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MULTISTAGE STRUCTURAL EVOLUTION OF THE END-CRETACEOUS–CENOZOIC WLEŃ GRABEN (THE SUDETES, NE BOHEMIAN MASSIF) – A CONTRIBUTION TO THE POST-VARISCAN TECTONIC HISTORY OF SW POLAND

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Abstract: Results of a new mapping and structural field study of the Wleń Graben (North Sudetic Synclinorium, SW Poland), made up of a post-Variscan volcano-sedimentary succession, were used to set up a new model of its multiphase tectonic evolution. The Wleń Graben constitutes a narrow tectonic trough, ca. 17.5 km long and up to 3.5 km wide, superimposed on the low-grade metamorphic rocks of the Kaczawa Metamorphic Unit and bounded by steep, NW−SE-oriented, normal and reverse faults. Previously, a simple, one-stage evolution of the graben was considered, with a single Alpine age intraplate compressional event responsible for the formation of the unit. The present study shows that the Late Cretaceous (post-Santonian?) evolution of the Wleń Graben was dominated by NW−SE-oriented, normal faults during the first, extensional stage of its formation. The central and southern parts of the graben were strongly affected by NW−SE-trending reverse faults and overthrusts, which reflect the second, probably latest Cretaceous to early Palaeogene(?) compressional event of tectonic deformation. Moreover, the whole area of the graben is dissected by sinistral strike-slip faults oriented perpendicular to the graben margins, representing the third stage of deformation (late Palaeogene–Neogene). The latest stage of evolution of the Wleń Graben includes a possible Neogene to Quaternary development of normal faults, interpreted here as gravitational collapse structures related to present-day morphology, rather than tectonically induced ones.

Key words: Brittle tectonics, tectonic trough, post-Variscan tectonics, post-Variscan cover, Bohemian Massif, Central Europe.

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INTRODUCTION

The Wleń Graben is one of the most prominent troughs in the North Sudetic Synclinorium (NE Bohemian Massif, SW Poland). The North Sudetic Synclinorium is a NW−SE-oriented geological unit developed owing to large-scale folding and faulting of the discontinuous volcano-sedimentary succession of the North Sudetic Basin, mainly between the end of Cretaceous and the Neogene (see reviews in Malkovsky, 1987; Żelaźniewicz *et al.*, 2011). The basin-fill rocks, representing a slightly deformed upper Carboniferous to Upper Cretaceous cover of the metamorphosed Variscan Sudetic basement, are preserved within a series of minor, fault-controlled synclines, grabens, half-grabens and horsts, separated by NW−SE and NE−SW-trending regional fault systems (Fig. 1).

The North Sudetic Synclinorium area has been the subject of considerable interest and early geological investigations since the 19th century (Raumer, 1819; Dechen, 1838; Lütke and Ludwig, 1838; Beyrich, 1855; Williger, 1882). Despite such a long history of research, the few tectonic studies, including the Wleń Graben area, were devoted to the analysis of regional, map-scale fault patterns (Hannik, 1926; Scupin, 1933; Milewicz, 1968a, 1997; Solecki, 1994, 2011), as well as studies on the orientation of joints and deformation bands (Solecki, 1988, 2011). Complex structural analysis of faults and fault slip data was conducted only for selected, individual outcrops, situated mainly in the northern part of the North Sudetic Synclinorium (Cymerman, 1998a; Sippel, 2009).

It was commonly assumed so far that the Wleń Graben is a fault-controlled depression formed owing to progressive compression lasting from the Late Cretaceous (Santonian?) to the Neogene (Milewicz, 1959, 1997; Gorczyca-Skała, 1977; Solecki, 1994). This hypothesis persisted in the following years (Solecki, 2011) and the compressive stress, which was supposed to lead to the graben formation was linked with the so-called "Laramide" phase of tectonic activity (orogenic phase sensu Stille, 1924) and in later works, with intraplate compressional tectonics (sensu Ziegler, 1987), related to the Cenozoic Alpine collision (Solecki, 1994, 2011). The tectonic boundaries of the graben were differently interpreted by various researchers (as either reverse or normal faults, dipping in one or opposite directions even at same localities; cf. maps by Kühn and Zimmermann, 1918; Zimmermann, 1932a, b; Milewicz, 1970a, b; Szałamacha, 1977; Milewicz and Frąckiewicz, 1983; Cymerman *et al.*, 2005). In this context, owing to the lack of structural and fault slip data related to the boundary faults of the graben as well as minor tectonic structures, the main questions that remain to be addressed concern the origin and structural evolution of the entire Wleń Graben area during the end of the Cretaceous as well as during post-Cretaceous times. Moreover, owing to its location in the peripheral, marginal part of the North Sudetic Synclinorium, the Wleń Graben appears to be a key element for deciphering the geological and structural history of the post-Variscan sedimentary cover of the Sudety Mts.

The main aim of this paper is to (1) provide a revised, up-to-date, detailed geological map of the Wleń Graben; (2) present the geometry and kinematics of its main tectonic structures; (3) present a comprehensive model of its end- and post-Cretaceous structural evolution, based on detailed structural analysis; and (4) correlate the stages of the Wleń Graben evolution distinguished with those recognised in other areas containing the post-Variscan sedimentary cover of the Sudety Mts.

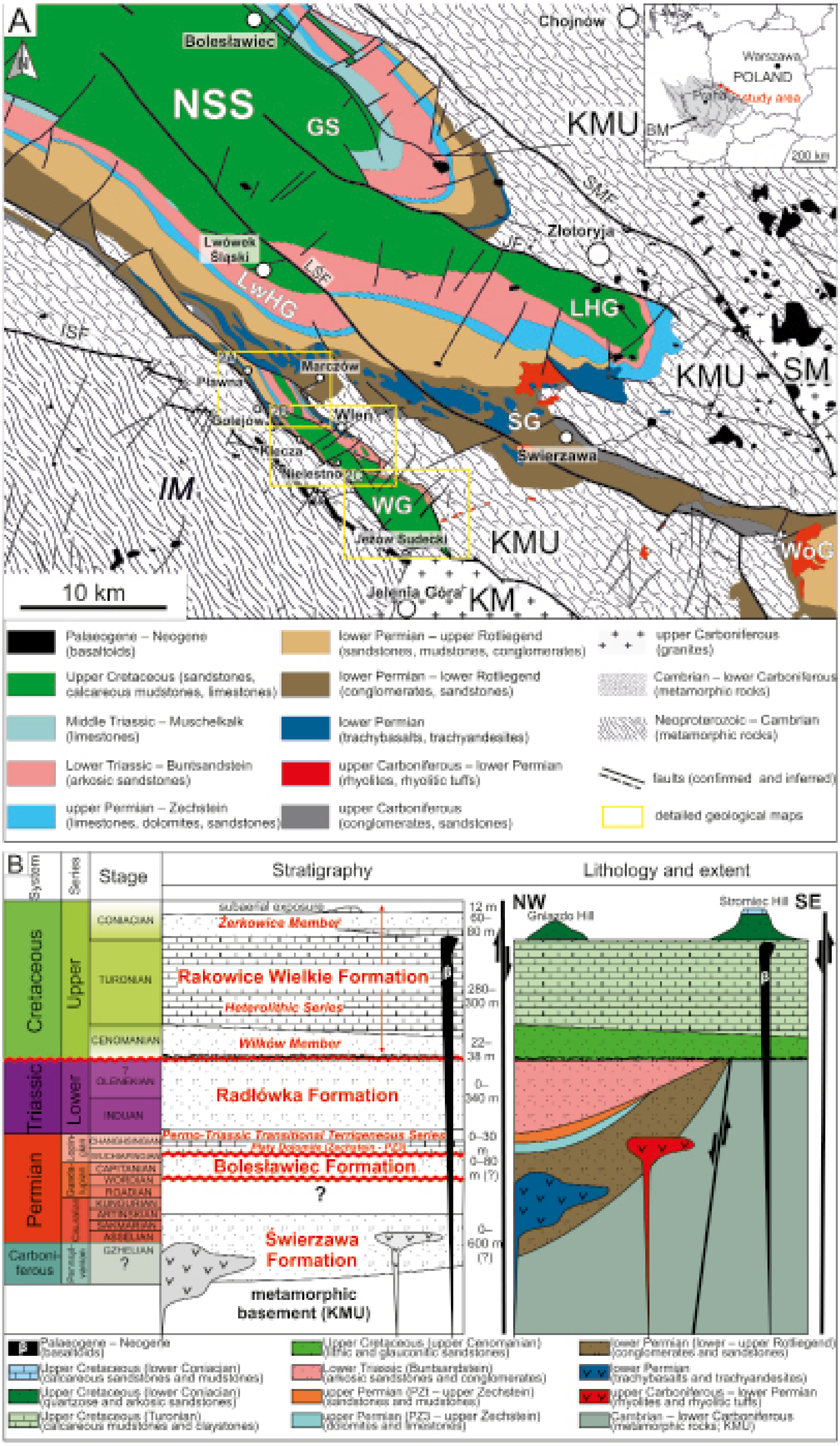
GEOLOGICAL SETTING AND PREVIOUS WORK

The Wleń Graben is located in the Western Sudety Mts., in an area north to northwest of the town of Jelenia Góra and south to southeast of the town of Lwówek Śląski (Fig. 1A). The sedimentary and volcanic rocks exposed in this area represent a cover of the deformed and metamorphosed Variscan Sudetic basement of the Kaczawa Metamorphic Unit, preserved within a fault-bounded, NW−SE-trending graben, ~17.5 km long, 2–3.5 km wide, and up to 600 m deep, that has developed in the southernmost part of the North Sudetic Synclinorium. The synclinorium as well as the Wleń Graben are composed of uppermost Carboniferous/lower Permian (Rotliegend) volcano-sedimentary rocks, overlain by upper Permian (Zechstein) to Lower Triassic (Buntsandstein) continental and Upper Cretaceous (upper Cenomanian to lower Coniacian) marine deposits (Fig. 1A, B). Locally, in the northern part of the synclinorium remnants of Middle Triassic (Muschelkalk) deposits also occur (cf. Fig. 1A; Chrząstek, 2002). In the traditional regional scheme proposed by Teisseyre *et al.* (1957), following Schwarzbach (1939), the Kaczawa Metamorphic Unit and North Sudetic Synclinorium are treated jointly as the so-called Kaczawa Unit.

The basement and structurally elevated shoulders of the Wleń Graben are made up of metasedimentary and metavolcanic rocks, assigned to the Kaczawa Metamorphic Unit (also referred to in the literature as the Kaczawa Metamorphic Complex or Kaczawa Slate Belt; cf. Baranowski *et al.*, 1990). This unit consists of a Cambrian to lower Carboniferous (Mississippian), low-grade- to anchimetamorphosed volcano-sedimentary succession that includes phyllites, metasandstones, metamudstones and crystalline limestones, as well as the products of submarine volcanism: metabasalts (pillow-lavas) and basaltic tuffites, metarhyolites, metarhyodacides, metadolerites and greenstones (cf. Baranowski *et al.*, 1990). These rocks were subject to multistage folding, faulting, and metamorphic processes in conditions of lower/middle greenschist facies during the Variscan orogeny (cf. Urbanek *et al.*, 1975; Baranowski *et al.*, 1990; Kryza and Muszyński, 1992; Cymerman, 2002).

In the Wleń Graben area, rocks of the Kaczawa Metamorphic Unit, defining the graben's basement and shoulders, are discordantly overlain by the volcano−sedimentary succession of the North Sudetic Synclinorium (cf. Fig. 1B). The oldest, upper Carboniferous to lower Permian clastic rocks, developed in the Rotliegend facies (Świerzawa Formation; see: Karnkowski, 1981; Śliwiński *et al.*, 2003) are exposed in the northern and central parts of the graben (Fig. 2A–C). These deposits consist mostly of poorly sorted, coarse-grained conglomerates and sandstones interpreted as alluvial fan and braided river deposits (Kowalski *et al.*, 2018a). Within the Rotliegend strata, up to 1,300 m thick in the North Sudetic Synclinorium area (cf. Milewicz, 1965), shallow, sub-volcanic intrusions (predominantly laccoliths and sills) occur, comprising trachyandesites, trachybasalts and rhyolitoids ("Lower Permian Volcanic Complex"; Milewicz, 1965; Kozłowski and Parachoniak, 1967; Awdankiewicz, 2006; Awdankiewicz *et al.*, 2014). Complexes of trachyandesitic laccoliths and sills reach a maximum thickness from 300 m in the vicinity of Wleń to ca. 500 m near Pławna. Moreover, along the

Fig. 1. Geological setting and simplified stratigraphy of the Wleń Graben. **A.** Simplified geological map of the North Sudetic Synclinorium (NSS) and the Wleń Graben (WG) with location of maps from Figure 2. BM – Bohemian Massif; GS – Grodziec Syncline; LHG – Leszczyna Half-Graben; LwHG – Lwówek Śląski Half-Graben; WoG – Wolbromek Graben; ŚG – Świerzawa Graben; KMU – Kaczawa Metamorphic Unit; IM – Izera Massif; ISF – Intra-Sudetic Fault; KM – Karkonosze Massif; SM – Strzegom-Sobótka Massif; JF – Jerzmanice Fault; LŚF – Lwówek-Świerzawa Fault; SMF – Sudetic Marginal Fault. Geological map based on Sawicki (1995) and Cymerman (2004). **B.** Simplified scheme, showing stratigraphy, lithology and extent and thickness of the volcano-sedimentary succession in the Wleń Graben. Stratigraphy redrawn and modified after Karnkowski, 1981; Milewicz, 1985; Śliwiński *et al.*, 2003.


A
Bolesławiec
Chojnów
NSS
GS
KMU
Warszawa
POLAND
study area
BM
200 km
SMF
Złotoryja
Lwówek Śląski
LSF
LwHG
LHG
ISF
Płóczki
Marczów
Pławna
Wleń
Golejów
SG
Klecza
Świerzawa
Nielestno
IM
WG
KMU
Jeżów Sudecki
WoG
10 km
Jelenia Góra
KM
SM
Palaeogene – Neogene (basaltoids)
Upper Cretaceous (sandstones, calcareous mudstones, limestones)
Middle Triassic – Muschelkalk (limestones)
Lower Triassic – Buntsandstein (arkosic sandstones)
upper Permian – Zechstein (limestones, dolomites, sandstones)
lower Permian – upper Rotliegend (sandstones, mudstones, conglomerates)
lower Permian – lower Rotliegend (conglomerates, sandstones)
lower Permian (trachybasalts, trachyandesites)
upper Carboniferous – lower Permian (rhyolites, rhyolitic tuffs)
upper Carboniferous (conglomerates, sandstones)
upper Carboniferous (granites)
Cambrian – lower Carboniferous (metamorphic rocks)
Neoproterozoic – Cambrian (metamorphic rocks)
faults (confirmed and inferred)
detailed geological maps
B
System
Series
Stage
Stratigraphy
Lithology and extent
Cretaceous
Upper
CONIACIAN
TURONIAN
CENOMANIAN
Triassic
Lower
OLENEKIAN
INDUAN
Permian
Carboniferous
subaerial exposure
Żerkowice Member
Rakowice Wielkie Formation
Heterolithic Series
Wilków Member
Radłówka Formation
Permo-Triassic Transitional Terrigeneous Series
Platy Dolomite (Zechstein - PZ3)
Bolesławiec Formation
?
Świerzawa Formation
metamorphic basement (KMU)
12 m
60–80 m
280–300 m
22–38 m
0–340 m
0–30 m
0–80 m (?)
0–600 m (?)
NW
Gniazdo Hill
Stromiec Hill
SE
Palaeogene – Neogene (basaltoids)
Upper Cretaceous (lower Coniacian) (calcareous sandstones and mudstones)
Upper Cretaceous (lower Coniacian) (quartzose and arkosic sandstones)
Upper Cretaceous (Turonian) (calcareous mudstones and claystones)
Upper Cretaceous (upper Cenomanian) (lithic and glauconitic sandstones)
Lower Triassic (Buntsandstein) (arkosic sandstones and conglomerates)
upper Permian (PZ1 – upper Zechstein) (sandstones and mudstones)
upper Permian (PZ3 – upper Zechstein) (dolomites and limestones)
lower Permian (lower – upper Rotliegend) (conglomerates and sandstones)
lower Permian (trachybasalts and trachyandesites)
upper Carboniferous – lower Permian (rhyolites and rhyolitic tuffs)
Cambrian – lower Carboniferous (metamorphic rocks; KMU)

southern boundaries of the graben there occur narrow dykes of rhyolitoids, oriented both parallel and perpendicular to its margins. Volcanic complex is overlain by lower Permian continental sandstones and conglomerates of fluvial origin with calcrete-type cementation (Bolesławiec Formation; cf. Raczyński, 1997; Raczyński *et al*., 1998; Śliwiński *et al*., 2003). The Rotliegend is discordantly covered by upper Permian marine deposits (Scupin, 1933; Eisentraut, 1939; Milewicz, 1966; Raczyński, 1997) assigned to the third Zechstein cyclothem (PZ3 <15 m thick; cf. Kowalski *et al*., 2018a), which consists of clastic carbonates, including dolomites ("Platy Dolomite"), as well as fine-grained sandstones and mudstones of the Permo-Triassic Transitional Terrigenous Series (PZt of Peryt, 1978). The upper Permian deposits almost concordantly pass upward into Lower Triassic sandstones and conglomerates (Buntsandstein of the Radłówka Formation; cf. Milewicz, 1968b, 1985; Mroczkowski, 1972), considered as the sediments of braided rivers (Mroczkowski, 1972; Kowalski, 2020). They attain a maximum thickness of up to 340 m (Kowalski, 2020) and thin out towards the SE – reaching only a few metres near Klecza and Czernica and being totally absent from the southern part of the Wleń Graben. In the northern part of the graben, Buntsandstein deposits are discordantly covered by the Upper Cretaceous marine strata (Rakowice Wielkie Formation; see Milewicz, 1997; Leszczyński, 2018), whereas in its southern part, Cretaceous strata lie directly on the metamorphic basement (near Płoszczyna and Czernica; Czernica-1 borehole; SPDPSH, 2019) or on coarse-grained Rotliegend deposits. The Cretaceous marine succession that is closest to complete, Cenomanian to Coniacian in age, is preserved in the axial part of the Wleń Graben, where it is considerably thick (up to 430 m; cf. Fig. 1B). The Cretaceous succession begins with the so-called "basal conglomerates" (up to 2 m thick), which pass upward into non-calcareous sandstones distinguished as the Wilków Member (upper Cenomanian "Lower Jointed Sandstone"; Raumer 1819). In the Wleń area, the Lower Jointed Sandstone comprises a horizon with a stable thickness of ca. 38 m (Łupki-4 and Czernica-1 boreholes; SPDPSH, 2019), to decrease to ca. 22 m to the south (Płoszczyna-1 borehole; SPDPSH, 2019). Above the upper Cenomanian sandstones, a monotonous succession of fine-grained, calcareous mudstones and siltstones occurs reaching a total thickness of ca. 280−300 m, noted for example in Nielestno-3 borehole (SPDPSH, 2019). The mudstone series is overlain by sandstones assigned to Żerkowice Member (Upper Jointed Sandstone; Milewicz, 1997; Leszczyński and Nemec, 2019) that are exposed in two localities in the central part of the graben (Gniazdo and Stromiec Hills) and considered to be the youngest Cretaceous sediments (lower Coniacian) in this part of the synclinorium (Gorczyca-Skała, 1977). Sedimentary rocks of the Wleń Graben are cut by basaltoid veins, Palaeogene and probably Neogene in age (see Milewicz and Frąckiewicz, 1988; Badura *et al*., 2006). Five exposures of basaltoid rocks were encountered during geological mapping; they occur as remnants of volcanic necks and narrow NE−SW-trending dykes. One of the basaltoid occurrences was drilled in the Wleń Graben basement near Jeżów Sudecki (B-5 borehole; Sroga *et al*., 2018), with a K-Ar radiometric date of 58.7 ± 5.9 Ma (Badura *et al*., 2006). The youngest, unconsolidated deposits occurring in the Wleń area (excluding alluvial and slope sediments) include Pleistocene sands and gravels of glacial origin, reaching 20 m in thickness (Milewicz and Frąckiewicz, 1988). They have not been considered in the mapping survey performed during this study.

Early structural data from the vicinities of Wleń were collected by Kunth (1863), who assumed that the Wleń Graben (German: Lähner Mulde) was a NW−SE-oriented, asymmetric syncline with the high dips of Cretaceous sandstones near the graben boundaries and overturned beds dipping below the metamorphic basement in the southern part of the graben. Scupin (1913) used the term 'tectonic graben' for the first time in reference to the Wleń Graben (Ger. Lähner Grabenmulde), pointing out that the southern and northern boundaries of this structure are reverse faults. On the serial maps of Prussia 1: 25 000 (Kühn and Zimmermann, 1918; Zimmermann, 1932a, b; sheets: Lähn, Altkemnitz and Hirschberg), the Wleń Graben's boundaries were shown as partly fault-controlled and partly as monoclines. Beyer (1933) indicated that the Wleń Graben is bound by steep, normal or reverse faults, being the result of the so-called "young Saxonian tectonics" (Ger. Jungsaxonische Einfaultung; Stille, 1925), which caused subdivision of the entire Kaczawa area into "synclinal grabens" and "horsts", in places representing anticlines.

The first detailed mapping study of the whole Wleń Graben at the scale of 1: 50 000 was by Kolb (1936), who subdivided the main graben structure into several sectors (Ger. Grabenstücken), separated by NW−SE- and NE−SW-oriented faults. From north to south these include: the Golejów (Ger. *Klein Röhrsdorf*), Klecza (Ger. *Ober Hußdorf*), Nielestno (Ger. Waltersdorf), Płoszczynka (Ger. Neu-Flachenseiffen) and Jeżów Sudecki (Ger. Grunau) sectors. Kolb (1936) also presented a hypothesis on the partially flexural development of the graben boundaries, which was supposed to have resulted from vertical motions of the Palaeozoic basement.

On the basis of his geological map of the northern part of the Wleń Graben, Gierwielaniec (1956) assumed that the northern boundary of the graben near the village of Łupki was a normal fault and the southern boundary, near Klecza, represented a flexure. He believed that owing to the distinct asymmetry of the graben, reflected in the "higher dip of the southern shoulder compared to the northern one". Milewicz (1959, p. 71) considered the graben as a tectonic structure bounded by steep reverse faults, formed owing to NNE−SSW compression.

The most comprehensive, monographic report on the geology of the Wleń Graben is that by Gorczyca-Skała (1977). This author suggested a structural inheritance of the graben's formation above the crestal part of a dome, developed in the metamorphic basement. On the basis of the attitude of bedding and joints in the sedimentary succession of the graben, she concluded that the Wleń Graben constitutes an asymmetric structure, bounded by parallel, NW−SE-oriented faults. The relative throw of the graben's floor on these faults was estimated from cross-sections (without any borehole data) to reach ca. 500 m, or more on the SW boundary fault. According to Gorczyca-Skała (1977), the boundaries of the

Wleń Graben are steep normal faults or, partly monoclines in the central and western part of the graben, whereas in its central part, the boundary monocline is overturned and the sedimentary rocks within the graben dip outwards, beneath the metamorphic basement. Additionally, the overturning of the Cretaceous strata is supposed to be the largest in the southern part of the graben, reaching 45° near Skowron Hill. Moreover, the graben is supposed to be dissected by ENE−WSW and E−W-trending faults, transverse to its axis, with a throw of up to several tens of metres and a steep dip of fault planes towards the NW. According to Gorczyca-Skała (1977), these faults are normal in character and linked to the development of the marginal dislocations of the graben, being the result of Tertiary compression. Gorczyca-Skała (1977) did not exclude strike-slip movements along these faults and indicated a distinct link between the orientation of faults and distribution of Neogene basaltoids. According to this author, an assessment of the exact time of graben formation is not possible. Its beginning may have taken place during the regression of the Late Cretaceous sea (due to the "Subhercynian tectonic phase"), whereas the lack of Tertiary deposits may indicate neotectonic activity. According to Gorczyca-Skała (1977) "the Laramide compression" of a NNE−SSW to NE−SW orientation had led to reactivation of already existing Variscan faults, resulting in the formation of a graben and overthrusts.

Milewicz (1970a) and Milewicz and Frąckiewicz (1988) suggested that the formation of the Wleń Graben was the result of block tectonics induced by "Alpine movements", which began after the Santonian. The NE−SW-oriented faults were formed between the middle and late Miocene, as indicated by basaltic volcanism.

The tectonics of the entire North Sudetic Synclinorium, including the Wleń Graben, was studied by Solecki (1994). He considered the Wleń Graben as a subordinate structure within the synclinorium, bounded by reverse faults formed during the "Alpine (mainly Laramide) movements". These faults were supposed to have developed during the reactivation of older faults that evolved during the Variscan Orogeny. Solecki (1994) considered also that the Variscan basement of the entire synclinorium was deformed in post-Variscan times (Saxonian tectonics) and that this type of deformation was characteristic of the Alpine foreland in Central Europe (his p. 40). Solecki (1994) also distinguished four main fracture systems in the NSS (J_1, J_2, J_3 and J_4) and indicated, as well, that the Wleń Graben was dominated by joints of system J_1, comprising two sets: J_1A with a strike of NE−SW (55°) and J_1B with a strike of NW−SE (325°), as well as system J_2, comprising fracture sets J_2A with a strike of NNE−SSW (25°) and J_2B with an average orientation of WNW−ESE (295°).

MATERIAL AND METHODS

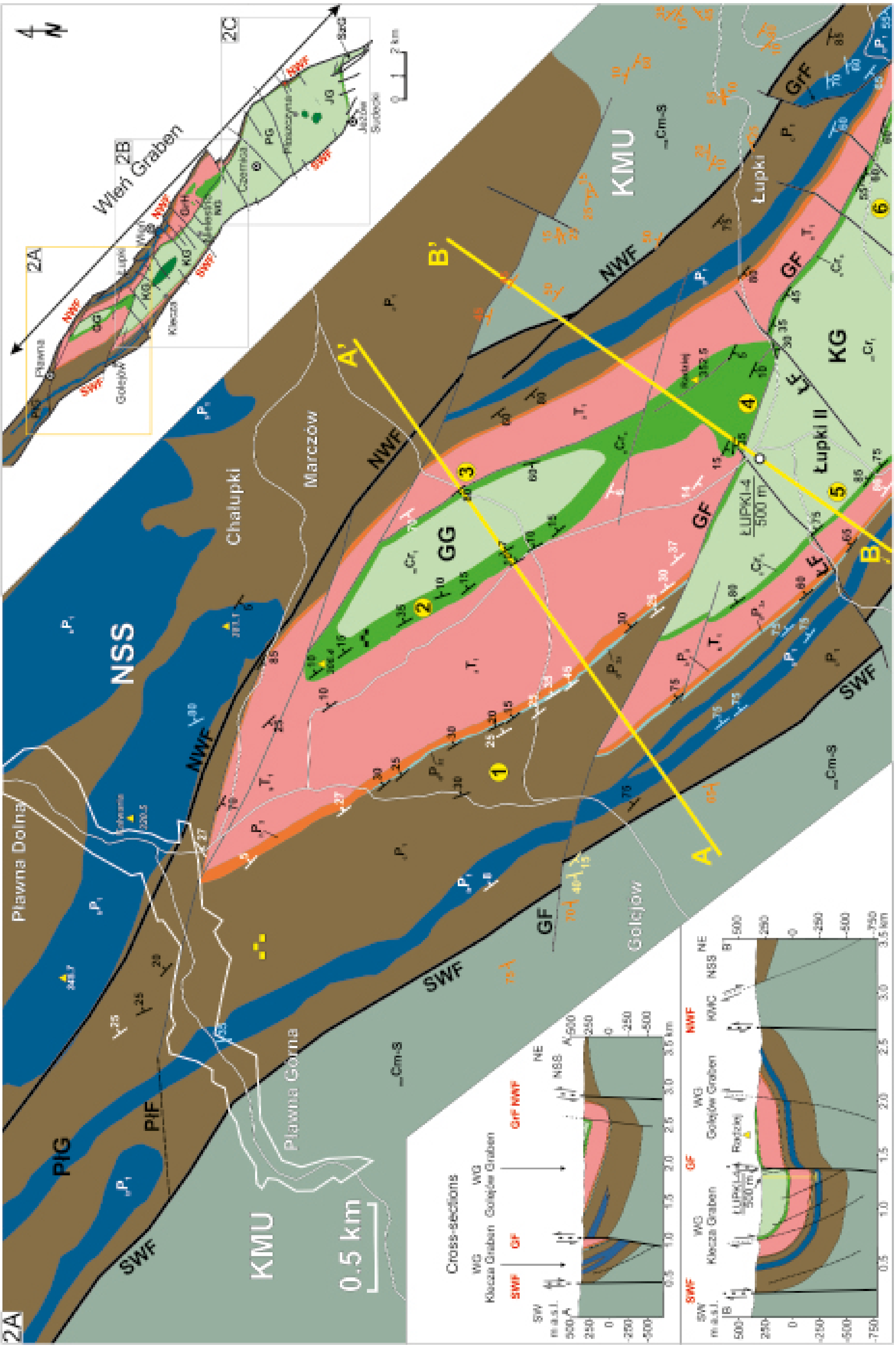
A structural study in the Wleń Graben area was carried out by the present author in 2015–2019, together with a geological mapping survey at the scale of 1:10 000. Structural data were collected in natural and artificial outcrops, such as tors, abandoned quarries and road crosscuts. The mapped area covered an area of ca. 60 km^2. An effect of the fieldwork – the new geological map of the Wleń Graben – was made with the help of LiDAR-based (Light Detection and Ranging) Digital Elevation Models (DEMs) of 1 x 1 m resolution. Elevation data were acquired from airborne laser scanning (ALS), conducted in Poland in 2011–2014 as part of the IT System of the Country's Protection against Extreme Hazards (ISOK). The results of the scanning were made accessible by the Polish Centre of Geodetic and Cartographic Documentation (CODGiK) as XYZ point data, with a density of ~4−6 point/m^2 and an average elevation error not exceeding 0.3 m (Report, 2011). The DEMs were used to detect regional stratigraphic and structural boundaries. The GIS software: Global Mapper v. 12.0 and Microdem Software v. 2015.8 (developed by Peter Guth) was used for the geological mapping survey. Five borehole logs, available from the central part of the Wleń Graben (cf. Gierwielaniec, 1998; SPDPSH, 2019), were used for the construction of cross-sections.

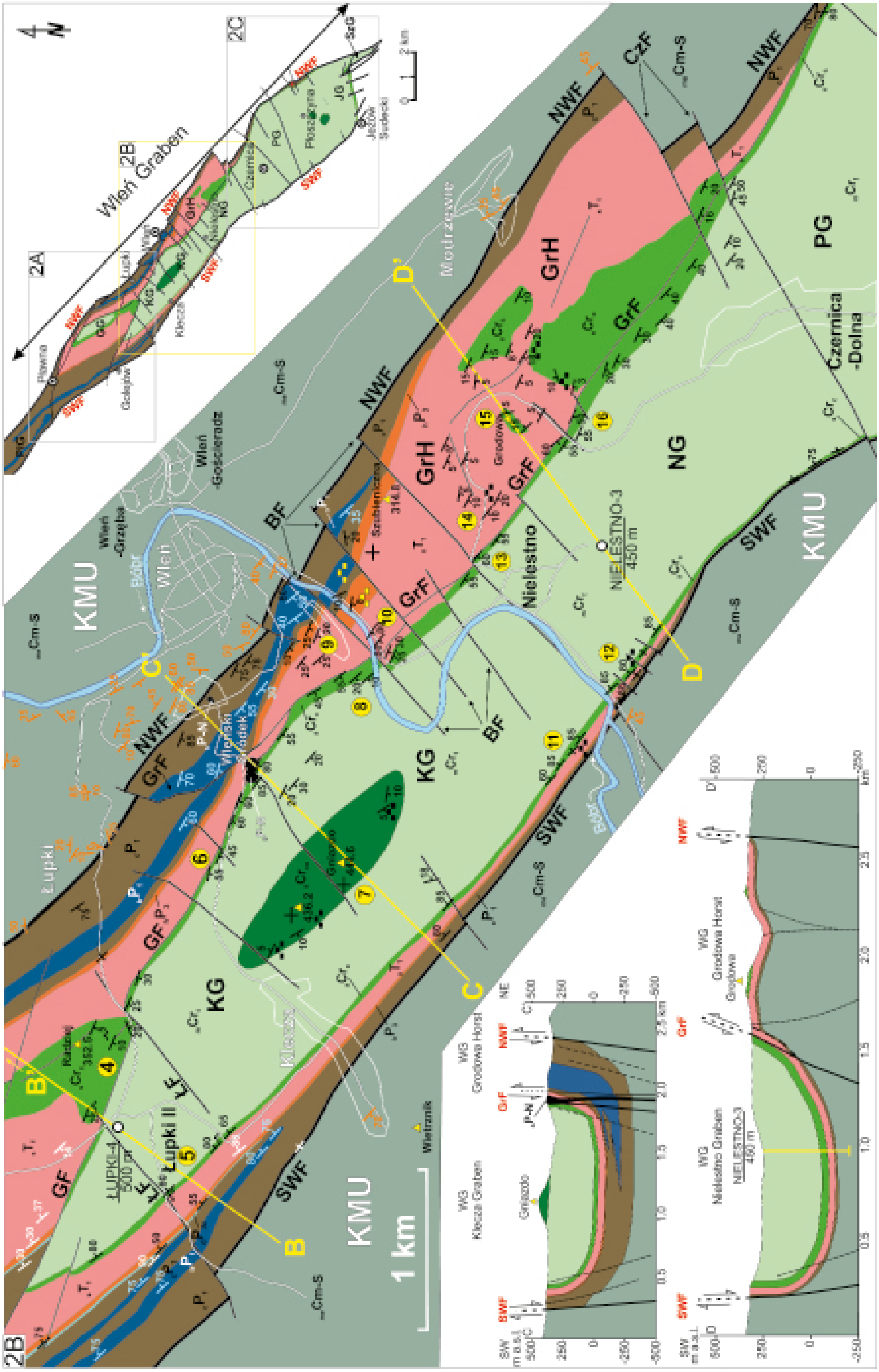
Approximately 3,260 structural measurements were made at 517 localities. The outcrops investigated were grouped into 21 representative sites for measurements (see Fig. 2 for their location). The measured structural features included bedding (1), joints (2), fault planes with striae (3) and deformation bands (4). Measurements of these structures are presented on β and π stereograms, made on the lower hemisphere of the equal-area Schmidt-Lambert net. Selected structures are also presented on rose diagrams (circular frequency polygon diagrams; cf. Davis, 1986).

Structural analysis of minor faults was concentrated on kinematic indicators (surface markings sensu Bahat, 1991), such as slickensides, striated ridges, hackles, grooves, low- and high-angle shears, en echelon cracks and others. Palaeostress tensors were calculated, using FaultKin8 and Orient 3.9.1 software (Vollmer, 2015). The graphical analysis of fault slip data included the kinematic method of "P" (shortening) and "T" (extension) axes (moment tensor analysis; cf. Angelier, 1984, 1994; Marrett and Allmendinger, 1990). To visualise the successive deformation stages in the Wleń Graben, the obtained P and T axes were presented as the so-called "beachball plots", showing shortening and extension quadrants. The relative ages of the deformation events were determined from the cross-cutting relationships between brittle structures. Photomicrographs of selected thin-sections were made using the NIS-Elements Basic Research software by Nikon.

RESULTS OF GEOLOGICAL MAPPING – NEW INSIGHTS INTO STRUCTURE OF THE WLEŃ GRABEN

A new geological map of the Wleń Graben by the present author provides the basis for the modified tectonic subdivision and geometry of this geological unit (Fig. 2A–C). The results of geological mapping show that the main graben is characterised by an asymmetric, irregular structure and consists of a series of minor, adjoining, grabens, half-grabens and horsts. They are separated by several mappable, NW–SE- and NNW–SSE-striking faults, as well as by NE–SW-trending discontinuities. These subunits


2A
2B
2C
Wleń Graben
NSS
KMU
PIG
PIF
NWF
SWF
GF
GrF
GG
KG
Pławna Dolna
Pławna Górna
Chałupki
Marczów
Gołejów
Łupki
Łupki II
ŁUPKI-4
500 m
A
A'
B
B'
0.5 km
Cross-sections
SW
NE
WG Kleczа Graben
WG Gołejów Graben
NSS
m a.s.l.


2B
2A
2C
Wleń Graben
KMU
KG
GrH
NG
PG
GrF
NWF
SWF
BF
CzF
Wleń
Nielestno
Łupki
Czernica -Dolna
NIELESTNO-3 450 m
ŁUPKI-4 500 m
1 km


Wleń Graben
Chrośnickie Kopy Range
KMU
PG
JG
SzG
KM
Jeżów Sudecki
Płoszczyna
Płoszczynka
Czernica Dolna
Czernica Górna
Strzyżowiec
NWF
SWF
CZERNICA-2
213 m
PŁOSZCZYNA-1
138 m
1 km

were previously referred to as *sections* or *segments* of the Wleń Graben (cf. Kolb, 1936; Milewicz, 1966; Gorczyca-Skała, 1977). From the NW they include the: Golejów, Klecza, Nielestno, Grodowa, Płoszczyna, Jeżów Sudecki and Szybowisko segments (cf. Gorczyca-Skała, 1977). The Grodowa and Szybowisko segments were not distinguished previously in the literature – their distinction here is the result of a new interpretations of borehole and structural data.

The first-order boundary faults of the Wleń Graben: the south-western boundary fault (SWF; Southern Wleń Fault of Gorczyca-Skała, 1977) and north-eastern boundary fault (NWF; Northern Wleń Fault of Gorczyca-Skała, 1977) are the most significant structural elements of the study area that separate the volcano-sedimentary succession of the Wleń Graben from its elevated shoulders (the rocks of the Kaczawa Metamorphic Unit and the North Sudetic Synclinorium in the NE termination of the graben; Figs 1, 2A–C). These faults have a total trace length of approximately 17 km (Southern Wleń Fault) and 18.5 km (Northern Wleń Fault) along the Wleń Graben. The Sothern Wleń Fault also constitutes the southwestern boundary fault of the North Sudetic Synclinorium. The total vertical displacement on these faults, as estimated from mapping and borehole data, reaches approx. 300 m in the northern part of the graben (see cross-section A-A' in Fig. 2A) and approx. 600 m in its southern part (see F-F' cross-section in Fig. 2C). Notably, the boundary faults of the Wleń Graben continue to the NW (Fig. 1) and run sub-parallel at a distance from several hundred metres to several kilometres to the Intra-Sudetic Fault, considered one of the most important structural discontinuities in the Sudetes (e.g., Aleksandrowski, 1995, 1998; Mazur *et al.*, 2020).

The northernmost segment of the Wleń Graben (Fig. 2A) is represented by an asymmetric, WNW–ESE-trending, rhomb-shaped, half-graben structure, termed here the Golejów Graben (GG; Kolb, 1936). In comparison with other subunits of the Wleń Graben, the Golejów Graben constitutes a relatively shallow, brachysynclinal depression with Cretaceous rocks (upper Cenomanian to lower Turonian) exposed in its central part. The Golejów Graben is delimited from the west and east by NW–SE- or WNW–ESE-trending, boundary faults of the Wleń Gaben: the Southern and Northern Wleń faults, respectively. The probable throw on the faults bounding the Golejów Graben estimated on the basis of geological cross-sections is ca. 200 m in its northern part to ca. 300 m in its southern part (see cross-sections on Fig. 2A). To the north, the Golejów Graben is delimited by the Pławna Fault, which constitutes the NW boundary of the Wleń Graben, separating it from another tectonic subunit within the North Sudetic Synclinorium – the Płóczki Graben (Fig. 2A). All the fault zones mentioned above are poorly exposed. Their occurrence is locally supported by field evidence of brittle deformation, such as breccias and gouges, found in small outcrops. These breccias (e.g., the one near Łupki village) are composed of sharp-edged phyllite clasts, > ten centimetres in diameter, embedded in fine-grained matrix of fault gouge.

The southern boundary of the Golejów Graben constitutes the WNW–ESE-trending Golejów Fault (GF; Gorczyca-Skała, 1977), one of the most important fault zones in the Wleń Graben. This fault zone is poorly exposed, with its main fault probably dipping steeply to the SW and the total throw amounting to 350 m at maximum (see cross-section B-B' on Fig. 2A). Clear map evidence of this fault can be observed in the vicinity of Łupki II village, where a Triassic/Cretaceous unconformity was noted at the surface on its upthrown side at ca. 300 m a.s.l. (southern slope of Radziej Hill), whereas in the downthrown side, this unconformity was drilled at ca. 50 m a.s.l. (in borehole Łupki-4; see cross-section B-B' on Fig. 2A). Numerous minor WNW–ESE-trending faults with an indeterminate throw have also

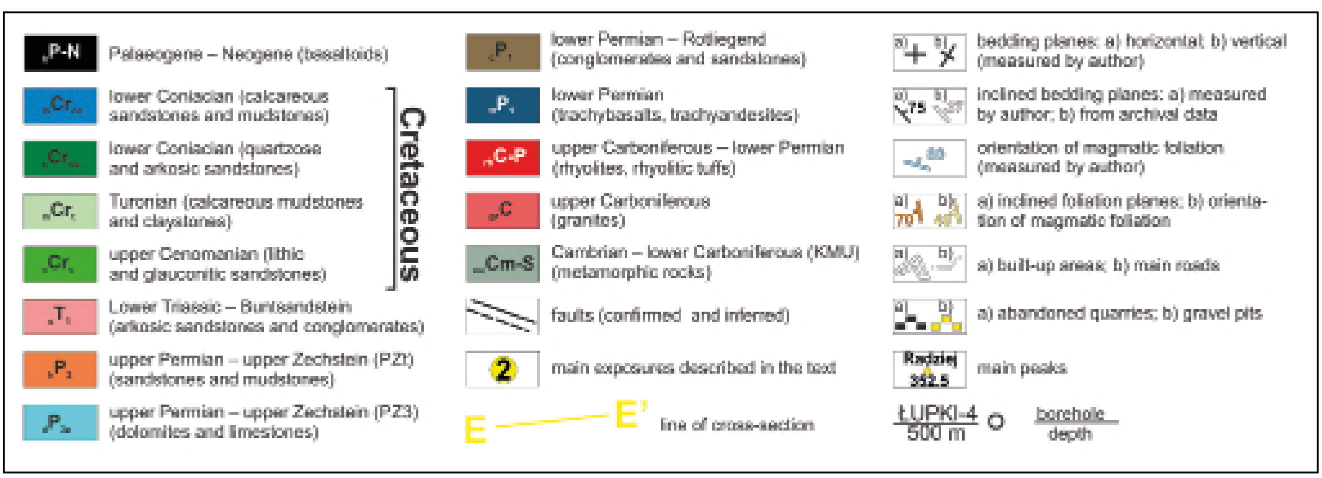


Fig. 2. Detailed geological maps (**A, B, C**) of the Wleń Graben, showing main structural features and locations of outcrops described in the text. Lines of cross-section are marked with yellow lines. Explanations of letter symbols: BF – Bóbr Faults; CzF – Czernica Fault; GG – Golejów Graben; GF – Golejów Fault; GrF – Grodowa Fault; GrH – Grodowa Horst; JG – Jeżów Sudecki Graben; JF – Jeżów Fault; KG – Klecza Graben; KM – Karkonosze Massif; KMU – Kaczawa Metamorphic Unit; NG – Nielestno Graben; ŁF – Łupki Faults; SWF – Southern Wleń Fault; PłG – Płóczki Graben; PłF – Pławna Fault; SWF – Southern Wleń Fault; SzG – Szybowisko Graben.

been noted within the Golejów Graben. Towards the south-east, the Golejów Fault splays off into the Grodowa Fault (GrF; Fig. 2A, B).

The central part of the Wleń Graben is structurally more complex, with the presence of at least three distinct, adjacent tectonic subunits (cf. Fig. 2B). The first of them involves the NW–SE-trending Klecza Graben (KG), in the literature also termed the Gniazdo Brachysyncline (Milewicz and Frąckiewicz, 1988), separated from the Golejów Graben to the north by the Golejów and Łupki Faults (ŁF; Fig. 2A, B). The flanks of the Klecza Graben are controlled by NW–SE-trending faults: the Southern Wleń Fault to the south-west as well as the Golejów and Grodowa Faults to the north-east. In the axial part of the Klecza Graben, the bottom of the Permian (Rotliegend) descends probably to an altitude of -200 m a.s.l. (see cross-section C-C' on Fig. 2B), hence the total throw on the Southern Wleń Fault may reach ca. 400 m, whereas the total, vertical displacement on the Golejów and Grodowa Faults is indeterminate and may reach ca. 200 m. In the widest part of the Klecza Graben, in its axial part, a morphologically uplifted block (horst?), composed of the youngest Coniacian sandstones, is preserved. Outcrops of these sandstones are clearly visible in recent topography and form a distinct outlier – the Gniazdo Hill (444 m a.s.l.; see cross-section C-C' in Fig. 2B). At the south-eastern termination of the Klecza Graben, there is a system of NE–SW-trending, strike-slip and normal faults, here named the Bóbr Faults (Fig. 2B). The zone of these discontinuities is the boundary zone between the Klecza Graben and the following subunit within the Wleń Graben, the Nielestno Graben (NG; Fig. 2B). The Nielestno Graben, like the Klecza Graben, is NW–SE-elongated and bounded by the Southern Wleń Fault to the south-west and by the Grodowa Fault to the north-east. In the vicinity of Nielestno village, this segment of the graben narrows to ca. 2 km in width and the bottom of the graben (the Permian basal unconformity), found in the Nielestno-3 borehole, is located at ca. -200 m a.s.l., and, hence, the total throw, both on the Southern Wleń Fault and Grodowa Fault must reach ca. 350 m (see cross-section D-D' in Fig. 2B). From the north-east through the Grodowa Fault, the Klecza and Nielestno Grabens lie adjacent to the subsequent, third tectonic unit, situated in the central part of the Wleń Graben – the Grodowa Horst (GrH). This structural high exposes mainly Lower Triassic sandstones, locally capped by those of upper Cenomanian (Fig. 2B). Detailed mapping shows that the Grodowa Horst constitutes an elevated block with a structural pattern typical for a doubly plunging syncline, with a fault-related, NW–SE-oriented brachyfold (?) occurring in its axial part (see cross-section D-D'; Fig. 2B).

The southern part of the Wleń Graben is much wider (up to 3.5 km; Fig. 2C) than the graben sectors described above. This part of the Wleń Graben displays a relatively simple structural pattern and is traditionally subdivided into two, nearly symmetrical graben structures, the Płoszczyna and Jeżów Sudecki grabens (PG and JG, respectively), separated by the Jeżów Fault (JF). The Płoszczyna Graben is separated from the Nielestno Graben to the north by NE–SW-trending, transverse fractures, i.e. the Czernica Faults (Fig. 2B, C; CzF). The Płoszczyna and Jeżów Sudecki Grabens both are characterised by well-defined, steep fault boundaries – the Southern Wleń Fault to the south-west and the Northern Wleń Fault to the north-east. The uplifted sides of these faults bring to the surface the Kaczawa metamorphic rocks of the Wleń Graben basement and define distinct topographic highs in the vicinity of Czernica and Płoszczyna villages (Chrośnickie Kopy Range; Fig. 2C). The morphological depression related to the down-faulted block (interior of the graben) is the most distinct among all the subunits within the Wleń Graben. As in the Klecza Graben, the central part of the Płoszczyna Graben contains a morphological elevation composed of the youngest rocks of the Wleń Graben – Coniacian sandstones, capped by calcareous, sandy mudstones, which compose a distinct, residual outlier (Stromiec Hill; 551 m a.s.l.), rising ca. 150 m above the flat bottom of the graben interior (see F-F' cross-section; Fig. 2C). The southern boundary of the Jeżów Sudecki Graben is not marked by a fault, but by a relatively steeply N-dipping (up to 40°) band of Cretaceous rocks, at the base of which the Kaczawa Metamorphic Unit of floor of the Wleń Graben is exposed.

The southernmost, relatively deep and narrow structure (up to 100 m wide and 300 m long), the Szybowisko Graben (SzG), represents the smallest subunit recognised within the Wleń Graben (Fig. 2C). It consists of upper Cenomanian to lower Turonian sedimentary rocks, bounded on both sides by steep, NNW–SSE-trending faults. This distinct, narrow graben was not described previously in the literature and metamorphic rocks of the Kaczawa Metamorphic Unit were shown in its place up to now on detailed geological maps (Zimmermann, 1932b; Szałamacha and Szałamacha, 1993). Distinguishing the Szybowisko Graben is possible on the basis of new data from the borehole Szybowisko 22B (cf. Sroga *et al*., 2018), in which a total of 88 m of Turonian marine mudstones were drilled, although the basement rocks of the Kaczawa Metamorphic Unit were not reached.

STRUCTURAL ANALYSIS

The structural framework of the Wleń Graben was elaborated on the basis of a population of structural measurements: bedding (n = 970), fractures (n = 1250), as well as faults and fault kinematic data (n = 806), which were collected from the area between Pławna Górna to the north and Jeżów Sudecki to the south across the entire area of the Wleń Graben.

Bedding attitude

On a regional scale, the orientation of bedding planes in the sedimentary strata as well as the magmatic foliation in the subvolcanic rocks reflect their position with regard to the axial parts of the Wleń Graben and its boundary faults (cf. Fig. 2A–C). In general, the bedding attitude of these rocks ranges from nearly horizontal or homoclinal in the central part of the graben (localities 1, 2, 4, 7, 15, 19; Figs 2A–C, 3A, B) to vertical (Fig. 3C) or even overturned in its marginal parts (localities 3, 5, 11, 12, 18, 20; Figs 2A–C, 3D). Locally, the orientation of bedding changes, owing to the presence of minor, transverse faults.

The interior of the Wleń Graben is characterised by the occurrence of the Upper Cretaceous sandstones and mudstones (Cenomanian to Coniacian), oriented nearly horizontally or gently dipping at 5 to 25° to the NE or SW. The sandstones that make up isolated, flat- or nearly flat-topped hills are associated with structural and morphological highs (e.g., Gniazdo, Grodowa and Stromiec Hills; localities 7, 15, 19; Fig. 2B, C), or exposed in deeply incised stream valleys (Chrośnicki Potok Valley, Świerkowa Dolina Valley). The south-western shoulder of the Wleń Graben is characterised by vertical or near vertical, NW–SE-trending Permian, Triassic and Cretaceous strata (e.g., localities 5, 11, 12, 18, 20; Figs 2B, 3C) rotated near the Southern Wleń Fault that, in general, dips at a high angle to the NE. Additionally, in the south-western part of the Wleń Graben, in the vicinity of Płoszczynka village, the beds of Cenomanian sandstones are overturned and dip at ca. 40 to 80° to the SW (locality 18; Figs 2C, 3D). Strong tilting of the bedding planes near the graben boundaries is linked with the presence of steeply dipping, normal and reverse faults (see chapter: Reverse faults and thrusts II) and represent flanking structures (Passchier, 2001; Coubal *et al*., 2014), related to them. A gradual decrease of the bedding dip in the rocks exposed near the marginal parts of the Wleń Graben is observed at a distance of ca. 70−100 m from the Southern Wleń Fault. The north-eastern shoulder of the Wleń Graben (Northern Wleń Fault zone) is poorly exposed. In locality 17 (Fig. 2C), steeply SW-dipping (up to 80°) to nearly vertical Permian and Cretaceous strata are observed in isolated, small outcrops (up to 2 m high, 5 m wide) in the vicinity of the fault zone. Towards the marginal part of the graben, the dips of the sedimentary strata increase from 20° to 90° at a distance of ca. 100 m. The effect of dip increase of the bedding planes in the Cretaceous rocks is also clearly visible in the Grodowa Fault zone (localities 6, 8, 10, 13, 16; Fig. 2B, C). The upper Cenomanian sandstones dip at high angles (up to 80°) to the SW along almost the entire trace of this fault. In the southern termination of the Wleń Graben, the Cretaceous strata lie directly and discordantly on metamorphic rocks of the Kaczawa Metamorphic Unit (Szybowisko Hill vicinity, locality 21; Fig. 2C) and dip at ca. 20 to 45° to the north.

Joints

In each type of sedimentary rock occurring within the Wleń Graben, two main systematic, conjugate sets of orthogonal or nearly orthogonal, bed-confined joints were distinguished (Figs 3, 4). These sets, designated here as J_1 and J_2, correspond to the J_2A regional joint system, distinguished by Solecki (1994) in the entire North Sudetic Synclinorium area. However, the orientation of these fractures differs slightly among the main lithological varieties of sedimentary rocks occurring within the Wleń Graben (coarse-grained sandstones and conglomerates – fine-grained mudstones) and the main pattern of fractures displays a distinct regularity on a regional scale. Set J_1 comprises fractures striking parallel (NW–SE) or subparallel to the graben boundaries, whilst set J_2 is approximately perpendicular to its orientation and is NE–SW-trending (Figs 3, 4). Joints assigned to these two sets are morphologically similar, their surfaces are usually planar and smooth, with apertures reaching a few millimetres, sometimes filled with Fe-oxide or hydroxide minerals. Independently, minor, fault-related joints occur near the fault zones.

In the central part of the graben as well as on in its gently inclined flanks, set J_1 is represented by normal and subnormal to bedding, vertical or nearly vertical, NW–SE and subordinately NNW–SSE-oriented fractures with dips of 75° to 90° (Figs 3, 4). Set J_2 consists of NE–SW-striking, steeply dipping (70°–85°) fractures, perpendicular to those of set J_1 (Figs 3, 4). A well-developed system of these pervasive joints can be observed in the Coniacian sandstones, cropping out in the axial part of the graben (on Gniazdo and Stromiec Hills, localities 7 and 19; Figs 2B, C, 3A, B, 4). Horizontal or gently dipping (5−10°, NW) sandstones are affected by, J_1 and J_2 orthogonal joint sets, perpendicular to the bedding and consistent in their strike (Figs 3A, B, 4). Joint surfaces usually do not show any evidence of shearing, but the presence of plumose structures, indicating a pure opening-mode origin (Pollard and Aydin, 1988), may be observed. A well-developed, orthogonal joint system, analogous to that at localities 7 and 19, may be observed in the upper Cenomanian and Lower Triassic sandstones, located in the central part of the Grodowa Horst, near Nielestno village (localities 14, 15). The sandstones that occur in these outcrops dip gently at 5° towards the NE or at 10−15° towards the NW and are affected by nearly orthogonal joints (dihedral angle: 75−90°) with a mean strike of NW–SE (set J_1) and NE–SW (set J_2). In all these cases, the joint sets display a constant orientation, with NW–SE and NE–SW-trending strike maxima.

Close to the graben fault boundaries and in the vicinity of minor, transverse faults, the orientation of the fractures differs slightly, attaining a much wider scatter of strike and increasing density. Accordingly, in the rocks exposed near the SW margin of the graben (localities 5, 11, 12, 18, 20; Fig. 2A–C), at a distance of approximately 50 m from the Southern Wleń Fault, set J_1 is rotated to horizontal or nearly horizontal positions (dips: 0°−30°), whilst set J_2 displays a well-defined, NE–SW trend, without any rotation along the horizontal axis (dips 65°−90°; Figs 3C, 4). An analogous joint pattern may be observed in the NE flank of the graben (locality 17; Figs 2C, 4), near the Northern Wleń Fault, where joint set J_1 displays a distinct rotation to horizontal, with normal to steeply inclined or vertically oriented bedding (Fig. 4). The significant dispersal of the fracture directions, as well as the N–S-oriented maxima are related to the presence of faults (locality 4; Figs 2A, 4) and the rotation of strata, whilst the dense fractures correspond to low- and high-angle Riedel shears (R and R' respectively), associated with strike-slip faults (see chapter: Strike-slip faults III).

Locally, clearly visible rotation of the joint sets (J_1 to the N–S and J_2 to the W–E) along vertical axes also is observed close to the transverse faults dissecting the central and southern parts of the graben (locality 4; Figs 2A, 4). These significant changes in the orientation of the orthogonal joint system were caused by strike-slip, mainly sinistral movements (see chapter: Strike-slip faults III).

Fig. 3. Main structural features of sedimentary rocks exposed in the Wleń Graben. Orientation of planar features presented as dip direction/dip angle. **A.** Systematic nearly orthogonal joints (J_1 and J_2), cutting thick-bedded, coarse-grained Coniacian sandstone (Upper Jointed Sandstone) exposed in the central part of the Wleń Graben. Abandoned quarry on W slope of Gniazdo Hill (locality 7). **B.** Gently dipping Coniacian fine-grained calcareous sandstones (Upper Jointed Sandstone) exposed on the top of Stromiec Hill in central part of the Wleń Graben (locality 19). Note the increasing density of joints. **C.** Vertically oriented Cenomanian sandstones (Lower Jointed Sandstone) exposed (locality 11) near the SW graben boundary (SWF). Note accumulation of *Lima* sp. shell moulds on a vertical bedding surface (see inset for close-up detail). **D.** Overturned Cenomanian sandstones and conglomerates (Lower Jointed Sandstone) exposed in an abandoned quarry on the NE slope of Skowron Hill (locality 19). Note that the sandstones are dipping gently at ca. 35° to the SW, below Kaczawa metamorphic rocks.

Faults and related structures

At least four genetically different sets of faults, numbered as populations I to IV, were recognised and analysed in most of the examined localities. They include two kinematic types of normal faults (populations I and IV), reverse faults and thrusts (population II), as well as strike-slip, mainly sinistral faults (population III). In outcrops, located in the marginal parts of the graben as well as close to the main transverse faults, all types of the fractures distinguished have been noted. Most of the fault planes were recorded in the Upper Cretaceous sandstones (upper Cenomanian and Coniacian) and occasionally in the Lower Triassic sandstones and conglomerates. Fault-slip data with the sense of shear were analysed for each fault plane.

Normal faults I

The oldest, generation I of fault structures observed in the Wleń Graben includes a population of normal faults I. These steeply dipping discontinuities date the initial stage of development of the graben and are observed at several localities, especially near the graben boundaries and in its interior. The normal faults can be grouped into two main systems: steep, faults of two opposite dip directions, with strikes parallel to that of the graben (NW–SE), below referred to as longitudinal faults, and transverse faults with NE–SW strikes, perpendicular to elongation of the the Wleń Graben. The latter occur sporadically and usually form fault sets with longitudinal faults.

Longitudinal normal faults are concentrated especially close to the main boundary faults of the Wleń Graben (the

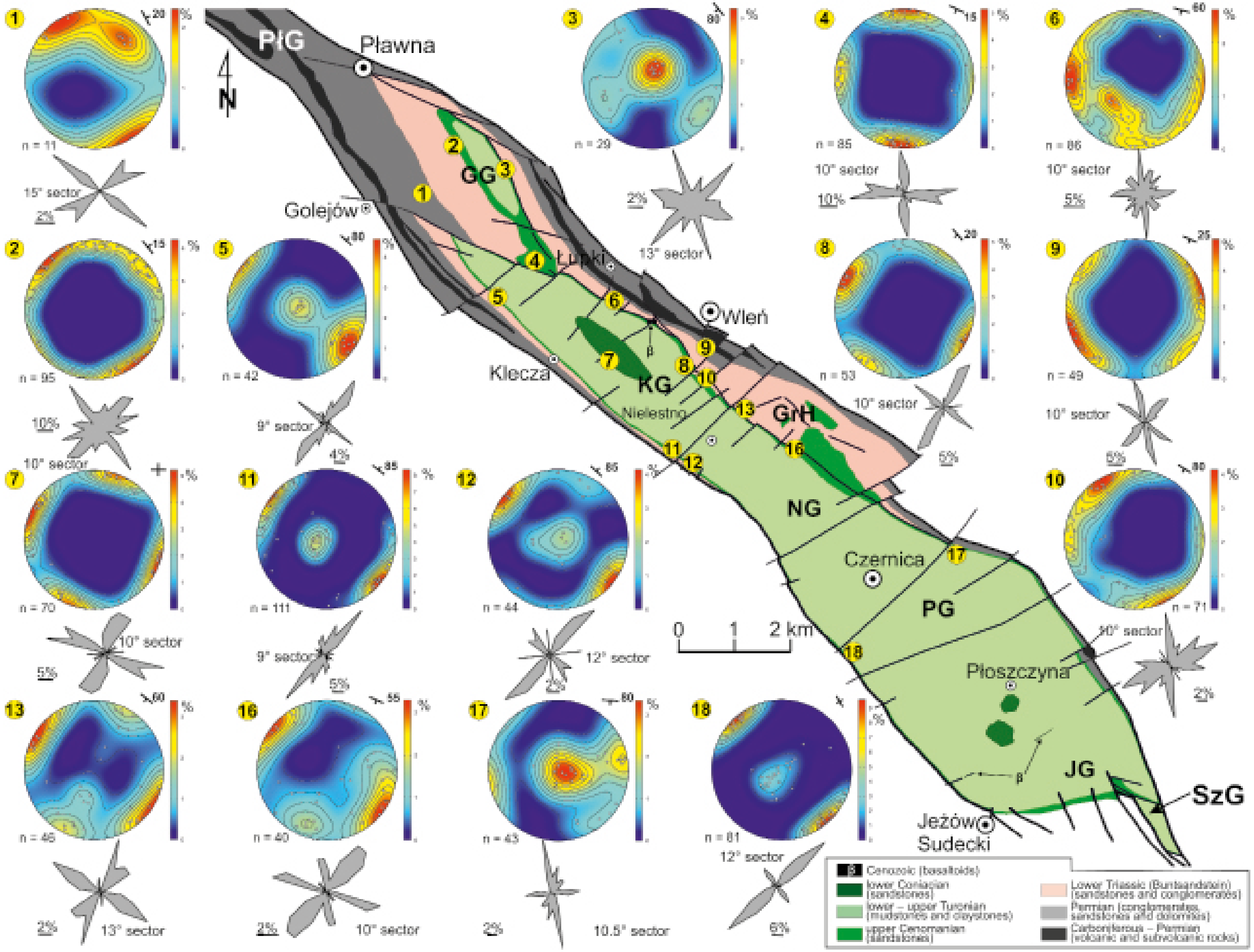


Fig. 4. Stereographic plots of poles to joints in sedimentary rocks of the Wleń Graben superimposed on the simplified tectonic map. Poles are shown as both points and contours (lower hemisphere, equal-area projection). Rose diagrams (circular frequency polygon diagrams) of joint strikes are superimposed on each plot (n – number of measurements at each site). Class intervals (°) and width of the sectors (%) are described beneath each rose diagram. The mean orientation of bedding at each locality is presented with a strike-and-dip symbol in the upper right.

Northern Wleń Fault and Southern Wleń Fault) and were observed in the upper Cenomanian sandstones exposed in several abandoned quarries (localities 5, 11, 12, 18, 20; Fig. 2A–C). In the well-exposed vicinity of the Southern Wleń Fault, near the villages of Łupki II, Nielestno and Płoszczynka, the normal faults are NW–SE-trending discontinuities, with dips ranging from ca. 60−85° towards the NE (Fig. 5A). The fault planes show a mainly planar or undulating geometry and occur directly on vertically or nearly vertically oriented bedding planes (Fig. 5B) or cut them obliquely (Fig. 5C). The surfaces of these faults commonly are polished and striated, highlighted by thin zones of secondary silicification and displaying the presence of straight slickensides. Well-preserved striations, asymmetric ridges and steps developed on the fault planes clearly indicate the normal-slip component of movements. However, most of these faults also exhibit traces of reactivation and the presence of steps, indicating a reverse sense of motion (see chapter: Reverse faults and thrusts II). However, normal displacement between individual fault-bounded blocks composed of upper Cenomanian sandstones is difficult to estimate in small outcrops; the total throw on these faults in the southern part of the Wleń Graben (Płoszczyna Graben), estimated from cross-sections and drill data (the Płoszczyna-1 borehole), reaches up to 600 m (see: cross-section F-F' on Fig. 2C). The steep, nearly vertical and normal-slip geometry of these discontinuities also is indicated by geophysical surveys (Szałamacha, 1978).

Well-exposed sets of longitudinal normal faults also were observed in the Buntsandstein, exposed in the downfaulted block of the Grodowa Fault zone (localities 9, 10, 14; Figs 2C, 5D). They include vertical and subvertical faults, related to steeply inclined bedding surfaces, displaying a simple or undulating geometry, NW–SW strikes and dips of 50° to 80°. Asymmetrical fault steps and short R-shear fractures observed on fault planes indicate normal movements. Fault breccia and fault gouges occur sporadically in the fault zones. The sets of normal faults are dissected by younger, reverse faults (Fig. 5D).

Transverse, NE–SW- or ENE–WSW-oriented faults, related mainly to joint set J_2 occur infrequently and only locally. Single fault planes were documented in localities, situated in close proximity to the graben boundaries (localities 11, 12, 18; Fig. 2B, C) and rarely in the graben interior, close to regional fault zones (localities 14, 15; Fig. 2B). Transverse faults do not display significant throws; they are usually planar and steeply inclined towards the NW or SE and form conjugate sets with longitudinal faults. Faults with similar geometry have been observed also within the graben interior, in horizontally or nearly horizontally lying Lower Triassic sandstones (locality 14; Fig. 5E, F). A conjugate system of oppositely dipping, NNE–SSW- and NW–SE-trending normal faults occurs there. Faults with a throw in the range of a few decimetres are mainly vertical and dissect the J_2 joint surfaces. Locally (locality 4; Fig. 2A), transverse normal faults occur close to sinistral strike-slip faults (see chapter: Strike-slip faults III). They can be genetically linked with younger phases of deformation.

Reverse faults and thrusts II

Reverse faults were noted at almost all localities near the graben boundaries, both in the Northern and Southern Wleń Fault zones and rarely in the graben interior. Their orientation is approximately the same as the direction of the graben elongation and the strike of its boundary faults (NW–SE striking faults; longitudinal faults below). In several of the outcrops analysed, the reverse faults are represented by reactivated normal faults. Locally, in the nearly horizontally lying sandstones in the central part of the Wleń Graben (Gniazdo Hill, locality 7; Fig. 2B) overthrusts and nearly horizontal slickenlines on bedding planes were observed.

Reverse faults are exposed mainly in the Southern Wleń Fault zone and were observed within the Cenomanian sandstones occurring near the SW boundary of the graben on the eastern slopes of Skowron Hill (SW part of Płoszczyna Graben; localities 18, 20; Fig. 2C). Along this segment of the Southern Wleń Fault, reverse faults usually display a planar geometry and include inclined or vertical, longitudinal discontinuities, with dips ranging at ca. 45−90°, both towards the NE and the SW (Fig. 6A). Towards the main fault plane of the Southern Wleń Fault, minor, gently dipping reverse faults and overthrusts were observed. However, the direct contact between the metamorphic (Kaczawa Metamorphic Unit) and Cretaceous rocks of the Wleń Graben is exposed only in two small outcrops, up to 2 m high, 5 m wide; the reverse character of the main fault is evidenced clearly by overturned bedding in sandstones, which locally dip at even 35° under the overthrusted metamorphic rocks (Fig. 3D). This allows the assumption that a series of dismembered blocks of metamorphic rocks, thrusted over vertically oriented or overturned upper Cenomanian strata, occurs in the area. Well-preserved, usually straight slickensides, asymmetric ridges and steps (see Doblas, 1998) can be found on individual fault planes (Fig. 6A). In the neighbourhood of the Southern Wleń Fault also observed were horizontal and subhorizontal overthrust surfaces, predominantly covered by slickensides and surface irregularities, such as distinct, crescent-shaped fractures ('lunate fractures'; see Petit, 1987; Doblas, 1998) and asymmetric cavities with long axes oriented transversely to the direction of movement. They were formed on the strongly polished surfaces of joint set J_1, which earlier had been rotated to the horizontal or nearly horizontal positions in the drag zone of the Southern Wleń Fault. The total displacements on these structures probably reach several metres.

Common structures within the upper Cenomanian, coarse-grained sandstones exposed in the southern segment of the Southern Wleń Fault, are high- and low-angle shear zones, referred to as deformation bands (e.g., Aydin, 1978; Aydin and Johnson, 1978; Fossen *et al*., 2007). They consist of two oppositely dipping conjugate pairs (sets), inclined at up to 60° towards the SW and NE, respectively (Fig. 6B). They usually are parallel to the bedding bisecting plane and exhibit a planar or rarely curvilinear geometry. Deformation bands are locally striated, dip to the SW and show small, centimetre-scale offsets, clearly indicating a reverse-slip or thrust regime. The density of deformation bands increases towards the main fault surfaces.

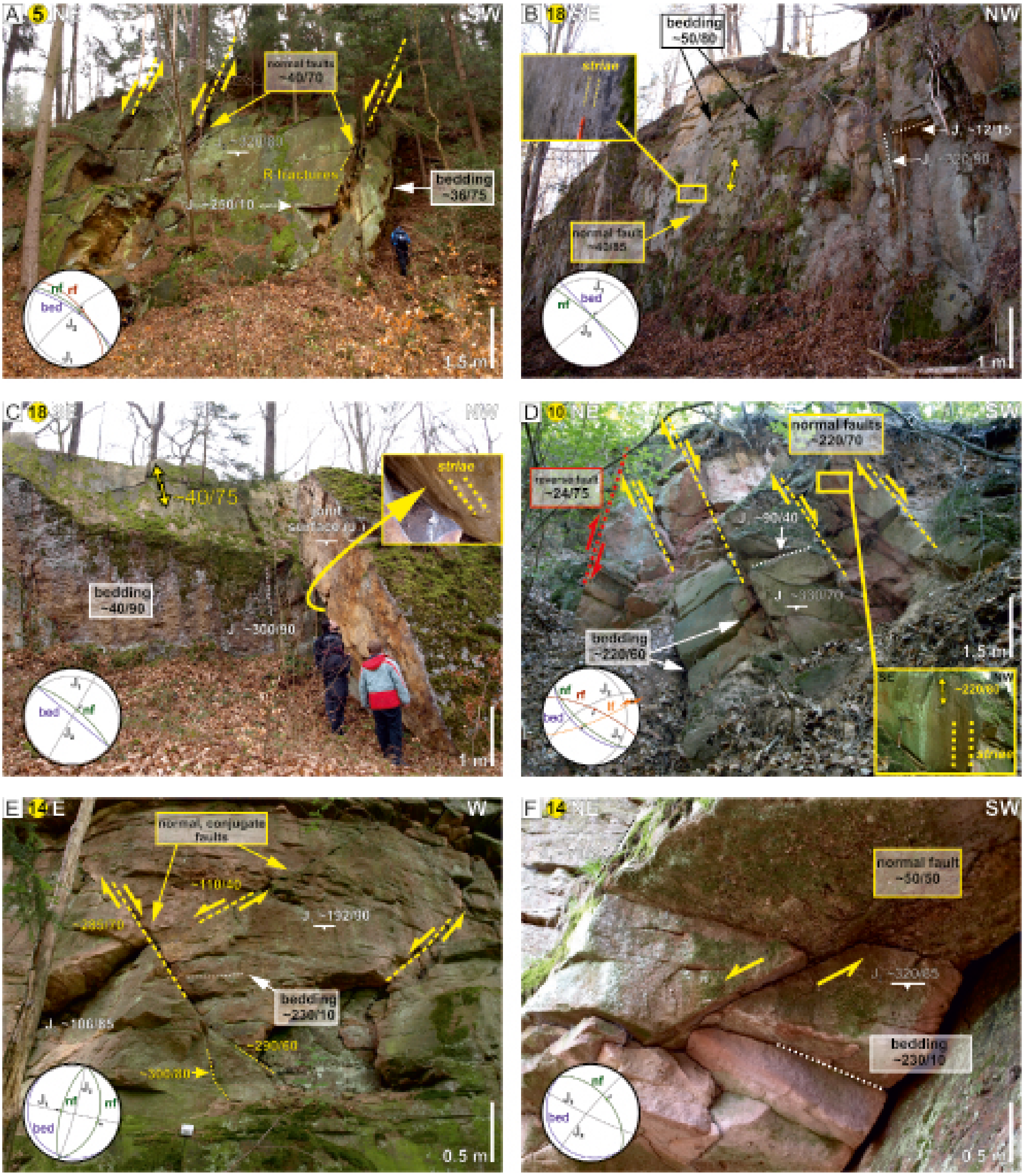


Fig. 5. Field examples of normal faults (population I) cutting the sedimentary rocks of the Wleń Graben. **A.** Sets of planar normal faults (nf on the great circle diagram) occurring directly on steeply inclined bedding planes (bed in the diagram) of upper Cenomanian sandstones exposed along the south-western limb of the Wleń Graben in locality 5. J_1 and J_2 joint sets are marked. Striae (lineation) on fault planes are presented as dots with arrows indicating the sense of displacement of the hanging wall block. **B, C.** Subvertical normal faults occurring on- (B) and cutting obliquely (C) vertically oriented bedding surfaces of upper Cenomanian sandstones exposed along the Southern Wleń Fault at locality 18. **D.** Sets of planar, subvertical normal faults occurring on the bedding surfaces of Lower Triassic sandstones in the Grodowa Fault zone (locality 10). Fault surfaces displaying well-preserved striations (see inset close-up detail). Normal faults are cut by a younger reverse (rf on the diagram) and strike-slip, sinistral faults (lf on the diagram). **E.** Sets of conjugate normal faults in nearly horizontal Lower Triassic sandstones, exposed in the Grodowa Fault zone (locality 14). **F.** Single normal fault with small offset of up to 0.5 m cutting Lower Triassic sandstones at locality 14. For location of study sites see Figure 2A–C.

Well-preserved planes of reverse faults and thrusts were observed also in the vicinity of Nielestno village, in the central sector of the Southern Wleń Fault, between the Klecza and Nielestno Grabens (localities 11 and 12; Fig. 2B). Reverse faults, which obliquely cut the vertical or overturned beds of upper Cenomanian sandstones (Fig. 6C, D) and Permian conglomerates (Fig. 6E), were encountered there. Well-developed slickensides and transversal steps occur on the surfaces of these faults, locally cut by younger, NE–SW-oriented, sinistral strike-slip faults. Overthrusts developed along the nearly horizontal surfaces of set J_1 are associated with steeply dipping reverse faults. They show small offsets, probably reaching up to 1 m. Conjugate sets of deformation bands are also common here.

Well-developed sets of reverse faults and thrusts are concentrated also at several outcrops, located in the vicinity of the Grodowa Fault. For instance, at localities 13 and 16 (Fig. 2B), situated in the NE part of the Nielestno Graben (hanging wall block of the Grodowa Fault), these discontinuities include WNW–ESE-trending overthrusts and reverse faults with dips ranging from 5 to 50°. Slickensides striae observed on fault planes reveal reverse and oblique-slip motion. Systems of conjugate deformation bands with small-scale offsets are associated with the reverse faults. Reverse faults were also observed in the footwall of the Grodowa Fault, within Lower Triassic sandstones exposed within the Grodowa Horst (locality 10; Figs 2B, 5D). They obliquely cut normal faults of population I and are associated with the subvertically oriented bedding planes of sandstones.

Pieces of evidence for deformation in a contractional regime were observed sporadically in the central part of the Wleń Graben. In the flat-lying Coniacian sandstones that crop out on the SW slopes of Gniazdo Hill (locality 7; Fig. 2B), sets of low-angle bedding-plane slip faults (see Adamovič and Coubal, 2012; equivalent to the "horizontal faults" in Angelier's 1994 classification) and arrays of deformation bands were observed. Strongly silicified fault planes of the faults recognised display the presence of straight slickensides indicating subhorizontal or oblique-slip shearing. In single beds of coarse-grained sandstones, conjugate pairs of deformation bands with centimetre-scale displacements occur as well (Fig. 6F).

Strike-slip faults III

Several fault planes with structures diagnostic for horizontal or oblique shear were recorded in the outcrops of sedimentary rocks across the entire Wleń Graben area. On a regional scale, strike-slip faults of population III cut the older fault structures described above, both normal faults I and reverse faults II, indicating a younger stage of deformation within the graben. In some cases, the horizontal or subhorizontal slickenlines observed on fault surfaces are superimposed on older, predominantly reverse faults. Most of the strike-slip faults in general trend NE–SW, perpendicular to the direction of elongation of the graben. They largely include steep, sinistral strike-slip faults with a normal or reverse component and, to a smaller extent, dextral faults, which have been observed in abundance in only one exposure (locality 16; Fig. 2B). The offsets of the correlatable lithostratigraphic units of sedimentary rocks, observed along the strike-slip faults in the Wleń Graben, probably indicate horizontal displacements in the fault zones maximally 200 m long (Fig. 2B).

The largest concentration of strike-slip faults, associated with transverse dislocations cutting the Wleń Graben, may be traced in an abandoned quarry situated in the southern part of the Golejów Graben, on the southern slopes of Radziej Hill (locality 4; Fig. 2A). The damage zone of this fault is well-exposed and consists of numerous NNE–SSW-trending, steeply dipping sinistral faults, which locally display arrays in the form of small-scale flower structures. Fault planes generally are strongly polished with well-developed, gently plunging (mainly towards the SSW and S) slickensides with striae (Fig. 7A). Subvertical and vertical faults are affected by low-angle R-shears, asymmetric steps and crescent or lunar fractures (see Petit, 1987), which apparently suggest a left-lateral nature of the fault motion (Fig. 7A). Fault surfaces that are hardly polished occasionally show the presence of centimetre-scale undulations, such as ridges and grooves (ridge-in-groove type striations; see Lin *et al.*, 2007). Dense jointing in the form of disjunctive, penetrative cleavage with no striae may be observed in close proximity to the sinistral faults (Fig. 7B). Fault breccias and gouges occur sporadically. In map view, the system of faults described displays sinistral separation of vertically oriented Cretaceous sandstones, reaching up to 150 m (cf. Fig. 2B).

Abundant NE–SW-trending strike-slip and oblique-slip faults, cutting the upper Permian, Lower Triassic and Upper Cretaceous (Cenomanian) strata, were documented in the in the footwall and hanging wall blocks of the Grodowa Fault zone. At locality 6, situated in the down-faulted block of the Grodowa Fault, within the Klecza Graben (Fig. 2B), the most commonly observed structures cutting the upper Cenomanian sandstones are NE–SW- to N–S-oriented fault planes of sinistral faults, with fault dips at 45−90°. Fault surfaces display slickensides and other kinematic indicators associated with sinistral strike-slip motion. Striated fault planes with a similar geometry and with a stable, NE–SW trend, crop out also in the vicinity of Wleń, both in the hanging and footwall blocks of the Grodowa Fault (localities 8 and 9; Figs 2B, 7C). Contrary to the faults described above, at locality 16 (Fig. 2B) dextral strike-slip faults occur, trending perpendicularly to the Grodowa Fault trace (Fig. 7D). These faults exhibit a combined pattern with longitudinal or oblique, NW–SE-, WNW–ESE- and N–S-oriented fault planes.

A significant set of sinistral, strike-slip faults was observed in the vicinity of Czernica village, at a locality where the Grodowa Fault connects with the Northern Wleń Fault (locality 17; Fig. 2C). Contrary to the fault planes observed in other localities within the Grodowa Fault zone, faults at this locality strike parallel both to the Northern Wleń Fault and the Grodowa Fault. This deformation shows a consistent, NNW–SSE strike and steep fault planes, which usually dip towards the SW. Abundant strike-slip striations show both sinistral strike-slip and oblique-slip movements. Strike- and oblique-slip faults, oriented perpendicularly to the Northern Wleń Fault, occur less frequently. Locally, synthetic sinistral faults, interpreted here as conjugate R-shears,

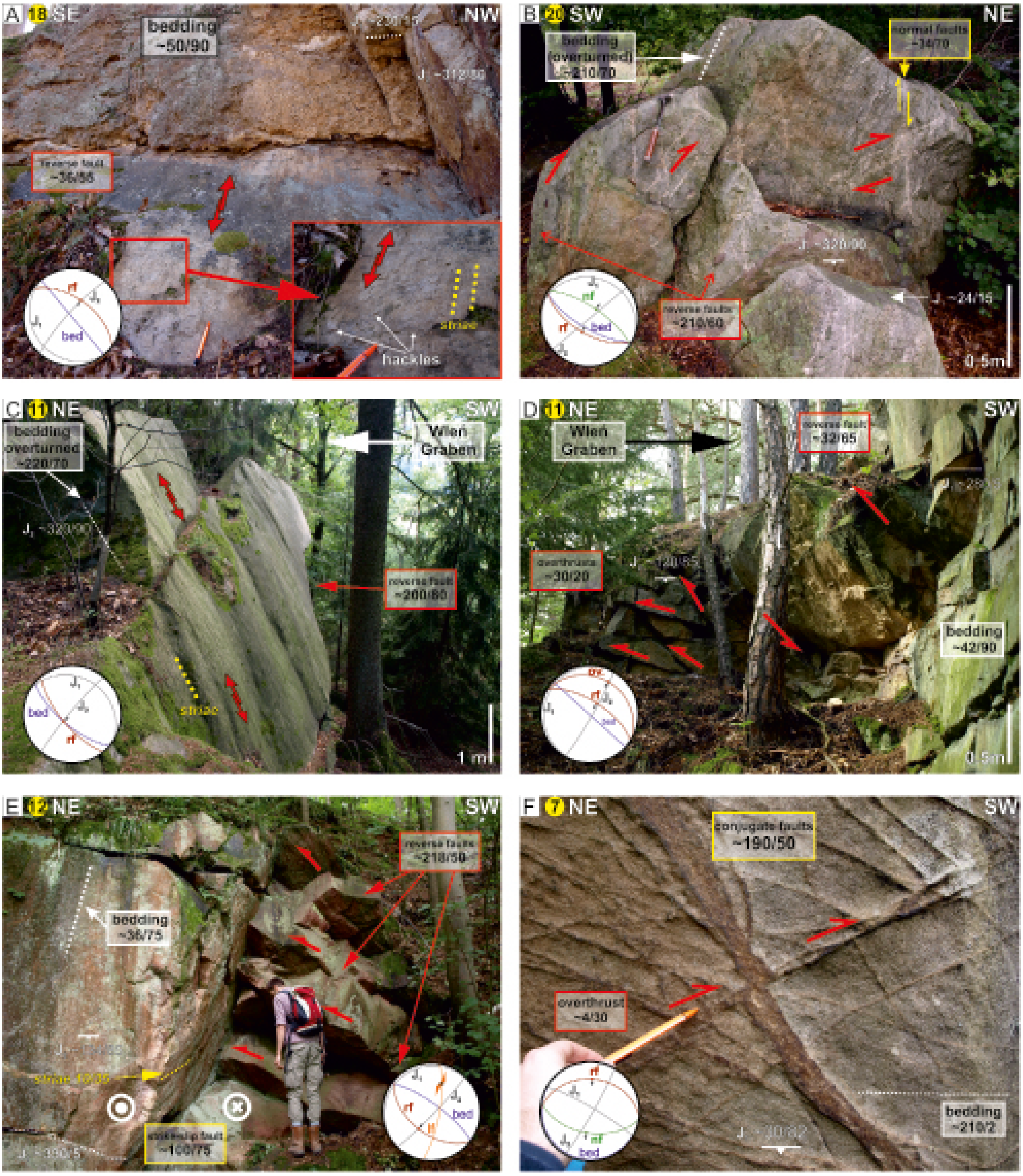


Fig. 6. Field examples of reverse faults cutting the sedimentary rocks of the Wleń Graben. **A.** Reverse fault cutting obliquely vertically oriented bedding planes of upper Cenomanian sandstones and conglomerates exposed along the Southern Wleń Fault at locality 18. The reverse fault represents a reactivated normal dip-slip fault. Note rotation of set J_1 to the nearly horizontal position. **B.** Conjugate sets of oppositely dipping planar shear bands cutting vertically oriented upper Cenomanian sandstones exposed along the Southern Wleń Fault at locality 20. Centimetre-scale offsets of SW-dipping bands indicate their reverse character. **C.** Reverse fault surface with well-developed striations cutting upper Cenomanian sandstones at locality 11. **D.** Striated reverse fault with associated thrusts cutting upper Cenomanian sandstones exposed within the south-western limb of the graben at locality 11 near the Southern Wleń Fault. **E.** Sets of reverse faults delimiting overthrusted packages of Permian conglomerates and sandstones in the Southern Wleń Fault zone near Nielestno at locality 12. Note the younger, sinistral strike-slip fault with well-developed striae cutting reverse faults in nearly vertically oriented sandstones. **F.** Conjugate pairs of deformation bands with centimetre-scale displacements within Coniacian sandstones exposed in the graben interior, Gniazdo Hill (locality 7). For other letter explanations see Figure 5.

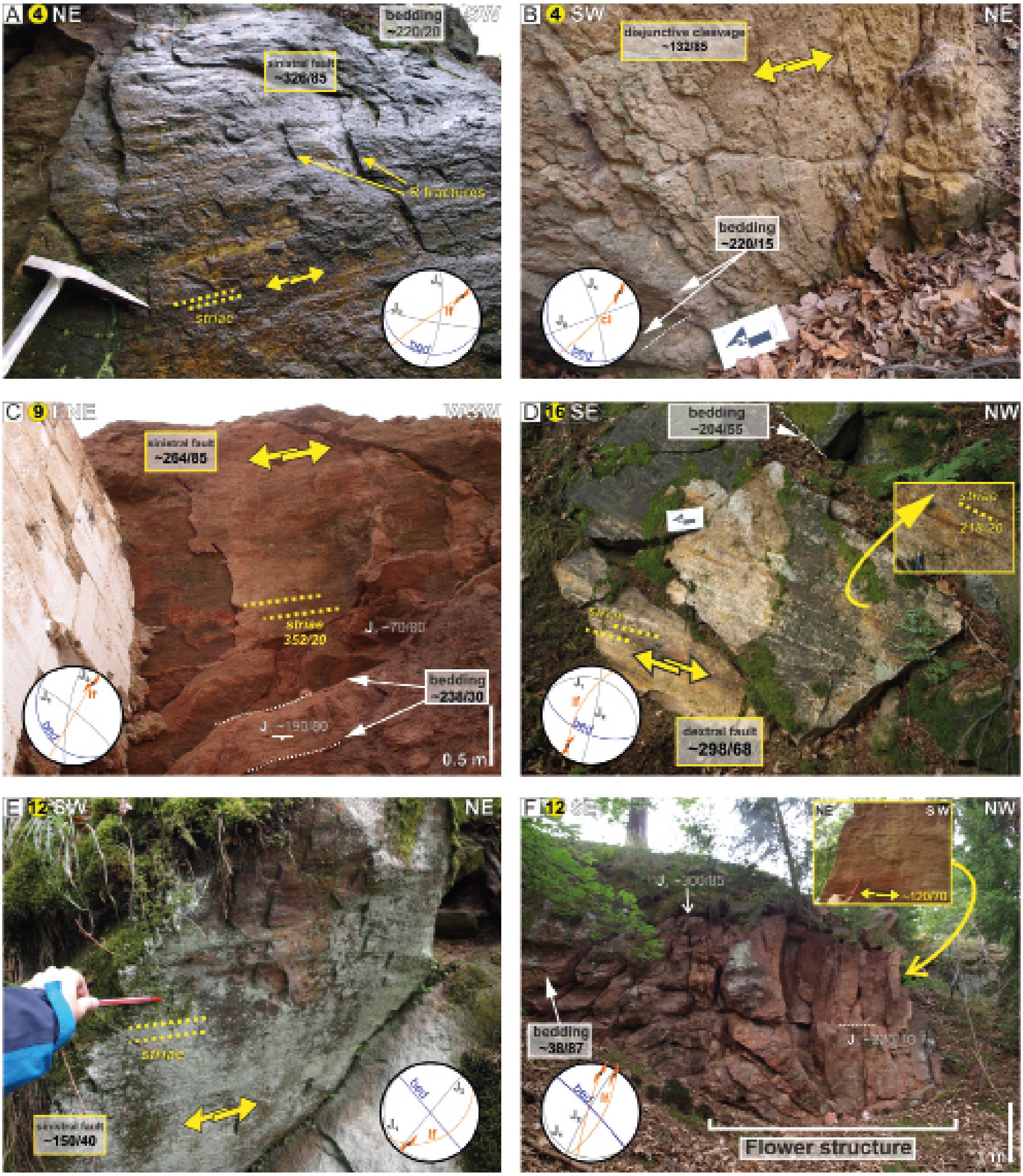


Fig. 7. Field examples of strike-slip faults cutting the sedimentary rocks of the Wleń Graben. **A.** Strongly polished and striated plane of a sinistral fault with well-developed R fractures in upper Cenomanian sandstones, exposed in an abandoned quarry on the western slopes of Radziej Hill (locality 4). **B.** Disjunctive, penetrative cleavage associated with NE–SW-oriented sinistral fault cutting upper Cenomanian sandstones in locality 4. **C.** Plane of a sinistral fault cutting the upper Permian sandstones exposed in the landslide scarp near Wleń (footwall of the Grodowa Fault; locality 9). **D.** Polished and striated surface of a dextral fault cutting steeply inclined upper Cenomanian sandstones in the Grodowa Fault zone (locality 16). **E.** Sinistral fault with well-developed crescent fractures within upper Cenomanian sandstones exposed on the footwall of the Southern Wleń Fault (locality 12). **F.** Small-scale flower structure associated with sinistral faults cutting upper Cenomanian sandstones exposed on the footwall of the Southern Wleń Fault at locality 12. For other letter explanations see Figure 5.

were observed. The fault pattern noted in this exposure indicates that several steep, oppositely dipping fault planes here may have formed a (negative?) flower structure, which trends towards the NNW–SSE.

The smallest number of strike-slip faults with a simple planar geometry, striking perpendicular to the Wleń Graben boundaries, was observed and measured at several localities along the Southern Wleń Fault, mainly in its hangingwall block (localities 11; 12; Fig. 2B). These faults generally are developed along surfaces of joint set J_2 and reveal both dextral and sinistral motion (Fig. 7E). They cut and displace normal and reverse, longitudinal faults and are characterised by slightly polished, NE–SW-trending surfaces with dip angles at 75 to 90º. Locally, fault surfaces are arranged into small-scale flower structures (Fig. 7F) and are affected by slickensides and plumose structures with subtle fringes. Well-developed surfaces of sinistral faults may also be observed in small outcrops of the Permian conglomerates and Lower Triassic sandstones near the Nielestno railway station, situated ca. 100 m to the NE from the Southern Wleń Fault (Fig. 2B). Low-angle surfaces of reverse faults and thrusts II, cut and displaced by strike-slip faults III, occur there (Fig. 6E).

Normal faults IV

The youngest fault structures of generation IV observed in the Wleń Graben are related to an extensional regime. They include normal faults, strictly related to joint surfaces and narrow zones of brecciation associated with them. The fault planes of these faults usually display no evidence of secondary silicification and commonly are accentuated by enrichment in iron oxides. In most of the cases analysed, displacement along these faults does not exceed several tens of centimetres. In some cases, the youngest, normal faults of generation IV are related to mass movement (probably the initial forms of landslides).

Sets of normal faults IV were observed only at a few localities, situated in the graben interior (locality 7; Fig. 2B) and sporadically near the Southern Wleń Fault. The largest concentration of these NE–SW-striking faults was measured in the exposures of Coniacian sandstones on Gniazdo Hill (locality 7; Fig. 2B). These faults are represented by reactivated and sheared, planar, rarely polished, and non-striated joint surfaces. Close to certain distinct fault planes, there occur minor features, such as horsetail splays that show little evidence of displacement, with an offset of not more than a few centimetres (Fig. 8A). The main fault plane is covered with poorly visible steps and the joint surface (set J_2) displays the presence of plumose structures, indicating a purely extensional origin (Fig. 8B). Within sandstones exposed at this locality, sets of listric faults also were noted (Fig. 8C). They include curvilinear, fault surfaces flattened downward and with brecciation zones associated with shearing along J_1 planes in its upper part, and along bedding planes in its lower part. Non-striated faults were also observed at the Skowron Hill (locality 19; Fig. 2C). They include normal faults, which affected the steeply inclined bedding surface associated with the Southern Wleń Fault, as well as joint surfaces of set J_2.

INDIRECT EVIDENCE OF TECTONIC ACTIVITY – GEOMETRY AND FEATURES OF INTRUSIVE VOLCANIC AND SUB-VOLCANIC BODIES

Taking into account the assumption that the geometry and mechanisms of emplacement of magmatic bodies may reflect regional (palaeo) stress conditions during their formation (e.g., Pollard, 1973; Adamovič and Coubal, 1999), analyses and field observations also were performed on distinct intrusions, occurring in the Wleń Graben and in its vicinity. A strict relationship of these intrusions with deeply-rooted faults, which could have been utilised as conduits for magma migration, has been suggested for the study area (Gorczyca-Skała, 1977; Cymerman *et al*., 2011). Attempts at linking the structural and palaeostress analysis with the geometry of intrusive, magmatic rocks also were undertaken by other authors for the NE part of the Bohemian Massif (Adamovič and Coubal, 1999; Coubal *et al.*, 2015).

Several intrusive bodies, which may be linked genetically with regional faults and past tectonic activity, occur in the sedimentary rocks that make up the Wleń Graben and the metamorphic rocks of its shoulders. They include occurrences of narrow, both alkaline and acidic volcanic and subvolcanic intrusions, especially dykes, and minor plug-like bodies, which formed from the late Carboniferous to the early Permian (rhyolites and trachybasalts; Fig. 2C) and – which is most important for the purpose of this study – in the Palaeogene to Neogene (?) (basaltic rocks; cf. Fig. 2A–C).

One of the possible manifestations of the earliest (late Carboniferous‒early Permian) tectonic activity along the present-day boundary faults of the Wleń Graben are systems of rhyolitoid dykes and sills, arranged linearly along the south-western block of the Southern Wleń Fault (locality 18; Fig. 2C). These igneous bodies, at least eight individual dykes, occur in the phyllites and sericite schists of the Kaczawa Metamorphic Unit. The dykes are strongly elongated, NW–SE- and subordinately NNW–SSE-oriented and reach maximum lengths of 350 m and maximum widths of up to 20 m. Rhyolitic clasts, derived from these intrusions, also were found in small outcrops, situated within the brecciation zone (fault core?) of the Southern Wleń Fault (locality 18; Fig. 2C). In addition, rhyolite dyke were drilled in the metamorphic basement of the Cretaceous rocks in the Płoszczyna Graben (Płoszczyna-1 borehole; SPDPSH, 2019), as well as in the south-eastern, elevated metamorphic shoulder of the graben, between the prolongation of the Southern and Northern Wleń faults, on the southern slopes of Szybowisko Hill (561.5 m a.s.l.; Sroga *et al*., 2018). According to Sroga *et al*. (2018), the rhyolitic bodies observed in several boreholes take the form of WSW–ENE-oriented dykes, steeply dipping towards the S and *"may be linked with activity of the Intra-Sudetic Fault"*. In addition, rhyolitic dykes, penetrating the phyllites and chlorite schists of the Kaczawa Metamorphic Unit, were mapped in the hanging-wall (south-western) block of the Northern Wleń Fault (Fig. 2C). They include NE–SW-oriented, linearly arranged bodies with lengths up to 400 m and widths up to

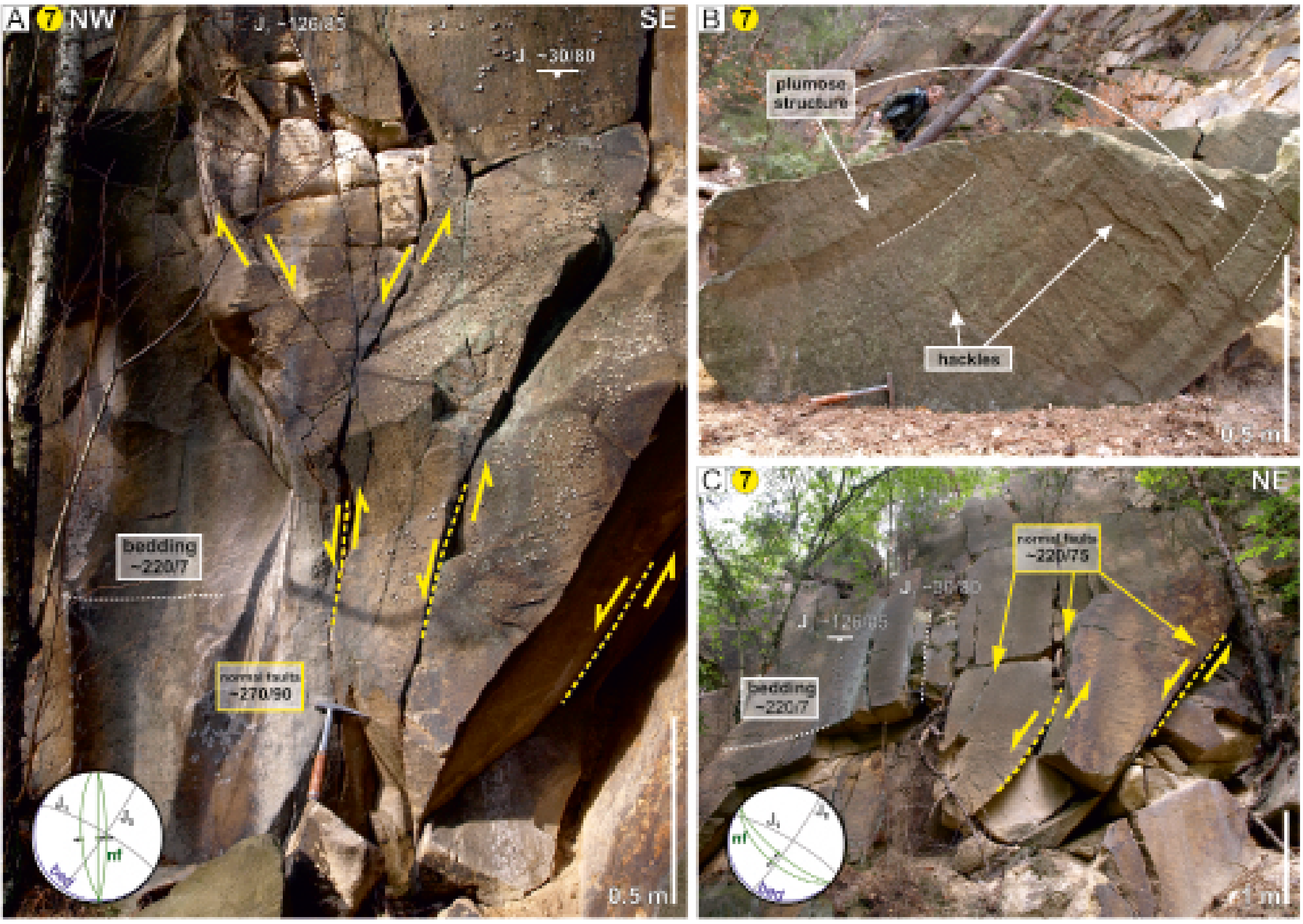


Fig. 8. Sets of normal dip-slip faults (population IV) cutting Coniacian sandstones, exposed in the Wleń Graben interior. **A.** Horsetail splay of fractures related to a normal fault cutting nearly horizontally oriented sandstones on Gniazdo Hill at locality 7. **B.** Plumose structure on the surface of joint set J_1 with visible steps and hackles, indicating small displacement between sandstones blocks (scattered block in an abandoned quarry at locality 7). **C.** Curvilinear, listric fault surfaces related and cutting obliquely J_1 joint surfaces within Coniacian sandstones exposed at locality 7.

70 m, which are perpendicular to the direction of graben elongation (cf. Fig. 2C). Single, plug- or dome-like forms of rhyolitic intrusions, clearly visible in the topography, occur also in the Northern Wleń Fault, reaching ca. 220 x 150 m in size. The presence of a mappable, NW–SE-oriented dyke of massive trachyandesites, 150 x 25 m in size, was determined in the neighbourhood of this rhyolitic intrusion (Fig. 2C).

Occurrences of Cenozoic alkaline basaltic bodies, cutting the sedimentary rocks of the Wleń Graben, have also been observed. Four of these bodies penetrate Cretaceous (lower Turonian) mudstones in the zone of NE–SW-trending faults, separating the Płoszczyna and Jeżów Sudecki Grabens (Fig. 2C). They include strongly elongated, dyke-type intrusions, which attain maximum lengths of 350 m and widths of 20 m. These dykes probably are linked genetically with a NE–SW-oriented Jeżów Fault (cf. Fig. 2C) that also perpendicularly cut the Northern- and Southern Wleń Fault boundary zones. This fault displays a sinistral separation that does not exceed 100 m. Single dykes with a similar geometry and with a length of ca. 100 m were noted by Zimmermann (1932b) near Czernica.

Three subsequent basaltic occurrences are situated also near Wleński Gródek in the Klecza Graben and Grodowa Horst and display a different, nearly isometric shape in map view (Fig. 2B). Probably, they represent fragments of pipe-like volcanic bodies, separated by a NE–SW-trending (strike-slip?) fault. Particularly interesting is the occurrence of nepheline basanites (Wagner, 1961), exposed in an abandoned quarry on an unnamed hill (386 m a.s.l.; Fig. 9A). This occurrence is known in the literature (Wagner, 1961; Gorczyca-Skała, 1977) and is protected as a natural monument. In the eastern part of this outcrop, the basalt contains several metre-scale sandstone xenoliths, which exhibit distinct columnar jointing (Fig. 9B). Xenoliths are composed of porous, thermally altered and partially melted upper Cenomanian sandstones (Fig. 9C), which include quartz grains with sizes up to ca. 1 mm and an almost completely silicified and melted matrix. Straight zones of intense shear, interpreted here as cataclastic deformation bands (Fossen *et al.*, 2007), were observed within thin sections of the sandstone xenoliths (Fig. 9C, D). These zones are characterised by zones of grain-size reduction (quartz grains with sizes up to 0.2 mm), about 0.5 mm wide. The central parts of the

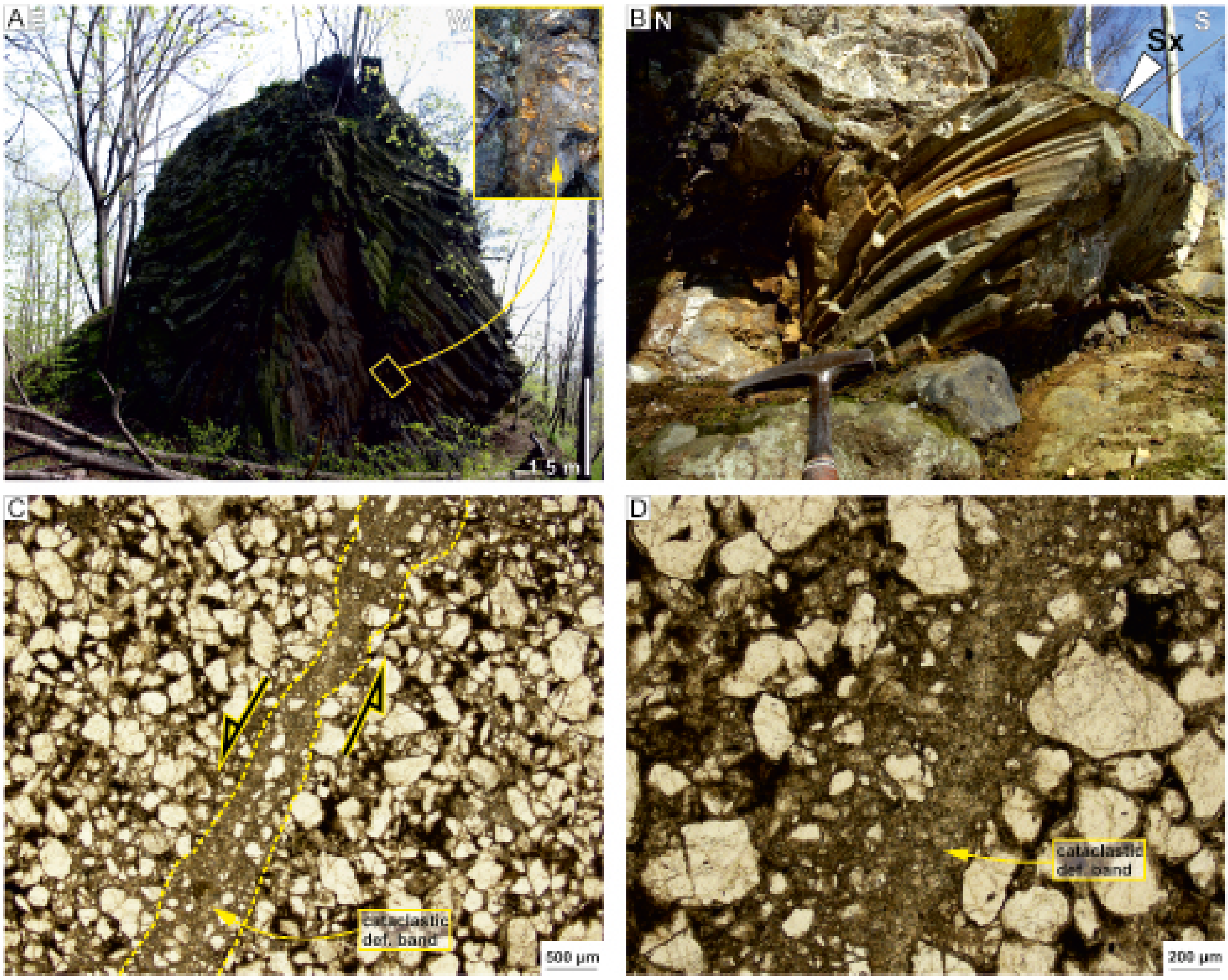


Fig. 9. Mesoscopic and microscopic features of nephelinite basanites from the Wleń Graben. **A.** Outcrop of nephelinite basanites with distinct columnar jointing exposed above the abandoned quarry, situated near Wleński Gródek (cf. Fig. 2B). Note the abundance of yellow sandstone xenoliths (see inset close-up detail) dispersed in the basalt. **B.** Thermally altered, metre-scale sandstone xenolith (Sx) with distinct columnar jointing in the exposure of basanites in Wle**ń**ski Gr**ó**dek. **C.** Microscopic view of thermally altered and partially melted sandstone xenolith. Note the straight cataclastic deformation band cutting the sandstone. Inferred sense of shearing is marked. **D.** Close-up of a cataclastic core of the deformation band surrounded by strongly fractured grains of the sandstone framework deformed during cataclastic flow. Note the distinct reduction of grain size within the deformation band.

deformation bands, referred to as the "cataclastic core" (sensu Fossen *et al.*, 2007), are surrounded by zones of strongly fractured, crushed and rotated quartz grains of the grain framework with numerous intergranular fractures (Fig. 9D). These features support the conclusion that the sandstones occurring as xenoliths were deformed during cataclastic flow processes, linked with the deformation of consolidated sedimentary rocks that earlier had been subjected to complete diagenesis. Therefore, their brittle character should not be linked with thermal changes, as suggested by Wagner (1961), but rather with brittle deformation prior to the basaltic intrusion. Owing to the potential, multi-stage rotation of xenoliths within the volcanic pipe during magma intrusion, it is not possible to reconstruct the primary orientation of the deformation bands. Despite this, these zones represent an important proxy of tectonic activity in the Wleń Graben area prior to the intrusion of basalts.

INTERPRETATION AND DISCUSSION

Structural interpretation and results of palaeostress analysis

On the basis of the superposition and mutual relationships between the documented deformational structures (cf. Fig. 10) and the geometry and spatial relationships between the faults and magmatic bodies, it can be assumed that a complex, at least four-stage development of the Wleń Graben took place from the Late Cretaceous until the present (Fig. 11). The following tectonic events can be distinguished:

1. The initial, extensional stage of the Wleń Graben formation, including displacement along brittle, NW–SE-oriented normal faults (Late Cretaceous);
2. A compressional event, which caused displacement along reverse faults and thrusts with NW–SE and NNW–SSE

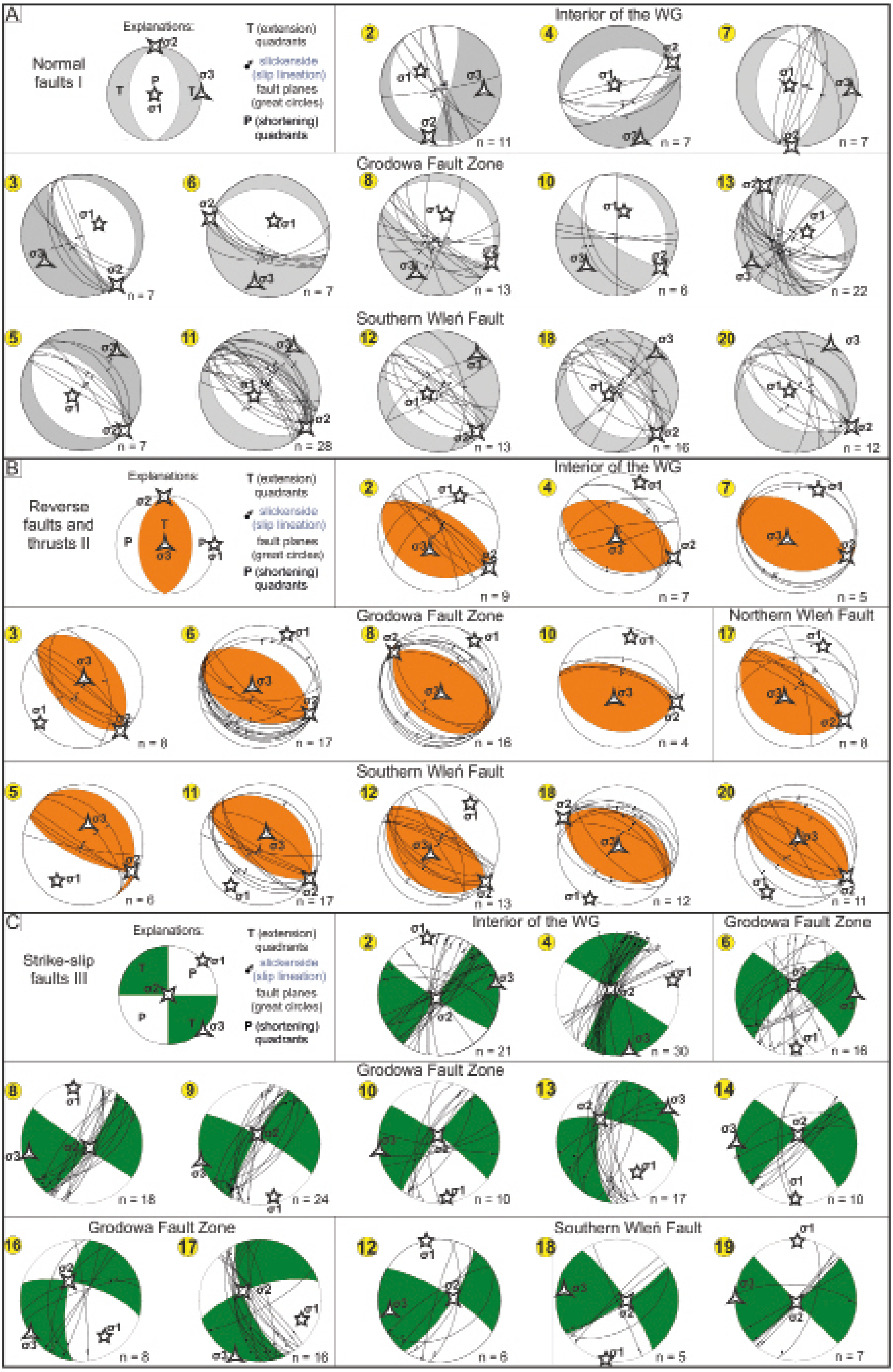


Fig. 10. Results of kinematic analysis of fault-slip data within the Wleń Graben. Fault planes of normal faults I (**A**), reverse faults and thrusts II (**B**) and strike-slip faults III (**C**) are presented as great circles. Striae on the fault planes are presented as dots with arrows indicating the sense of displacement of the hanging wall block. The "beachball plots" obtained from moment tensor analysis show shortening (P) and extension (T) quadrants.

orientations (latest Cretaceous–early Palaeogene). The formation of basaltic dykes with a NE–SW orientation (perpendicular to the Wleń Graben trend), caused by NW–SE extension, was probably linked with this stage (early Palaeogene; ca. 58−60 Ma);

3. A stage of strike-slip deformation, during which perpendicular, NE–SW-oriented, sinistral strike-slip faults were formed, transversely cutting the main structure of the graben (late Palaeogene–Neogene?);
4. A stage of "gravitational collapse" of the tectonic graben structure, recorded mainly in the central part of the graben as high-angle, brittle normal faults and tectonic breccias (Neogene–Quaternary?).

Extensional (1) stage

The role of normal faults in the formation of the Wleń Graben appears to be evident and marks the initial stage of the first, regional-scale, tectonic event, associated with NE–SW-oriented, Late-Cretaceous extension in the south-eastern part of the North Sudetic Synclinorium. It is evidenced by the palaeostress orientation, computed from fault slip data (Fig. 10A), which at most localities analysed point to permanent, NE–SW-oriented extension during brittle normal faulting (faults parallel to the graben elongation; Fig. 10A). Local changes in the orientation of extension are related to small-scale, conjugate normal faults, observed in the central part of the graben (locality 7) and WSW–ENE-oriented faults, probably related to younger strike-slip movements (locality 4). This indicates that the study area was strongly affected by brittle normal faulting before the tectonic event of NE–SW-oriented regional compression, particularly evident in the marginal parts of the Wleń Graben.

All the observed normal faults were formed along the surfaces of tilted bedding planes or/and joint surfaces, predominantly of set J_1, and constitute the oldest, brittle deformation structure in the study area. The earliest stage of development of these faults comprises most probably displacements along and between the most prominent NW–SE-trending faults in the study area – the Northern and Southern Wleń faults, referred to as regional faults. These faults probably were already active at least as early as in the terminal phases of the Variscan orogeny in the rocks of the Kaczawa Metamorphic Unit, and reactivated later in the post-Variscan cover. This is evidenced by numerous volcanic and subvolcanic intrusions, especially late Carboniferous to early Permian dykes, arranged parallel to the Northern and Southern Wleń faults. Hence, these dislocations already constituted zones of crustal weakness earlier and were reactivated in an extensional regime during Late and post-Cretaceous times.

The first, Late Cretaceous (Santonian?) stages of graben formation were probably dominated by large-scale bending of blocks, composed of sedimentary and volcanic rocks and their basement (Fig. 11A). This deformation stage was termed by other authors the flexural phase of deformation (Gierwielaniec, 1956; 1998; Gorczyca-Skała, 1977). During Late Cretaceous times, the consolidated strata became gradually steeper and cut by normal faults (Fig. 11B) and then deflected and dragged, owing to friction during the growth of normal faults (e.g., Fossen, 2010). This process, which is evident particularly in the marginal parts of the graben as well as in the Grodowa Fault zone, was strengthened in the next stage of (compressional) deformation. The geometry

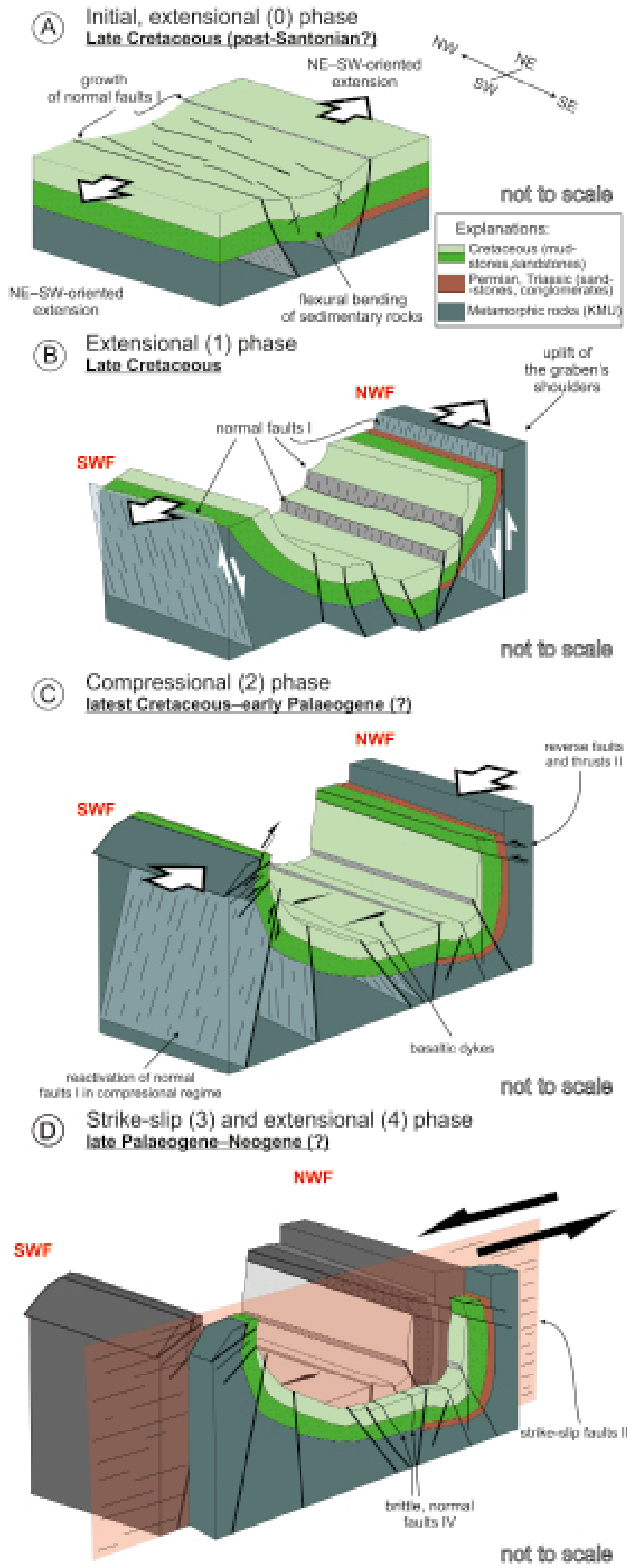


Fig. 11. Schematic depiction of the end-Cretaceous to Cenozoic structural evolution of the Wleń Graben, based on structural analysis and cross-cutting, mutual relationships between the brittle structures.

and structural distribution of normal faults indicates that the extensional stage of deformation controls the present-day graben structure and later episodes of brittle faulting (reverse faulting and sinistral, strike-slip faulting) led to a slight remodelling of the graben architecture. This is confirmed by occurrences of normal faults (without manifestations of reverse faulting), observed at almost all localities in the graben and near its boundaries. The most obvious example of normal faulting is in the southern part of the graben (Płoszczyna Graben; Fig. 2C), where the throw along the steeply inclined, normal fault surface (this fault was reactivated later by reverse faults; cf. Cymerman *et al.*, 2005) reaches almost 600 m. In contrast to previous opinions (Gorczyca-Skała, 1977; Solecki, 1994), the normal faults should not be linked genetically with the compressional, reverse faults, because they occur mostly as individual discontinuities, with no relation to the reverse faults. This also is confirmed by field evidence of normal faults being reactivated by reverse faults and their cross-cutting, mutual relationships.

Compressional (2) stage

The oldest population of normal faults I is overprinted- and cross-cut by younger, compressional-mode structures, including high-angle, reverse faults and thrusts II. These brittle structures mostly cross-cut obliquely normal faults or were formed during reactivation of these faults and indicate the phase of tectonic inversion of the Wleń Graben, which took place probably from latest Cretaceous to early (?) Palaeogene times. This tectonic episode was correlated previously with the so-called "Laramian phase" of the Alpine orogeny (cf. Stille, 1924, 1925; Solecki, 1994). The regional, compressional regime in the Wleń Graben area is confirmed by the results of kinematic analysis of reverse faults (Fig. 10B), which point to NE–SW- and locally WNW–ESE-oriented, subhorizontal compression along the Southern and Northern Wleń faults, as well as minor, parallel faults. Apart from the measured reverse faults, the most distinct mappable evidence for compressional deformation in the study area are blocks of the Kaczawa Metamorphic Unit basement overthrusted onto Cretaceous (upper Cenomanian) rocks of the Wleń Graben in its south-western part (Fig. 3D). This fact, noted already in the 19th century (Kunth, 1863), is to the present day considered as the proven manifestation of a compressional deformation regime (Solecki, 2011).

Most of the observed reverse faults developed on structural surfaces, previously faulted in an extensional regime. Thus, the oldest stage of development of contractional faults included the reactivation of normal faults, followed by a phase of low-angle thrusting, affecting the earlier rotated joint surfaces (Fig. 11C). This process was strengthened in the next step of regional compression and is particularly evident in the southern part of the graben, resulting in the overturning of the sedimentary rocks. Drag and deflection structures occurring within the south-eastern segment of the Southern Wleń Fault show steep dips and overturning of bedding, increasing towards the boundary fault (Fig. 2C). During the strongest compressional events, packages of metamorphic rocks also were sheared and overthrust on a small scale over the sedimentary rocks of the Wleń Graben. Regional-scale flanking structures co-occur with zones of intense silicification and brecciation of quartz grains, also on a micro scale. They generally include conjugate sets of shear bands, pointing to directions of compressional movements similar to those obtained from fault slip data (Figs 6B, 10B).

Compressional stress probably was transferred also onto the central parts of the Wleń Graben. This is evidenced by subhorizontal shear and sets of low-angle, bedding-plane-slip-type faults found in locality 7 (Figs 2B, 6F).

Strike-slip (3) stage

The sinistral and to a lesser extent dextral strike- and oblique-slip faults, oriented perpendicularly to the direction of graben elongation, postdate the main stage of compressional deformation in the study area. The palaeostress pattern, computed from fault-slip data in the Wleń Graben, displays a relatively uniform N–S- to NNW–SSE-oriented and minor NW–SE- oriented direction of the main stress axis (σ_1) during the episode of strike-slip faulting (Fig. 10C). This palaeostress was responsible for the distinct segmentation of the main, NW–SE-trending regional faults by transverse faults (Fig. 2A–C). The strike-slip faults cut and displace both normal faults I and reverse faults II. However, it should be not excluded that the strike-slip stage of Wleń Graben development was related to a compressional (2) event as well as to an independent, younger phase of (transpressional?) faulting, not linked with the compressional regime.

Macroscopic fault planes, formed during the regional phase of strike-slip deformation, exhibit prominent, horizontal or nearly horizontal arrays of slickensides, with well-developed ridge-in-groove-type striations (Lin *et al.*, 2007). The locally occurring disjunctive cleavage and distinct R-shears with no evidence of prominent displacement correspond with these fault surfaces, related to NE–SW-oriented regional shearing. However, the presence of regional-scale strike-slip faults was confirmed by structural analysis in outcrops; their occurrence was also confirmed by mapping (Fig. 2). Map-scale evidence of NE–SW strike-slip faulting include regional faults that occur in the marginal parts of the graben, where sedimentary strata were dragged and rotated to vertical positions, owing to normal and reverse faulting. Thus, in the marginal parts of the graben, the true maximum horizontal displacement may be estimated directly from the sinistral separation of the stratigraphic units. These displacements, measured on a map scale, do not exceed 200 m. Strike-slip movements also are evidenced by the anticlockwise rotation of joint sets in the closest vicinity of the mapped and measured discontinuities observed, e.g. at localities 4, 6, 9, 10 (see circular frequency polygon diagrams in Fig. 4).

Dextral strike-slip and oblique-slip faults were measured in the Wleń Graben only locally (locality 16), especially in the Grodowa Fault Zone, and trend parallel to this fault zone. Although dextral strike-slip faults are not very common in the outcrops, this does not imply that there was no right-lateral shearing in the Wleń Graben area. For instance, the rhomb-shaped geometry of the Golejów Graben on a map scale (Fig. 2A) may indicate its formation under strike-slip conditions. Unfortunately, boundary faults of this subunit are poorly exposed and therefore the hypothesis cannot be verified. It is worth noting that the possibility of a dextral strike-slip character of this dislocation also was suggested by Milewicz (1997).

Extensional (4) stage – gravitational collapse

Brecciation zones and brittle, non-striated normal faults reflect the latest, gravitationally induced phase of Wleń Graben development, also postulated by Solecki (1994, 2011). Gravitationally induced deformation probably is linked with the formation of the graben structure and thus emergence of a morphological gradient between the elevated flanks of the graben and its interior. This led to the reactivation of joint surfaces in an extensional regime as well as previously developed faults and brecciation zones related to them. In the central part of the graben, reactivation of joints, both of sets J_1 and J_2, was probably caused by lateral spreading of morphologically elevated massifs. Lastly, these deformations may also be linked with the development of the valley network. Therefore, extensional faults should be treated as gravitational collapse structures (sensu Hesthammer and Fossen, 1999) related to the present-day morphology, rather than to tectonically induced ones. Manifestations of such deformation also include landslides, occurring in the study area, particularly in the middle part of the Wleń Graben (Kowalski, 2017b, 2018; Kowalski *et al*., 2018b). Their development was initiated probably along older faults and fault zones. However, the possibility should not be excluded that the development of brittle, normal faults is related to a subsequent, initial extensional (tectonic) phase of graben development.

Regional implications

Owing to its location in the southernmost, terminal part of the North Sudetic Synclinorium, the Wleń Graben is a crucial area for understanding and deciphering the deformational history of the post-Variscan sedimentary cover in the Sudety Mts. Despite the fact that the compressional stage of development was considered by previous authors to be the key phase of development of the entire graben structure (cf. Gorczyca-Skała, 1977; Solecki, 1994, 2011), the results obtained in this study differ considerably from previously proposed tectonic models.

It is widely considered that during the Late Cretaceous (85−66 Ma), the entire area of the Bohemian Massif and its NE flank underwent regional-scale uplift and exhumation, which led to the formation of regional-scale horst-and-graben systems (Malkovský, 1987). It also is accepted widely that the reactivation of pre-existing faults in this area finds its expression in the palaeogeographic and tectonic inversion of several sedimentary basins, located in and on the peripheries of the Bohemian Massif (Malkovský, 1987; Schröder, 1987; Ziegler *et al*., 1995), including both the North- and Intra-Sudetic Synclinoria. This phenomenon was linked with the inversion stage of post-Variscan sedimentary basins in the NE Bohemian Massif (Bergerat, 1987; Ziegler *et al*., 1995; Kozdrój and Cymerman, 2003; Mazur *et al*., 2005; Ziegler and Dèzes, 2007; Kley and Voigt, 2008). The process of Late Cretaceous progressive uplift of the Bohemian Massif also is strongly evidenced by thermochronological data obtained, e.g., from the Eastern Sudetes, which point to a record of regional, rapid cooling of Cretaceous deposits, which previously were buried at significant depths of ca. 4 km (Aramowicz *et al*., 2006; Danišík *et al*., 2012; Botor *et al*., 2019; Sobczyk *et al*., 2020). These rapid changes in thermal regime, however, at the same time indicate a relatively high exhumation rate (ca. 300m/Ma) for the Cretaceous succession (Danišík *et al*., 2012).

The results of palaeostress analysis of compressional structures in the study area partially correspond to those obtained from other regional fault structures dissecting the NE part of the Bohemian Massif (Malkovský, 1987; Cymerman, 1990, 1998a; Don and Gotowała, 2008; Sippel, 2009; Sippel *et al*., 2009; Coubal *et al*., 2014, 2015; Nováková, 2014). For example, in the fault zone of the Main Lusatian Fault, one of the most prominent brittle-fault structures in the NE Bohemian Massif, a series of polygenetic faults and thrusts related to compressive stress were observed (Coubal *et al.*, 2014, 2015).

A separate, very important regional issue is the cause and origin of NE–SW-oriented basaltic dykes, developed initially as deep fissures for the emplacement of basaltic magmas. Two tectonic scenarios may explain this process: (1) general, NW–SE-oriented regional-scale extension, corresponding with, for example, strike-slip movements; or (2) NW–SE-oriented extension, caused by NE–SW-trending shortening processes related to compressional stress. According to the results of the structural analysis presented here, the second scenario is more plausible, owing to the fact that the basaltic dykes occur mainly in a region, where reverse faults are abundant. The orientation of dykes is consistent and parallel to the principal stress axis (σ_1), obtained for the compressional (2) stage of the graben development. A similar hypothesis was suggested earlier (Gorczyca-Skała, 1977) and a similar mechanism of development of basaltic-group intrusions was also proposed for the vicinity of the Main Lusatian Fault (cf. Scheck *et al.*, 2002; Coubal *et al.*, 2015). Coubal *et al.* (2015) give examples of dykes of the polzenite-group volcanics, which are oriented transversely to the trace of the NW–SE-oriented Main Lusatian Fault, and were interpreted to have been developed in a reverse fault regime. Strike-slip faults are extremely rare within this segment of dislocation (Coubal *et al*., 2015), as in the southern part of the Wleń Graben. Hence, deep tensional fractures that led to the formation of basaltic intrusions may have formed as a direct result of NW–SE-oriented extension during the NE–SW compressional event of Wleń Graben development. Dykes, cross-cutting Wleń Graben basement rocks, have been dated and thus are the only indirect benchmark indicating a stage of compressional tectonic deformation in the graben. Deformation bands found in sandstone xenoliths in the basalt neck at the Wleński Gródek locality point to tectonic activity prior to the time of intrusion. Although this basaltic occurrence was never dated, a similar occurrence of basaltic rocks near Jeżów Sudecki (southernmost part of the Wleń Graben) was dated as early Palaeogene (Paleocene; Badura *et al*., 2006). If it may be assumed that the basaltic neck preserved in Wleński Gródek has a similar age, then the tectonic activity in the present-day Wleń Graben area could have commenced in the early Palaeogene.

This paper for the first time indicates a significant role of regional-scale sinistral strike-slip faulting in the deformation of the primary graben structure and probably of the entire North Sudetic Synclinorium area. Strike-slip deformation was probably initiated in the late Palaeogene or early (?) Neogene times and resulted in subdivision of the graben into segments, separated by NE–SW-trending dislocations. This stage of deformation corresponds to the views of Cymerman (1999), who pointed to sinistral, transpressional deformation in the entire Sudety Mts. area during the Miocene as indicating a stress field, dominated by the NNE–SSW- to NNW–SSE-oriented direction of the principal stress axis (σ_1). Cymerman (1999) also showed that the development of NE-SW-trending sinistral, strike-slip faults caused the formation of numerous folds and reverse faults, observed, e.g. in the N part of the North Sudetic Synclinorium (e.g., Raciborowice Górne locality).

However, the issue of large-scale NW–SE-trending strike-slip movements in the Wleń Graben remains unsolved. The possibility of late Carboniferous−early Permian sinistral strike-slip displacements along the nearby Intra-Sudetic Fault, has been suggested (cf. Aleksandrowski, 1998; Cymerman, 1998b). Nevertheless, post-Cretaceous strike-slip deformation along boundary faults of the Wleń Graben remains speculative. There are no manifestations of NW–SE-oriented shearing in the outcrops, located along the Southern Wleń Fault, and the observed kinematic indicators on the fault surfaces point only to normal and then reverse movements. It may be assumed, however, that evidence of strike-slip deformations is not visible, owing to its overprinting by younger deformation, but there are no data to confirm this idea. Distinct, left-lateral, NW–SE-oriented faults observed along the Grodowa Fault are sporadic. They may be the result of minor, transpressional movements related to the compressional stage of evolution of the graben. It is also not clear if brittle displacements along the Southern Wleń Fault correspond to those along the Intra-Sudetic Fault. Therefore, although the subbasins and grabens, situated within the North- and Intra Sudetic Synclinorium, display distinct features pointing to their strike-slip, mainly transtensional origin (cf. Uličný 1999, 2001; Grygar and Jelinek, 2003; Wojewoda, 2007, 2009; Wojewoda *et al*., 2016; Kowalski, 2017a), this is not evident in the study area.

CONCLUSIONS

The Wleń Graben is one of the best examples of end-Cretaceous to Cenozoic brittle faulting in the NE Bohemian Massif. Multiphase, tectonic processes resulted here in the development of a tectonic graben, bounded by steep, NW–SE-oriented, normal and reverse faults. This led to the preservation of almost the entire post-Variscan sedimentary succession, encompassing upper Carboniferous/lower Permian to Upper Cretaceous strata.

A revised subdivision of the Wleń Graben into tectonic subunits as well as several cross-sections oriented perpendicular to the graben boundaries, were constructed for the first time on the basis of borehole data and GIS-based detailed mapping surveys. This allowed the reliable and precise recognition of the geological structure of this unit. Although the area of the Wleń Graben was the subject of intensive research by many generations of geologists, its structure was interpreted as a result of simple, NE–SW-oriented progressive compression, which took place between the Late Cretaceous and Neogene.

The present mapping survey and structural study indicated a four-stage tectonic development of the graben since the Late Cretaceous (post-Coniacian). The first tectonic stage included the development of the main structure of the tectonic graben with a NW–SE orientation, due to the propagation and growth of NW–SE-oriented normal faults (1). This stage was probably preceded by large-scale bending and folding of sedimentary and volcanic rocks, due to basement block movements. The subsequent deformation stage comprised (2) a compressional event with a NE–SW or locally N–S direction of the principal stress axis (σ_1) and the formation of reverse faults or overthrusts (latest Cretaceus–early Palaeogene). A structural and tectonic connection between the emplacement of basaltic magma (early Palaeogene; ca. 58−60 Ma) and compressional NE–SW-oriented regional (palaeo) stress conditions is suggested. The next (3) phase of tectonic development included strike-slip movements, during which sinistral, NE–SW-oriented faults were formed (late Palaeogene–Neogene (?)). This graben structure was subjected to the last (4) phase of "gravitational collapse" (Neogene–Quaternary), which consisted of slight displacements along brittle normal faulting in an extensional regime. Evidence of almost all these deformations in the Wleń Graben area were observed in the boundary fault zones, indicating their multiphase character and polygenic origin. Indirect conclusions on the tectonic activity of the graben were drawn from the analysis of sandstone xenoliths, found in basaltic rocks, as well as the age of basaltic dykes occurring in the southernmost part of the graben (Jeżów Sudecki locality). Taking into account the limitations and doubts in dating the deformation phases, all stages of graben development mentioned above can be distinguished only on the basis of the mutual relationships between the documented brittle structures, whilst their real timing still remains an unsolved problem.

A separate issue, strictly linked with extensional- and compressional phases of deformation, are flanking structures related to marginal faults. The development of these structures concentrated along the main faults of the Wleń Graben, the Southern and Northern Wleń faults, and probably originated during the normal faulting phase, possibly continued during the compressional stage of deformation. The small sizes of the exposures and the lack of borehole data in the marginal parts of the graben do not allow a full and precise reconstruction of their geometry. Recognition of the detailed structure of the marginal parts of the graben requires detailed geophysical surveys, such as seismic reflection methods.

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