphic outlines. Lithic grains are less abundant, including granitoid, gneiss, sericite and mica schist and quartzite of up to 1 mm in size, with a small admixture of larger grains up to pebble size. The grain framework is cemented by a kaolinite and illite matrix with rare pseudomorphs after feldspars. A ferruginous matrix locally occurs, giving the rock a characteristic pinkish or reddish colour.

Sedimentary facies

The Buntsandstein deposits in the WG show trough cross-stratification and subordinate planar cross-stratification (facies St/SGt and Sp/SGp, respectively; Table 1 and Figs 4, 5). Cross-stratified bed sets are fining upwards, with a thickness of 0.3-0.7 m and a lateral extent of up to 4-5 m (Figs 3C, 4A, 5). They are bounded by erosional surfaces. Common architectural elements are also palaeochannels, up to 4 m wide, and shallow, trough-shaped asymmetrical scour-and-fill features (Figs 3C, 4B, 5). The basal parts of channel-fills typically consist of clast-supported gravel (facies Gm and GSm; Tab. 1) in the form of continuous channel lags, especially in the southern part of the study area (locality 5). In the middle and northern parts of the WG (localities 3, 4, 6), such continuous gravel lags are relatively rare and, instead, the basal channel-fill horizons show scattered and locally imbricated disc-shaped pebbles (Fig. 3C). Basal surfaces of sand-filled channels are locally covered with current crescent and drag groove casts (Figs 4C, 5). Planar cross-strata sets, up to 20 cm thick (facies Sp, SGp; Figs 4D, 5), occur locally, especially in outcrops in the Chrośnicki Potok valley. These cross-strata sets contain pseudo-imbricated, dark-brown or reddish, muddy to sandy elongate intraclasts, up to 15 cm in length (Fig. 4E).

Outcrops at the western edge of the Grodowa Horst (localities 4, 6) shows the cross-stratified sandstone facies passing locally upwards into flat-based and laterally more extensive, medium to coarse-grained sandstones with planar parallel stratification (facies Sh and SGh; Fig. 4F). They occasionally show parting lineation and horizons of linguoid current-ripple cross-lamination (facies Src; Figs 3C, 4F, G). The ripple forms are asymmetrical, with a spacing ranging from 2.5 to 4 cm (Fig. 4G). Isolated interlayers of dark brown mudstones (facies Fm), draped with a micaceous film and up to 2 mm thick, are common in the upper parts of the beds of facies Sh and SGh.

In the central part of the study area (localities 6, 7), the cross-stratified sandstones are commonly interbedded with fine-grained sandstones containing mudstone and siltstone interlayers. These fine-grained deposits form continuous horizons, up to 5 cm thick, at the top of trough cross-stratified or planar parallel stratified sandstones. They show flat parallel lamination (facies FSh) with occasional evidence of symmetrical wave ripples and sporadic asymmetrical current ripples (facies Srw and Src, respectively). The ripple forms have a spacing of up to 3 cm and rather straight crests. Well-developed wave ripples with a spacing of up to 4 cm and small-scale loading were observed in vertical sections at locality 6 (Fig. 4H). Occasional loaded ripples (Fig. 4I) and sole marks were also observed on the lower surfaces of sandstone beds at locality 3.
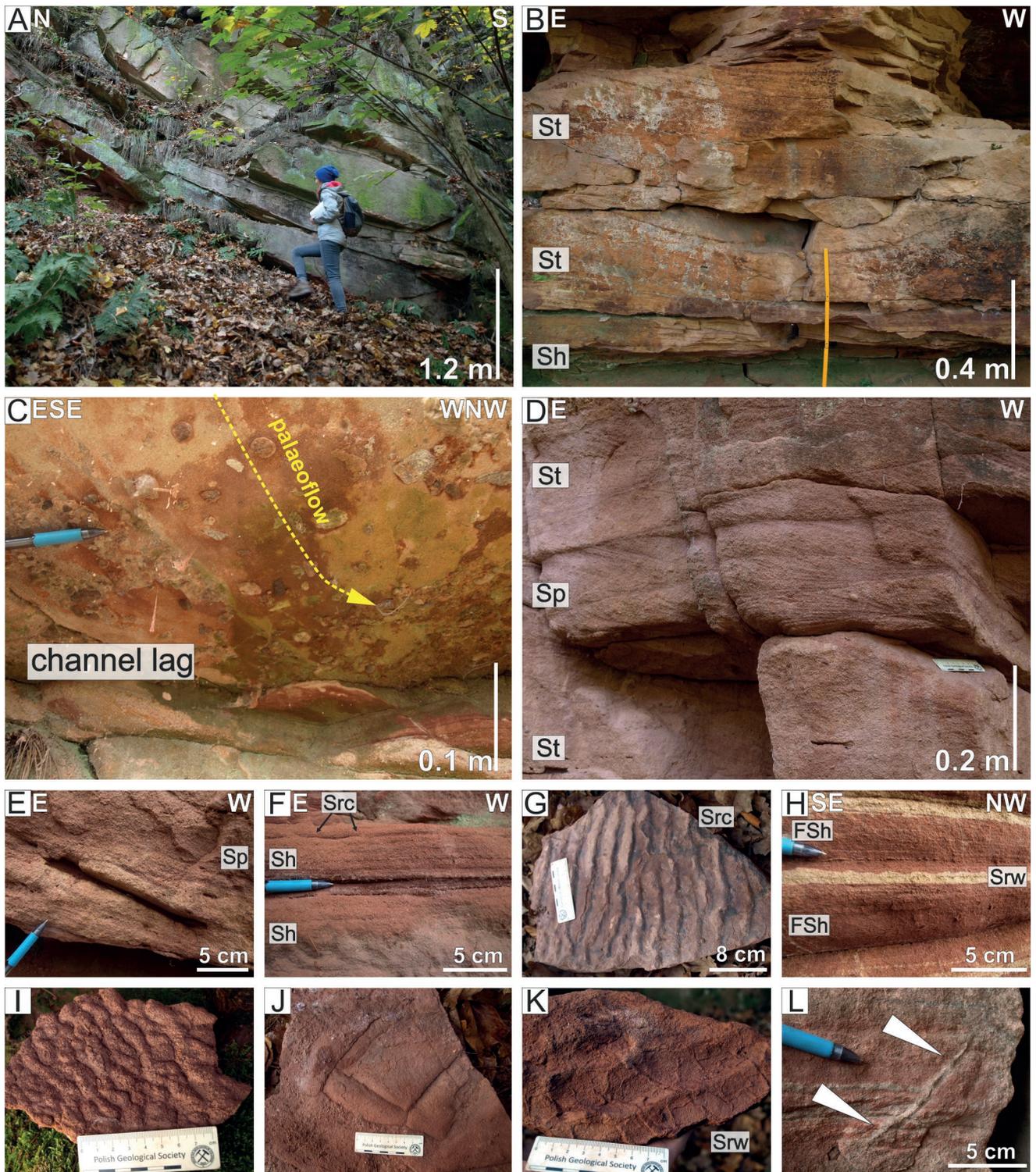
Fig. 4. Sedimentary features of the Buntsandstein in the Wleń Graben. **A.** Repetitively stacked sandstone beds with trough cross-stratification (locality 3), forming packages bounded by sharp, concave-upward erosional surfaces. **B.** Trough cross-stratified sandstones (facies St) underlain by planar parallel-stratified sandstones (facies Sh); locality 6. **C.** Basal surface of channel-fill sandstone with scattered and locally imbricated disc-shaped pebbles (channel lag) and with current crescent casts; locality 6. **D.** Sandstones with trough cross-stratification (facies St) and planar tangential cross-stratification (facies Sp); locality 6. **E.** Dark-brown, elongate mudstone intraclast in trough cross-stratified sandstone, locality 6. **F.** Sandstone beds of facies Sh separated by planar erosional surface and overlain by facies Src (code as in Table 1); locality 6. **G.** Linguoid, asymmetrical current ripples with a spacing of up to 4 cm on the upper bedding surface of sandstone facies Src; locality 4. **H.** Fine-grained deposits of facies Srw and FSh (code as in Table 1); locality 6. **I.** Loaded, asymmetrical current ripples on the lower bedding surface of fine-grained sandstone facies Src; locality 3. **J.** Sand-filled polygonal mud crack on the lower bedding surface of sandstone; locality 3. **K.** Mud cracks superimposed on a rippled bedding surface of fine-grained sandstone facies Srw; locality 3. **L.** Suspected bioturbation structure in the form of single curved burrow; vertical outcrop section, locality 6.

Sporadically, especially in outcrops in the Chrośnicki Potok valley (locality 6), occur beds of very well sorted, fine-grained sandstones, up to 2 mm thick, showing sub-horizontal planar stratification. These extensive sandstone sheets show flat bases and intrasets of asymmetrical ripples with occasional evidence of adhesion ripples. They pass upwards into muddy deposits (facies Fm) with a variety of sedimentary structures indicating subaerial conditions, such as small- and large-scale polygonal mud cracks as well

as raindrop imprints. Large polygonal mud cracks observed at locality 3 have lengths of the longer margins of up to 20 cm and depths of up to 2 cm (Fig. 4J). They co-occur with load structures formed at the boundary between the channel-fill pebbly sandstones and the underlying massive mudstones of facies Fm. Mud cracks co-exist with wave ripple forms at the top of sandstone bed (Fig. 4K) and are locally filled with fine-grained sand. Uncertain bioturbation structures, in the form of isolated, poorly preserved curved
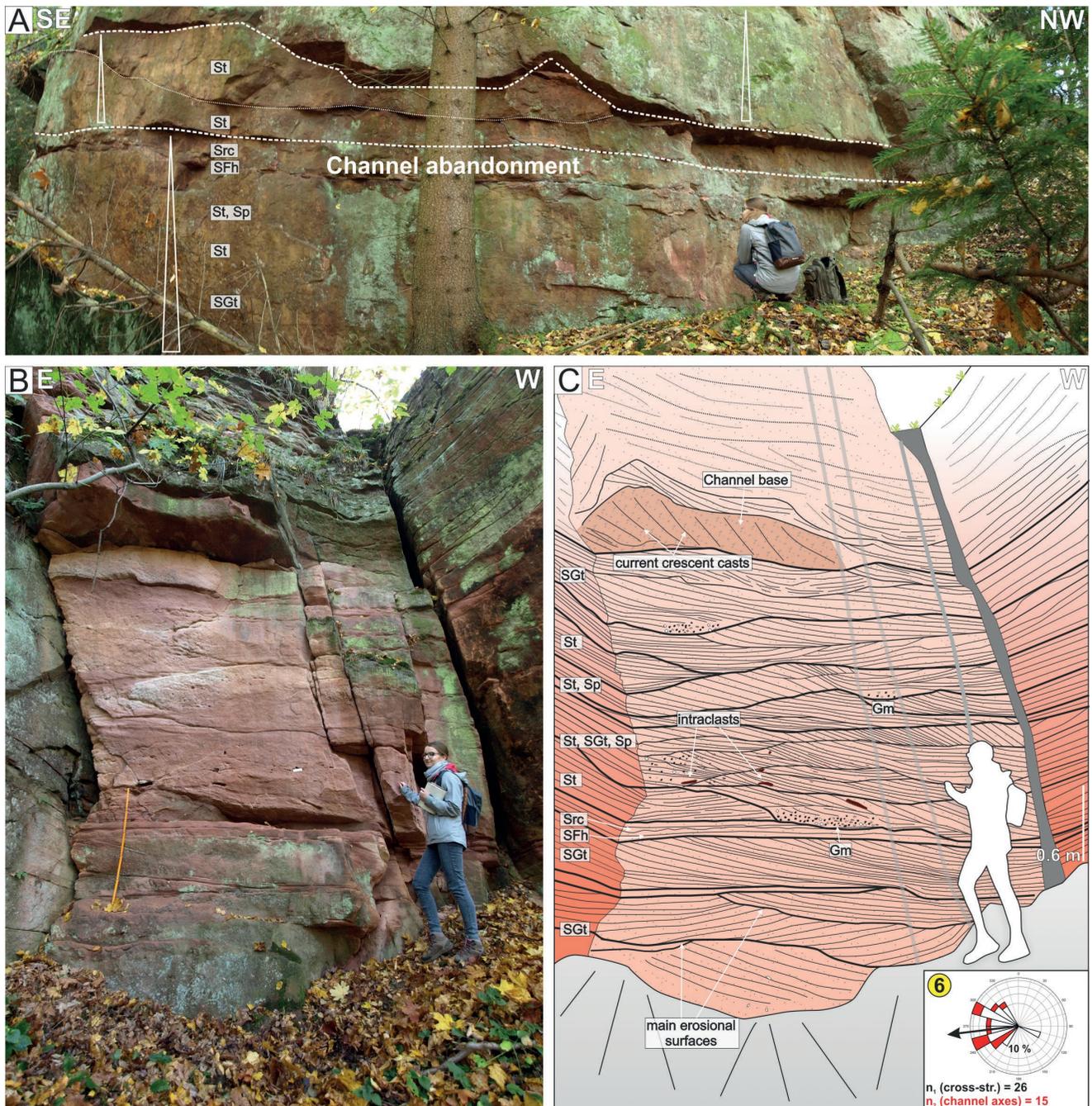

Fig. 5. Outcrop-scale geometry and main architectural elements of Buntsandstein in the middle sector of the Wleń Graben (locality 6, abandoned quarry in the Chrośnicki Potok valley). Facies code as in Table 1. **A.** Vertically stacked, cross-cutting palaeochannels. The lower channel-fill (facies SGt, St and Sp) is capped with fine-grained facies SFh and Src and overlain erosively by successive channel-fills composed of facies St. **B, C.** Outcrop view and detailed sketch showing vertically stacked, cross-cutting shallow palaeochannels. The inset rose diagram summarizes palaeocurrent data: the orientation of cross-stratification (white rose) and channel axes (red rose) with their mean direction (black arrow).

horizontal burrows, are extremely rare (Fig. 4K). Possible tetrapod footprints(?) were found on the basal surface of sandstone bed at locality 3 (Fig. 6).

Environmental interpretation

The Buntsandstein succession in the WG is interpreted as deposits of narrow, relatively shallow and laterally unstable, braided fluvial channels with sandy bedload and poorly preserved lateral transition to overbank deposits. The channels were a few metres wide and less than 0.7 m deep. Channel-fill deposits are trough cross-stratified facies St and SGt with a basal channel-floor lag of facies GSm and SGm (Tab. 1). The trough cross-stratified facies St and SGt and subordinate planar cross-stratified facies Sp and SGp represent migration of 3D and 2D dunes, respectively (Harms *et al.*, 1982), possibly developed as mid-channel small bar forms (e.g., Miall, 1977; Collinson, 1996).

The spatial trend of palaeochannels and their internal flow directions indicate consistent sediment transport towards the north and northwest, parallel or oblique to the present-day boundaries of the WG (cf. Fig. 3A, C). Planar parallel-stratified sandstones with parting lamination (facies Sh and SGh, Tab. 1) indicate deposition by rapid flow in the upper flow regime (Simons and Richardson, 1963; Harms *et al.*, 1982), extending sideways beyond the channel margins as sheet-flood (e.g., McKee *et al.*, 1967; Miall, 1977, 1978, 1996).

The fine-grained facies Fm, FSh and Fb (Tab.1) were deposited in floodplain areas formed outside the fluvial channels and over abandoned channels (e.g., Miall, 1976; Collinson, 1996). The laterally discontinuous, lens-shaped lithosomes of these facies suggest deposition in small, seasonally flooded topographic depressions rather than in extensive floodplains. The depressions could host shallow, seasonally drying ephemeral lakes, as indicated by wave ripples, mud cracks and raindrop imprints. Sheets of the very well sorted, sub-horizontally stratified fine-grained sand within overbank deposits are probably of aeolian origin (cf. aeolian sand sheets in Glennie, 1970; Hunter, 1977), supporting the notion of periodical land-surface dryness.

Lower to Middle(?) Triassic in the Krzeszów Brachysyncline and Łączna Elevation

Spatial extent and stratigraphy

The Triassic in the Polish part of the ISS crops out within two tectonic subunits: the Krzeszów Brachysyncline (KB) to the north and the adjoining Łączna Elevation (LE) to the south (Figs 2, 7; cf. Kowalski, 2017). The Buntsandstein deposits are exposed as two narrow belts, trending NW–SE and located close to the western and eastern margins of the KB. Outcrops of the Buntsandstein in the LE occur near the village of Łączna in the Czarna Struga valley (Fig. 7).

Fig. 6.   Suspected tetrapod footprints (marked with white arrows) on a sandstone basal bedding surface; locality 3.

The Triassic succession in the KB is distinctly bi-partite. Its lower part consists typically of arkosic to lithic pinkish sandstones (probable time-equivalent of the Radłówka Formation in the Wleń Graben) that pass upwards into a distinct horizon of kaolinitic 'slab' sandstones. The latter sandstone unit used to be called Weißer Kaolinsandstein by earlier German geologists in the region (Berg and Dathe, 1910; 1940) and is referred to as the Devét Křížu Member or Barchoviny Member in the Czech southern part of the ISS (Holub, 1972; Mikuláš *et al.*, 1991; Wojewoda *et al.*, 2016). These kaolinitic sandstones in the study area occur only in the Zawory Ridge near Jawiszów (locality 9, Fig. 7) and in the Góra Świętej Anny (locality 8, Fig. 7), with the preserved thickness estimated at 10–15 m.

The Triassic in the KB attains a maximum thickness of 150 m in vicinity of Łączna in the LE area (Fig. 7). Triassic is nearly lacking in the northwestern part of the KB, where the Cretaceous rests unconformably directly on the Permian Rotliegend. The only exception is a single occurrence of the kaolinitic slab sandstones with mudstone intercalations in an abandoned quarry in the Góra Świętej Anny (locality 8).

Lithology and petrography

The Triassic succession in the KB is in many aspects similar to that exposed in the WG. The Buntsandstein deposits of the Bohdašin Formation (name from the Czech part of the ISS) consist mainly of sandy and subordinate gravelly facies (Fig. 8 and Tab. 1). These are poorly to moderately sorted, pink to yellowish-grey, medium- to coarse-grained sandstones with interbeds of conglomerate. They are loosely cemented and used to be mined as sand and gravel in a few small abandoned pits. Sandstones are arkosic arenites, locally quartz and arkosic wackes. They are typically composed of angular to subrounded quartz grains from 0.3 to 0.6 mm and up to 2 mm in size, with an up to 10% admixture of strongly kaolinized, white feldspars with automorphic or hypautomorphic outlines. Lithic grains occur as an admixture of up to 15%, including clasts of gneisses, granites, quartzites, volcanic rocks (rhyolites and trachyandesites) and mica schists. Clasts of Permian(?) sandstones and conglomerates also occur.

The Buntsandstein sandstones are cemented with a clayey kaolinite matrix and contain scattered pebbles and cobbles of subrounded to well-rounded vein quartz, granitoid, gneiss, quartzite and volcanic rocks. Sporadically observed are lenticular interlayers and intraclasts of dark-brown mudstones and siltstones.

The lowermost part of the kaolinitic sandstones, directly above the arkosic sandstones of the Bohdašin Formation, comprises coarse-grained, weakly lithified and strongly kaolinized arkosic wackes. Towards the top of the succession, the sandstones are whitish to pale grey in colour, well sorted, medium- and coarse-grained sub-lithic and sub-arkosic arenites with a distinct, bedding-parallel platy parting. Framework grains range from 0.5 to 0.8 mm in size, with an admixture of grains up to 1 mm. Sub-angular to sub-rounded and rounded, monocrystalline, in places polycrystalline, quartz grains dominate (70 to 80%). Kaolinized feldspar grains (up to 10%) and lithic fragments (mostly gneisses, quartzites, granites, granodiorites, rarely rhyolites) are the remaining components of the grain framework. Most of the lithic grains, probably remnants of mica schists, are strongly sericitized and kaolinized. The sandstone matrix contains predominantly kaolinite with a small admixture of illite.
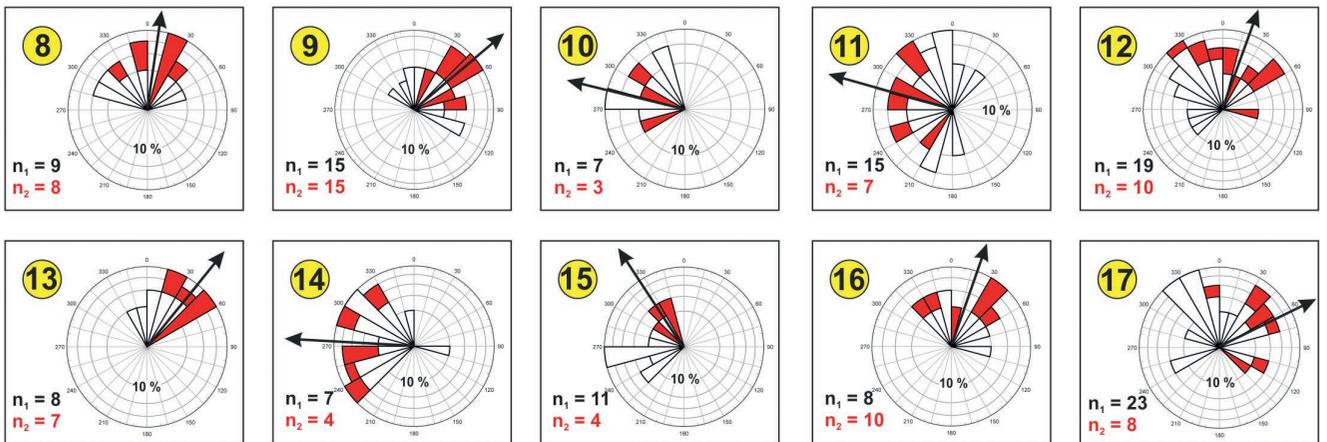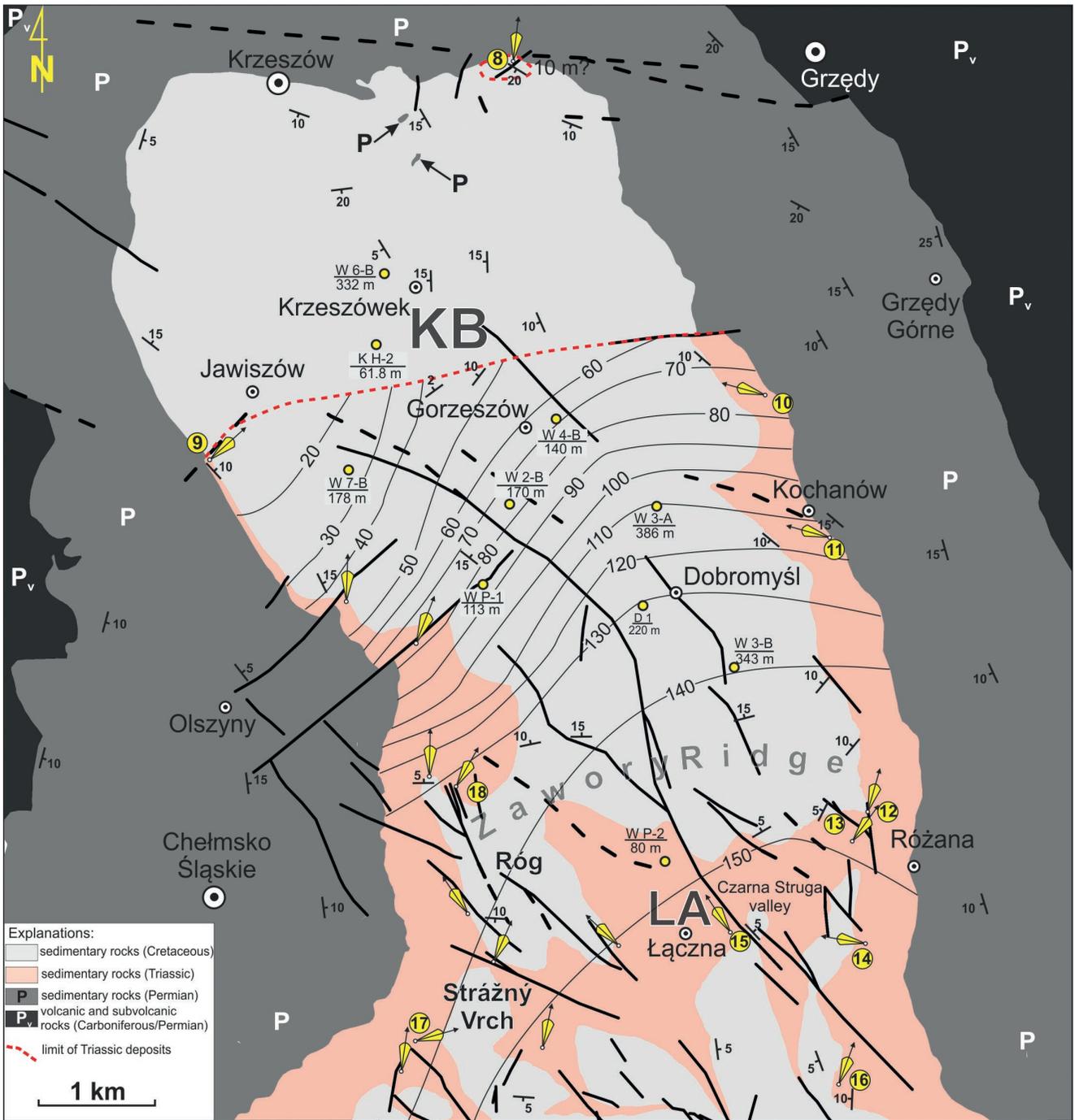
Sedimentary facies

The lower to middle part of the Bohdašin Formation is composed almost exclusively of trough and planar cross-stratified sandstones and pebbly sandstones (facies St, SGt, Sp and SGp; Tab. 1 and Fig. 8), with sparse intercalations of muddy facies along the middle part of the KB eastern margin (localities 10, 11). Similarly as in the WG area, the sandstones typically consist of trough cross-strata sets with an asymmetric, lenticular internal geometry (facies St; Fig. 9A–D). Erosional cosets of trough cross-strata are fining upwards and attain thicknesses of ca. 0.2 to 0.7 m, with a maximum lateral extent of up to 5 m. Abundant locally are scattered reddish and purple muddy or sandy intraclasts (Fig. 9G). Above the trough cross-strata sets occur planar cross-stratified sandstones and pebbly sandstones (facies Sp, SGp; Fig. 9A, E) as well as sandy ripple cross-laminae sets up to 3 cm thick. Planar cross-strata sets, especially at locality 13, show internal low-angle reactivation surfaces.

Conglomeratic facies GSm and SGm (Tab. 1) occur mainly in the southern part of the study area, near the village of Łączna (locality 15; Fig. 9F). Towards the north, continuous horizons of imbricate gravel lag disappear and are replaced by lenses of the matrix-supported gravel of facies SGm, containing mainly quartz and lithic pebbles.

In the middle part of the KB (around the village of Kochanów, localities 10, 11), intercalations of heterolithic fine-grained deposits occur above the coarse-grained cross-stratified facies (Fig. 9H). They comprise planar-laminated or structureless fine-grained sandstones and mudstones (facies FSm and Fm, Tab. 1), attain up to 30 cm in thickness and form discontinuous beds resting on trough cross-stratified sandstones. Mudstones (facies Fm) are predominantly massive and strongly fractured, but locally show flat or wavy lamination and sparse wave and current ripples. Bioturbation structures have not been observed.

The kaolinitic sandstones overlying the Bohdašin Formation are in their lower part characterised by cross-stratified facies St, SGt, Sp and SGp (Fig. 9I, J), much like the underlying Triassic succession in the KB. Cross-strata cosets are up to 0.5 m thick, show upward fining and have erosional lower boundaries covered by thin (up to 5 cm)

Fig. 7.   Detailed geological map of the Krzeszów Brachysyncline (made by the present author) with the marked extent and northern limit of Buntsandstein and the location of outcrops and relevant boreholes. The measured mean transport directions for each locality are superimposed on the map. The rose diagrams below the map show the measured orientation of cross-stratification (white roses) and channel axes (red roses) with their mean direction (black arrows) for selected localities.

Fig. 8. Synthetic sedimentological logs from selected Buntsandstein outcrops in the Krzeszów Brachysyncline (localities 8–13 in Fig. 7). Indicated in the logs are the component sedimentary facies and other observed features. Facies letter code as in Table 1.

conglomeratic layers. These discoloured, white to pale-grey sandstones contain scattered muddy intraclasts of reddish to brown colour (Fig. 9J).

The upper part of the kaolinitic sandstones consists of the "slab sandstone" facies Sh and St (Fig. 9J). The vertical transition from the underlying cross-stratified sandstones to the "slab sandstones" is in most cases gradational, but locally marked by a thin, one clast-thick conglomerate lag that contains strongly kaolinized pebbles of metamorphic and igneous rocks up to 6 cm in size. The conglomerate passes upwards parallel-stratified sandstones and pebbly sandstones (facies Sh and SGh), forming tabular beds 0.1 to 0.2 m in thickness. Strata are slightly inclined (up to ca. 5º) towards the north and northwest. Bed boundaries are marked by grain-size changes and accumulation of mica flakes. In a small outcrop on the western slope of the Strážný Vrch hill (LE area, locality 17), symmetrical and partly bifurcated ripples were observed on a bedding surface (Fig. 9K) in the topmost part of the kaolinitic sandstone unit, ca. 0.5 m below the Triassic/Cretaceous unconformity. Recognizable are trough-shaped, shallow (5 to 30 cm deep) scour-and-fill features filled with cross-stratified sand (Fig. 9J) bearing pale grey to greenish grey rip-up mud clasts. These features resemble wave-generated, nearshore rip channels (Allen, 1982).

Small-scale trough stratification is also common in small tors in the northern part of Róg Hill and in the Jawiszów quarry (locality 9). In the latter quarry, on the bottom bedding surface of a sandstone block shows a network of bioturbation structures in the form of a polygonal system of tunnels, oval in cross-section (Fig. 9L), representing root traces or tunnels formed by invertebrates. In the northernmost part of the KB, near Krzeszów (Góra Świętej Anny, locality 8), the uppermost part of the kaolinitic sandstones shows thin (up to 1 cm) intercalations of massive, locally strongly bioturbated coaly mudstones (facies Fm, Fb; Fig. 9M). Palynological analysis of these deposits (M. Svobodova, J. Kvaček and A.T. Halamski, pers. comm.) revealed unidentified, partly structured phytoclasts with no determinable pollen and seeds (palynomorphs). Therefore, their age cannot be univocally determined based on pollen analysis. The coaly mudstones are underlain by planar parallel-stratified sandstones with scarce remnants of symmetrical ripples.

Environmental interpretation

The main part of the Triassic succession in the KB resembles closely the Lower Triassic in the WG and is similarly interpreted as fluvial deposits. They are predominantly the channel-fill deposits of sandy-gravelly, mixed-load braided streams, ca. 0.6 m deep and up to 5 m wide. Trough (facies St, SGt) and planar cross-stratification (facies Sp, SGp) indicate 3D and 2D dunes, respectively (Harms et al., 1982), probably forming mid-channel bar forms (Miall, 1996; see Table 1). Numerous low-angle reactivation surfaces, especially common in planar cross-strata sets, point to changes in river water stage (Collinson, 1970). All of the measured palaeocurrent directions indicate consistent sediment transport towards the north, northwest and northeast, probably towards the axial part of the basin (Figs 7, 8). Fine-grained deposits (facies FSh, Fm and Fb), attributed to overbank

sedimentation (Tab. 1; Miall, 1977, 1978, 1996), were almost totally removed by erosion in the southern part of the KB and occur only in the form of brownish rip-up clasts in channel-fill sandstones. Poorly preserved, massive fine-grained overbank deposits occur as discontinuous horizons only in the middle sector of the KB (localities 10, 11). The lack of well-preserved overbank deposits implies unstable, laterally mobile stream channels (e.g., Miall, 1977, 1978, 1996; Collinson, 1996). It is possible that fine-grained deposits tended to accumulated at the flanks of fluvial channel tracts, which are presently non-preserved. However, it also cannot be precluded that the reddish mudclasts in the Triassic alluvium were derived from the Permian Rotliegend that crops out at the KB margins.

The trough cross-stratified lower part of the kaolinitic sandstones (facies St, SGt; localities 8, 9) resembles the underlying Triassic deposits and is similarly interpreted to be of fluvial origin. Transport directions point consistently to the north (Figs 7, 8). The green-greyish and locally brownish mudclasts observed at locality 9 (Jawiszów) are most probably intraformational.

The upper part of the kaolinitic sandstones represents a transition from fluvial and shallow lacustrine environment. The floodplain lake was an ephemeral body of standing water, as indicated by mud-cracks and adhesion ripples (localities 8, 9), but it is uncertain if it was a playa because evaporites are lacking and also plant-root casts might preclude an elevated water salinity. It is likely that the floodplain environment involved a mosaic of merging and disconnecting stagnant water bodies (cf. Collinson, 1996). Abundant streamflow supply of plant detritus is indicated by coaly mudstone intercalations (facies Fm, Fb) in cross-stratified sandstones. Symmetrical and partly bifurcated wave ripples (facies Srw) in the "slab sandstones" indicate wave action. The scour-and-fill features at locality 9 (Jawiszów quarry), if not formed by stream flash floods entering the lake, may then be shallow nearshore rip channels related to episodically strong wind action (cf. Allen, 1982; Sayah et al., 2004).

DISCUSSION

Sedimentary environments and palaeogeographic development

This integrated cartographic and sedimentological study has shed new light on the Permo-Triassic palaeogeography in the Sudetic KB and WG areas (Fig. 10). Facies analysis shows that the Early Triassic terrestrial sedimentation in these areas was dominated by fluvial depositional environments typical of the continental Buntsandstein in Central Europe (e.g., Feist-Burkhardt et al., 2008; Bourquin et al., 2009; Bachmann et al., 2010). This palaeoenvironmental interpretation does not differ significantly from the earlier palaeogeographic notions proposed for the study areas by Mroczkowski (1969) and Mroczkowski and Mader (1985). Main differences pertain to the range of observed sedimentary structures, significance of particular lithofacies, the primary extent of Triassic deposits, as well as the allocyclic and autocyclic controls on their sedimentation.
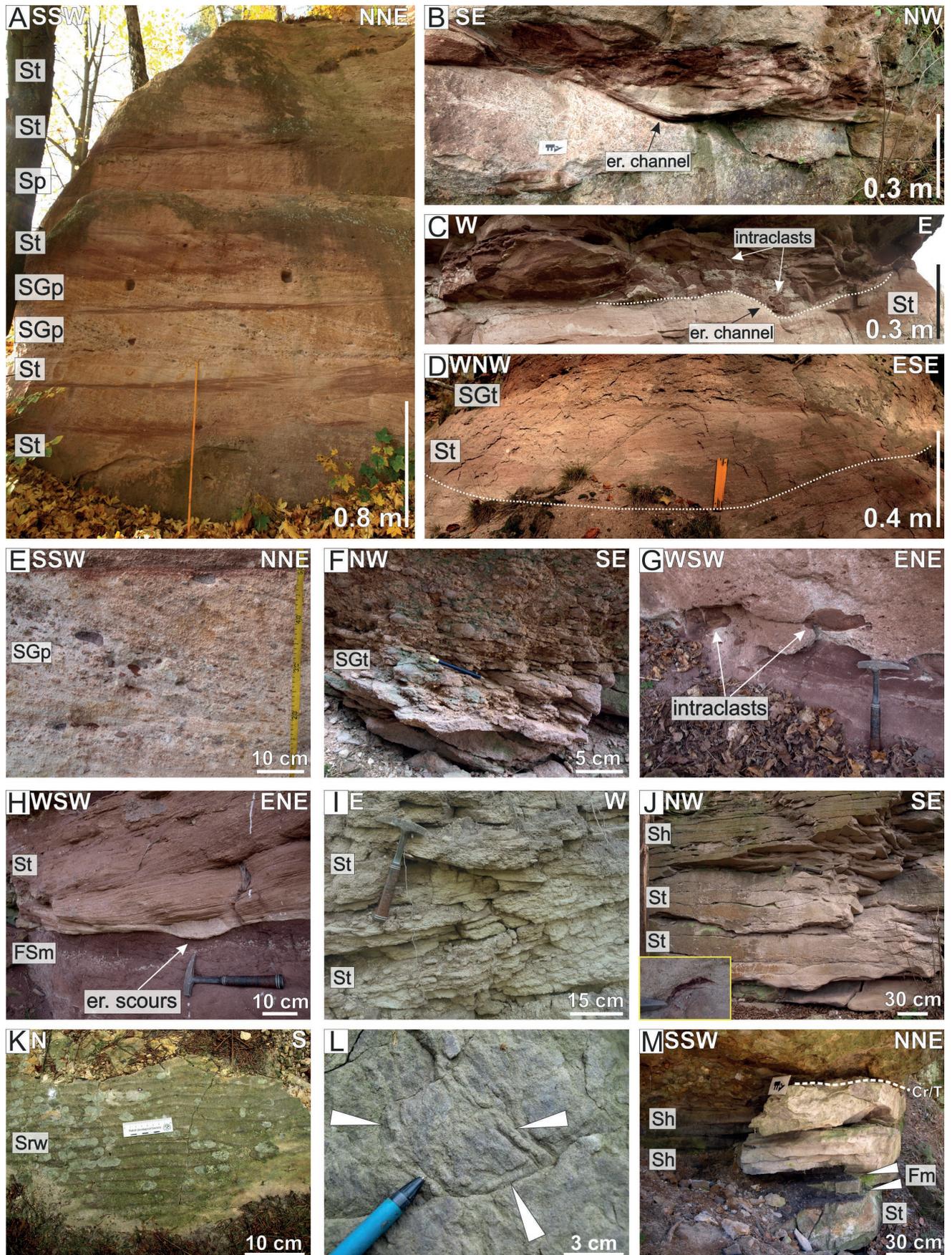
Fig. 9. Outcrop details of the Lower (A–H) to Middle? Triassic (I–M) in the Krzeszów Brachysyncline. For localities, see Fig. 7. Lithofacies letter code as in Table 1. **A.** Multiple channel-fill deposits exposed in an abandoned quarry near Łączna (locality 13). View parallel to palaeoflow (transport to the right). Note the erosional boundaries of cross-strata sets and bar reactivation surfaces. **B.** Sand-filled

Based on the lithofacies and palaeocurrent directions, it is concluded that the WG and KB areas in the Early Triassic were parts of an inland alluvial plain (inland braidplain *sensu* Mroczkowski and Mader, 1985; endorheic drainage basin *sensu* Dorsaz *et al*., 2013) with dominantly north-westward and northward fluvial drainage (Fig. 10). Individual fluvial channels were up to a few metres wide and less than 1 m deep. The rivers carried a mixed gravel and sand bedload in the form of 3D and 2D dunes, evolving into mid-channel bars. The regional climate was semi-arid, with sparse vegetation and limited chemical weathering, whereby the riverbanks were unstable and the channels were subject to frequent lateral shifting – restricted only by inherited topography. Vertical changes in the mean palaeocurrent directions in both the KB and WG areas show a variance of around 40º (cf. Figs 3A, C, 7, 8), which suggests a similar pattern of fluvial drainage and channel lateral mobility.

Fine-grained overbank deposits are nearly lacking, represented by mudclasts. Such deposits were poorly developed, probably in small seasonal ponds, and were sparsely preserved in the alluvial system of laterally unstable river channels. It was suggested that overbank fines, especially in the WG area, could have been winnowed by wind during drier seasons (Mroczkowski, 1972; Mroczkowski and Mader, 1985). Extensive floodplains were lacking, although some local ponds probably evolved into shallow, ephemeral "terminal" lakes.

Sedimentation in alluvial settings lasted probably throughout nearly the entire Early Triassic. In the late Early Triassic, kaolin-rich, regolith-type covers developed locally on the top of the Bohdašin Formation in the present-day KB area, probably due to its slow tectonic uplift. These weathering covers formed *in situ*, without significant redeposition, as evidenced by well-preserved stratification in the lowermost, strongly weathered part of the kaolinitic sandstones, similar to the stratified underlying arkosic sandstones. There is no evidence that a similar weathering cover developed in the present-day WG area, although it could have been removed by erosion. Fluvial sedimentation resumed in the KB area in the latest Early to Middle(?) Triassic, locally with ephemeral lake deposits and bioturbated coaly mudstones in the topmost part of the kaolinitic sandstones (locality 8; Jerzykiewicz, 1971). The bioturbated horizons and accumulation of organic matter within the kaolinitic sandstones

are recognized for the first time by the present study. This new evidence may indicate a transition from semi-arid to more humid climate at the end of the Early Triassic, or possibly a wetter local floodplain with ephemeral lake facies. The exact age span of the kaolinitic sandstones is uncertain and its hypothetical extension into the Middle(?) Triassic is considered herein with a due caution.

The Triassic topographic configuration of the WG and KB sub-basins, as well as their sediment-sourcing pattern within the context of NSS and ISS, were at least partly inherited from the Permian and possible even late Carboniferous time (cf. Fig. 10A, B). The present study, as well as earlier palaeogeographic reconstructions, indicate that the WG and KB areas began to develop as independent depocentres already during the Early Permian (Fig. 10A), with fluvial sedimentation interrupted by volcanic activity (Kozłowski and Parachoniak, 1967; Awdankiewicz, 1999, 2006). The KB and WG areas differed probably in topography and tectonic subsidence rate. The extent and thickness of Buntsandstein show that the KB area in the Early Triassic was a relatively narrow sedimentary sub-basin with a fluvial drainage network superimposed upon a single axial depocentre (Fig. 10C; Kowalski, 2017). The outline of the central part of this sub-basin generally conforms to the present-day outline of the KB. There is little doubt that the Buntsandstein in the KB area represents the preserved core part of a larger sub-basin. However, the Buntsandstein succession obviously covered a wider area than its present-day outcrop, and its primary extent remains debated and is practically impossible to determine. In the late Early to Middle(?) Triassic, at least two smaller depocentres formed in the KB area, separated by an elevation trending NW–SE. Such development is evidenced by the erosional relics of kaolinitic sandstones within the present-day elevations near Łączna and Krzeszów (Kowalski, 2017) and the lack of similar deposits in the KB centre (Wojtkowiak *et al*., 2009). The occurrence of kaolinitic sandstones as relics in presently elevated areas is attributed to the formation of tectonically controlled depocentres within the KB sub-basin at the end of the Early Triassic (Kowalski, 2017), yet without significant change in the inherited pattern of local fluvial drainage (Fig. 10).

In contrast to the KB, no distinct single depocentre developed in the WG area in the Early Triassic. A tectonic graben, with outliers oblique or perpendicular to the present-day

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scour-and-fill troughs incised in fine-grained, dark-brown mudstones (locality 11). **C.** Large mudstone intraclasts at the base of fluvial palaeochannel (locality 11). **D.** Asymmetrical scour-and-fill trough filled with cross-stratified sand (facies St); view oblique to palaeoflow (locality 13). **E.** Solitary set of tangential planar cross-strata in pebbly sandstone (facies SGp); note the dark-brown mudclasts resting on the bedform lee side (locality 13). **F.** Trough cross-stratified conglomerates and sandy conglomerates (facies SGt) in the southern part of the KB (locality 15). **G.** Large, oval intraclasts, up to 60 cm in length, in the uppermost part of a mudstone unit, with smaller similar intraclasts scattered in the overlying trough cross-stratified sandstone (locality 11). **H.** Massive mudstone horizon of facies FSm overlain by trough cross-stratified sandstone with shallow erosional scours at the base (locality 11). **I.** Trough cross-stratification in the strongly weathered lowermost part of the kaolinitic sandstones (locality 18). **J.** Planar parallel stratification (facies Sh) and trough cross-stratification (facies St) in the kaolinitic "slab sandstones", scoured by small channels 0.1 to 0.3 m in thickness (locality 9); the inset close-up shows an isolated, brown-coloured muddy intraclast within trough cross-strata set. **K.** Symmetrical, partly bifurcated wave ripples (facies Srw) on the upper bedding surface of kaolinitic sandstone (locality 17). **L.** Irregular network of bioturbation structures at the base of fine-grained kaolinitic sandstone, interpreted as plant-root traces or possible tunnels formed by invertebrates (locality 9). **M.** Thin (up to 1 cm) intercalations of massive coaly mudstones (facies Fm) within the kaolinitic sandstones at the Góra Świętej Anny (locality 8); note the Triassic/Cretaceous unconformity (Cr–T) marked by thick conglomerate layer in the photograph upper part.
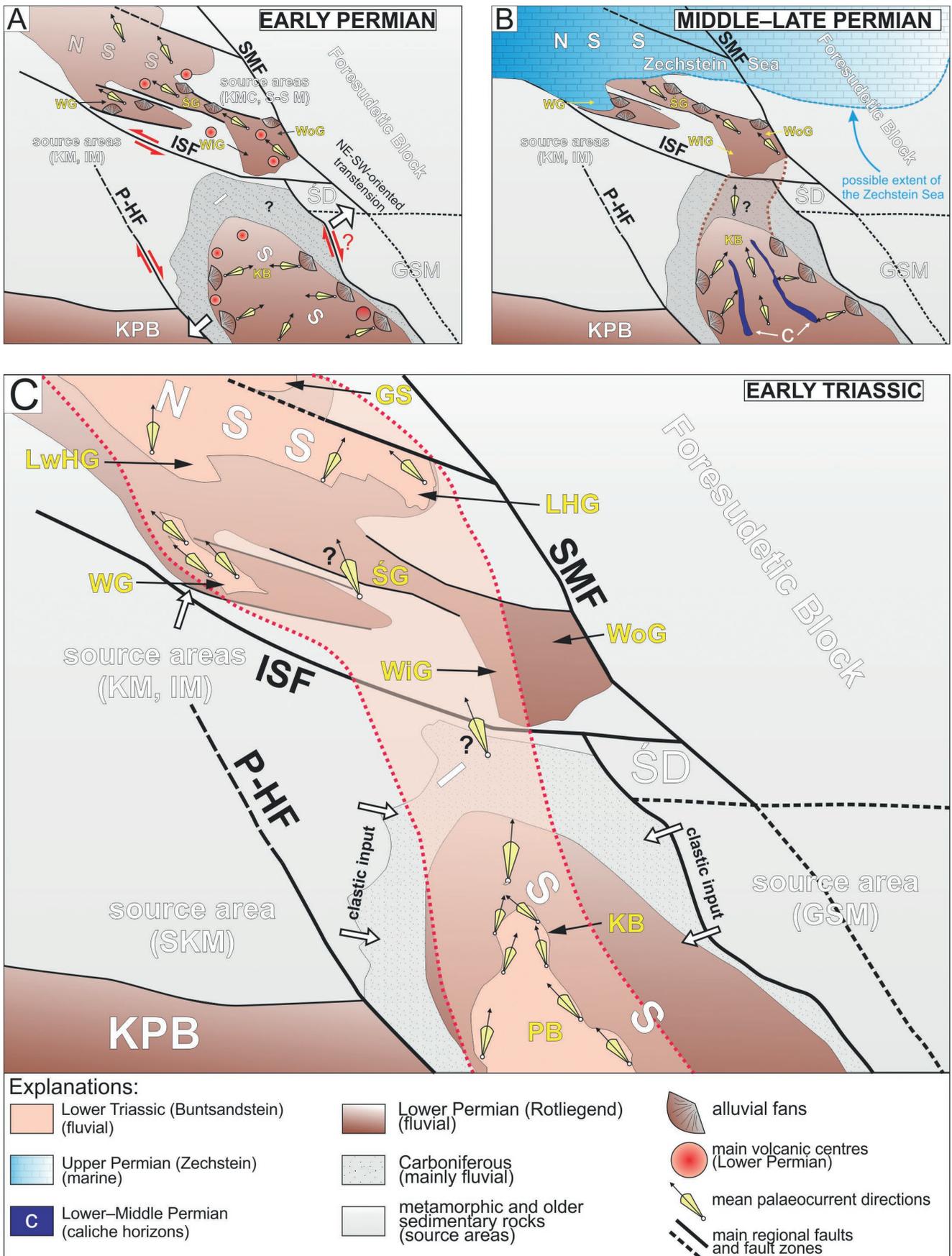
Fig. 10. Schematic palaeogeographic evolution of the marginal parts of the North Sudetic and Intra-Sudetic basins in the Early Permian to Early–Middle(?) Triassic. Note the hypothetical sediment source areas and the postulated interconnection of the WG and KB areas (brown and red dashed lines). Location of the Permian volcanic centres after Awdankiewicz (1999, 2006). Possible sense of movement on the regional fault zones in the Early Permian after Aleksandrowski (1995), Uličný (2001) and Wojewoda (2007). For discussion, see text.

WG, formed there already in the Late Carboniferous or Early Permian (Milewicz and Frąckiewicz, 1988). This morphological depression lost its topographic relief by the Early Triassic, filled in by the Rotliegend alluvial fans and braided-river deposits and then invaded by the Zechstein epicontinental sea (Fig. 10B; Kowalski *et al*., 2018a). The WG area thus inherited a NW-inclined topography of the Zechstein plain, whereby the Buntsandstein fluvial drainage followed the NW and N direction of the earlier Rotliegend drainage (Fig. 10C; cf. palaeocurrent directions in Fig. 3A, C). Subsidence may have been slightly more pronounced in the Grodowa Horst area, where the Buntsandstein thickness reaches ca. 100 m (Fig. 3B). The regional trend of a NW-increasing thickness of the Buntsandstein is observed in the whole NSS area, reaching 360 m in vicinity of Lwówek Śląski and ca. 800 m near Bolesławiec (Berezowska and Berezowski, 1982). The earlier interpretive map of Buntsandstein in the WG, assuming a uniform thickness of ca. 100 m (Milewicz, 1968), is thus considered incorrect in the light of the present mapping study and available borehole data.

It should be emphasized that the Zechstein Sea did not reach the KB area (Fig. 10B), which must have been elevated in relation to the WG area both in the Permian and the Early Triassic. Deposition in the Intra-Sudetic Basin (ISS) at that time was terrestrial, dominated by alluvial fan and braided river environments (Dziedzic, 1961; Śliwiński, 1980, 1981, 1984). Therefore, the Permo–Triassic sedimentary succession in the middle part of the KB area cannot be interpreted as a "transition […] with complete passage from Zechstein marine near-shore carbonates […] via coastal plain sediments to inland fluvial plain deposits" (Mroczkowski and Mader, 1985). The boundary between the Permian and the Triassic deposits in the KB area (localities 10, 11) is an erosional unconformity (Fig. 8). If an early Permian age of the Chełmsko Śląskie Beds (Śliwiński, 1980, 1981, 1984) is assumed, the minimum time gap corresponding to this unconformity would be ca. 20 Ma. This estimate implies to a possible break in sedimentation in the KB area encompassing the whole Late Permian. The WG area at that time hosted a shallow embayment of the Zechstein Sea, where sedimentation on a muddy coastal plain was eventually replaced in the Early Triassic by a fluvial environment (Kowalski *et al*., 2018a).

Regional implications

The investigated WG and KB areas are tectonically cut-off regional relics of an Early Triassic larger continental sedimentary basin (cf. Szyperko-Teller and Moryc, 1988; Feist-Burkhardt *et al*., 2008; Bachmann *et al*., 2010). The Buntsandstein sedimentation in these areas was recognizably controlled by the inherited pre-Triassic basin topography and influenced by local morphological factors. According to the existing palaeogeographic reconstructions, the WG and KB areas in the Early Triassic were situated in the southernmost, enclosed part of the Polish Buntsandstein Basin, forming the southeastern part of the Triassic Germanic Basin (Fig. 1). The Bohemian Massif was the southernmost elevated flank of this basin, with no connection to the Tethys

Ocean (Feist-Burkhardt *et al*., 2008; Bachmann *et al*., 2010). The sediment source areas for this Sudetic basinal complex, comprising the ISS and NSS, were the Variscan orogenic belts and post-Variscan granitoids at the N/NE fringe of the Bohemian Massif: the Orlica Massif and Kudowa Granite Massif to the south, the Góry Sowie Massif to the east, and the South Karkonosze Massif to the west (Mroczkowski, 1972; Mroczkowski and Mader, 1985). Petrographic composition of the Buntsandstein indicates that the sediment to the WB and KB areas was sourced mainly from the Kaczawa Metamorphic Complex and the Karkonosze-Izera Massif located to the north, south and southeast (Fig. 10C; see also Mroczkowski, 1972, 1977). Local aeolian dune fields may have developed in the Early Triassic at the highland margins of the Sudetic Buntsandstein basinal complex, as suggested for the eastern part of the Karkonosze Piedmont and the southernmost part of the ISS (Uličný, 2004).

The KB and WG areas are located today at a distance of ca. 40 km from one another, probably slightly smaller than originally, and are separated by crystalline units devoid of Mesozoic rocks. However, contrary to the suggestion by Mroczkowski (1972), the ISS and NSS must have been linked in the Permian (Fig. 10B) and Triassic (Fig. 10C), and by marine straits in the Late Cretaceous (Uličný *et al*., 2009; Leszczyński and Nemec, 2019), as indicated by palaeotransport directions. Wojewoda *et al.* (2016) and Kowalski (2017) suggested that the ISS, including the KB area, might have been affected by a marine incursion of the Röt Sea in the latest Early Triassic, which would necessarily include the WG area. There is so far no clear evidence to support this hypothetical notion, although the upper Lower to Middle Triassic marine carbonate deposits (Röt and Muschelkalk) are known from the Grodziec Syncline area (NSS; cf. Chrząstek, 2002), ca. 25 km to the north of the WG. Likewise, unsupported remains the suggestion by Durkowski *et al*. (2017) that the Triassic kaolinitic sandstones in the Grodziec Syncline within the NSS were deposited "during a marine transgression, in a lagoonal environment with a significant influence of low-flow regime rivers". There is no documented Upper Triassic, Jurassic and Lower Cretaceous deposits, in the Sudetic region, although this stratigraphic gap can be attributed to the tectonic uplift and erosion related to the onset of the Alpine orogeny. This issue is highlighted by the lack of Triassic deposits between the KB and WG areas, similarly as between the northern WG and the southern part of the adjacent Lwówek Śląski Half-Graben (Figs 2, 10C). These areas are separated by tectonic horsts and show Triassic thickness of up to 300–360 m near their margins, which implies cut-off relics of an originally broader Buntsandstein basin. The marine Upper Cretaceous overlies unconformably the Buntsandstein in the WG area and in the adjacent Lwówek Śląski Half-Graben (NSS), which points to a combined effect of the Alpine tectonism and eustasy (cf. Leszczyński and Nemec, 2019).

The notion of a Triassic to Late Cretaceous regional uplift and erosion is supported by the lack of Triassic deposits in the middle and northern parts of the KB along a transverse fault oriented NE–SW (Fig. 7). Kaolinitic sandstones occur only as an erosional relic at locality 8 in the northernmost

part of the KB. Such an isolated occurrence of Triassic deposits suggests that they originally covered a larger area than presently observed. Moreover, the thickness of Triassic deposits in the Czech part of the ISS increases gradually towards the NW (Prouza *et al.*, 1985), whereas in the KB it consistently decreases in that direction, from the village of Łączna towards Gorzeszów over a distance of ca. 5 km (Fig. 7). Such a local abrupt decrease of thickness is probably a result of the gradual uplift of the KB area between the Middle Triassic and Late Cretaceous, with coeval tilting of the underlying block along faults oriented NE–SW. The removal of Triassic rocks from the uplifted block by pre-Cenomanian erosion and uplift made the marine Upper Cretaceous rest unconformably on the Permian in the northern part of the KB (Figs 2, 7). A similar effect of pre-Cenomanian uplift and erosion is observed in the WG, where the thickness of Triassic deposits decreases towards the SE with no evidence of source-proximal alluvium (fanglomeratic facies) and hence in no relation to the sub-basin original margin.

CONCLUSIONS

The present paper addressed the Triassic depositional palaeoenvironment and palaeogeography in the Wleń Graben and Krzeszów Brachysyncline – two distinct tectonic subunits and little-studied outliers of the North Sudetic and Intra-Sudetic synclinoriums at the NE fringe of the Bohemian Massif. New revised geological maps of these study areas are presented, together with the Triassic synthetic isopach and palaeogeographic maps based on the field mapping, borehole data and measured palaeotransport directions.

Due to the lack of biostratigraphic data, the age of deposits was determined solely on the basis of their stratigraphic position. The Lower Triassic (Buntsandstein) in the Wleń Graben area was deposited after the Late Permian (Zechstein) marine transgression. In the Krzeszów Brachysyncline area, it was deposited with a ca. 20 Ma gap directly on the Lower Permian (Rotliegend). In the Late Permian, the Wleń Graben area constituted a shallow-marine embayment of the Polish Zechstein Basin, whereas the Krzeszów Brachysyncline area was an elevated terrain subject to denudation.

The Early Triassic palaeotopography in the Wleń Graben and Krzeszów Brachysyncline areas of the North Sudetic and Intra-Sudetic basins was inherited from the Permian topographic configuration of these basins. The two areas were probably interconnected and were parts of a broader, gently NW-sloping endorheic alluvial plain drained by shallow braided rivers. The petrographic composition of Buntsandstein indicates sediment provenance from the surrounding Variscan low mountain belts, elevated crystalline blocks and post-Variscan granitoid massifs, including erosion of Permian deposits.

The Buntsandstein sedimentary facies in the study areas are consistent with the general notion of Early Triassic semi-arid climatic conditions in the Central Europe. The kaolinitic sandstones at the Buntsandstein top (?Middle Triassic) seem to indicate an increased climate humidity, with pronounced chemical weathering of sediment in uplifted areas and the formation of "terminal" lakes in local depressions, accumulating degraded washout plant detritus.

The Wleń Graben and Krzeszów Brachysyncline areas, as isolated outliers, are crucial relics of the Triassic Sudetic basinal complex at the NE fringe of the Bohemian Massif, as they indicate a broad endorheic basin dissected topographically by pre-Cenomanian tectonics. The primary extent of this sedimentary basin is difficult to reconstruct, but the present study reveals its broad extent with an array of interconnected sub-basins and local depocentres. The study as a whole contributes to an understanding of the Triassic palaeoenvironment and palaeogeography at the Polish fringe of the Bohemian Massif.

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