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ZECHSTEIN MARINE DEPOSITS IN THE WLEŃ GRABEN (NORTH SUDETIC SYNCLINORIUM, SW POLAND) – NEW INSIGHTS INTO THE PALAEOGEOGRAPHY OF THE SOUTHERN PART OF THE POLISH ZECHSTEIN BASIN

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Abstract: This paper presents the results of sedimentological studies of Zechstein marine deposits occurring in the Wleń Graben, a tectonic unit located in the southeastern part of the North Sudetic Synclinorium (NSS; Western Sudetes, SW Poland). Owing to poor exposure, small thickness, and lack of palaeontological data, the stratigraphy and age of these rocks were determined solely on the basis of analogies with adjacent areas. New findings described here, including faunal remains (remains of bivalves, including *Liebea* sp.), geopetal structures, clastic fills of halite crystals, moulds and bioturbation, shed new light on the environmental interpretations of the Zechstein in this part of the NSS. It should be assumed that at least two types of deposit may be assigned to the marine Zechstein in the Wleń Graben area, namely sparitic and microsparitic dolomite (PZ3) and the overlying deposits of the heterolithic series (PZt). These deposits were formed during the late Zechstein transgression, when the study area was in the marginal southwesternmost part of a newly formed shallow-marine bay of the Polish Zechstein Basin. In the central part of the present-day Wleń Graben, a shallow-marine bay (lagoon?) was dominated by carbonate sedimentation. A north-dipping mud plain, periodically flooded by a shallow sea, occurred in the southern part of the area. The paper summarises the present state of research on Permian deposits in the Wleń Graben, the first comprehensive lithostratigraphic scheme is suggested, and a new concept of the palaeogeographic evolution of the area in the Early and Late Permian is proposed.

Key words: Polish Zechstein Basin, dolomites, Permian/Triassic Transitional Terrigenous Series (PZt), North Sudetic Synclinorium, Wleń Graben.

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INTRODUCTION

The distribution, range and facies characteristics of marine Zechstein deposits in the North Sudetic Synclinorium (NSS; Lower Silesia; Fig. 1) have raised interest and controversies among numerous researchers already since the mid-19th century (von Dechen, 1838; Grunewaldt, 1851; Geinitz, 1861; Langenhan, 1899). Despite such a long history of research, the extent of the southern coastline of the shallow-marine Zechstein Basin in Lower Silesia still remains unclear (Eisentraut, 1939; Peryt, 1978; Raczyński, 1997). Numerous authors, studying the facies development of Zechstein deposits in this region (Scupin, 1931; Peryt, 1978; Raczyński, 1996; see Table 1), constructed regional stratigraphic schemes based on lithology and comparison with the classical areas in Germany. The regional distinctiveness of the Zechstein stratigraphic scheme in the Sudetes has persisted to the present day, despite the fact that stratigraphic studies of these deposits have not been performed on some geological units since the 1970s (Milewicz, 1966; Gorczyca-Skała, 1977). Reconstruction of the palaeogeography and sedimentary conditions in the area, mainly in the southern part of the NSS, is hampered, for example, by local facies variation and the fragmentary preservation of Zechstein

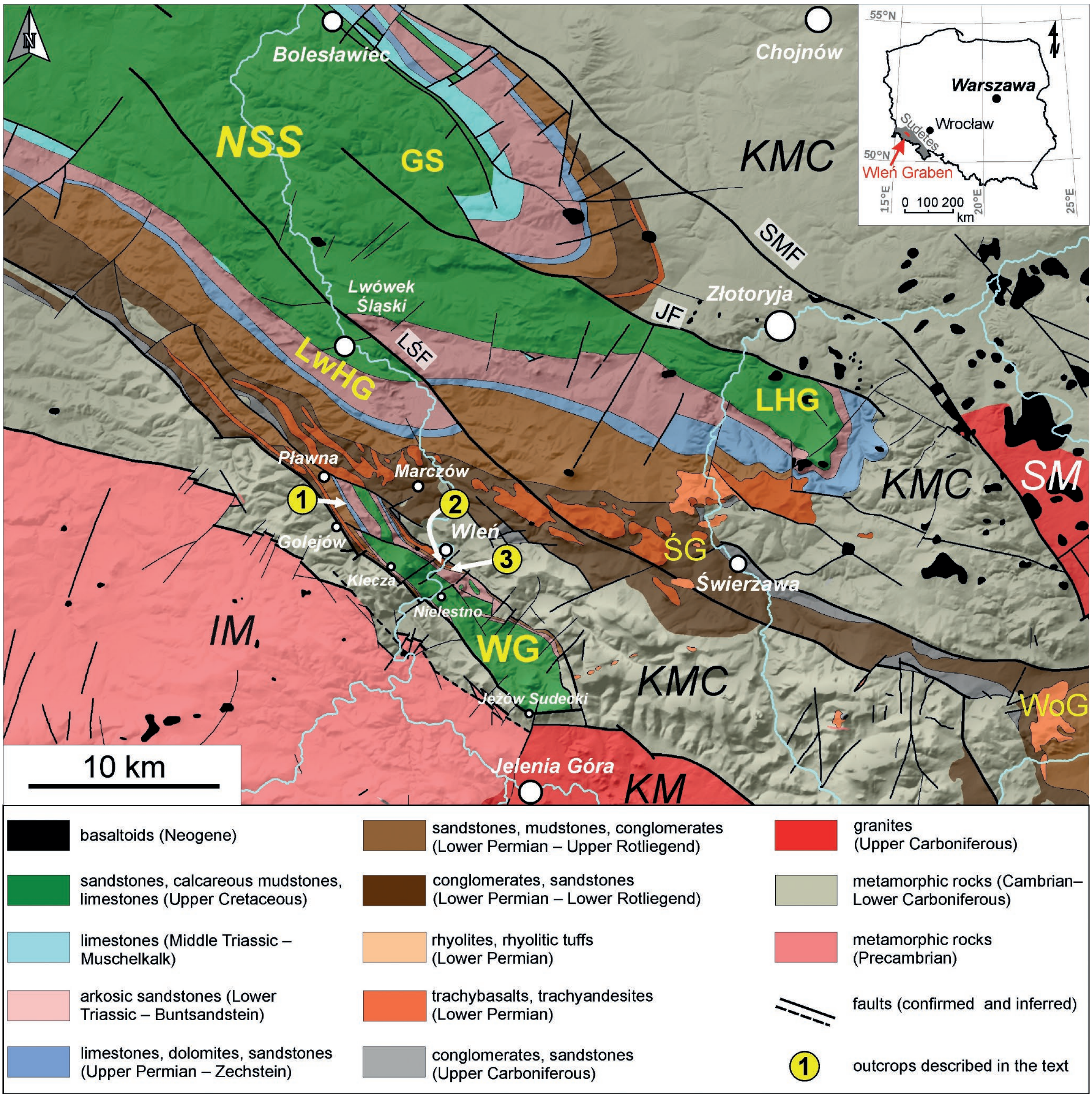

Fig. 1. Simplified geological map of the North Sudetic Synclinorium (NSS) and the Wleń Graben (WG) with locations of outcrops described in the text. Explanations: GS – Grodziec Syncline; LHG – Leszczyna Half-Graben; LwHG – Lwówek Śląski Half-Graben; WoG – Wolbromek Graben; ŚG – Świerzawa Graben; KMC – Kaczawa Metamorphic Complex; IM – Izera Massif; KM – Karkonosze Massif; SM – Strzegom-Sobótka Massif; JF – Jerzmanice Fault; LŚF – Lwówek-Świerzawa Fault; SMF – Sudetic Marginal Fault. Map superimposed over an SRTM DEM with a resolution of 90 m. Geological map based on Sawicki, 1995 and Cymerman, 2004.

rocks within minor tectonic subunits (Scupin, 1931; Eisentraut, 1939; Raczyński, 1997). One of these units is the Wleń Graben (WG), which constitutes the southeastern prolongation of the NSS. Owing to poor exposure and the small thickness of the deposits assigned to the Zechstein in the Wleń Graben, their stratigraphy was determined on the basis of analogies with the Lwówek Śląski Half-Graben, located at a distance of over 15 km to the north (Milewicz, 1966).

So far, the results of previous research do not provide evidence of the primary extent of Zechstein deposits in the Wleń Graben, based on their lithology (Milewicz, 1966; Gorczyca-Skała, 1977). Up to now, descriptions of Zechstein deposits in the area were based on a few exposures not exceeding 2–3 m in height, as well as a few research excavations, related to geological mapping surveys (Milewicz and Frąckiewicz, 1983, 1988). Difficulties in the recognition of Upper Permian sedimentary rocks have also resulted from numerous tectonic deformations (Groczyca-Skała, 1977). Moreover, it has been stated that the calcareous deposits of the Zechstein in the Wleń Graben do not contain any fossils

Table 1

Regional litostratigraphic subdivisions of the Zechstein deposits in the NSS area, proposed by various authors (modified after Raczyński, 1997)

<table>
<tr><td colspan="2">Scupin (1931)</td><td colspan="2">Peryt (1978)</td><td colspan="4">Raczyński (1996)</td></tr>
<tr><td>Zo3</td><td>Oberer Zechsteinsandstein</td><td colspan="2">Buntsandstein (Lowermost part)</td><td>Permo-Triassic Transitional Series</td><td rowspan="3">Upper Zechstein</td><td colspan="2">PZt</td></tr>
<tr><td>Zo2</td><td>Plattendolomit mit Schizodus rotundatus</td><td>Platy Dolomite Ca3</td><td>Leine Z3</td><td>Platy Dolomite Upper Zechstein</td><td colspan="2">PZ 3</td></tr>
<tr><td>Zo1</td><td>Unterer Zechsteinsandstein</td><td rowspan="5">Terrigenous Series</td><td rowspan="5">Werra Z1</td><td>Septarian shales
Upper Zechstein (lower) sandstones</td><td></td><td rowspan="7">PZ 1</td></tr>
<tr><td>Zm</td><td>Dolomitische Kalke mit Letten</td><td>Middle Zechstein limestones and shales</td><td>Middle Zechstein</td><td rowspan="5">Ca1</td></tr>
<tr><td rowspan="5">Zu</td><td>Gervillienschichten</td><td>Lead bearing marls</td><td rowspan="5">Lower Zechstein</td></tr>
<tr><td>Kupfermergel</td><td>Copper bearing marls</td></tr>
<tr><td>Zweischalermergel</td><td>Patchy marls</td></tr>
<tr><td>Basalkalke</td><td colspan="2">Basal limestone</td><td>Basal limestone</td></tr>
<tr><td>Zechsteinkonglomerat</td><td colspan="2" rowspan="2">Rotliegend</td><td>Basal conglomerate</td><td>S1</td></tr>
<tr><td colspan="2">Rotliegendes</td><td colspan="4">Rotliegend</td></tr>
</table>

unmistakably indicating a marine setting (Milewicz, 1966; Gorczyca-Skała, 1977). Despite that, on the basis of the lithology of carbonate rocks (mainly dolomites) in the area, it has been considered *a priori* that the Wleń Graben was located “near the sea shoreline oscillating within the present boundaries of the graben” (Milewicz, 1966, p. 73). So far, a comprehensive lithological or lithostratigraphic column has not been presented for the Wleń Graben and the area lacks a detailed petrographic description of the Zechstein deposits; the descriptions of particular units also strongly differ between authors (cf. Milewicz, 1966; Kłapciński, 1967; Gorczyca-Skała, 1977). This paper aims to fill this gap and solve the issues mentioned above. The focus of this paper is also a summary of the existing knowledge of the Zechstein deposits in the Wleń Graben.

In addition to a discussion and new facts on the issues presented above, the authors have documented their findings of a fossil fauna (remains of bivalves, including *Liebea* sp.), geopetal structures, clastic fills of halite crystals, moulds and bioturbation. As well, the calcareous siltstones and sandstones, unconformably overlying the uppermost Rotliegend occurring in the Nielestno area, contain accumulations of clastic infillings of cubic halite crystals (edges up to 0.5 cm in length) and extensive bioturbation. These finds shed new light on the interpretation of the sedimentary conditions of the Zechstein in this part of the NSS. A proposal of a comprehensive lithostratigraphic column for the marine Zechstein deposits in the Wleń Graben is presented, as well as a review of the palaeogeographic development of this area in the Permian.

GEOLOGICAL SETTING

The study area is located in the Western Sudetes between Golejów village in the north and the town of Wleń in the south. Zechstein deposits cropping out in this area are preserved in the Wleń Graben, a tectonic subunit located in the southeastern part of the NSS (e.g., Kolb, 1936; Teisseyre *et al.*, 1957; see Figs 1, 2). The NSS is composed of weakly deformed Upper Carboniferous (Pennsylvanian), Permian and Triassic sedimentary and volcanic rocks, which together with the Upper Cretaceous deposits comprise the so-called upper Kaczawa Stage (Teisseyre *et al.*, 1957). These sediments, both continental and marine in origin, as well as products of Permian volcanic processes, filled the North Sudetic Basin (NSB) at various stages of its development (Śliwiński *et al.*, 2003). The NSB started to develop during the Late Carboniferous (Pennsylvanian; Milewicz and Górecka, 1965; Wojewoda and Mastalerz, 1989; Mastalerz and Raczyński, 1993; Solecki, 1994) within basement metamorphic rocks, assigned to the Kaczawa Metamorphic Complex (KMC; cf. Baranowski *et al.*, 1990). The first stage of NSS formation included the development of at least two narrow, intramontane troughs (tectonic grabens) near the present-day towns of Świerzawa and Wleń, due to large-scale regional extension of the KMC basement in the termi-

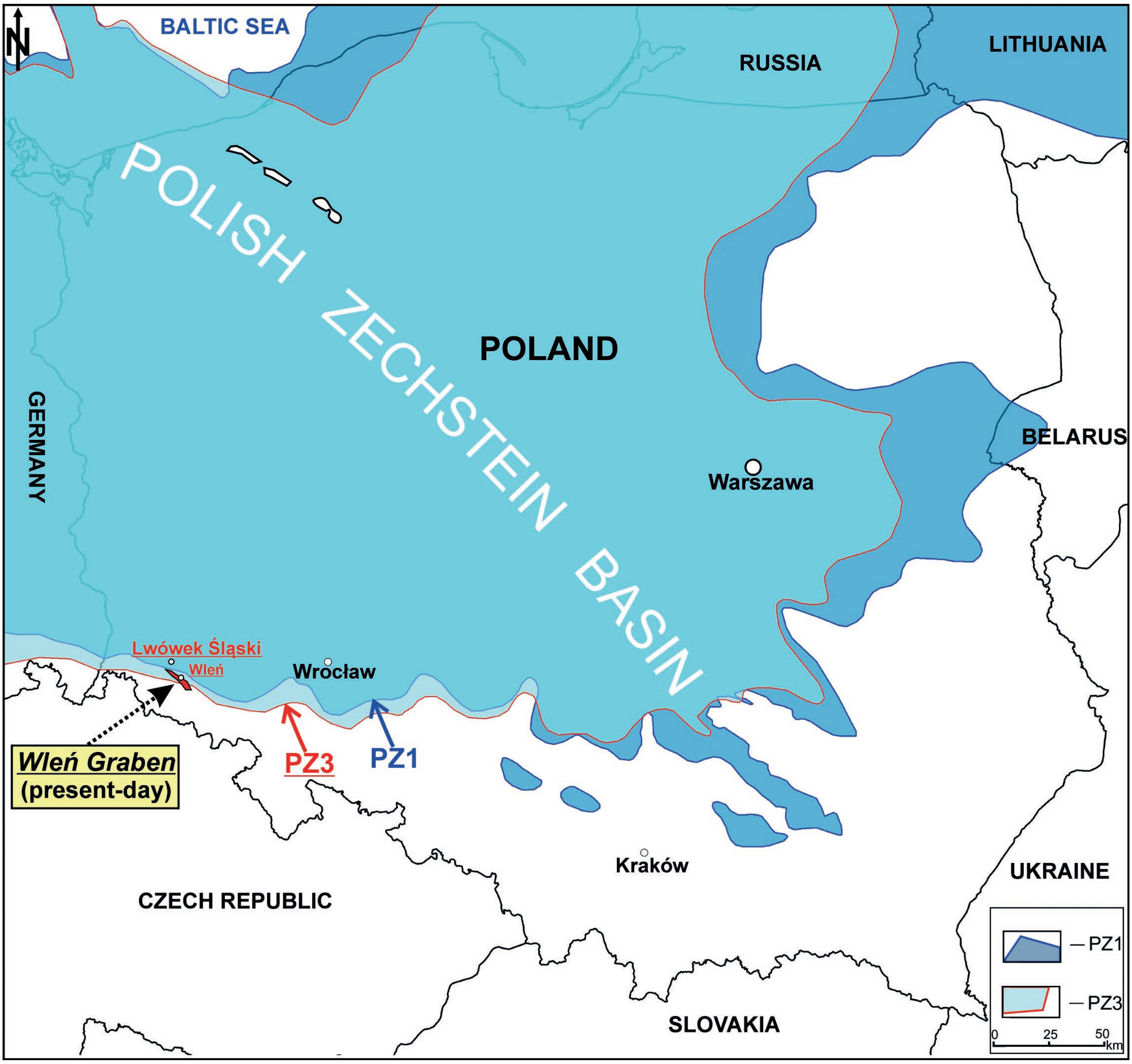

Fig. 2. Location of the present-day Wleń Graben in relation to the original extent of the PZ3 and PZ1 cyclothems in the Polish Zechstein Basin (modified after Wagner *et al*., 1980; Wagner, 1994).

nal phases of the Variscan orogeny (cf. Ostromęcki, 1973; Milewicz and Frąckiewicz, 1988; Baranowski *et al*., 1990; Solecki, 2011). In the Early Permian, these depressions gradually expanded and became filled with coarse sediments of alluvial fans formed in the foreland of mountain ranges, as well as sediments of gravel-bedded rivers (Milewicz, 1985; Wojewoda and Mastalerz, 1989). At present, these deposits occur across the entire NSS area, reaching a thickness up to 450 m, and are assigned to the Świerzawa Formation (Milewicz, 1985; Śliwiński *et al*., 2003). Locally, especially in the Świerzawa Graben area, Permian lacustrine deposits occur (Mastalerz, 1990; Mastalerz and Nehyba, 1997). Periodically in the Early Permian (Rotliegend), intensive volcanic activity took place in the NSS area (Kozłowski and Parachoniak, 1967; Awdankiewicz, 2006). It is evidenced by occurrences of alkaline and acidic, both extrusive and subvolcanic magmatic bodies, which are mostly represented by trachyandesites, trachybasalts and rhyolitoids (Awdankiewicz, 2006). The volcanic rocks are commonly associated with tuffs and pyroclastic rocks. The volcanic rocks are assigned to the Wielisławka Formation and reach a thickness of up to 300 m in the Wleń area (subvolcanic trachyandesites; Awdankiewicz, 2006). The youngest Rotliegend deposits in the NSS area are assigned to the Bolesławiec Formation and reach a thickness of between 200–400 m. They include continental sandstones and conglomerates of fluvial origin with calcrete-type cementation (Raczyński, 1997; Raczyński *et al*., 1998; Śliwiński *et al*., 2003).

The Rotliegend rocks are covered by Upper Permian (Zechstein) marine deposits (Scupin, 1931; Eisentraut, 1939). These deposits were formed after a rapid, marine transgression, which probably took place in the present-day area of southwestern Poland ca. 257.2 Ma ago (cf. Gradstein *et al*., 2012; Kiersnowski, 2013 and discussion in: Szurlies, 2013; Hounslow and Balabanov, 2016). The study area was then located at the southern and southwestern margins of the epicontinental Zechstein sea, in the Southern Permian Basin (e.g., Raczyński 1997; Peryt *et al*., 2010; Hara *et al*., 2013; Fig. 2). Zechstein deposits that crop out in the NSS area are condensed in thickness and are assigned to the first (PZ1 = 50 to 120 m thick) and third (PZ3 <15 m thick) Zechstein cyclothems (cf. Table 1; Peryt, 1978). Deposits of the first cyclothem (PZ1 Werra) in the lower part consist of carbonates, including a limestone-dolomitic series and a marly series, up to 30 m thick, in the eastern part of the NSS (e.g., Raczyński, 1997; Biernacka *et al*., 2005). They contain copper-bearing marls that were subject to exploitation till the end of the 20th century. The carbonate rocks were formed within a nearshore carbonate platform, with well documented sea-level oscillations (Raczyński, 1997). The upper part of the PZ1 comprises sandstones and siltstones in the eastern part of the NSS (Leszczyna Half-Graben) and evaporites (anhydrite and gypsum) in the western part of the NSS (Grodziec Syncline). The presence of deposits representing the second cyclothem (PZ2 Stassfurt) is disputed (Raczyński, 1997). The uppermost part of the Zechstein succession in the NSS is represented by the Platy Dolomite assigned to the third cyclothem PZ3 (Ca3; 10–15 m thick) and consisting of shallow-water sediments, containing *Calcinema* together with bivalves and gastropods (Raczyński, 1997). These deposits are overlain by fine-grained sandstones and mudstones, assigned to the so-called Permian/Triassic Transitional Terrigenous Series (PZt), described in the literature as the youngest Zechstein deposits in the study area (Raczyński, 1997). They are interpreted as the sediments of a muddy coastal plain. The Permian strata are conformably overlain by deposits assigned to the Lower Triassic (Buntsandstein; Mroczkowski, 1972). They include pink and red sandstones, and arkosic conglomerates, interpreted as the sediments of ephemeral braided rivers (Mroczkowski, 1972). They are assigned to the Radłówka Formation (Milewicz, 1985). In the Wleń Graben the Lower Triassic attains a thickness of up to 190 m. Sedimentary and volcanic rocks of the NSS and locally metamorphic rocks of the KMC are discordantly covered by Cretaceous marine strata (Scupin, 1913; Milewicz, 1997; Chrząstek and Wojewoda, 2011). Sedimentary rocks of the NSS are cut by basaltoid veins of Neogene age.

The boundaries of the NSS are mostly tectonic in character (see Fig. 1). The sedimentary and volcanic rocks composing the NSS are cut by NW-SE-oriented and subordinately NE-SW-oriented faults (e.g., Cymerman, 2004). These faults subdivide the NSS into smaller tectonic subunits, such as grabens, half-grabens and horsts (Teisseyre *et al*., 1957). Usually they occur in the eastern part of the NSS and include (from the north) for example, the Leszczyna and Lwówek Sląski half-grabens, and the Wleń, Świerzawa, Wleń and Wolbromek grabens (Fig. 1). The Wleń Graben constitutes a narrow tectonic unit, ca. 17.5 km long and up to 3.5 km wide, which is bounded by steep, NW-SE-oriented, normal and reverse faults (Kolb, 1936; Gorczyca-Skała, 1977). It is formed of sedimentary-volcanic Carboniferous, Permian, Lower Triassic and Upper Cretaceous rocks. Stratigraphic schemes accepted for other areas of the NSS are used for the sedimentary and volcanic rocks exposed in the Wleń Graben. The graben basement and adjacent rocks are metamorphic rocks of the KMC. They include metabasites and sericite, chlorite and graphite schists, assigned to the Cambrian-Silurian (Milewicz and Frąckiewicz, 1983; Baranowski *et al*., 1990).

METHODS

Studies of the Zechstein deposits were carried out in 2015–2018, during a geological mapping survey of the northern part of the Wleń Graben at a scale of 1:10 000. Fieldwork was focused especially on the description and measurement of the textural and structural features of sedimentary rocks. The Zechstein deposits were macroscopically described and logged in the field with the use of standard sedimentological techniques and lithofacies codes (Miall, 1985; Zieliński and Pisarska-Jamroży, 2012). The textural and structural features of each sedimentological unit distinguished were observed and described in terms of palaeo-depositional environment. The investigations of outcrops included measurements of the orientation and position of the main structural surfaces and direct indicators of flow directions (orientation of cross-bedding, axes of erosional channels and smaller structures, e.g. ripple marks). Representative samples of dolomite from the exposures at Golejów (samples G1-G14 collected every 10 cm) and dolomite from deposits of the heterolithic series, derived from exposures in the main escarpments and the colluvium of the landslide at Wleń (sample W1), were collected for further analysis. Polished samples and thin sections were made from the rock samples.

Petrographic analysis of the thin sections was performed with the use of a Nikon Eclipse LV100N POL polarizing microscope. Photomicrographs and measurements of the diameters of grains and crystals in the samples were made with the application of the NIS-Elements Basic Research software by Nikon. Calcimetric analysis was used to determine the variable content of $CaCO_3$ and $CaMg(CO_3)_2$ in the succession. At first, the rock samples were dried at about 150 ºC and then ground in a pestle grinder. Next, 5 g of powdered rock was taken from each sample and analysis of the content of $CaCO_3$ and $CaMg(CO_3)_2$ was tested with the application of Calcimeter ver. 2.1e by Tercja.

PERMIAN DEPOSITS IN THE WLEŃ GRABEN

Pre-Zechstein deposits

In the Wleń Graben, excluding its southern part (see Fig. 1), undivided sedimentary rocks representing the Lower Permian occur. In the NSS area they are assigned to the lower (Autunian) as well as upper Rotliegend (Saxonian; cf. Milewicz, 1985) and form the basement of deposits, assigned to the Zechstein (Milewicz, 1966; cf. Fig. 3). These rocks include mainly conglomerates, which have been distinguished in the NSS area as the Wielisławka (lower Rotliegend) and Bolesławiec (upper Rotliegend) formations (Śliwiński *et al*., 2003). However, these terms were not used for strata from the Wleń Graben (Milewicz and Frąckiewicz, 1983). Apart from conglomerates, sandstones, siltstones and claystones also occur.

Permian rocks in the Wleń Graben are exposed at the surface in two NW-SE-oriented belts, subparallel to the boundaries of the tectonic graben. The belts are up to 7 km long and 0.5 km wide. The western belt runs from Golejów in the north to Klecza in the south. The eastern belt encompasses a series of exposures from Marczów in the north to Nielestno in the south. Further to the south, Permian rocks do not occur in the Wleń Graben, where the overlying Cretaceous strata directly overlie the metamorphic basement. The basement of the Rotliegend conglomerates in the entire Wleń Graben is composed of metamorphic rocks of the KMC, as evidenced in boreholes located in the central part of the graben. Near the graben boundaries, Permian sedimentary rocks make contact directly with metamorphic rocks of the KMC along dip-slip normal and reverse faults. The Rotliegend rocks usually are covered by a continuous layer of Quaternary deposits and their few natural exposures are restricted only to deeply incised stream valleys near Wleń.

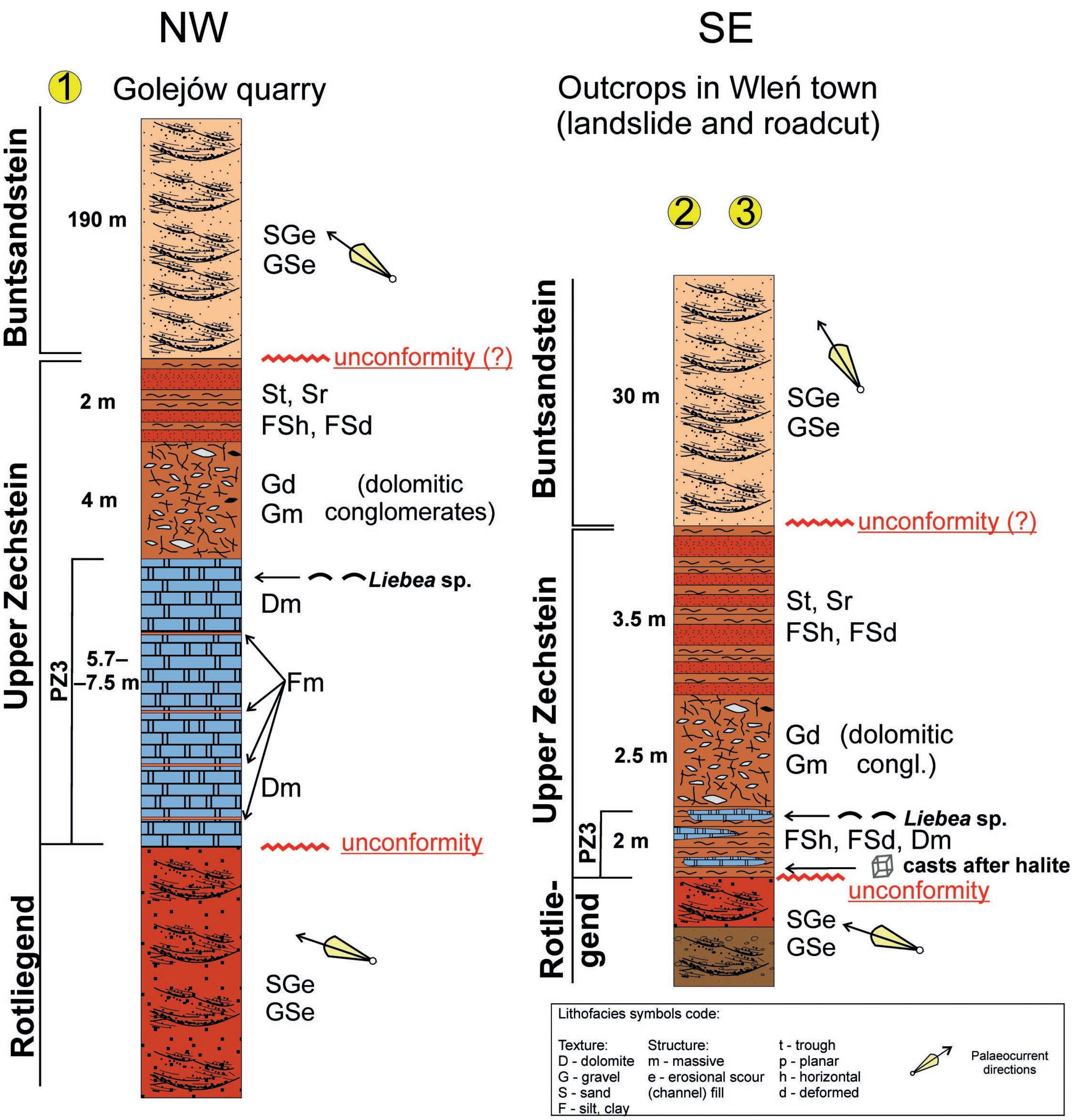

Fig. 3. Comprehensive stratigraphic sections of the Zechstein deposits at the Golejów (loc. 1) and Wleń (loc. 2, 3) localities. Sedimentological features observed within each sedimentological unit are marked. See text for explanations.

Near Wleń and Golejów, the Rotliegend is represented by deposits of continental origin – polymictic, poorly sorted conglomerates and sandstones (GSe and SGe facies; Figs 3, 4A). The conglomerates are dark-brown or reddish-brown in colour. Their framework material is composed of clasts of milky quartz, granitoid, rhyolite, trachybasalt, and metamorphic rocks – sericite schist and gneiss, subordinately quartzite and crystalline limestone (Fig. 4A, B). The clasts have diameters of between 0.3–18 cm and, according to the Powers (1953) scale, are characterised by very low and low roundness (0.5–1.5), being dominated by sharp-edged and semi sharp-edged grains (Fig. 4). The quartz grains have spherical or elongated shapes. Ellipsoidal and discoidal quartz grains are characterised by the largest diameters (up to 15 cm) and the highest degree of roundness. The clastic material of the framework is usually dispersed, and displays very poor and poor sorting (σ = 0.7–2.0, according to Pettijohn *et al.*, 1987; see Fig. 4A). The matrix of the framework includes fine- and medium-grained, brown coloured sand composed of quartz and lithic clasts. The cement includes clay minerals and iron oxides, which impart a red-brownish colour to the rock. Within the conglomerates, there are interbeds of fine- and very fine-grained quartz sandstone. The framework of these interbeds is represented mainly by sharp-edged and semi sharp-edged quartz grains, up to 150 µm in diameter and with a very low degree of roundness (0.5–1.5). Mica flakes occur sporadically. The matrix in the sandstones is represented by clay minerals enriched with Fe oxides. In the topmost parts of the Rotliegend, there commonly occur carbonate cements, interpreted as calcrete horizons. Palaeosoils show various stages of calcite cementation – from initial to almost mature forms. Hard pan layers do not occur.

The conglomerates display a distinct bedding (Fig. 4C). The beds attain thicknesses from ca. 30 cm to ca. 1 m, and normal graded bedding occurs within the up to 1 m thick beds. Conglomerate beds commonly contain symmetrical and asymmetrical erosional troughs, with widths reaching 2 m and depths – up to 40 cm (Fig. 4C). The troughs are filled with gravel and sand, forming sets of laminae from

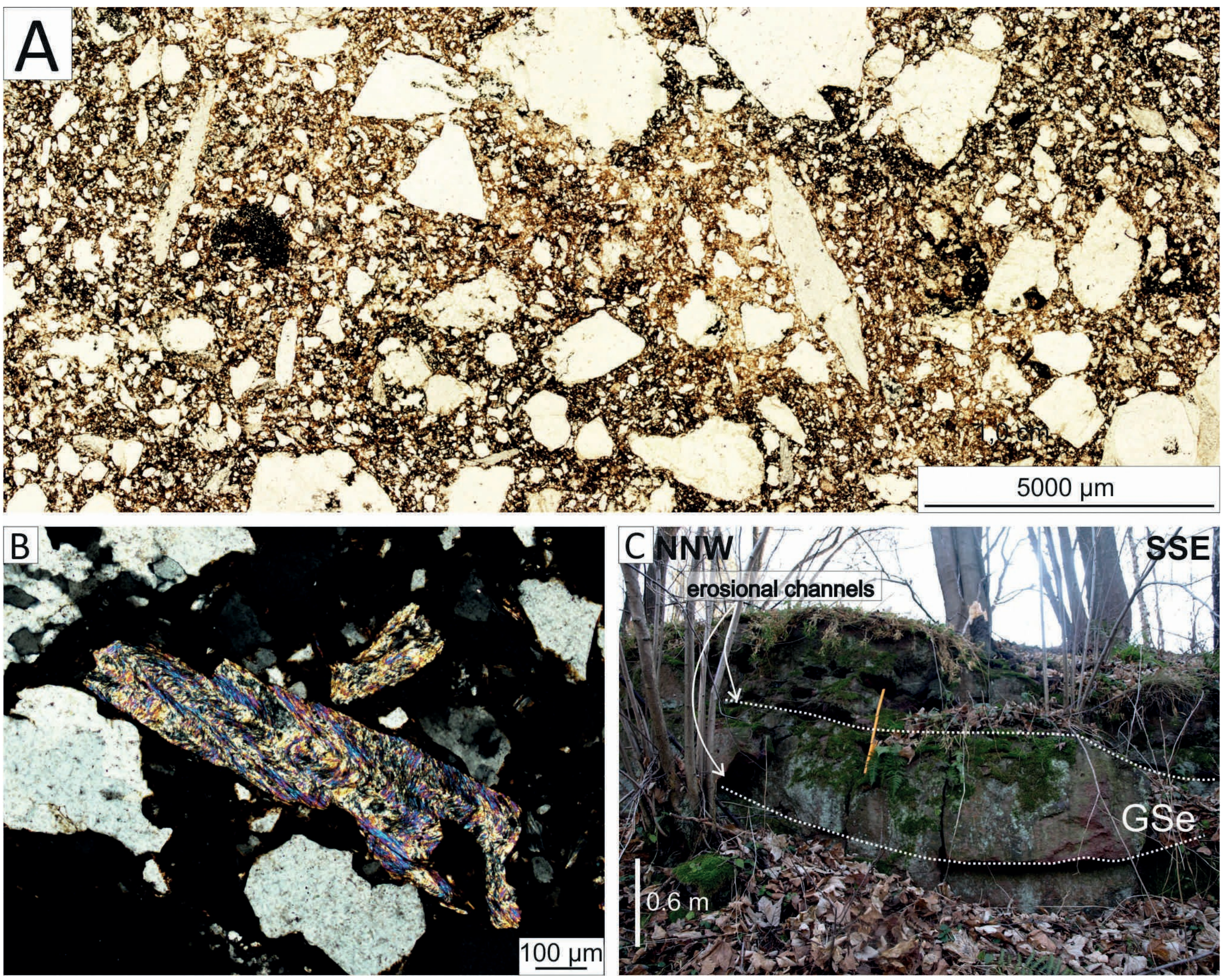

Fig. 4. Sedimentological features of the Lower Permian (Rotliegend) deposits exposed in the central part of the Wleń Graben (loc. 3). **A.** Microscopic view of poorly-sorted, fine-grained conglomerate. **B.** Microscopic view of sharp- and semi-sharp-edged grains of strongly folded mica schist and polycrystalline quartz, which form the framework of poorly-sorted sandstones and conglomerates (crossed polars). **C.** Outcrop of cross-bedded, Rotliegend conglomerates (GSe facies; cf. Fig. 3) in a roadcut, located to the east of Wleń (loc. 3). Basal, erosional surfaces of WNW-ESE-oriented troughs (channels) are marked by white, dotted lines.

20 to 50 cm thick with dips reaching 35º. The laminae make contact at low angles (planar cross-bedding) with the top and base of the sets within the erosional troughs. The bedding is usually emphasised by the presence of clasts with their longer axes inclined according to the dip of the laminae. Much more common is the filling of troughs with gravel material, characterised by chaotically distributed clasts. Erosional troughs, measured in the exposures located to the SE of Wleń, have a WNW-ESE-oriented longer axis and a WNW and subordinate NW dip (Fig. 4C).

Zechstein deposits in the Wleń Graben – extent and stratigraphy

Zechstein deposits occur in the northern and central parts of the Wleń Graben (Fig. 1) and are developed as thin-bedded dolomites and calcareous dolomites with a total thickness of ca. 7.5–9 m (in the vicinity of Golejów and Marczów) to about 1 m (in the vicinity of Nielestno). They occur directly on calcareous conglomerates and sandstones (the so-called "boundary" or "transgressive conglomerate") of unknown thickness. Transgressive Zechstein conglomerates unconformably overlie the coarse-grained deposits of the Lower Permian (Rotliegend; Fig. 3). To the north of Wleń, carbonate Zechstein deposits occur along the western boundary of the graben, from Pławna Górna in the north to Łupki Drugie in the south. These occurrences of Zechstein deposits are narrow, NW-SE-oriented exposures, within which the bedding of the carbonate rocks steeply dips to the NE at angles of between 30–90º. The carbonate rocks were exploited in this area for local requirements in three narrow and deep quarries, located in the vicinity of Golejów and Łupki II. Above the distinct horizon of dolomites occur heterolithic deposits (fine-grained sandstones, siltstones and claystones), referred to in the literature as the Permian/Triassic Transitional Terrigenous Series (PZt). Within heterolithic deposits occur intercalations of dolomitic conglomerate. They are covered by arkosic sandstone, assigned to the Lower Triassic (Buntsandstein) on the basis of facies criteria (Fig. 3). The precise boundary between the Upper Permian (Zechstein) and Lower Triassic has not been determined so far. Some authors accept lithological (e.g., Gorczyca-Skała, 1977) and structural criteria for distinguishing both lithostratigraphic units in the field; however, difficulties in their differentiation are often indicated.

To the NE of Wleń, Zechstein deposits were noted by Milewicz (1959) along the eastern boundary of the graben in a narrow belt from near Marczów in the north to Nielestno in the south (Fig. 1). So far, it has been assumed that these rocks are not exposed at the surface and were recovered only in a few excavations made for the purpose of geological mapping (Gorczyca-Skała, 1977). Some reports even have stated that Zechstein deposits do not occur at all along the eastern boundary of the graben (Gierwielaniec, 1956). In the eastern part of the graben, Zechstein strata were noted near Łupki as a 2.5 m thick dolomite horizon (Gorczyca-Skała, 1977). It overlies siltstones and claystones with intercalations and lenses of dolomite and passes gradually upwards into fine-grained heterolithic deposits of the PZt (Fig. 3). Towards the south (vicinity of Klecza and Wleń), a distinct carbonate horizon does not occur and is replaced by fine-grained sandstones and siltstones with intercalations of dolomites up to over 1 m thick.

At present, almost no exposures of Zechstein carbonate rocks described in the literature are accessible. The only larger exposure of dolomite and limestone, about 1.6 m thick, occurs in the northernmost quarry near Golejów (loc. 1; Figs 1, 3). In 2016, the upper part of the Zechstein deposits was exposed in the escarpment of a freshly formed landslide (Kowalski *et al*., 2018b), covered by arkosic sandstones of the Buntsandstein (loc 2). The thickness of the exposed succession was about 6 m, of which the Buntsandstein accounted for about 2 m. As well, in a roadcut located to the east of Wleń, only small (up to 2 m) exposures of Rotliegend conglomerates occur, overlain by fine-grained sandstones and siltstones (loc. 3).

Despite the small thickness and strong tectonic deformation of the Zechstein deposits, attempts to create stratigraphic subdivisions of the Zechstein in the Wleń Graben have been undertaken for a long time. Scupin (1931) distinguished two stages of the Zechstein – the lower stage, encompassing calcareous conglomerates, and the upper stage, including platy, thin-bedded dolomites. Only the platy dolomites were considered to be marine in origin. Gierwielaniec (1956) subdivided the Zechstein deposits near Golejów into middle and upper Zechstein, emphasising, however, that their subdivision on maps is not possible, owing to the lack of palaeontological data. Milewicz (1966) subdivided the Zechstein deposits of the Wleń Graben into the lower, middle and upper, assigning the massive (platy) dolomites to the upper Zechstein. Gorczyca-Skała (1977) stated that the tri-partite division of the Zechstein in the Wleń Graben proposed by Milewicz (1966) is difficult to accept, owing to the strong lithological variability of the units, tectonic deformation and small thicknesses. The Zechstein of the Wleń Graben was completely omitted in later, more detailed biostratigraphic and lithostratigraphic reports devoted to the Zechstein deposits in the NSS (Raczyński, 1997).

Zechstein deposits in the Wleń Graben – lithology and petrography

Dolomites

The clastic deposits of the Rotliegend occurring in the vicinity of Golejów and Wleń are covered by recrystallized dolomites and calcareous dolomites with clay intercalations (Dm and Fm facies; Fig. 3), previously assigned to the upper Zechstein (PZ3 Leine). Near Golejów, the dolomites form a continuous horizon, up to 7.5 m thick, whereas in exposures at Wleń they occur as lenses and discontinuous beds within fine-grained siltstones and sandy siltstones. According to some authors (Gierwielaniec, 1956; Milewicz, 1966; Gorczyca-Skała, 1977), these deposits directly overlie transgressive conglomerate of unknown thickness (at present lacking exposure). On the basis of calcimetric analysis, the dolomite content in the massive dolomite rocks varies between 69–94.98%, while the calcite content maximally reaches about 18% (Table 2). The values of the insoluble residue range between 0.4–24 %. In the exposure at Golejów, the dolomites display low variability in petrographic and chemical composition in vertical profile. They include mainly sparitic and microsparitic dolomites, which mainly comprise subhedral and anhedral, tightly packed crystals with diameters of 20 to 625 µm and a massive, disorderly texture (Fig. 5A). The intercrystalline boundaries are usually curved or oblate. Within the dolomites occur also dispersed grains of poorly rounded, detrital quartz with diameters of 20 to 320 µm. Locally pores are filled with euhedral dolomite crystals with diameters up to 2 mm (Fig. 5B).

The massive dolomites, occurring in exposures near Golejów, show a distinct stratification. Particular beds are up to 30 cm thick and their boundary surfaces dip to the NE at angles of up to 35º (Fig. 5C). The bedding is commonly emphasized by the presence of stylolites, with accumulations of quartz grains or clay minerals forming discontinuous layers. Generally, no sedimentary structures were recognized, although small-scale, horizontal bedding and cross-bedding were observed within a 10 cm bed in the middle part of the succession at Golejów (Fig. 5D).

In the vicinity of Wleń, sandy sparitic and microsparitic dolomites occur, with a disorderly, massive texture, where anhedral carbonate crystals forming the grain framework have diameters up to 200 µm (Fig. 5E). In addition to dolomite, there are clay minerals or single, poorly rounded grains of very fine or fine quartz with diameters up to 150 µm. Following the analyses of the $CaCO_3$ content (Table 2), the rocks studied are dolomites and calcareous dolomites. Numerous stylolites and fractures, filled with clay minerals and Fe oxides, are a characteristic feature (Fig. 5F). Locally, fractures and pores or vugs, up to 1 mm wide, occur, filled with clay minerals or secondary rhombohedral dolomite with crystal diameter up to 500 µm.

Within the head scarps of the landslide in Wleń, dolomites and limestones occur as lenses, with thicknesses of up to over 10 cm and widths of up to 0.5 m. They were encountered in reddish-brown siltstones and claystones. Polished samples made of the dolomitic lenses show the presence of bivalve remains (Fig. 6A) and geopetal structures, filling voids beneath the shells (Fig. 6B). They occur parallel to the bedding in the sandy dolomites and usually form convex-up shell accumulations (Fig. 6C). Locally, the arrangement of small shells, not exceeding 3 mm in diameter, is chaotic. The voids after shells are in places filled with secondary sparite cement. In the limestones at Golejów, polished samples and thin sections from the upper part of the succession show also the presence of perpendicular cross-sections across (probably) bivalve shells (Fig. 6D). They occur as voids, display sharp boundaries, emphasised by iron compounds, and are filled with subhedral and anhedral dolomite crystals with diameters of up to 300 µm.

Dolomitic conglomerates

Above the Zechstein dolomites there are oligomictic conglomerates (dolomitic conglomerates; Gm and Gd facies; Fig. 3), which also have been referred to as sedimentary breccias (Gierwielaniec, 1956). They have been noted in the exposures at Golejów above the platy dolomites, as well as in loose, scattered blocks, recovered from the landslide colluvium in Wleń. These conglomerates are matrix-supported and almost entirely formed of sharp-edged or semi-rounded clasts of grey- and cream-coloured dolomites (Fig. 7A). Subordinately, small (up to 1 cm) quartz grains occur. The diameter of the dolomitic grains forming the framework varies from 3 mm to 10 cm, but the largest dolomite clast ever noted has a diameter of 30 cm (exposure at Golejów; Fig. 7B). According to the Powers (1953) scale, the dolomitic grains forming the framework are characterised by very low and low roundness (0.5–1.5), with sharp-edged and semi sharp-edged grains dominant. Locally, the dolomite grains are distinctly rounded and show evidence of plastic deformation (Fig. 7C). The matrix of the grain framework is composed of fine- and medium-grained sand with grains up to 200 µm in diameter, brown-coloured, with a quartz and lithic clasts with a low and very low degree of roundness (0.5–1.5) dominant. The matrix is composed mainly of clay minerals and Fe oxides, which give the rock a reddish-brown colour. Mica flakes occur sporadically.

Owing to the poor state of the exposures of dolomitic conglomerates at Golejów, their structural features remain poorly known. Kolb (1936) presented a photograph of the currently inaccessible outcrop in the Golejów Quarry, in which erosional troughs dissecting the uppermost part of the platy dolomite are visible. The troughs are apparently filled with dolomite clasts and megaclasts. In previous re-

Table 2

Results of calcimetric analyses
of the G1-G14 (loc. 1)and W1 (loc. 2) samples.

Sample	$CaCO_3$	$CaMg(CO_3)_2$	Amount of carbonate component	Insoluble residue
	[%]			
G1	4.7	95.0	99.7	0.3
G2	7.6	82.7	90.3	9.7
G3	8.5	90.3	98.8	1.2
G4	11.7	88.3	100.0	0.0
G5	11.4	88.6	100.0	0.0
G6	4.4	85.5	89.8	10.2
G7	4.3	80.0	84.3	15.8
G8	4.2	71.0	75.2	24.8
G9	8.1	85.3	93.4	6.6
G10	4.4	94.1	98.5	1.5
G11	18.6	75.0	93.6	6.4
G12	15.2	75.5	90.7	9.3
G13	9.4	79.6	90.0	10.0
G14	13.9	69.6	83.5	16.5
W1	5.0	83.0	88.0	12.0

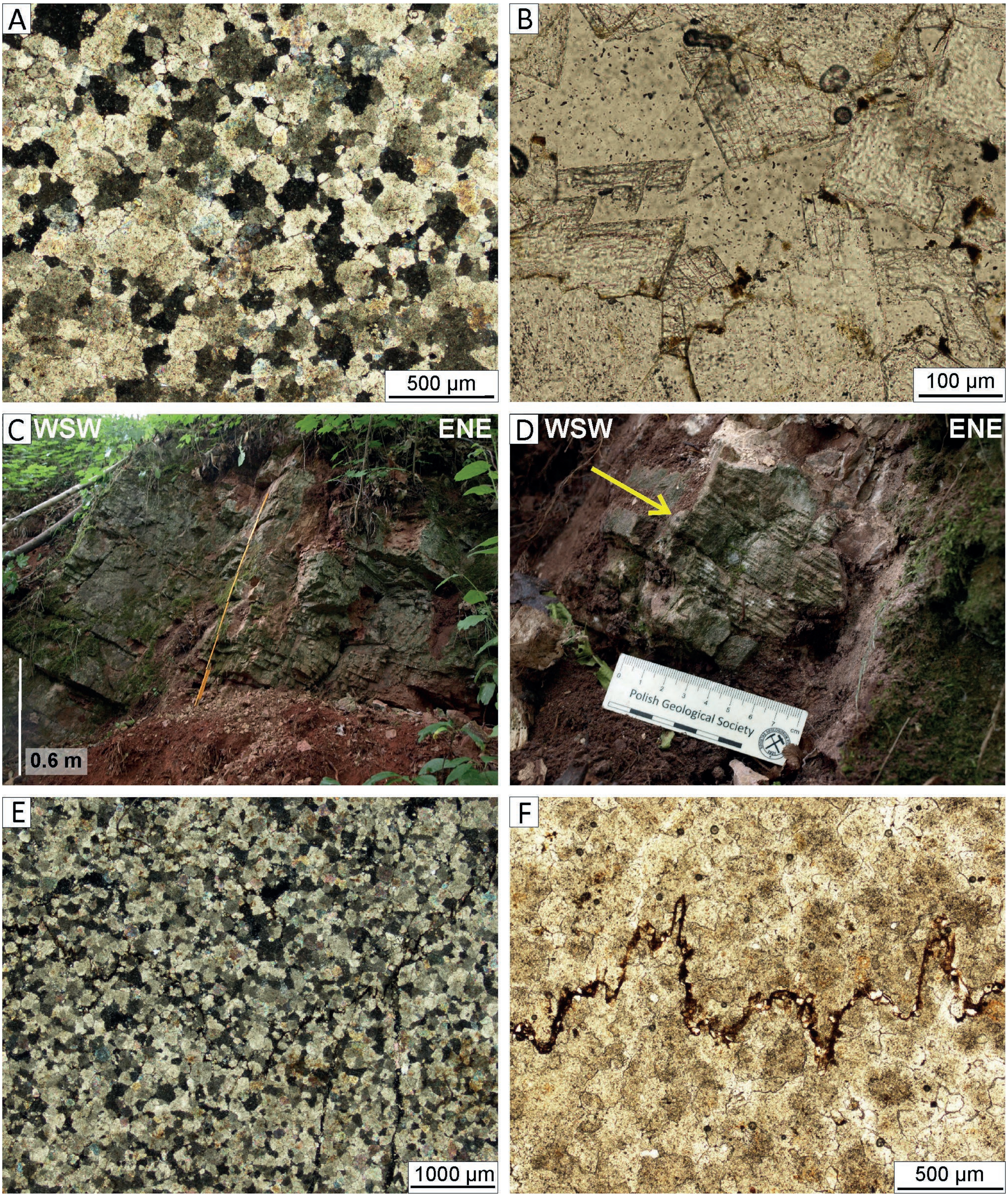

Fig. 5. Sedimentological features of Upper Permian (Zechstein) carbonate deposits exposed in the northern (loc. 1; Golejów Quarry) and central part (loc. 2; landslide at Wleń) of the Wleń Graben. **A.** Microscopic view of sparitic dolomite composed of tightly packed, anhedral crystals (sample G4; Golejów Quarry). **B.** Irregular void within sparitic dolomite filled with secondary, rhombohedral dolomite crystals (sample G6; Golejów Quarry). **C.** Exposure of thin-bedded, tectonically inclined massive dolomites in Golejów Quarry (loc. 2). Particular beds are up to 30 cm thick and their boundary surfaces dip at angles up to 35° to the NE. **D.** Small-scale horizontal bedding (marked by yellow arrow) in a massive dolomite bed in the middle part of the succession at Golejów (loc. 2). **E.** Microscopic view of sparitic and microsparitic dolomite composed of anhedral crystals (sample W1; loc. 2; landslide in Wleń). **F.** Stylolites with accumulations of quartz grains developed in sparitic dolomites (sample W1; loc. 2; landslide in Wleń).

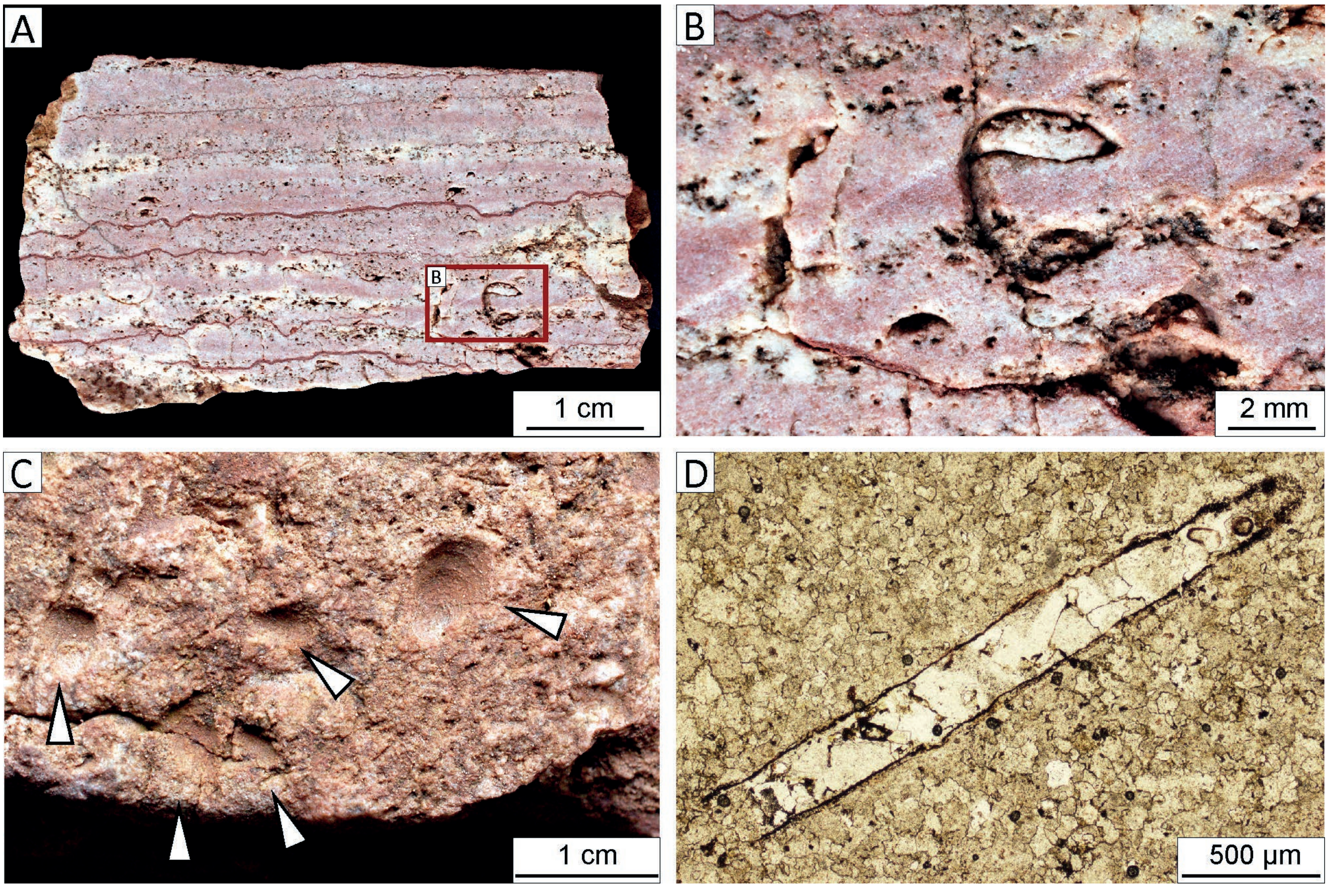

Fig. 6. Bivalve remains in Zechstein dolomites in the Wleń Graben (loc. 1, 2). **A.** Polished slab of sandy dolomite (cross-section perpendicular to bedding surface) collected from the landslide scarp at Wleń (loc. 2). Note the presence of convex-up shell accumulations, composed of small (up to 3 mm) remains of *Liebea* sp., and geopetal structures parallel to the bedding surface (locally highlighted by stylolites). **B.** Perpendicular cross-section across the geopetal structure with void after shell filled with secondary sparite cement. **C.** Basal surface of a dolomite bed with convex-up accumulations of shells of *Liebea* sp. (marked by arrows). **D.** Microscopic view of perpendicular cross-section across (probably) bivalve shell filled with subhedral and anhedral dolomite crystals with diameters up to 300 µm. Sharp shell boundaries emphasised by iron compounds are visible.

ports (Scupin, 1931), the bottom surface of these troughs was described as a tectonic overthrust within the Zechstein deposits. At present, dolomitic conglomerates are exposed in a small outcrop, located in the upper part of the Golejów Quarry for a distance of about 5 m (Fig. 7B). They are distinctly bedded and usually ungraded, although reversed graded bedding frequently may be observed within the beds. The beds are lens-shaped with thicknesses up to 1 m and widths up to 2.5 m. Dolomite clasts usually display a chaotic distribution.

In the conglomerate blocks, collected in the landslide colluvium in Wleń, the dolomite clasts in cross-sections perpendicular to bedding indicate a characteristic circular pattern (Fig. 7D). These structures are asymmetrical, with a longer diameter of ca. 15 cm and a shorter diameter of ca. 6 cm. In the central parts of these structures, fractured and chaotically distributed sharp-edged clasts occurred, whereas in the marginal parts there are concentrically arranged, strongly fractured dolomite clasts with diameters of up to 6 cm. A sandy matrix occurs between the clasts and in some cases, lamination is preserved (Fig. 7D).

Heterolithic series

Deposits of the heterolithic series (FSh, FSd, St and Sr facies; Fig. 3) occur in the northern part of the Wleń Graben (vicinity of Golejów) above dolomitic conglomerates and platy dolomites, whereas in the central part of the graben (vicinity of Wleń and Nielestno) they rest directly on Rotliegend conglomerates (Fig. 8A). Locally in these deposits in the vicinity of Wleń, interbeds of dolomites occur in the form of small lenses. The extent of the deposits of the heterolithic series PZt is consistent with the extent of the Rotliegend continental sediments. The PZt consists of fine- and very fine-grained sandstones with a low and medium degree of roundness (0.5–1.5; Fig. 8B). The clastic material displays poor or medium sorting (σ = 0.7–2.0, according to Pettijohn *et al.*, 1987). Within the dense framework sharp-edged and semi-sharp-edged quartz grains predominate and subordinately lithic clasts occur with diameters of up to 300 µm. The quartz grains usually have elongated shapes; ellipsoidal and discoidal grains are most common. The cement and matrix of the framework is composed of clay minerals with pseudomorphs after feldspars, as well as

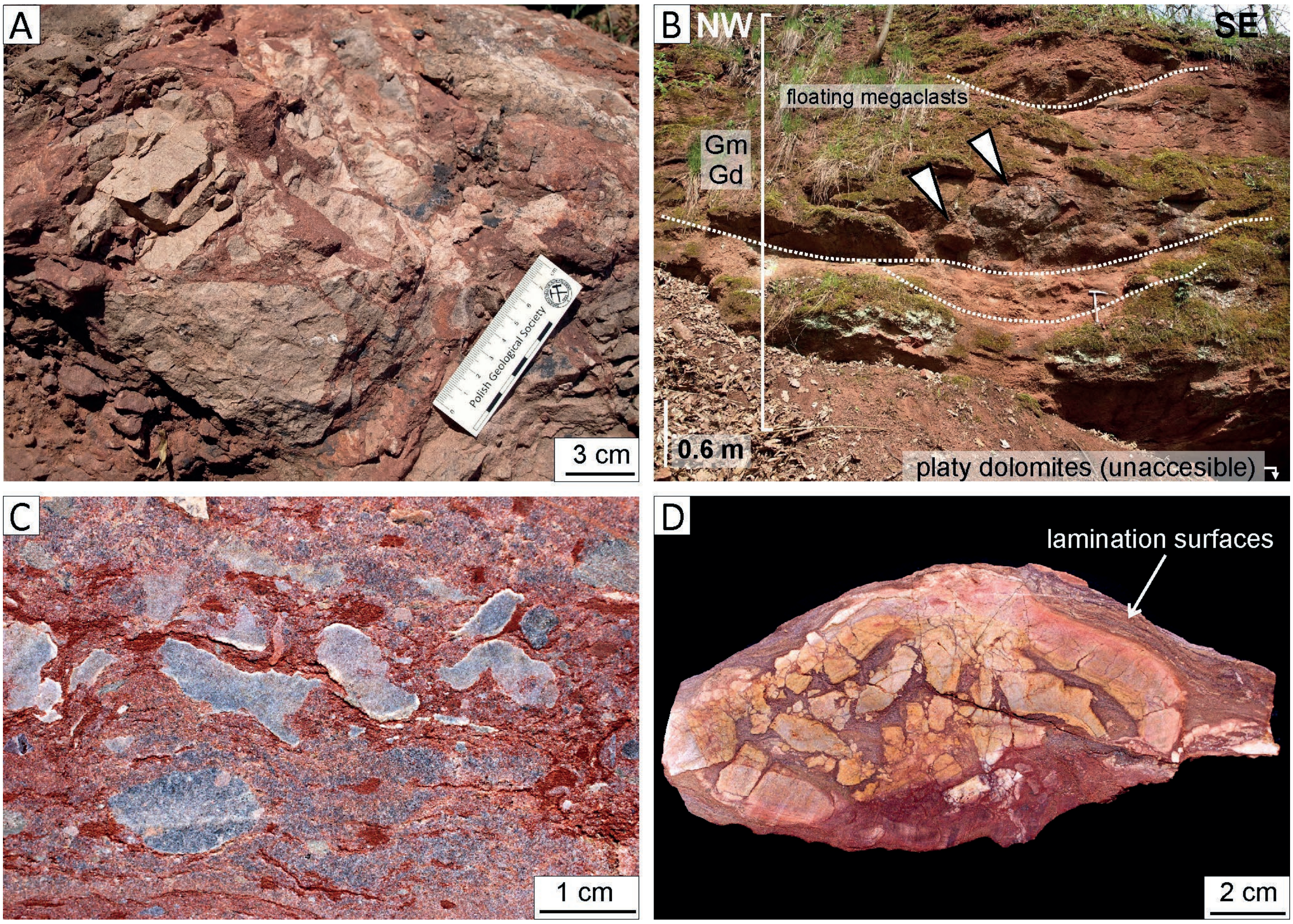

Fig. 7. Sedimentological features of Upper Permian (Zechstein) dolomitic conglomerates exposed in the northern (loc. 1; Golejów Quarry) and central part (loc. 2; landslide at Wleń) of the Wleń Graben. **A.** Matrix-supported conglomerate with chaotically arranged, sharp-edged clasts of grey dolomite (block derived from the landslide colluvium in Wleń, loc. 2). **B.** Exposure of dolomitic conglomerates in the lower part of the Golejów Quarry (loc. 2). Note that the lens-shaped beds (white dotted lines) contain chaotically arranged clasts and megaclasts of dolomite (marked by arrows). See Fig. 3 for lithofacies code explanations. **C.** Distinctly rounded and plastically deformed dolomite clasts within conglomerate (polished slab, cross-section perpendicular to the bedding surface) collected from the landslide colluvium in Wleń (loc. 2). **D.** Concentrically arranged, strongly fractured dolomite clasts within (probably) slump fold structure. Sample collected from landslide colluvium in Wleń (loc. 2).

iron oxides giving the rock a cherry-red colour. Anhedral dolomite crystals with diameters of up to 200 µm form a significant admixture within the cement. Locally, laminae composed of clay minerals occur with thicknesses of up to 0.5 m.

Deposits of the heterolithic series are usually stratified. The sedimentary structures observed consist mainly of planar and trough small-scale ripple cross-lamination and subordinate horizontal lamination (Fig. 8C). The bedding boundaries are marked by grain size and colour changes from dark-brown and red to grey or white. The lower boundaries of the sand beds are mostly sharp (erosional), less frequently gradational, whilst the upper and lower boundaries of silty and clayey intercalations are usually gradational. Normal graded bedding usually occurs in the heterolithic beds – the sandy beds pass upwards into structureless laminae of silty and clay sediments. The thickness of the clay laminas is up to 0.5 cm, while the sand beds are up to 2 cm thick. Within the sandy material, ripple mark cross-bedding, both trough- and planar-shaped, commonly occur. The bedding is usually asymmetrical, with S- and SW-dipping cross-laminae. Symmetrical wave ripples locally occur. The sandy laminae observed in cross-sections perpendicular to the bedding have thicknesses of up to 1 mm and usually dip to the N and NW.

In an exposure near the Nielestno-Wleń road, about 10 cm above the erosional boundary with the Roliegend, accumulations of sandstone and mudstone casts after halite crystals of evaporitic origin occur in the sandy siltstones (Fig. 8D, E). The forms are very well-preserved and have been noted on the bottom of bedding planes of the very fine-grained sandstones and subordinately the siltstones. Mostly, they include cube-shaped, regular forms, with edges up to 0.5 cm long. In some cases, linear traces of the dragging of these crystals have been observed on the bedding planes (Fig. 8D). These traces are up to 4 cm long and their widths do not exceed 1 mm. Subordinately, bioturbation occurs (Fig. 8E).

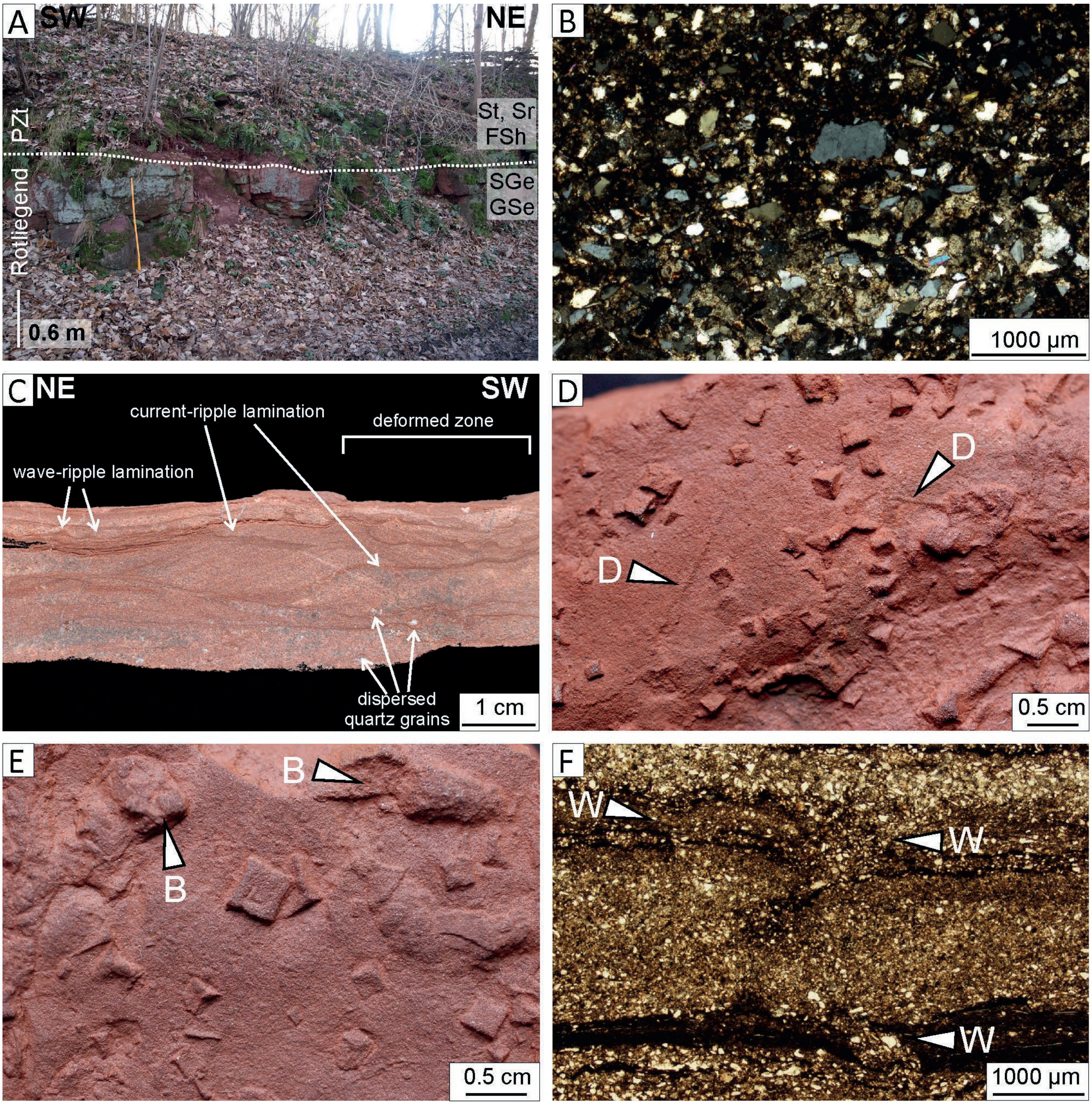

Fig. 8. Sedimentological features of the Transitional Terrigenous Series (PZt) deposits exposed in the central part of the Wleń Graben (loc. 2, 3). **A.** Outcrop of the Rotliegend-Zechstein boundary (white dotted line) between Nielestno and Wleń (loc. 3). See Fig. 3 for lithofacies code explanations. **B.** Microscopic view of fine-grained sandstone (PZt) mainly composed of sharp-edged and semi sharp-edged quartz grains and subordinately lithic clasts cemented with clay minerals with small admixture of dolomite cement (loc. 3). **C.** Polished slab of fine-grained sandstone with clay intercalations (cross-section perpendicular to bedding surfaces) collected from loc. 2. Well-preserved, NW-dipping, current-ripple cross-lamination and wave-ripple cross-lamination are visible. Right part of sample is strongly disturbed. **D.** Accumulations of sandstone and mudstone casts after halite crystals preserved on the basal surface of the bedding plane within the sandy siltstones of PZt. Linear traces of dragging of these crystals (D; marked by arrows) are visible. **E.** Close view of casts after halite crystals and linear bioturbation channels (B; marked by arrow); bottom surface of sandstone bed). **F.** Microscopic view of disturbed lamination surfaces (W – water-escape structures; marked by arrows) within fine-grained, cross-stratified sandstone.

In the topmost part of the PZt, the bedding and stratification of the fine-grained deposits is strongly disturbed (FSd facies). Structures, related to liquefaction and strong deformation, both brittle and ductile in origin, commonly occur. In the fine-grained sandstones, siltstones and calcareous claystones, there are clastic dykes, water-escape structures (Fig. 8F), normal and listric synsedimentary faults, breccias, diffusion chambers and collapse structures on different scales (Kowalski *et al*., 2018a).

Buntsandstein

The rocks of the heterolithic series pass conformably or almost conformably into Lower Triassic (Buntsandstein) deposits. They consist of poorly sorted, weakly cemented, red-brownish, through pink to yellowish-grey sandstones, with small admixture of conglomerate (SGe and GSe facies; Fig. 3). In the framework of the sandstones, there are grains of quartz, strongly kaolinitized white feldspars with distinct automorphic or hypautomorphic outlines and minor lithic grains. The clastic material displays poor or medium sorting (σ = 0.7–2.0, according to Pettijohn *et al*., 1987). The degree of roundness (according to Powers, 1953) reaches values of 0.5–1.5. Within the framework, sharp-edged and semi sharp-edged quartz grains with diameters of up to 1000 μm predominate. The cement and matrix are composed of clay minerals with pseudomorphs after feldspar. Within the sandstones, dispersed pebbles of well-rounded milky quartz, granitoid, gneiss, sericite schist and subordinate quartzite are common.

The Lower Triassic deposits usually display distinct, trough cross-stratification. The single lens-shaped beds attain thicknesses from ca. 20 cm to ca. 1 m. The beds are composed of stratified sand and gravel, which fill laterally asymmetrical, erosional troughs with widths reaching 4 m and depths of about 1 m. The sand beds contain admixtures of well- and sub-rounded intraformational mud clasts up to 5 cm in diameter. The lower and upper boundaries of the sand beds are mostly sharp (erosional).

The Lower Triassic (Buntsandstein) sandstones are interpreted as ephemeral, sandy and gravel braided river deposits (Mroczkowski, 1972). In the stratigraphic schemes for the NSS, it is commonly accepted that the Permian and Triassic deposits are distinguished from each other on the basis of their sedimentological and lithological features: types of cross-bedding, and changes in colour and grain size, as well as petrographic composition. The Triassic rocks are characterised by the appearance of distinctly lighter, more variable colours, an increase of the average grain size, the replacement of silt and clay intraclasts by quartz, and less rounded extraclasts.

INTERPRETATION AND DISCUSSION

On the basis of the studies performed within this research, it may be assumed that at least two types of deposit, differing in lithology and origin, may be assigned to the marine Zechstein in the Wleń Graben area, namely sparitic and microsparitic dolomite with shell accumulations of the bivalve *Liebea* sp. and the overlying deposits of the heterolithic series PZt with pseudomorphs after halite crystals. The thickness of these deposits in the Wleń Graben is much reduced by comparison with other areas of the NSS located northwards, in which marine Zechstein deposits have been noted and documented (e.g., Milewicz, 1966).

From the observations made during this study, a new palaeogeography can be suggested, not only in relation to the Zechstein deposits, but also for the older Rotliegend rocks. The tectonic graben, formed in the present-day Wleń Graben in the Late Carboniferous and Early Permian (Milewicz and Frąckiewicz, 1988), had a WNW-ESE orientation and its boundaries were oblique or even perpendicular to the present fault-related boundaries of the Wleń Graben (Fig. 9A). This is evidenced by the directions of palaeotransport, observed within the Rotliegend alluvial fan and fluvial deposits, indicating the supply of material from the ESE to the WNW, subordinately from the SE to the NW (Figs 4C, 9A). The possibility cannot be excluded that the area of this tectonic graben was connected in the Early Permian with the Świerzawa and Wolbromek troughs existing at that time in the south-easternmost part of the NSS (Ostromęcki, 1973). The textural features of Rotliegend strata (composition and poor sorting) occurring in the WG indicate that the source areas for these sediments were elevated massifs, composed of KMC rocks, but also the Karkonosze-Izera Massif, located to the north, south and south-east from the present-day Wleń Graben (Fig. 9A). The absence of Rotliegend strata in the southern part of the Wleń Graben confirms the concept of a transverse orientation of the Permian tectonic graben in relation to the boundaries of the present-day structural depression.

As a result of further, progressive extension of the basement, in the middle part of the Early Permian, intense volcanic activity took place across the whole area of the NSS (Kozłowski and Parachoniak, 1967), including also its south-eastern part. This is evidenced by occurrences of alkaline magmatic bodies, preserved within the present-day boundaries of the Wleń Graben, represented mostly by subvolcanic trachyandesites and trachybasalts.

In the area to the north of Wleń, a marine transgression preceded by a regressive episode in the entire NSS area took place in the Late Permian (Zechstein). The sea entered the study area from the north on a morphologically diversified basement, formed of Rotliegend conglomerates and volcanic rocks (trachybasalts as well as trachyandesites). Coarse-grained clastic rocks earlier underwent early diagenesis, induced by calcrete-type carbonate cements as well as volcanic activity. As a result of the marine transgression, a shallow-marine bay (lagoon?) dominated by carbonate sedimentation was formed in the vicinity of Golejów (Fig. 9B). According to palaeogeographic reconstructions, this bay was in the south-westernmost part of the Polish Zechstein Basin (Fig. 2; Peryt *et al*., 2010), far away from the connection with the open oceans – the Tethys Ocean and the North Sea (cf. Wagner, 1994; Peryt *et al*., 2010; García-Veigas *et al*., 2011). The transgression of the Zechstein sea encroached from the north-west, from the present-day Barents Sea area (cf. Wagner *et al*., 1978; Wagner and Peryt, 1997; Peryt *et al*., 2010). However, a temporary connection of the peripheral, SE part of the Polish Zechstein Basin with the Tethys Ocean is tentatively suggested (Peryt *et al*., 2010). It is widely accepted that during the Zechstein times, the NSS as well as the Wleń Graben constituted the marginal, enclosed part of the basin, delineated by elevated areas (Fig. 9; Peryt, 1978; Raczyński, 1997). The extent of the sea in the late Zechstein exceeded the original extent of the early Zechstein transgression in the northern parts of the NSS area (Fig. 2; Peryt, 1978); thus, the deposits of marine origin of cyclothem PZ1 do not occur in the Wleń Graben, and the dolomite of cyclothem PZ3 rests directly on the Rotliegend conglomerates.

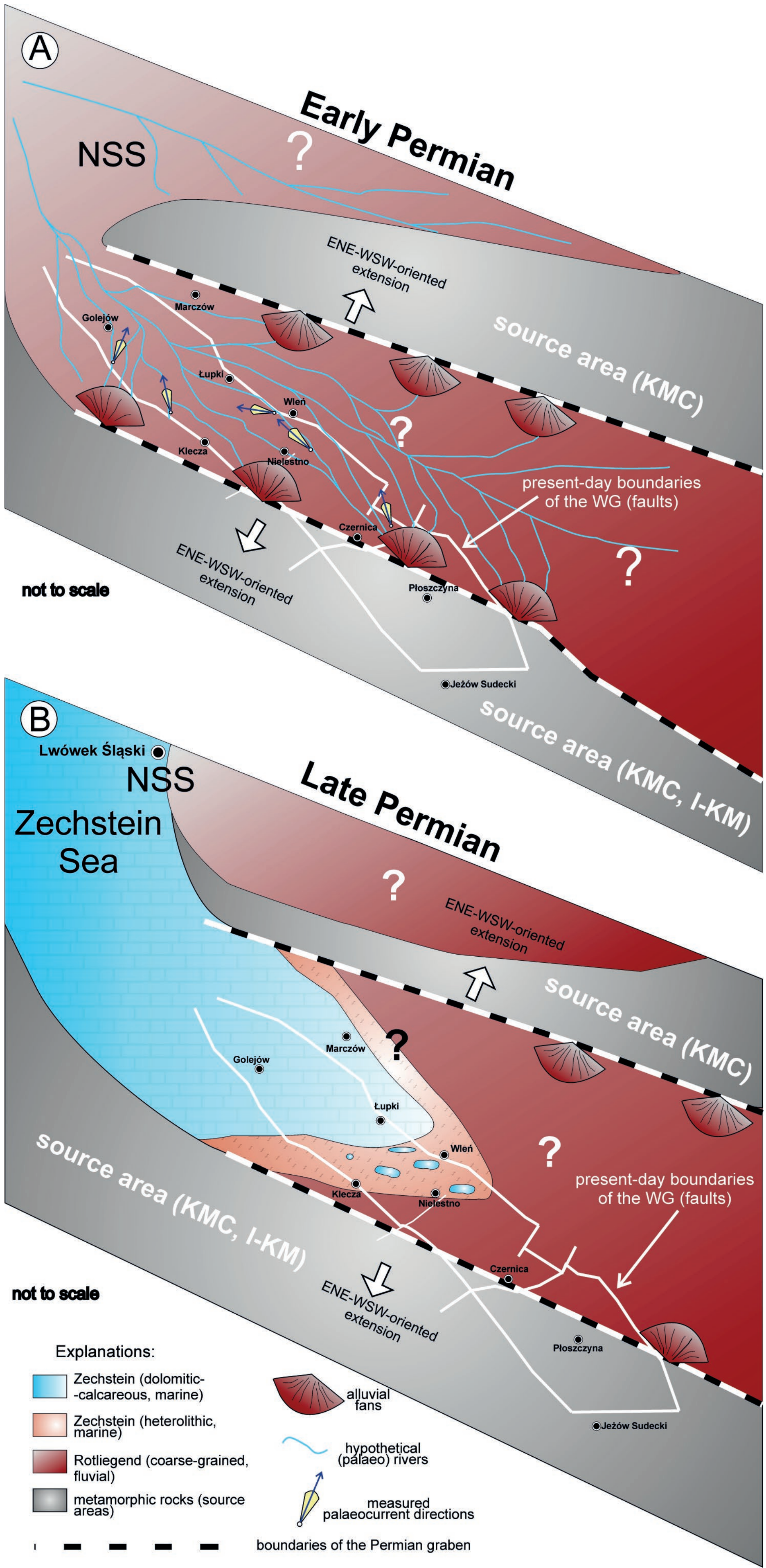

Fig. 9. Schematic evolution of the present-day Wleń Graben area during Early and Late Permian times. Note the oblique (WNW-ESE) orientation of the Permian trough axis and its boundaries in relation to the present fault-related boundaries of the Wleń Graben (NW-SE). Explanations: KMC – Kaczawa Metamorphic Complex; NSS – North Sudetic Synclinorium; I–KM – Izera – Karkonosze Massif; WG – Wleń Graben. See the text for further explanation.

Sparitic and microsparitic dolomites, the typical carbonate deposits assigned to the third (PZ3) Zechstein cyclothem, are interpreted in the neighbouring areas as sediments of a shallow-water carbonate platform with small lagoons (Raczyński, 1997). The most typical fossils occurring in these deposits are epifaunal bivalves *Liebea* sp., capable of living in high-energy settings. These bivalves are so far the only fossils encountered in the carbonate rocks in the vicinity of Wleń. The dominance of bivalves in fossil communities is characteristic for the coastal, nearshore facies of the NSS (Raczyński, 1997). On the contrary, in the study area there is no evidence of other fossils typical for the PZ3 deposits, such as encrusting foraminifera as well as calcareous algae of *Calcinema permiana* (King) (cf. Śliwiński, 1990; Raczyński, 1997). The lack of these fossils in the study area probably was caused by the strong recrystallization and diagenesis of the dolomites (cf. "Dolomites" chapter above). Although the presence of *Liebea* sp. fossils does not allow for an unequivocal determination of the stratigraphic position of the rocks that contain them, their assignment to the PZ3 Platy Dolomite (Ca3; Upper Zechstein), based on analogies with the neighbouring areas (cf. Milewicz, 1966), seems justified.

So far, the platy dolomites have been referred to as marine deposits, despite the lack of direct palaeoenvironmental indicators, which would support their marine origin (Milewicz, 1966). Moreover, in the neighbouring area of the Intra-Sudetic Synclinorium, lithologically similar varieties of dolomite were interpreted as continental calcrete deposits (Śliwiński, 1980). Similarly, in the Wleń Graben area, the abundance of carbonate cements in the upper part of the Rotliegend was the reason for their erroneous classification as marine Zechstein deposits (Milewicz, 1966). Eventually, this resulted in the incorrect estimation of the thickness of Zechstein deposits in the Wleń Graben at about 30 m (Milewicz, 1966), whereas in fact they reach a total thickness of about 13 m near Golejów and up to 9 m near Wleń (Fig. 3).

One valuable diagnostic lithostratigraphic and palaeoenvironmental feature, found also for the first time in the Zechstein deposits of the Wleń Graben, is the presence of casts after halite crystals in the PZt deposits. Horizons with such structures have been described earlier from the Lwówek Śląski and Leszczyna half-grabens from deposits underlying the Platy Dolomite Ca3 (Mastalerz and Raczyński, 1993; Raczyński, 1996, 1997). In these areas, the horizons represent a coastal, clastic equivalent of the evaporitic series, known from the western and northern part of the NSS (Raczyński, 1997). Until now, deposits of the heterolithic series have been interpreted as sediments of the third cyclothem (PZ3; Raczyński, 1997) of a muddy coastal plain, formed during the regression of the sea. Observations performed in this study have confirmed this concept. It is evidenced by a rich inventory of sedimentary structures, characteristic of shallow-water sedimentary settings, dominated by waves and periodic marine currents. These structures include wave and current ripple marks, occurring within fine-grained sandy and silty deposits of PZt. The dips of laminae within the current ripple marks indicate NW- and NE-oriented palaeocurrent directions. In the central part of the graben, heterolithic deposits lie directly on clastic rocks of the Rotliegend, where a distinct horizon of massive dolomite does not occur. Casts after halite crystals found in these deposits indicate that during the Late Zechstein marine transgression, the area was located in the marginal, southern part of a shallow-marine basin. It is therefore quite probable that on a muddy plain, local depressions formed and were occupied by shallow, ephemeral salt lakes, where carbonates also could precipitate. Small-scale, wave-ripple lamination observed within the heterolithic deposits shows that the depth of individual, probably isolated water bodies did not exceed a few decimetres. The view of proximity of the land area is confirmed also by findings of tetrapod trackways in similar deposits, occurring in the Lwówek Śląski Half-Graben (Raczyński *et al*., 1998). The absence of a continuous dolomite horizon at the boundary of the Zechstein heterolithic series on the Rotliegend indicates a diachronous boundary between these two stratigraphic units.

Above the platy dolomite in the northern part of the Wleń Graben (loc. 1) and within the heterolithic series in its central part (loc. 2), coarse-clastic dolomitic conglomerates occur. They constitute a distinct lithological unit within the Zechstein deposits in the study area, which does not occur in other parts of the NSS. Conglomerates most probably represent the sediments of submarine slumps. This view is evidenced by the following sedimentary features of these deposits: (1) reverse graded bedding, coupled with the presence of floating dolomite megaclasts; (2) extremely poor rounding of dolomite clasts from the underlying platy dolomite or dolomite lenses occurring in the Wleń area; and (3) the presence of structures resembling slump folds in the Wleń area. A landslide origin of these deposits has been already suggested. Scupin (1931), Kolb (1936) and Gierwielaniec (1956) indicated that an angular unconformity occurs near the top of the platy dolomites. Scupin (1931) considered this discordance to be the result of a tectonic overthrust. In turn, Gierwielaniec (1956), on the basis of the observations of the "clayey shale", occurring between the dolomite and the overlying dolomitic conglomerates, interpreted the discordance as the basal surface of a submarine slump ("submarine sediment slide"). A similar suggestion was made by Kolb (1936). Distinct erosional troughs, filled with dolomite clasts visible in the historical photograph presented in Kolb (1936), may confirm the possibility of the occurrence of a slump above the platy dolomites during Late Permian times in the study area.

A separate issue is the presence of numerous deformation structures of a pre- and post-consolidation nature within the deposits assigned to the terrigenous transitional series PZt. In the northern part of the Wleń Graben, such deformation features have not been described so far, although they commonly occur in the vicinity of Wleń and Nielestno. The authors interpret these structures as the result of a multi-scale fluidization of the sediment following a seismic shock (Kowalski *et al*., 2018a). The presence of such features in the same stratigraphic position in other parts of the NSS (Durkowski *et al*., 2017) and also in the Fore-Sudetic Homocline, indicates a common, transregional nature of these phenomena, making them perfect correlation horizons. These structures were not described in detail in this article and will be the subject of a future publication.

SUMMARY

Geological mapping surveys and sedimentological studies conducted in the Wleń Graben area indicated that the southernmost part of the NSS contains deposits should be assigned to Zechstein rocks of marine origin. So far, their stratigraphic position has not been clear and was determined solely on the basis of analogies with adjacent areas. In the strongly recrystallized sparitic and microsparitic dolomites, occurring in the vicinity of Golejów and Nielestno, geopetal structures and accumulations of the bivalve *Liebea* sp. occur, whereas the overlying strata of the heterolithic series PZt contain pseudomorphs after halite crystals. These are the only palaeoenvironmental proxies found in these deposits after over a hundred years of research on the Zechstein in the Wleń Graben. These findings, coupled with detailed geological mapping surveys, have allowed the construction of the first comprehensive lithostratigraphic column for the Zechstein of the area.

Carbonate deposits (PZ3) in the Wleń Graben were formed after a marine transgression, which took place in the late Zechstein (Late Permian). In effect, to the north of Wleń (in the vicinity of Golejów and Marczów), a shallow-marine bay (lagoon?) was dominated by carbonate sedimentation. The Zechstein sea encroached from the north onto a local depression, which had an orientation corresponding to a WNW-ESE-oriented tectonic graben that formed there in the Late Carboniferous – Early Permian. The shallow-water environment of the marine bay became populated by organisms with a high tolerance to high-energy conditions, such as the bivalve *Liebea* sp. Storms probably occurred frequently in the bay, as evidenced by numerous horizons of residual storm lags, composed of crushed bivalve shells in a convex-up position.

The thickness of carbonate deposits is strongly reduced in the Wleń Graben area in relation to the remaining areas of the NSS, located to the north. Dolomites and calcareous dolomites in the vicinity of Golejów attain a thickness of ca. 7.5 m, whereas in the vicinity of Wleń they occur only as lenses or discontinuous beds, not exceeding 1 m in thickness.

Above the sparitic dolomites in the vicinity of Golejów and resting directly on continental Rotliegend strata in the vicinity of Nielestno-Wleń, there are sandy siltstones and fine-grained sandstones, assigned to the Terrigenous Transitional Series PZt. During the Late Zechstein transgression, the area of today’s Nielestno was in the marginal south-westernmost part of a newly formed, shallow-marine bay of the Polish Zechstein Basin. A north-sloping mud plain, periodically flooded by a shallow sea, occurred in this area. This is confirmed by sedimentary features of the heterolithic series PZt, including structures formed in very shallow, marine conditions – small-scale, wave- and current-ripples. Small carbonate lenses within the PZt deposits as well as concentrations of pseudomorphs after halite crystals indicate that the area of the periodically flooded, muddy coastal plain comprised also shallow depressions covered by isolated water bodies and shallow, ephemeral salt lakes, which did not exceed a few decimetres in depth. Evaporation and carbonate precipitation periodically took place in these marine-fed lakes. The concept of a marine bay, bounded from the south by a land area, is also confirmed by finds of tetrapod tracks collected from similar deposits in the Lwówek Śląski Half-Graben. Deposits of the heterolithic series, occurring above the PZ3 Platy Dolomites near Golejów, were formed during the regression of the sea from the third Zechstein cyclothem and are the facies equivalents of deposits occurring directly above the Rotliegend in the vicinity of Nielestno.

The deposits of submarine flows and landslides as well as numerous pre- and post-consolidation deformation structures, occurring within the heterolithic series PZt in the entire Wleń Graben area, represent a separate issue. These deposits indicate tectonic and seismic activity in the area after a transgressive episode in the Late Zechstein. In the central part of the Wleń Graben, the deformation features include structures related to large-scale sediment liquefaction. These phenomena are interpreted in adjacent areas as being the result of large-scale sediment deformation, caused by seismic phenomena. This idea seems to be justified, owing to the transregional scale of these structures and their age restriction only in the transition between the Late Permian and the Triassic.

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REFERENCES

Awdankiewicz, M., 2006. Fractional crystallization, mafic replenishment and assimilation in crustal magma chambers: geochemical constraints from the Permian post-collisional intermediate-composition volcanic suite of the North-Sudetic Basin (SW Poland). *Geologia Sudetica*, 38: 39–61.

Baranowski, Z., Haydukiewicz, A., Kryza, R., Lorenc, S., Muszyński, A., Solecki, A. & Urbanek, Z., 1990. Outline of the geology of the Góry Kaczawskie (Sudetes, Poland). *Neues Jahrbuch für Geologie und Paläontologie*, 179: 223–257.

Biernacka, J., Borysiuk, K. & Raczyński, P., 2005. Zechstein (Ca1) limestone-marl alternations from the North-Sudetic Basin, Poland: depositional or diagenetic rhythms? *Geological Quarterly*, 49: 1–14.

Chrząstek, A. & Wojewoda, J., 2011. Mesozoic of South-Western Poland (the North Sudetic Synclinorium). In: Żelaźniewicz, A., Wojewoda, J. & Ciężkowski, W. (eds), *Mezozoik i Kenozik Dolnego Śląska*. WIND, Wrocław, pp. 1–10. [In Polish, with English abstract.]

Cymerman, Z., 2004. *Tectonic map of the Sudetes and the Fore-Sudetic Block, 1:200 000*. Państwowy Instytut Geologiczny, Warszawa.

Dechen, H., von, 1838. Das Flözgebirge am nördlichen Abfall des Riesengebirges. *Karsten's Archiv für Mineralogie*, 11: 1–103.

Durkowski, K., Sokalski, D. & Wojewoda, J., 2017. Pre- and post-consolidated sediment deformations in the Transitional Terrigeneous Series PZt (Zechstein/Lower Buntsandstein) in the Grodziec Syncline, Sudetes: process interpretation and regional implications. *Biuletyn Państwowego Instytutu Geologicznego*, 469: 155–176. [In Polish, with English summary.]

Eisentraut, O., 1939. Der niederschlesische Zechstein und seine Kupferlagerstätte. *Archiv für Lagerstättenforschung der Preußischen Geologischen Landesanstalt*, 71: 1–116.

García-Veigas, J., Cendón, D. I., Pueyo, J. J. & Peryt, T. M., 2011. Zechstein saline brines in Poland, evidence of overturned anoxic ocean during the Late Permian mass extinction event. *Chemical Geology*, 290: 189–201.

Geinitz, H. B.,1861. Die Dyas oder die Zechsteinformation und das Rotliegende. Heft I: Animalischen Ueberreste der Dyas. Verlag von Wilhelm Engelmann, Leipzig, 512 pp.

Gierwielaniec, J., 1956. Geological structure of the area to the North of Lubomierz. *Biuletyn Instytutu Geologicznego*, 106: 61–92. [In Polish, with English summary.]

Gorczyca-Skała, J., 1977. Geologic structure of the Wleń Graben. *Geologia Sudetica*, 12*:* 71–100. [In Polish, with English summary.]

Gradstein, F. M., Ogg, J. G., Schmitz, M. & Ogg, G., 2012. *The Geological Time Scale 2012*. Elsevier, Amsterdam, 1176 pp.

Grünewaldt, M., 1851. Über die Versteinerungen des schlesischen Zechsteingebirges. *Zeitschrift der Deutschen Gesellschaft*, 3: 241–276.

Hara, U., Słowakiewicz, M. & Raczyński, P., 2013. Bryozoans (trepostomes and fenestellids) in the Zechstein Limestone (Wuchiapingian) of the North Sudetic Basin (SW Poland): palaeoecological implications. *Geological Quarterly*, 57: 417–432.

Hounslow, M. W. & Balabanov, Y. P., 2016. A geomagnetic polarity timescale for the Permian, calibrated to stage boundaries. *Geological Society, Special Publications*, 450: 61–103.

Kiersnowski, H., 2013. Late Permian aeolian sand seas from the Polish Rotliegend Basin in the context of palaeoclimatic periodicity. *Geological Society, Special Publications*, 376: 431–456.

Kolb, W., 1936. Tektonische Untersuchungen im Gebiet des Lähner Grabens. *Jahrbuch der Preußischen Geologischen Landesanstalt*, 56: 93–124.

Kłapciński, J., 1967. The Permian of North-Western Sudetes and of the Fore-Sudetic area with special consideration of the Upper Permian Copper Deposits. In: Teisseyre, H. (ed.), *Przewodnik XL Zjazdu Polskiego Towarzystwa Geologicznego. Geologia i surowce mineralne Sudetów Zachodnich. Zgorzelec, 24–27 sierpnia 1967*. Wydawnictwa Geologiczne, Warszawa, pp. 88–118. [In Polish, with English summary.]

Kowalski, A., Raczyński, P. & Wojewoda, J., 2018a. Zasięg morza cechsztyńskiego na obszarze synklinorium północnosudeckiego w swietle nowych danych sedymentologicznych z rowu tektonicznego Wlenia. In: Kędzierski, M., Gradziński, M. (eds), *Polska Konferencja Sedymentologiczna POKOS 7. Góra Św. Anny, 4–7 czerwca 2018 r. Materiały konferencyjne*. Polskie Towarzystwo Geologiczne, Kraków, p. 80. [In Polish.]

Kowalski, A., Wajs, J. & Kasza, D., 2018b. Monitoring of anthropogenic landslide activity with combined UAV and LiDAR-derived DEMs – a case study of the Czerwony Wąwóz landslide (SW Poland, Western Sudetes). *Acta Geodynamica et Geomaterialia*, 15: 117–129.

Kozłowski, S. & Parachoniak, W., 1967. Wulkanizm permski w depresji północnosudeckiej. *Prace Muzeum Ziemi*, 11: 191–221 [In Polish.]

Langenhan, A., 1899. Über einige Zechsteinversteinerungen aus Schlesien. *Jahresbericht der Schlesischen Gesellschaft für Vaterländische Kultur*, 77: 44–52.

Mastalerz, K., 1990. Lacustrine successions in fault bounded basins: 1. Upper Anthracosia shale (Lower Permian of the North Sudetic Basin, SW Poland. *Annales Societatis Geologorum Poloniae*, 60: 75–106.

Mastalerz, K. & Raczyński, P., 1993. Litostratygrafia i ewolucja basenu północnosudeckiego w karbonie i permie. In: Mastalerz K. (ed.), *Baseny sedymentacyjne: Procesy, osady, architektura. Przewodnik II Krajowego Spokania Sedymentologów.* Instytut Nauk Geologicznych Uniwersytetu Wrocławskiego, Wrocław, pp. 90–97. [In Polish.]

Mastalerz, K. & Nehyba, S., 1997. Comparison of Rotliegende lacustrine depositional sequences from the Intrasudetic, North-Sudetic and Boskovice basins (Central Europe). *Geologia Sudetica*, 30: 21–57. [In Polish, with English summary.]

Miall, A. D., 1985. Architectural element analysis: a new method of facies analysis applied to fluvial deposits. *Earth-Science Reviews,* 22: 261–308.

Milewicz, J., 1959. Notes on the tectonics of Lwówek Śląski (Lower Silesia). *Kwartalnik Geologiczny*, 3: 1024–1032. [In Polish, with English summary.]

Milewicz, J., 1966. The Zechstein of the Wleń Graben. *Kwartalnik Geologiczny,* 10: 63–73. [In Polish, with English summary.]

Milewicz, J., 1985. A proposal of formal stratigraphic subdivision of the infill of the North Sudetic Depression. *Przegląd Geologiczny*, 33: 385–389. [In Polish, with English summary.]

Milewicz, J., 1997. Upper Cretaceous of the North Sudetic depression. Litho-and biostratigraphy, tectonics and remarks on raw materials. *Acta Universitatis Wratislaviensis,* 1971, *Prace Geologiczno-Mineralogiczne*, 61*:* 1–58. [In Polish, with English summary.]

Milewicz, J. & Frąckiewicz, W., 1983. *Szczegółowa Mapa Geologiczna Sudetów. Arkusz Wleń 1:25 000*. Wydawnictwa Geologiczne, Warszawa. [In Polish.]

Milewicz, J. & Frąckiewicz, W., 1988. *Objaśnienia do Szczegółowej Mapy Geologicznej Sudetów. Arkusz Wleń 1:25 000*. Wydawnictwa Geologiczne, Warszawa, 75 pp. [In Polish.]

Milewicz, J. & Górecka, T., 1965. Preliminary remarks on the Carboniferous in the North-Sudetic Depression. *Kwartalnik Geologiczny*, 9: 113–114. [In Polish, with English summary.]

Mroczkowski, J., 1972. Sedimentation of the Bunter in the Northsudetic Basin. *Acta Geologica Polonica*, 22: 351–377. [In Polish, with English summary.]

Ostromęcki, A., 1973. Development of the Late Paleozoic sedimentary basins of the Kaczawa Mts. *Annales Societatis Geologorum Poloniae*, 43: 319–362.

Peryt, T., 1978. Outline of the Zechstein stratigraphy in the North Sudetic Trough. *Kwartalnik Geologiczny*, 22: 59–82. [In Polish, with English summary.]

Peryt, T. M., Geluk, M. C., Mathiesen, A., Paul, J. & Smith, K., 2010. Zechstein. In*:* Doornenbal, J. C. & Stevenson, A. G. (eds), *Petroleum Geological Atlas of the Southern Permian Basin Area*. EAGE Publications b.v., Houten, pp. 123–147.

Pettijohn, F. J., Potter, P. E. & Siever, R., 1987. *Sand and Sandstone*. Springer-Verlag, New York, 518 pp.

Powers, M. C., 1953. A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology*, 23*:* 117–119.

Raczyński, P., 1996. *Paleontologiczne i sedymentacyjne wskaźniki warunków powstawania osadów w cechsztynie niecki północnosudeckiej*. Ph.D. thesis, University of Wrocław. [In Polish.]

Raczyński, P., 1997. Depositional conditions and paleoenvironments of the Zechstein deposits in the North-Sudetic Basin (SW Poland). *Przegląd Geologiczny*, 45: 693–699. [In Polish, with English summary.]

Raczyński, P., Kurowski, L., & Mastalerz, K., 1998. Litostratygrafia i ewolucja basenu północnosudeckiego na przełomie paleozoiku i mezozoiku. In: Wojewoda, J. (ed.), *Ekologiczne Aspekty Sedymentologii. Tom 1. Meteriały VII Krajowego Spotkania Sedymentologów, Wojcieszów 2-4 lipca 1998 r*. WIND, Wrocław, pp. 75–100. [In Polish]

Sawicki, L., 1995. Geological map of Lower Silesia with adjacent Czech and German territories (without Quaternary deposits). Państwowy Instytut Geologiczny, Warszawa.

Scupin, H., 1913. Die Löwenberger Kreide und ihre Fauna. *Palaeontographica – Supplement* 6: 1–275.

Scupin, H., 1931. Die Nordsudetische Dyas. Eine stratigraphisch-palaogeographische Untersuchung. *Fortschritt Geologie-Paläontologie*, 27: 1–245.

Solecki, A., 1994. Tectonics of the North Sudetic Synclinorium. *Acta Universitatis Wratislaviensis*, 1618, *Prace Geologiczno-Mineralogiczne*, 65: 1–38.

Solecki, A., 2011. Structural development of the epi-Variscan cover in the North Sudetic Synclinorium area. In: Żelaźniewicz, A., Wojewoda, J. & Ciężkowski, W. (eds), *Mezozoik i Kenozik Dolnego Śląska*. WIND, Wrocław, pp. 19–36. [In Polish, with English abstract.]

Szurlies, M., 2013. Late Permian (Zechstein) magnetostratigraphy in Western and Central Europe. *Geological Society, Special Publications*, 376: 73–85.

Śliwiński, W., 1980. A model for caliche formation in the continental Permian deposits of southwestern Intra-Sudetic Basin, Soutwestern Poland. *Geologia Sudetica*, 15*:* 83–101.

Śliwiński, W., 1990. Zechstein deposits in environs of Niwnice (SW Poland). *Przegląd Geologiczny,* 38: 180–186. [In Polish, with English summary.]

Śliwiński, W., Raczyński, P. & Wojewoda, J., 2003. Sedymentacja utworów epiwaryscyjskiej pokrywy osadowej w basenie północnosudeckim. In: Ciężkowski, W., Wojewoda, J. & Żelaźniewicz, A. (eds), *Sudety Zachodnie: od wendu do czwartorzędu*. WIND, Wrocław, pp. 119–126. [In Polish.]

Teisseyre, H., Smulikowski, K. & Oberc, J., 1957. *Regionalna geologia Polski, t. III,*

Sudety, z. 1. Polskie Towarzystwo Geologiczne, Kraków, 300 pp. [In Polish.]

Wagner, R., 1994. Stratigraphy and evolution of the Zechstein basin in the Polish Lowlands. *Prace Państwowego Instytutu Geologicznego*, 146: 1-75. [In Polish, with English summary.]

Wagner, R. & Peryt, T. M, 1997. Possibility of sequence stratigraphic subdivision of the Zechstein in the Polish Basin. *Geological Quarterly*, 41: 457–474.

Wagner, R., Piątkowski, T. S. & Peryt, T. M., 1978. Polish Zechstein Basin. *Przegląd Geologiczny,* 26: 673–686. [In Polish, with English summary.]

Wagner, R., Pokorski, J. & Dadlez, R., 1980. Palaeotectonics of the Permian Basin in the Polish Lowlands. *Geological Quarterly*, 24: 553–569. [In Polish, with English summary.]

Wojewoda, J. & Mastalerz, K., 1989. Climate evolution, allo- and autocyclicity of sedimentation: an example from the Permo-Carboniferous continental deposits of the Sudetes, SW Poland. *Przegląd Geologiczny*, 37, 4: 173–180. [In Polish, with English summary.]

Zieliński, T. & Pisarska-Jamroży, M., 2012. Which features of deposits should be included in a code and which not? *Przegląd Geologiczny,* 60: 387–397. [In Polish, with English abstract.]