


Post – Conference excursion guide

Late- to post-Variscan structural evolution of tectonic grabens on top of the Góry Sowie Massif

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The area situated at the NE margin of the Bohemian Massif (BM), located between the Middle Odra Fault in the NE and the Upper Elbe Fault Zone in the SW (Fig. 1), and traditionally referred to as the Sudetes (e.g. Aleksandrowski et al., 1999; Don and Żelaźniewicz, 1990; Kryza et al., 2004; Mazur et al., 2006), exposes a mosaic of fault-bounded, multiply deformed, Variscan crystalline basement units covered by unmetamorphosed rocks of lower Carboniferous (Mississipian) to Upper Cretaceous age. In the Sudetes these sedimentary-volcanic successions are preserved within large-scale synclinorial structures as well as smaller, but still kilometre-scale grabens (Don and Żelaźniewicz, 1990; Głuszyński and Aleksandrowski, 2022; Solecki, 1994). These features are usually downthrown or downfolded into the Variscan crystalline basement. Apart from the two main synclinorial structures located in the Sudetes – the Intra-Sudetic and the North-Sudetic synclinoria (Augustyniak and Grocholski, 1968; Dziedzic and Teisseyre, 1990; Nemec et al., 1982; Solecki, 1994), the late Paleozoic sedimentary successions occur locally on top of the crystalline Variscan basement. Remnants of once much more widespread Carboniferous sedimentary succession are preserved on top of the Góry Sowie Massif (GSM) – a high- to medium-grade metamorphic unit, situated in the Central Sudetes (Cymerman, 1998; Grocholski, 1967; Żelaźniewicz, 1987). The GSM is a triangular-shaped, fault-bounded unit (Fig. 1) composed of migmatitic paragneissess, with subordinate orthogneiss, metabasite and felsic granulite bodies (Grocholski, 1967; Gunia, 1999; Jastrzębski et al., 2021; Tabaud et al., 2021; Żelaźniewicz, 1990, 1987). The paragneisses of the GSM originated probably from flysch-like graywackes as well as pelitic sediments of middle to early Cambrian age (Gunia, 1999; Tabaud et al., 2021; Żelaźniewicz, 1987), whilst magmatic protolith of orthogneiss is dated at the late Cambrian to Early Ordovician (Kröner and Hegner 1998; Kryza and Fanning 2007). The rock protolith of gneisses was metamorphosed under amphibolite facies conditions at c. 380-370 Ma (Van Breemen et al., 1988), whereas felsic granulite and peridotite bodies had undergone earlier (at c. 400 Ma; Brueckner et al., 1996; O'Brien et al., 1997), ultra high pressure–high temperature (UHP–HT) granulite facies metamorphism.

Metamorphic processes had ceased in the Late Devonian (Cymerman, 1998; Jastrzębski et al., 2021; Żelaźniewicz, 1987) and were followed by rapid exhumation of the massif at the end of the Devonian (Bröcker et al., 1998; Żelaźniewicz, 1987).

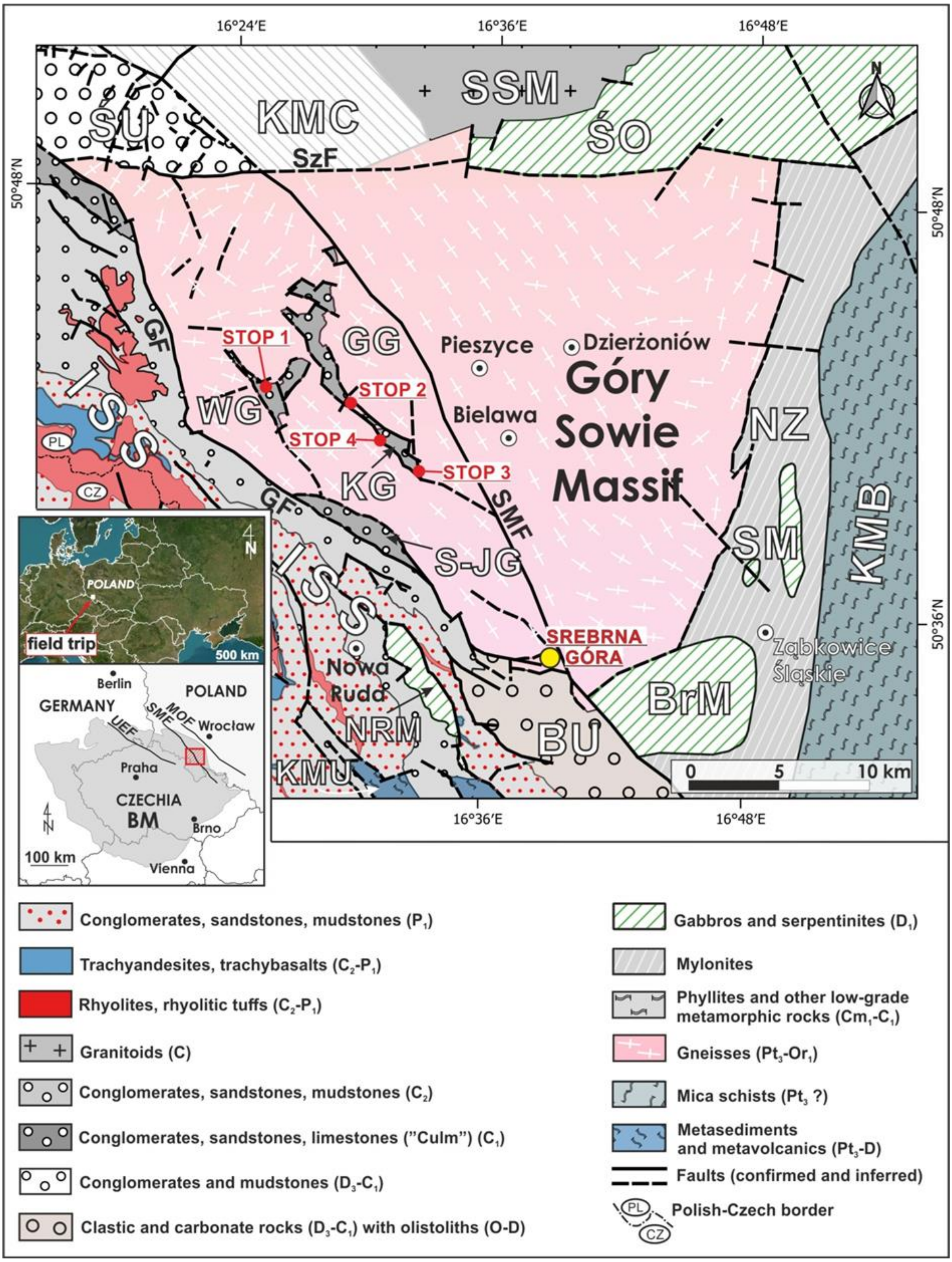

Fig. 1. Tectonic sketch map of the Góry Sowie Massif and surrounding tectonic units (compiled after Sawicki, 1995 and based on author's own data), together with their location in the Bohemian Massif and Central Europe (inset). Abbreviations: BrM – Braszowice Ophiolite Massif, BU – Bardo Unit, GG – Glinno Graben, ISS – Intra-Sudetic Synclinorium, KG – Kamionki Graben, KMB — Kamieniec Metamorphic Belt, KMC – Kaczawa Metamorphic Complex, KMU – Kłodzko Metamorphic Unit, NRM – Nowa Ruda Ophiolite Massif, NZ – Niemcza Shear Zone, S-JG – Sokolec-Jugów Graben, SM – Szklary Ophiolite Massif, SSM – Strzegom-Sobótka Granitoid Massif, ŚO – Ślęża Ophiolite Massif, ŚU – Świebodzice Unit, WG – Walim Graben. Faults: GF – Głuszyca Fault, SMF – Sudetic Marginal Fault, SzF – Szczawienko Fault.

The Góry Sowie Massif is currently interpreted as an allochtonous terrane assigned jointly to the Teplá-Barrandian/Bohemian microplate, located close to the northern peripheries of Gondwana during Cambrian–Ordovician (Catalán et al., 2021; Franke and Żelaźniewicz, 2023; Jastrzębski et al., 2021; Tabaud et al., 2021).

The metamorphic unit of the GSM is dissected by NW-SE and NE-SW striking fault zones (Fig. 1; Grocholski 1967; Żelaźniewicz 1987; Cymerman 2004). The most prominent of these is the NW-SE-trending Sudetic Marginal Fault which separates the elevated, southwestern part of the massif (Sowie Mts Block), from its northeastern, downthrown part situated on the Fore-Sudetic Block. To the NW the GSM borders - across the Szczawienko Fault - with the Świebodzice Unit (in the older literature also called the Świebodzice Depression or Świebodzice Synclinorium; Teisseyre 1956; Nemec et al. 1980; Porębski 1981; Porębski 1990) which contains up to 4 km thick succession of strongly deformed and folded, coarse clastic and minor carbonate syn- to late orogenic Upper Devonian (?)–lower Carboniferous sediments. The late orogenic clastic Carboniferous deposits of the Intra-Sudetic Synclinorium as well as the syn- to late orogenic, Devonian(?)–lower Carboniferous sedimentary rocks of the Bardo Unit occur to the west and south of the Góry Sowie Massif, respectively. These units are also bordered by and separated from the GSM by regional-size fault zones (Fig. 1).

Remnants of the Mississipian sedimentary succession resting on top of the GSM are known only from the uplifted Sowie Mts Block located to the southwest of the Sudetic Marginal Fault (Fig. 1). This succession, historically referred to as the "*Culm of the Sowie Mountains*" (Łapot, 1988, 1986; Oberc, 1972; Żakowa and Żak, 1962), is preserved within a number of small, mainly NW-SE trending, fault-bounded grabens and half-grabens. These tectonic units include: the Walim, Glinno, Kamionki and Sokolec-Jugów grabens. Although the remnants of the GSM's sedimentary cover preserved within these grabens have been addressed in several, mainly paleontological and petrographic studies (Łapot, 1986, 1988; Muszer, 2014; Muszer et al., 2016a; Żakowa, 1960, 1966a; Żakowa and Żak, 1962), their structural characteristics have received little attention. The main goal of the post-conference field trip is to discuss the structural evolution of these intriguing tectonic features, which probably represent erosional relics of an originally broader late-Variscan basin system. The field trip stops are located within the Walim (WG; Stop 1), Glinno (GG; Stop 2) and Kamionki grabens (KG; Stops 3,4; Fig. 1).

The Carboniferous sedimentary succession of the Sowie Mountains – lithology and stratigraphy

The Carboniferous strata preserved within the tectonic grabens of the GSM include middle Viséan(?) to Namurian(?) continental and marine deposits (Fig. 2) (Muszer et al., 2016a, 2016b; Żakowa, 1960, 1966a; Żakowa and Żak, 1962). These deposits can be considered as stratigraphic equivalents of the adjacent tectonic units, i.e. the Intra-Sudetic Synclinorium (Dziedzic and Teisseyre, 1990; Mastalerz, 1995; Teisseyre, 1975); the Świebodzice Depression (Nemec et al., 1980; Porębski, 1990, 1981) and the Bardo Structure (Haydukiewicz, 1990; Wajsprych, 1978), and occur within isolated, narrow tectonic grabens or half-grabens (Oberc, 1972).

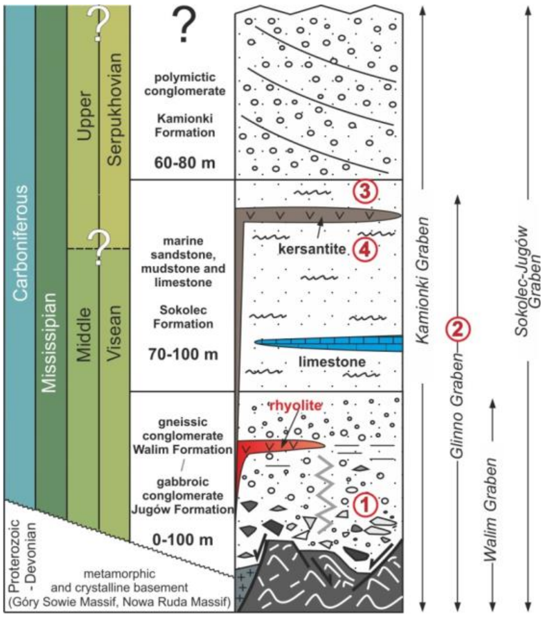

Fig. 2. Simplified scheme showing stratigraphy, lithology, extent and thickness of the sedimentary succession in the tectonic grabens developed on top of the Góry Sowie Massif.

The Carboniferous sedimentary succession of the GSM attains 300 metres in thickness and has been subdivided lithologically into three informal lithostratigraphic members (Łapot, 1986; Żakowa, 1966a; Żakowa and Żak, 1962). The succession begins with poorly sorted, "gneissic" and "gabbroic" conglomerates and sedimentary breccias (Fig. 3) that overlie the GSM metamorphic basement. The name Walim Formation is proposed here for these deposits which are exposed locally over the GSM. The conglomerates are interpreted by the present author as deposits of alluvial fans developed along tectonically active, high-relief margins of a wider intramontane (?) basin. The conglomerates pass upward (and possibly laterally) into marine sandstones and mudstones, up to 100 m thick. Based on findings of macrofauna, these deposits were primarily dated at the late Viséan (Żakowa, 1960; Żakowa and Żak, 1962) whereas Muszer et al. (2016) suggest that they may represent Namurian(?). The marine sandstones and mudstones were previously informally assigned to the Sokolec Beds (Żakowa, 1966b) and currently are referred here to as the Sokolec Formation. The uppermost member of the Carboniferous succession in the GSM consists of a ca. 80 m-thick, Namurian(?) polymictic conglomerate, well exposed in the central and northern sectors of the Kamionki Graben (Żakowa and Żak 1962) and within the Sokolec-Jugów Graben (not described here). The conglomerate, assigned by the present author to the Kamionki Formation, is interpreted as deposit of fan deltas which entered the early Carboniferous basin from the north and north-west.

Fig. 3. Poorly sorted conglomerates of the Walim Formation composed of gneissic and migmatite pebbles and boulders; outcrop near the "Dino" market in Walim (GPS coordinates: 50° 42' 15.64" N, 16° 26' 20.96" E).

Walim Graben

The Walim Graben (WG) constitutes a distinct, irregularly-shaped, fault-bounded tectonic feature, ca. 3 km long and up to 1,3 km wide, which trends from NNW to SSE, mainly along the Walimka stream valley (Fig. 4). The basement and shoulders of the graben are built of Góry Sowie metamorphic rocks, mainly gneisses (biotite gneisses, migmatites and migmatite gneisses; Grocholski, 1965). The boundary fault zones of the graben, referred to as the Western- and Eastern Walim Faults (the WWF and EWF, respectively; Fig. 4), separate the sedimentary fill of the graben from its crystalline-rock shoulders.

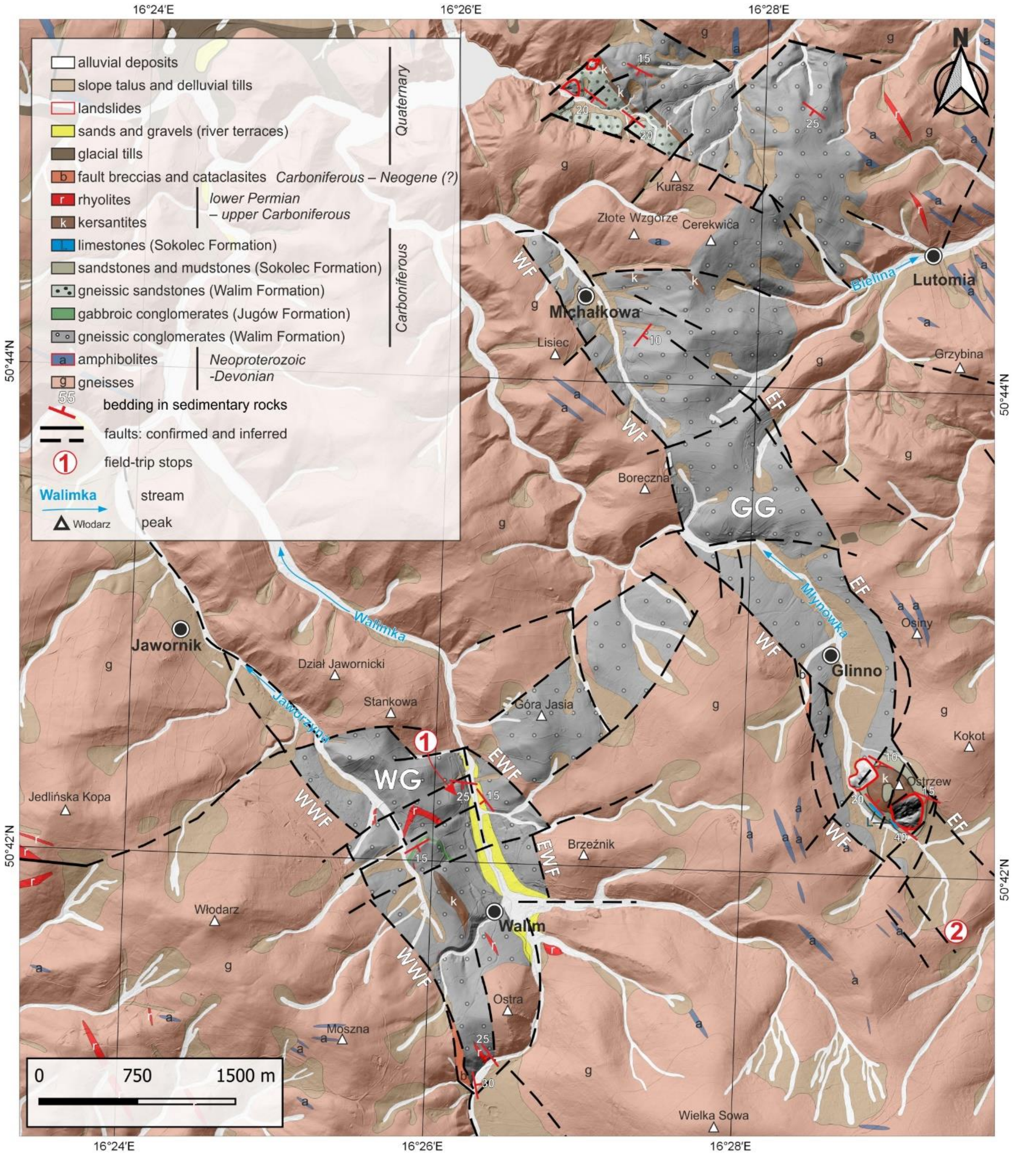

Fig. 4. Geological map of the Walim and Glinno Grabens (for location see Figure 1) showing location of field trip stops. Basement geology simplified from Grocholski (1962); geology of sedimentary rocks based on author's own maps. Extent of Quaternary deposits drawn by Joanna Brytan (PGI-NRI). Abbreviations: GG – Glinno Graben, EF – Eastern Glinno Fault, EWF – Eastern Walim Fault, WWF – Western Walim Fault, WF – Western Glinno Fault, WG – Walim Graben.

The vertical and (possible) horizontal displacement components associated with certain faults cannot be unambiguously determined due to a lack of borehole data. The southernmost part of the WG is a narrow, NNW-SSE trending, fault-bounded block filled with gneissic conglomerates of the Walim Formation and separated to the west from the gneissic basement horst by a cataclasite zone, up to 600 m long and ca. 80 m wide (Fig. 4). In the southernmost part of the graben occurs a narrow dyke of (upper Carboniferous(?)) rhyolitoid, oriented parallel to the graben's margins. The central sector of the graben also exposes gneissic conglomerates and is cut by transverse, WSW-ENE trending faults which do not display significant throws. The gneissic conglomerates dip at 15–25° towards the S and SW (Fig. 4) and interfinger with gabbroic conglomerates of the Jugów Formation (Fig. 4). The entire sedimentary succession of the WG is cut by upper Carboniferous(?) rhyolite and kersantite dykes and sills. Toward the NNW the Walim Graben narrows to a width of ca. 800 m. In the northernmost segment of the graben, its boundary faults probably converge and are buried under the Quaternary alluvial deposits of the Jaworzyna stream valley.

To the northeast of the Walim, the Eastern Walim Fault separates the main graben from an unnamed, smaller NE-SW half-graben structure covered by a thin carpet of gneissic conglomerates.

Glinno Graben

The Glinno Graben (GG) is another example of a tectonic graben with asymmetric, irregular structure, c. 7.5 km long and up to 1.5 km wide (Fig. 4). It extends from the head of the Bojanicka Woda stream in the north, through the vicinity of the village of Michałkowa, to the head of the Młynówka stream south of Glinno (Fig. 5).

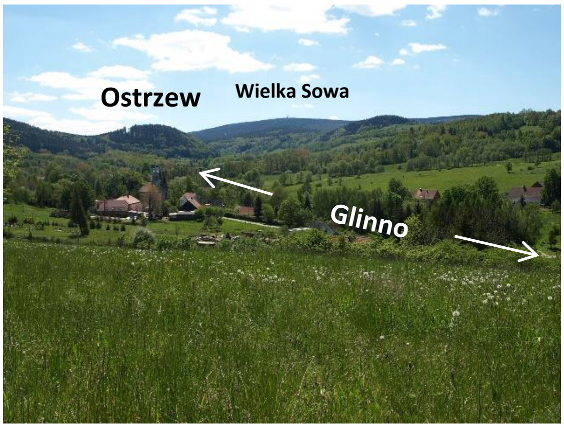

Fig. 5. Morphological depression related to the Glinno Graben. View from the north. Ostrzew hill (713 m a.s.l.) rises ca. 150 m above the flat bottom of the graben interior filled with gneissic conglomerates of the Walim Formation. The hill is built of sandstones and mudstones of the Sokolec Fromation intruded by kersantite sill (cf. Fig. 4). Wielka Sowa (1015 m a.s.l.) – the highest top of the Góry Sowie Mountains built of gneisses of the GSM is in the background.

The GG consists of at least three distinct, tectonic subunits. In the the northernmost part of the graben, a WNW-ESE trending half-graben structure exposes gneissic conglomerates and sandstones of the Walim Formation. The strata are poorly exposed, dip gently at 15 to 20° to the SW (Fig. 4) and are cut by narrow, WNW-ESE-trending lamprophyre dykes. To the east of the Bojanicka Woda stream head, the half-graben described is bounded by a NNE-SSW-oriented, fault-bounded gneissic block covered by gneissic conglomerates that rest directly on the metamorphic basement of the Góry Sowie Massif. To the S and SW, the block merges with the main body of the GG, bounded by nearly-parallel, NW-SE-trending faults, here named as the Western and Eastern Glinno faults (WF and EF, respectively) and exposes only gneissic conglomerates. The mappable faults have a total trace length of ca. 6.5 km (WF) and 4 km (EF), respectively. The southernmost part of the GG contains a morphological elevation built of sandstones and mudstones (Sokolec Formation), which together form a distinct, residual outlier (Ostrzew hill; 551 m a.s.l.), elevatad ca. 150 m above the flat bottom of the graben interior (see description of Stop 3). Ostrzew hill is well visible from the Stop 2 of our field trip. The southern boundary of the Glinno Graben is defined by the NE-SW trending unnamed fault which is covered in the stream head of Młynówka by delluvial sediments. The main boundary faults of the GG continue to the SE into the Western and Eastern Kamionki Faults, respectively (Fig. 1).

Kamionki Graben

On the map, the Kamionki Graben (KG) constitutes a narrow, triangular-shaped, fault-bounded tectonic feature, ca. 4 km long and up to 500 m wide, which trend SE to NW to the west from the Kamionka stream valley. The graben structure coincides with the morphological depression in the Góry Sowie Mountains (Fig. 6).

The graben is formed on crystalline basement of Góry Sowie (partly migmatic paragneisses with minor serpentinite and amphibolite bodies; Gawroński, 1961; Grocholski, 1967; Fig. 7). The boundary fault zones of the graben, referred to here as the Western- and Eastern Kamionki and Pniaki faults (the WF, EF and PF respectively; Fig. 7), separate the sedimentary fill of the graben from its crystalline-rock shoulders. All these fault zones are manifested by distinct rectilinear escarpments and arrays of water springs and peat bogs. The fault zones extend laterally into the metamorphic basement of the GSM (Fig. 7).

The vertical and possibly horizontal displacement components related to particular faults cannot be unambiguously determined from the mapping data. The position of the basal Carboniferous unconformity, intersected by hydrogeological boreholes at 110 and 143 m below the surface, does not allow for an unequivocal determination of the vertical displacement component of the graben's floor on the boundary faults (Fig. 7).

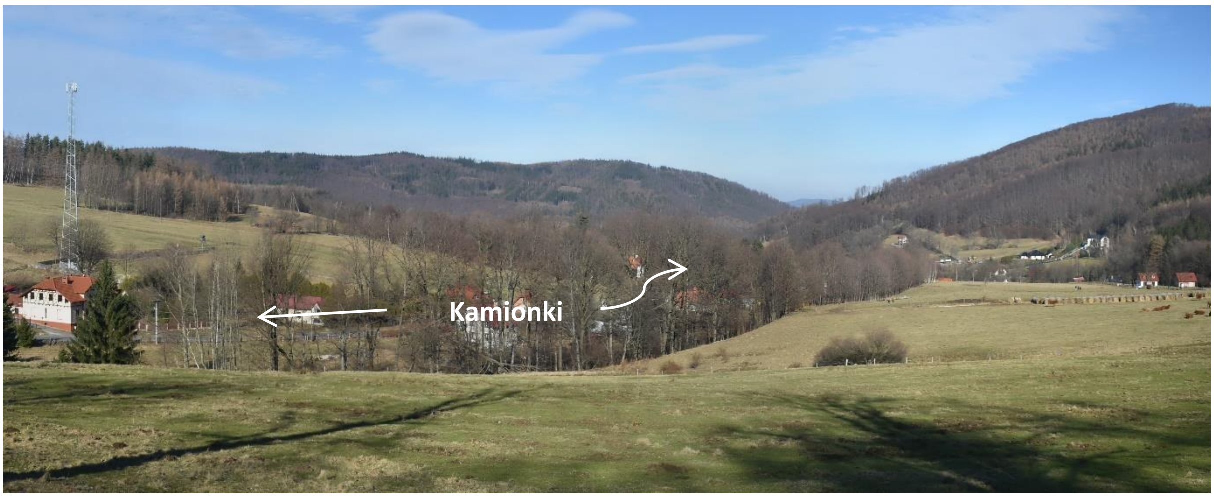

Fig. 6. Morphological depression related to the Kamionki Graben. View from the south. Kamionki village and the valley of the Kamionka stream are visible. Several outcrops of Carboniferous strata are located along the stream (Stop 3).

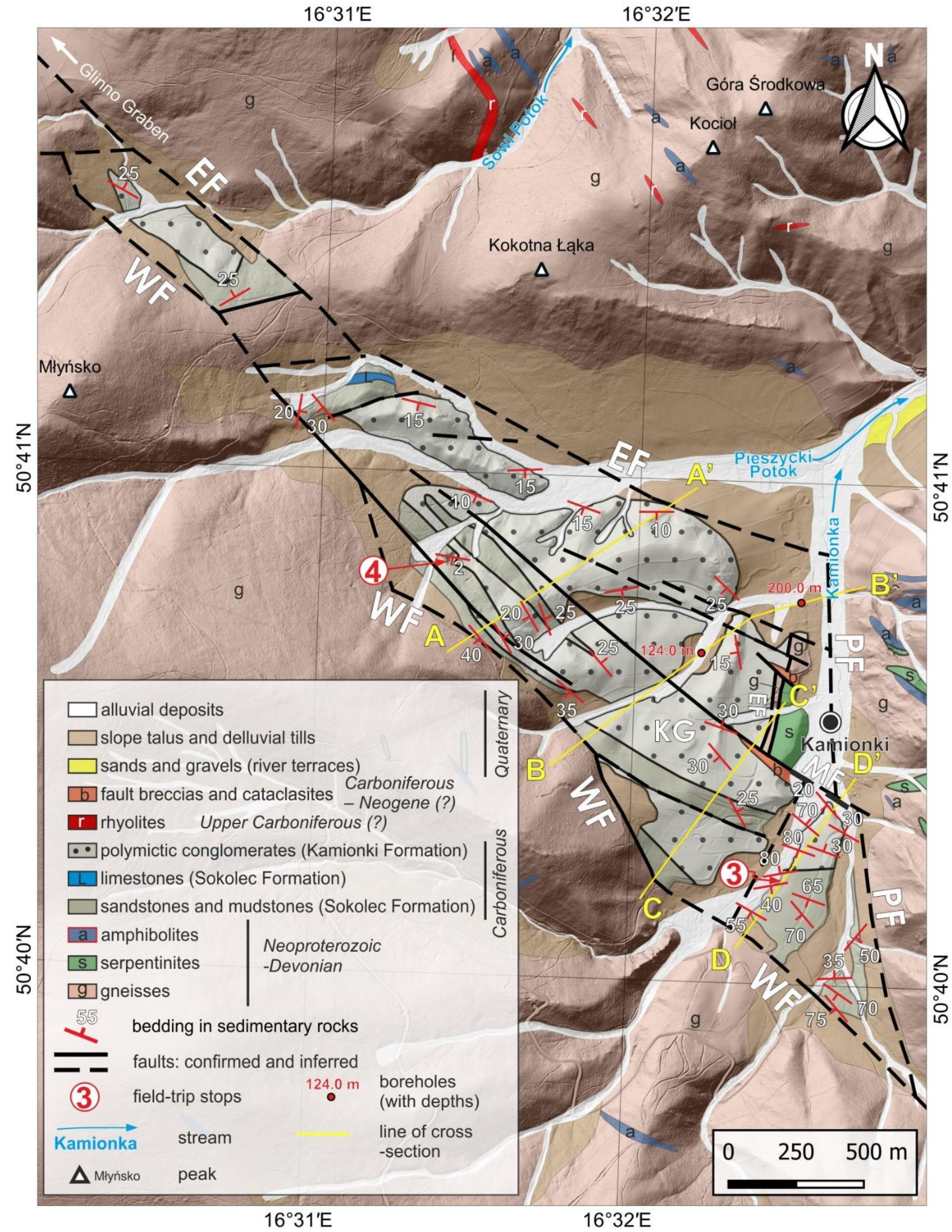

Fig. 7. Geological map of the Kamionki Graben (for location see Figure 1). Locations of geological cross-sections presented in Figure 8 (AA', BB', CC' and DD'). Cross-section C-C' was performed among others based on interpreted, SRT-P and ERT geophysical profiles (Kowalski and Pacanowski, 2024). Note the location of field trip stops referred to in the text and of two boreholes. Basement geology simplified from Gawroński (1961), geology of sedimentary rocks based on author's own geological mapping. Abbreviations: KG – Kamionki Graben, EF – Eastern Kamionki Fault, PF – Pniaki Fault, WF – Western Kamionki Fault.

The geological map and cross sections of the Kamionki Graben (Figs. 7 and 8) show the WNW-ESE trending faults which divide the graben's fill into several blocks. The north-westernmost part of the KG represents a single narrow NW-SE trending block (the Młyńsko Graben of Oberc, 1972) filled with Carboniferous sandstones and conglomerates and separated from the main graben body by a basement horst occuring between the WSW-ENE striking boundary faults of the graben. The northern part of the graben is characterised by the occurrence of Namurian(?) polymict conglomerates exposed along the Eastern Kamionki Fault and dipping at 15–25° towards the S and SW (Fig. 7). The structure of this part of the KG is well constrained due to exposure of the conglomerates as small-scale tors. Towards the east, the strike of the bedding within the conglomarates changes from E-W to nearly N-S. In this portion of the graben, the Pniaki Fault is oriented approximately N-S and buried under the Kamionka stream valley alluvial deposits (Fig. 7). The western part of the graben exposes NW-SE trending mappable folds with sandstones exposing anticline hinges (Figs 7,8).

In general, the limbs of these nearly symmetric folds dip moderately ca. 25–40° towards the NE and SW with their axes plunging gently to the NW and SE. The map-scale folds, oriented parallel to the structural trend of the graben, are cut by faults trending parallel or sub-parallel to the fold axes. The lowermost fill member of the KG, the gneissic conglomerate of the Walim Formation, is nowhere exposed at the surface in the KG and has not been intersected by hydrogeological boreholes made in the central part of the graben. However, the gneissic conglomerates most probably occur at the bottom of the downfaulted, northernmost part of the graben (Fig. 8, A–A' cross section). On the other hand, these conglomerates are well exposed within the Glinno Graben, located ca. 2 km towards the NW of the KG (Figs 1, 4; Żakowa 1960; Oberc 1972). The middle segment of the KG is dismembered by the NW-SE trending Middle Kamionki Fault (MF). The fault shows up to 50 m of throw gradually decreasing towards the NW, and it divides the overall graben structure into two smaller domains, the southern of almost nearly rhomboidal shape and the northern triangular one. Geological mapping revealed the existence of distinct cataclasite zones up to 50 m wide, aligned along the southern and northern sectors of the fault zone (Figs 7,8), between sedimentary rocks and their metamorphic basement. These zones consist of fault gouges and breccias composed of angular fragments of gneiss. To the NE of the Middle Kamionki Fault, the graben is cut by two, relatively minor, NW-SE trending discontinuities (Figs. 7, 8). Towards the SE the KG narrows to ca. 50 m in width and exposes Viséan sandstones, which are folded and probably thrusted over the crystalline basement (cross-section DD', Fig. 8). At the southernmost end of the graben, the Western Kamionki and the Pniaki faults converge to form a single, NNW-SSE striking fault.

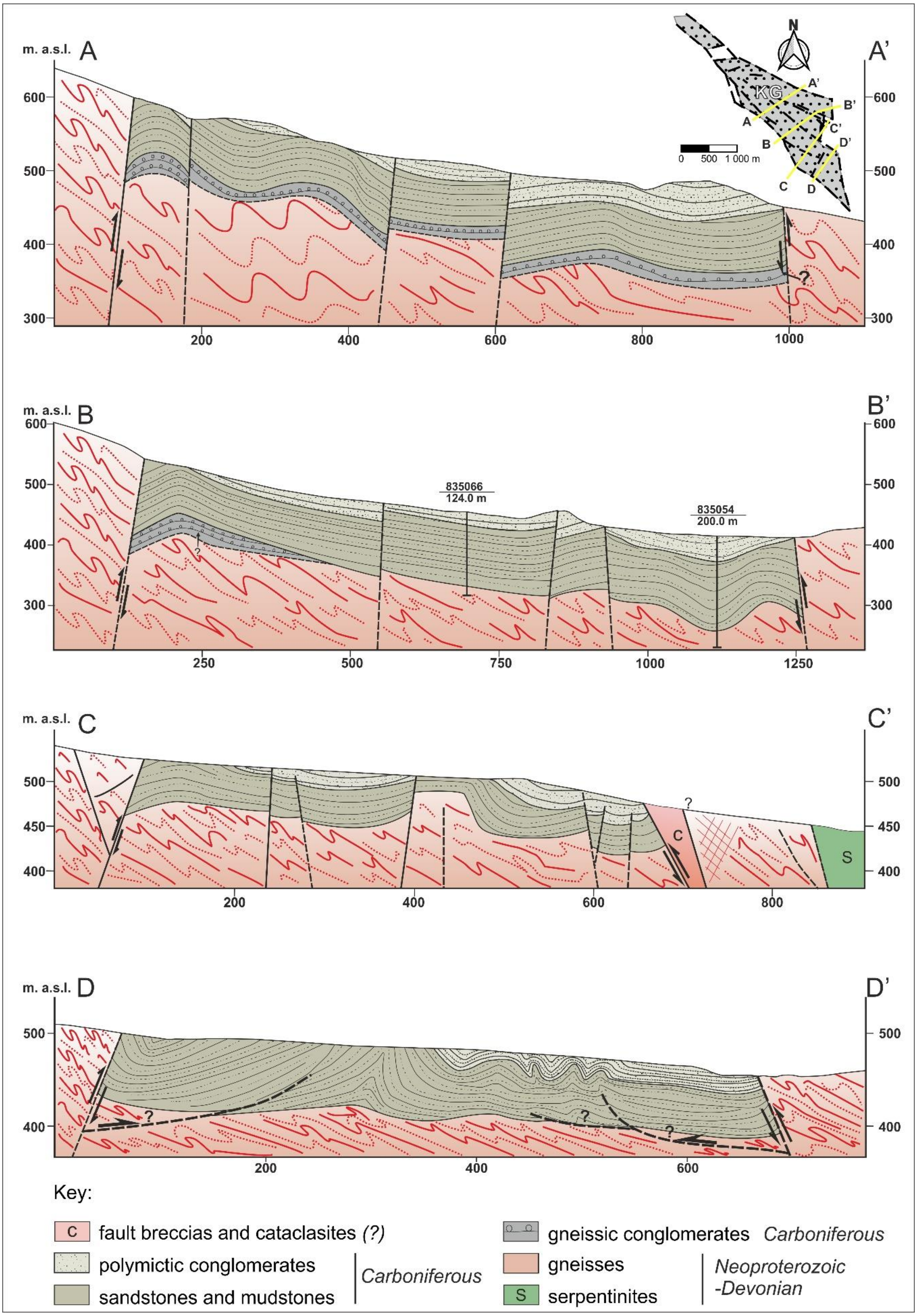

Fig. 8. Geological sections across the Kamionki Graben based on mapping field traverses, borehole data and geophysical profiles (C-C' cross-section based on: Kowalski and Pacanowski, 2024). See inset map in the upper right corner and Figure 7 for location of each of the cross-section.

Structural evolution of tectonic grabens on top of the Góry Sowie Massif – an example of the Kamionki Graben

Due to the very limited number of outcrops, sparse fault-slip data and the lack of a clear Meso-Cenozoic geological record in the uplifted area of the Góry Sowie Block, a precise reconstruction of its structural evolution faces considerable difficulties. Nevertheless, the evolution of tectonic grabens developed on top of the GSM can be roughly reconstructed, using the criteria of the superposition and relationships between the ductile and brittle tectonic deformation structures preserved in the sedimentary and metamorphic rocks of the KG area. Palaeostress data from adjacent geological units exposing younger, slightly deformed lower Permian to Upper Cretaceous strata, may also be useful in this task. Based on the results of geological mapping, structural analysis and geophysical survey (Kowalski, Pacanowski, 2024), the interpretation proposed here assumes a relatively complex, polyphase (at least four-stage) development of the Kamionki Graben area, began in the Carboniferous and lasted until the late Cenozoic.

The Carboniferous succession of the Góry Sowie Massif was folded (and, locally, also probably thrusted over the gneissic basement) into the WNW-ESE to W-E and, less frequently, NW-SE oriented folds at the end of the Mississipian (Namurian (?)) epoch. The fold axes (Figs 9, 10) are nearly perpendicular to the direction of the interpreted NNE-SSW to N-S horizontal compression at the NE forelands of the Bohemian Massif during the end-Variscan orogeny (Mazur et al., 2020). Meso-scale folds affecting the Carboniferous strata of the KG will be presented at Stop 3 of this field trip. The fold structures of similar geometry are widespread in the Carboniferous strata deposited in the system of late-orogenic, collision-related, foreland- and intra-montane basins that developed at the NE and E margins of the Bohemian Massif (e.g. Hartley and Otava 2001; Bábek et al. 2004; Narkiewicz 2007; Mazur et al. 2010; Narkiewicz 2020). The meso-scale folds attributed to this regional shortening event are the most common structures in the southernmost portion of the Kamionki Graben between its boundary faults. The average shortening (P) axis orientation obtained from dextral faults (referred to as the I fault population; Fig. 9) in the Kamionki Graben reflects similar, overall NNE-SSW to NE-SW compression direction (Fig. 9). Therefore, it cannot not be excluded that the transpression generated by the strike-slip dextral (?) displacements may have played an active role in the folding process.

The formation of the Kamionki Graben included displacements along NNW-SSE to NW-SE striking high-angle faults (Fig. 10). They have occurred over a long period between the Namurian (Late Mississipian) and Neogene, starting someone between the late Carboniferous and early Permian. The development of the graben must have occurred only slightly after the folding of the Carboniferous succession and is correlated by the author with a significant, late Carboniferous–early Permian regional uplift and erosion, associated with the gravitational collapse of the newly formed Variscan orogen (e.g. Mazur et al. 2006). Various parts of the GSM were then progressively exhumed and supplied gneissic detritus to the surrounding sedimentary basins, e.g. the Intra-Sudetic (Mastalerz, 1996), the Świebodzice (Nemec et al., 1980; Porębski, 1981) and the Bardo (Wajsprych, 1978) basins.

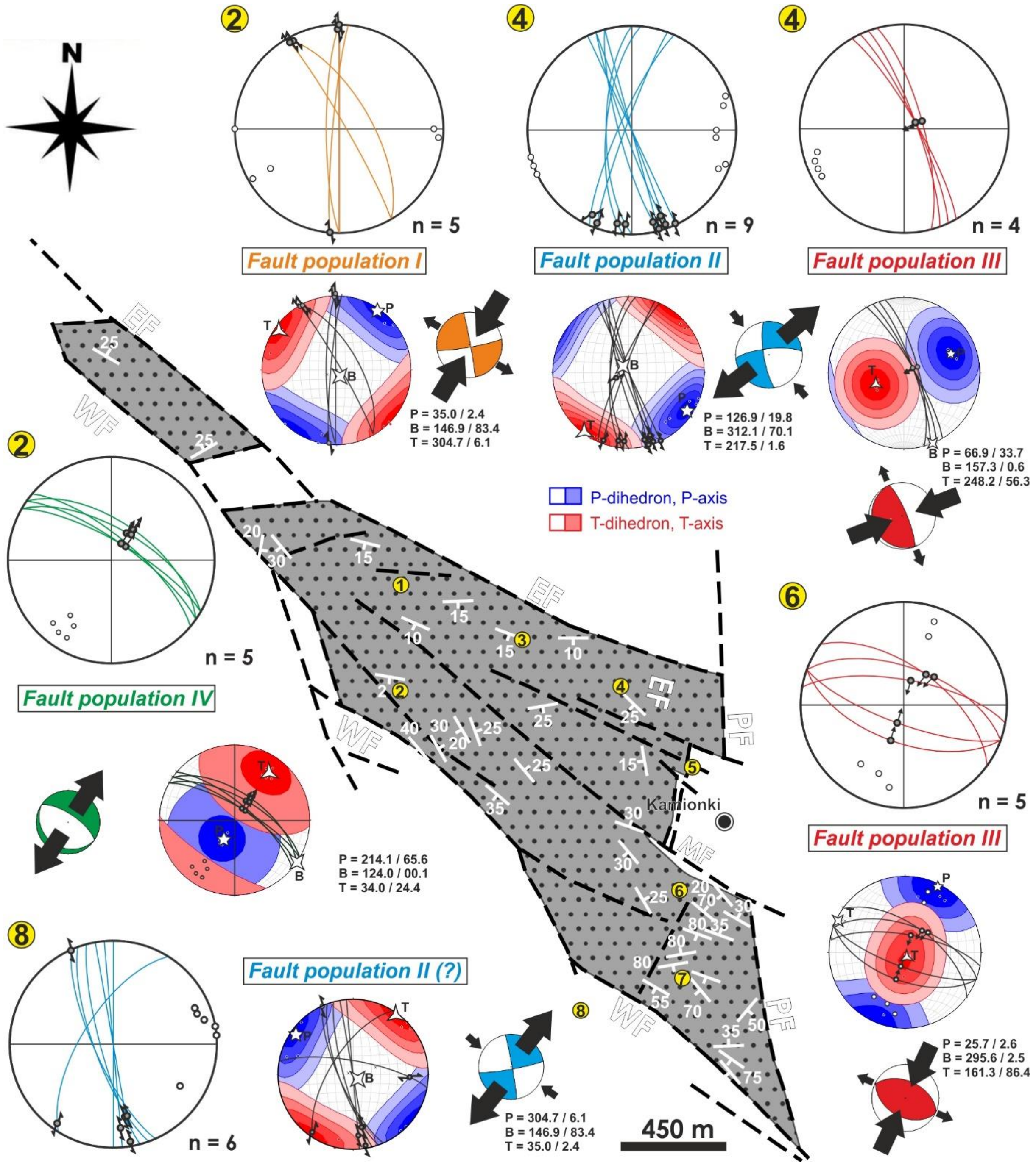

Fig. 9. Kinematic data collected on minor faults and interpretation of the principal axes of finite strain ellipsoids calculated using PBT method – moment tensor analysis for the four homogenous fault systems (populations) I–IV distinguished in the Kamionki Graben. The collected fault planes orientations are presented on the great circle diagrams with marked poles. Striae on fault planes are presented as dots with arrows indicating the sense of displacement of the hanging wall block. The inset "beachball plots" obtained from moment tensor analysis show shortening (P) and extension (T) quadrants.

On the other hand, Aramowicz et al. (2006), postulated, on the basis of apatite fission-track dating (AFT), that the shoulders of the Kamionki Graben, together with the entire Góry Sowie Block, were probably partly covered by Carboniferous and Permian sediments during the late Carboniferous and Permian times. These results suggest a significant episode of burial under a thick cover of Paleozoic clastic sediments.

Based on the above, the author interprets the NNW-SSE to NNE-SSW striking, strike-slip (mainly sinistral) faults of the population II (Fig. 9) as the result of NE-SW to WNW-ESE regional extension (transtension) in the late-Carboniferous–early Permian times (Fig. 10). These faults must have been reactivated during the latest, successive tectonic events affecting the Carboniferous succession preserved on top of the Góry Sowie Massif (Fig. 10). Sinistral movement along the nearby Intra-Sudetic (Głuszyca) Fault, striking parallel to the Kamionki Graben, between the late Carboniferous and early Permian has been postulated by Aleksandrowski et al. (1997). The inferred, late Carboniferous–early Permian extensional stage correlates (was coincidental?) with the widespread subsidence event associated with the initial stages of development of the Polish Basin (Krzywiec et al., 2022). The formation of kersantite and rhyolite dykes with a predominant NW-SE to NNW-SSE orientation, which are exposed in the Góry Sowie Massif area (Awdankiewicz, 2007; Grocholski, 1967), as well as the emplacement of volcanic and sub-volcanic bodies in the adjacent Intra-Sudetic Basin (Awdankiewicz, 2022, 1999), appear to be genetically linked to this evolutionary stage.

The Late Cretaceous–Paleogene uplift of the Góry Sowie Massif along the Sudetic Marginal- and Głuszyca faults to the NE and SW, respectively, must have resulted in a subsequent erosion of the mountainous part of the massif (Fig. 10). The uplift was due to the Late Cretaceous–Palaeogene, regional, NE-SW-oriented tectonic compression and the concomitant inversion, which affected the western and central European Alpine foreland (Głuszyński and Aleksandrowski, 2022; Kley and Voigt, 2008; Mazur et al., 2005; Rosenbaum et al., 2002; Voigt et al., 2021). An average orientation of shortening (P) axis calculated from fault population III (Fig. 9) corresponds to the regionally reported paleostress and regional-tectonic data documenting this Late Cretaceous–early Cenozoic deformation of the NE fringe of the Bohemian Massif (Coubal et al., 2015; Głuszyński and Aleksandrowski, 2022; Kowalski, 2021; Novakova, 2015; Pešková et al., 2010; Sobczyk and Szczygieł, 2021). Relatively uniform, NE-SW to ENE-WSW oriented compressional stress regime is interpreted as a result of far-field effects of the Europe-Iberia-Africa plate convergence at ca. 86–70 Ma (Kley and Voigt, 2008; Rosenbaum et al., 2002). A broad range of similarly oriented, inversion structures (both brittle and ductile) related to this deformation event is commonly observed throughout Central Europe in the foreland of the Alpine-Carpathian deformation front (Głuszyński and Aleksandrowski, 2022; Kley and Voigt, 2008; Kozdrój and Cymerman, 2003; Krzywiec et al., 2022, 2018; Mazur et al., 2005; Voigt et al., 2021). These structures include low- to high-angle reverse and normal faults, thrusts delimiting basement highs, inverted basins and grabens, as well as marginal troughs (Voigt et al., 2021). The total amount of denudation of the Góry Sowie massif, linked with this tectonic event is estimated at 4–8 km (Aramowicz et al., 2006) and at least 4 km for the adjacent Intra-Sudetic Basin (Botor et al., 2019). Based on the apatite fission track (AFT) data and thermal modelling results, Danišik et al. (2012) argued that the reverse faults and low-angle thrusts were active in the Sudetic region between 85-70 Ma.

Normal faults of the population IV (Figs 9, 10), oriented nearly parallel to the graben's elongation are likely associated with the most recent stage of the brittle deformation linked to the NE-SW-oriented extensional regime. These faults are parallel to the strike lines of the NW-SE oriented faults that displace sedimentary rocks within the KG. This stress orientation can be correlated with the youngest brittle deformations revealed by fault-slip data and recorded in the vicinity of the Sudetic Marginal Fault (Krzyszkowski and Olejnik, 1998; Krzyszkowski and Pijet, 1993; Migoń et al., 2023; Różycka et al., 2021). A sub-recent neotectonic transformation of the pre-existing faults cannot be excluded in the study area. Neotectonic, extensional fault reactivation may have influenced the formation of the present-day valley network, especially of the Kamionka river valley. The rectilinear course of this valley may be explained by the fault activity.

Another important issue is origin of the systematic joints in the studied sedimentary rocks. The WNW-ESE to NW-SE and NE-SW trending joint sets, similar to those from the grabens on top of the GSM, were also observed within the Permo-Mesozoic rocks exposed in the nearby Intra-Sudetic and North-Sudetic synclinoria (Jerzykiewicz, 1968; Solecki, 1994). Although these latter joint sets are interpreted as Late Cretaceous–early Palaeogene in age (Głuszyński and Aleksandrowski, 2022; Jerzykiewicz, 1968; Solecki, 2011), it cannot be excluded that in the study area the initiation and development of the joint pattern was linked with stress field that had occurred during the waning stages of the Variscan orogeny. Such late Variscan joints were eventually rotated during successive phases of brittle and ductile deformations. Due to limited number of outcrops in the Kamionki Graben area this issue requires systematic research in the future, also in the areas of adjacent tectonic units composed mainly of strongly folded Carboniferous sedimentary strata (i.e. the Świebodzice Depression and the Bardo Structure; cf. Oberc 1972; Wajsprych, 1978; Porębski 1990).

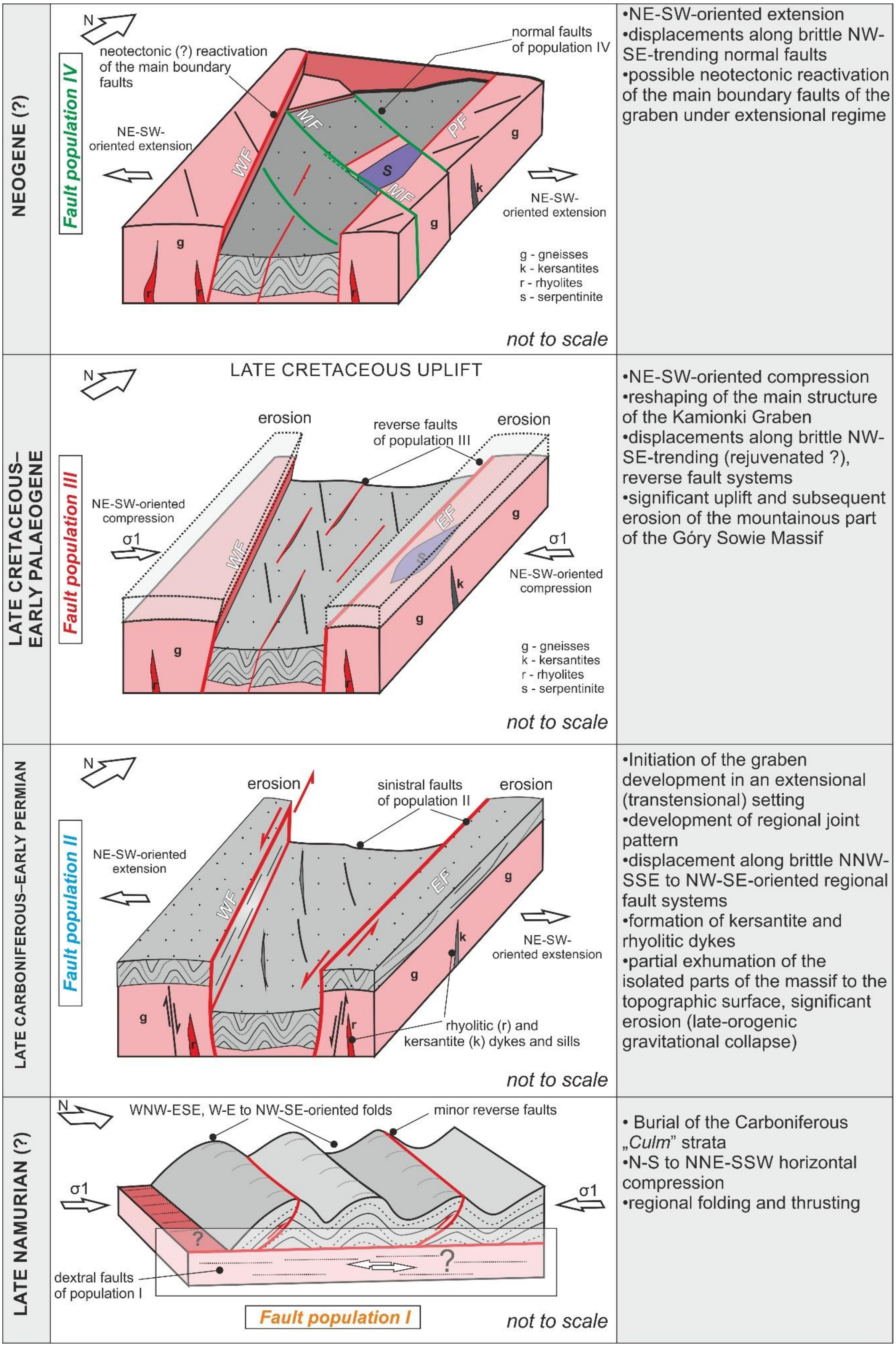

Fig. 10. Schematic model showing evolution of the Kamionki Graben. For further explanations see the text.

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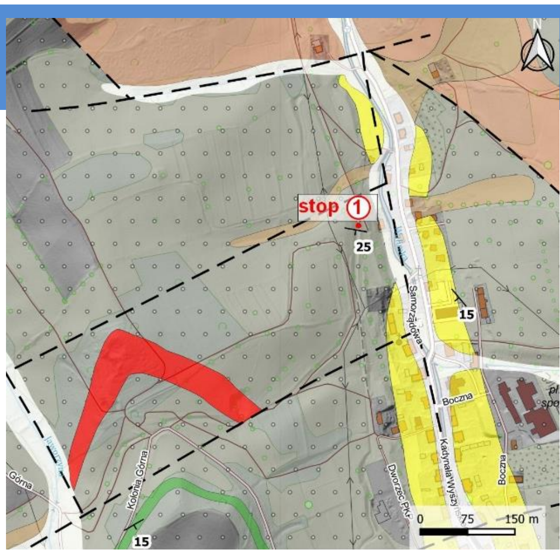
Stop 1 – Walim



Abandoned railway cut

GPS coordinates: 50° 42' 19.07" N, 16° 26' 10.97" E

Stratigraphy: Walim Formation, lower part
(middle – early late Viséan?)
Described problems: Walim Graben:
structural geometry and characteristics,
syn-tectonic deposition,
alluvial fan conglomerate

An abandoned railway cut located in the northeasternmost part of the Walim Graben exposes gneissic conglomerate of the Walim Formation (the lowermost member of the GSM Carboniferous succession; cf. Fig. 2). The continuous part of the outcrop is c. 60 m long and up to 2.5 high and consists of extremely poorly sorted conglomerate dipping 15-25° SSW. The grain framework is typically clast-supported, less often matrix-supported, with clasts ranging in size from pebbles to boulders and matrix composed of medium- to coarse grained lithic sandstone (Fig. 11A). Both grain size distribution and roundness of clasts is bimodal. In general, smaller clasts are angular to subangular, while the largest ones ranging from moderate to well rounded. The largest, well-rounded migmatic gneissic clast observed in an outcrop attains 2.2 m in diameter (Fig.11A). Results of petrographic analyses by Łapot (1986), show that the conglomerate is monomictic and its clasts are dominated by petrographic varieties of gneisses – migmatic and fibrous gneisses, biotite-oligoclase paragneisses, orthogneisses and other metamorphic rocks as well as massive quartz.

Seemingly, the rock does not show evidence of internal organisation and its clast fabric appears to be chaotic (Fig. 11A). The bedding within conglomerates is poorly visible, and is either planar or slightly undulatory. In the basal parts of beds, elongated clasts are locally imbricated (a (p) a (i) fabric). In the upper parts of beds, clasts reveal weak a-axis pseudoimbrication which is parallel to the bedding planes. Indistinct inverse grading is also visible. Measurements of large population of clast long axes (a-axes; n=394) show their preferred orientation (Fig. 11A). Given the average (inferred) orientation of pebbles parallel to the palaeotransport direction, as well as their imbrication, the interpreted inclination of palaeoslope is from NNW to SSE (Mo=342.8°).

The conglomerates of the Walim Formation are interpreted to have formed as deposits of clast-rich, cohesionless subaerial debris flows which occurred in proximal zones of alluvial fans (Fig. 11B). The fans developed along tectonically active, high-relief, WNW-ESE-oriented(?) fault margins of a wider basin. Petrographic composition of clasts suggests that the Góry Sowie Massif was the source area of the clastic material. Gabbroic pebbles, present in conglomerates of the Walim Graben c. 500 m of the SW from the described outcrop, were probably derived from an area of the present-day Intra-Sudetic Basin, situated W and SW of the Intra-Sudetic Fault (Głuszyca Fault; cf. Fig. 1). Gabbros were drilled there at the base of the Upper Carboniferous deposits (Ihnatowicz, 2001). This suggests a significant episode of palaeogeographic inversion of the Intra-Sudetic area during the late Carboniferous.

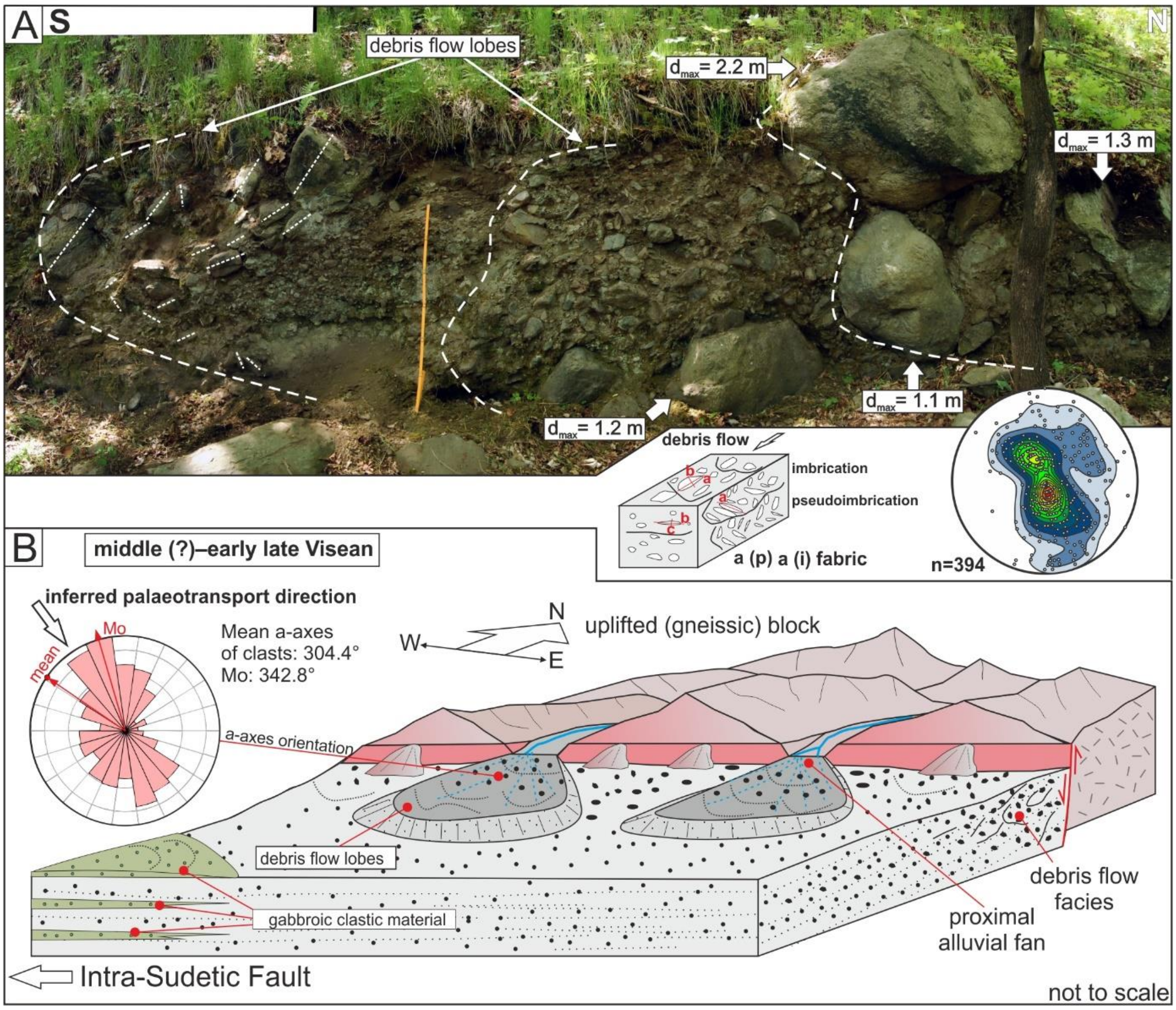
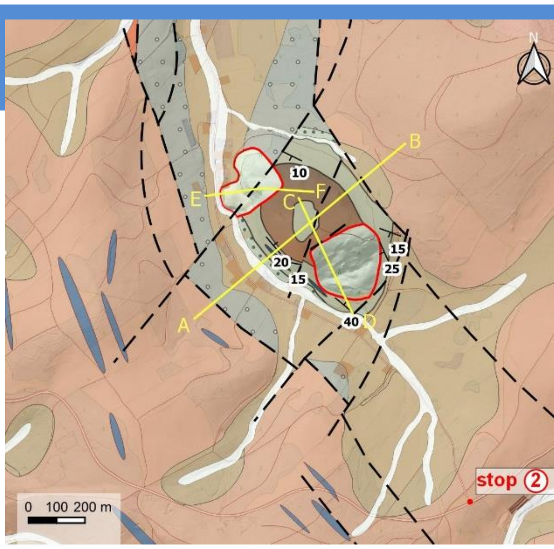


Fig. 11. A. Outcrop of gneissic conglomerates of the Walim Formation in Walim (stop 1). White dashed lines indicate interpreted fronts of debris flow lobes on proximal alluvial fan. Inset blockdiagram shows an idealized alignement of pebbles a-axes during clast-rich, cohesionless subaerial debris flow (inspired and modified after Harms et al., 1975). B – Palaeogeographic reconstruction of the present-day Walim Graben area in the early Carboniferous (middle(?) – early late Viséan). Inset rose diagram shows orientation of long a-axes of pebbles measured in outcrop and interpreted palaeotransport direction.

Stop 2 – Glinno



Viewpoint
GPS coordinates: 50° 41' 49.26" N, 16° 29' 27.95" E

Stratigraphy: marine sandstones and mudstones of the Sokolec Formation (Upper Viséan (?)) intruded by upper Carboniferous kersantite

Described problems: Glinno Graben: structural geometry and characteristics, structurally controlled landslides developed on slopes built of sedimentary and igneous rocks

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Stop 2 is located at the southern edge of the Glinno Graben (Fig. 12). To the north of the viewpoint, situated on the gneissic bedrock of the Góry Sowie Massif, gneissic conglomerates and sandstones of the Walim Formation are overlain by sandstones and mudstones with limestone intercalations (Żakowa, 1960) of the Sokolec Formation. These strata define an erosional outlier – Ostrzew hill – which is well visible from the viewpoint. In the uppermost part of the flat-topped hill, the Carboniferous sedimentary rocks are intruded by upper Carboniferous (?) kersantite forming a sill-like intrusion (Awdankiewicz, 2007; Grocholski, 1965; Łapot, 1986; Fig. 13; 14A). The hill is capped by sandstones which are the youngest preserved Carboniferous deposit in the Glinno Graben.

Two rotational, bedrock-controlled landslides have been recognized by the present author on the north-western and south-eastern slopes of Ostrzew hill (landslide 1 and landslide 2, respectively in Figs 12, 13). The landslides are hardly accessible and will be not presented during the field trip. The landslides affected densely forested, steep slopes (inclined by 25–33°) over an area of 3.3 and 4.4 ha. Mass movements developed within kersantites and underlying sedimentary rocks of the Sokolec Formation. In the nearly flat-lying kersantite and in the sandstones, two main join sets (J_1 and J_2) were determined (Fig. 14B–D). Structural measurements show that the landslide slip surfaces and detachment developed partly along the joint planes (Kowalski, 2018). The mass movements resulted in transfoming once homogeneous rock into separate blocks, predominantly along nearly vertical joints of J_2 set. A similar displacement mechanism operated in the north-western part of the massif, where orientation of steep J_2 joints in kersantite coincides with the orientation of the main landslide scarp. Lithological and geomechanical contrast between the resistant, rigid kersantites and underlying, strongly fractured sandstones and mudstones was also an important factor that controlled the slope instability and further landslide motion.

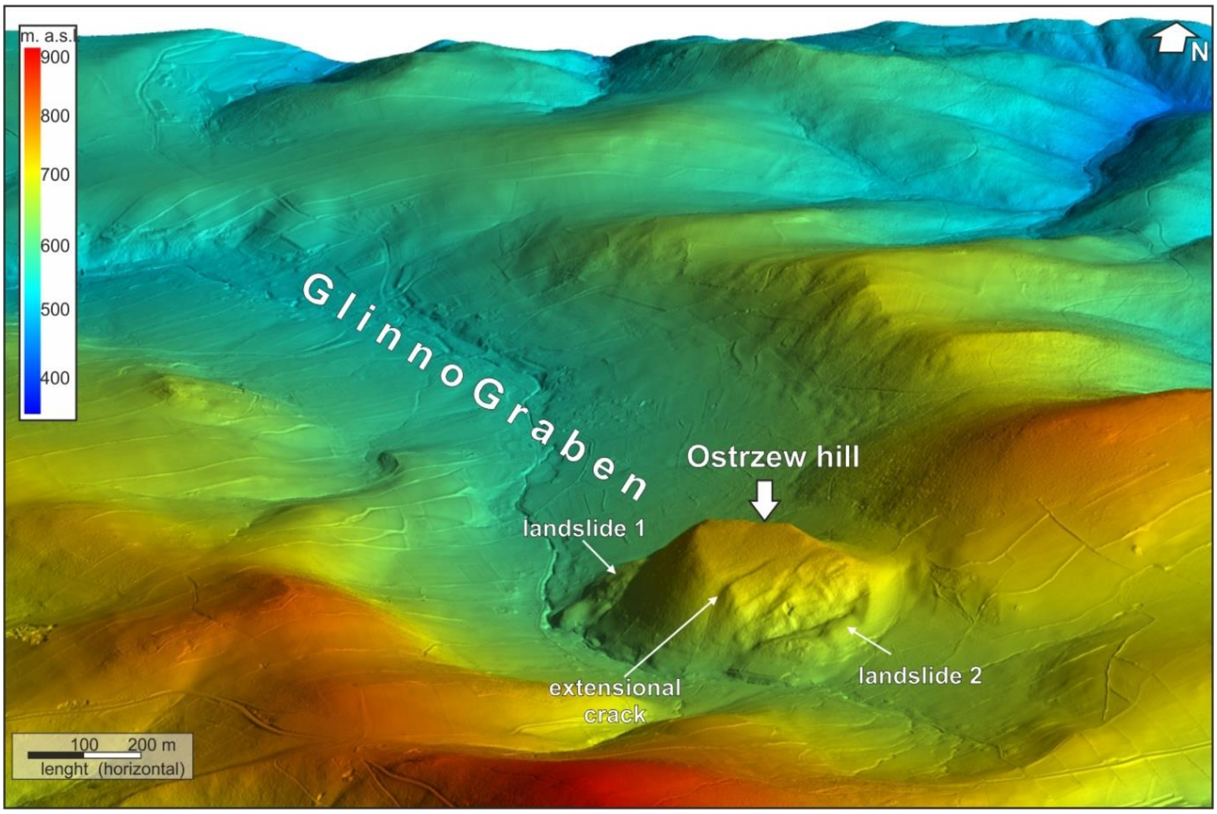


Fig. 12. LiDAR-based three-dimensional model of the southern part of the Glinno Graben. The two landslides described in the text are indicated by arrows. 1.5 x vertical exaggeration.

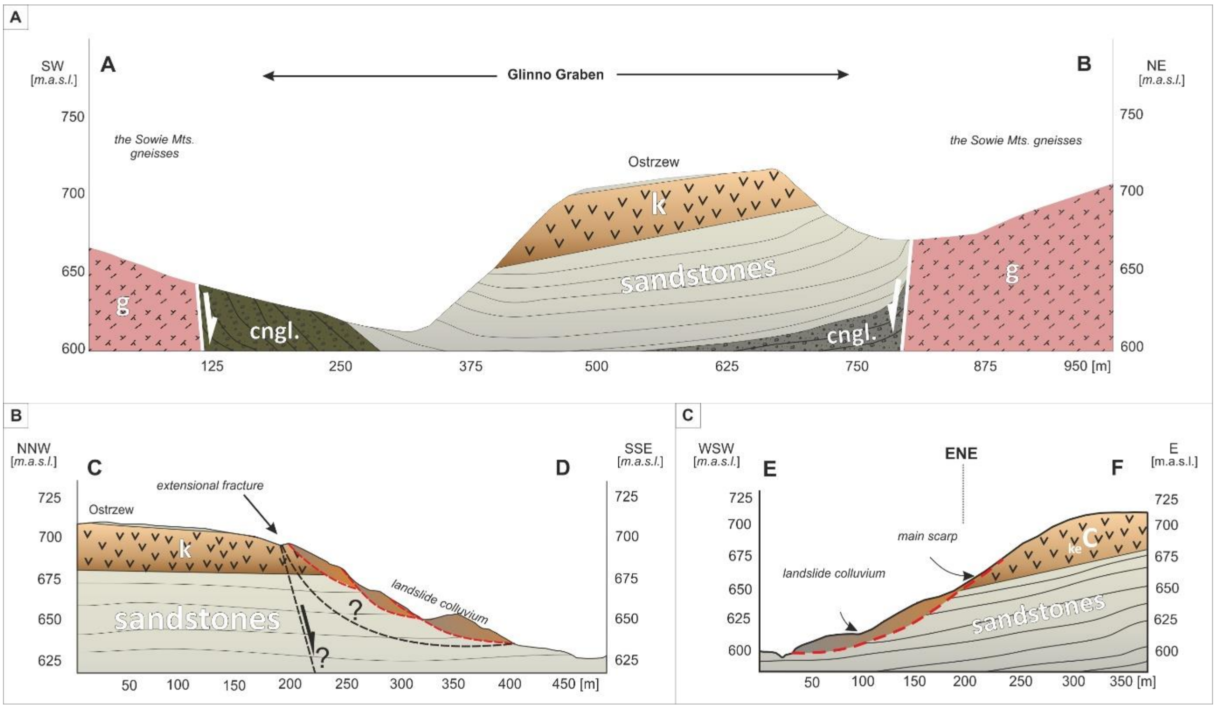


Fig. 13. Geological cross-sections through the Glinno Graben (A) and of the landslides on Ostrzew hill (B). Geological cross sections after Grocholski, 1962, supplemented and modified by the author (Kowalski, 2018). The geology as in Fig. 4.

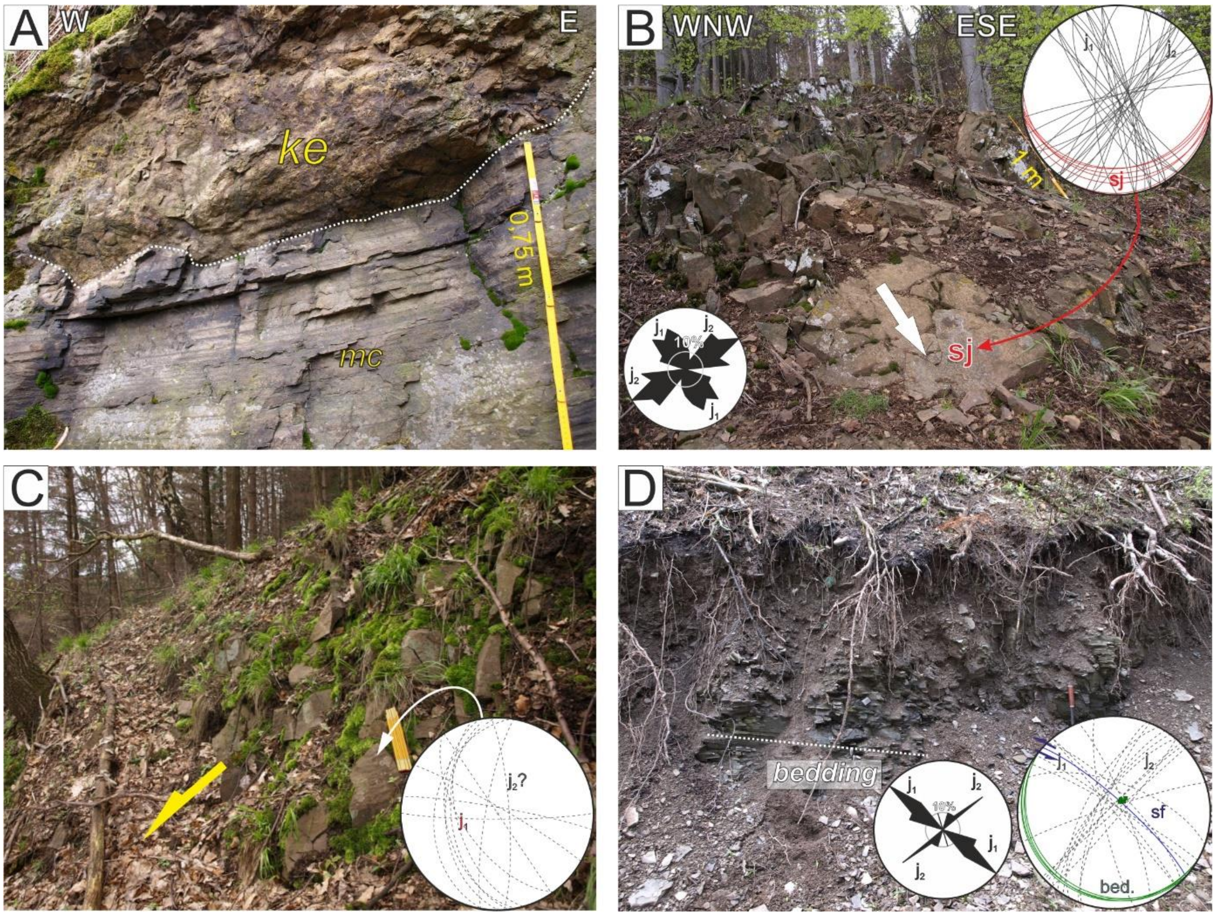
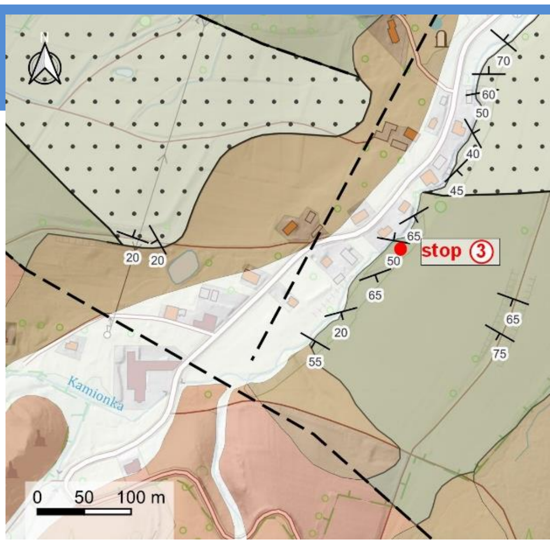


Fig. 14. Landslides on Ostrzew hill. A – sharp contact between kersantite (top) and sandstone of the Sokolec Formation (bottom) within landslide block in the quarry below the summit of Ostrzew hill (south-eastern landslide). B – head scarp of the south-eastern landslide. Stereogram showing two sets of joints: NW-SE/NNW/SSE (j_1) and NE-SW/ENE-WSW (j_2) and set of sheeting joints (sj). Arrow indicates the direction of mass movements on the main scarp of the landslide. C – secondary scarp that cutting the displaced kersantite block within the landslide colluvium of the north-western landslide. Arrow indicates the direction of mass movements on the main scarp of the landslide. D – outcrops of sandstones and mudstones exposed in the lower, western slope of Ostrzew Mt. (*in situ*). Great circle and pole point diagrams showing two sets of joints (j_1, j_2) and bedding planes (bed., green). J_2 set of joints is reactivated by strike-slip faults (sf).

Stop 3 – Kamionki



Kamionka stream valley

GPS coordinates: 50° 40' 12.10" N, 16° 32' 27.78" E

Stratigraphy: marine sandstones and mudstones of the Sokolec Formation (Upper Viséan (?))

Described problems: Kamionki Graben: structural geometry and characteristics, late-Variscan folding of the lower Carboniferous strata

In the southernmost part of the Kamionki Graben, in exposures of the Sokolec Formation located along the Kamionka stream valley, minor folds are relatively common. On the valley's eastern slopes these folds display very gentle, open geometry with interlimb angles of 70–110°; Fig. 15A). Towards the north there occur horizontal upright folds, commonly of chevron geometry with angular and sharp hinges, commonly displaying chevron-like profiles (Fig. 15B). They exhibit nearly vertical axial planes and horizontal hinge lines with wavelengths of 1 to 3 m. The asymmetric to moderately-inclined, N-vergent folds with southern limbs dipping gently (up to 15°) to the S, and northern limbs inclined nearly 80° to the S, are also present (Fig. 15C).

The fold axes in the Kamionki Graben trend predominantly W-E to WSW-ENE, suggesting the N-S to NNE-SSW direction of tectonic shortening (Fig. 15D). The hinge zones of the anticlines occasionally contain nearly vertical, planar axial cleavage. Within the northern limbs of asymmetric folds, reverse minor faults dipping up to about 60° toward the NE have been developed. Some reverse faults were also observed (Fig. 15D).

The described fold structures developed most probably during Namurian(?) epoch at the waning stages of the Variscan orogeny. A transpression related to strike-slip (dextral?) displacements may have played an active role in the folding process (Kowalski and Pacanowski, 2024). No mesoscopic folds have been observed in sandstones exposed in the opposite, north-western part of the graben. In this part of the graben a series of NW-SE-trending map-scale folds occur. These folds are attributed here to the Late Cretaceous – early Palaeogene trans-regional tectonic shortening event, which had likely led to reactivation of the main boundary faults of the graben as well as to large-scale, gentle folding of the Carboniferous strata, visible only in map-view (cf. Fig. 8).

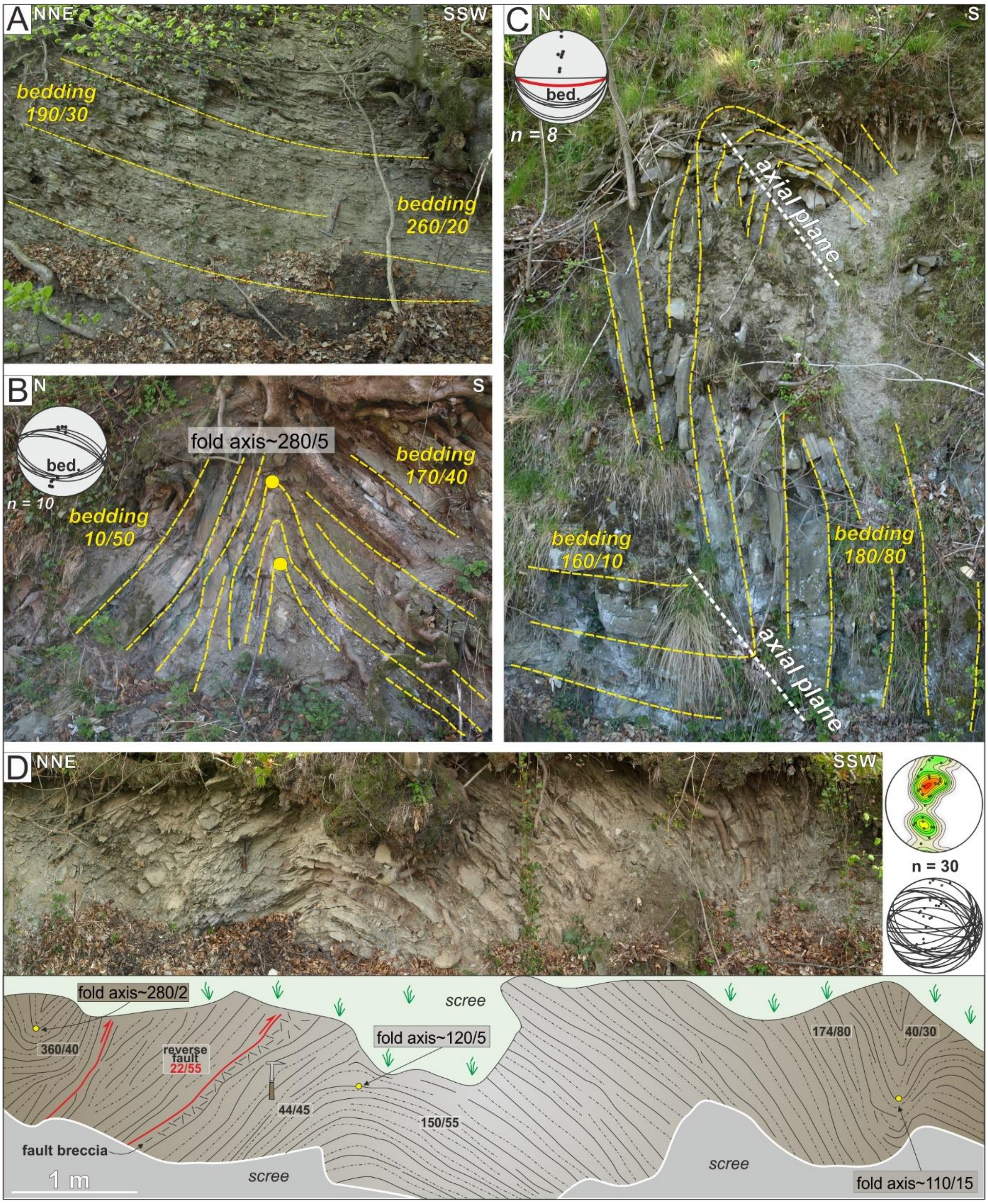
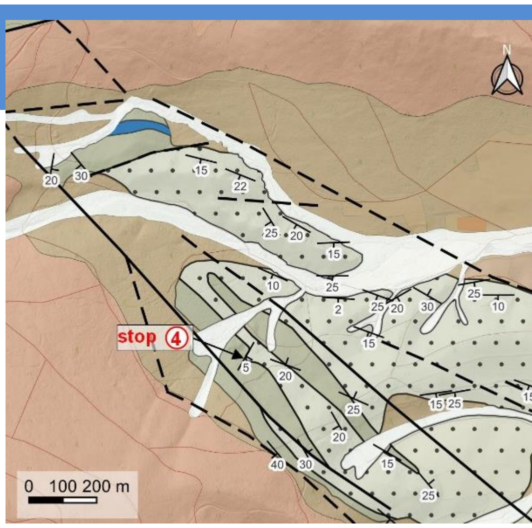


Fig. 15. Mesoscale folds in Carboniferous sandstones exposed in the southernmost part of the Kamionki Graben (see Figure 2 for locations). The bedding attitudes (shown as yellow dashed lines) are described with dip direction/dip angle. Inset stereoplots are showing bedding orientation (bed). A – northern limb of a gentle syncline. B – upright, tight, nearly symmetric anticline with chevron profile, vertical axial plane and horizontal hinge line (stop 4). C – inclined, asymmetric folds affecting sandstone beds with axial plane dipping nearly 60° to the S (red great circle) (stop 4). D – open to tight, E-W to WNW-ESE-trending folds, cut by two minor reverse faults in the NNE part of the stream valley profile.

Stop 4 – Kamionki



Abandoned quarry

GPS coordinates: 50° 40' 49.51" N, 16° 31' 24.83" E

Stratigraphy: marine sandstones and mudstones of the Sokolec Formation (upper Viséan (?)), conglomerates of the Kamionki Formation (upper Visean – Namurian (?))

Described problems: Kamionki Graben: structural geometry and characteristics, sedimentology of the Carboniferous marine deposits (upper Viséan–Namurian (?))

An abandoned quarry in the northwestern part of the Kamionki Graben, close to the Western Kamionki Fault (main boundary fault of the Kamionki Graben; cf. Fig. 7), exposes the uppermost part of the marine Sokolec Formation and the sedimentary contact with the overlying polymictic conglomerates of the Kamionki Formation (Żakowa and Żak, 1962). The most representative outcrop is situated in the south-eastern wall of the quarry and reveals c. 10 m thick sedimentary succession (Fig. 16A). The marine sandstones dip ca. 5–10° towards the ESE (Fig. 16A). The lower part of the succession consists of medium- to coarse-grained, poorly-sorted lithic sandstones with mm-thick mudstone intercalations. The sandstones are well-bedded and reveal distinct platy parting. Bed thickness ranges from 0.05 to 0.4 m. The lower surfaces of beds are predominantly sharp, with undulatory or flat boundaries displaying abundant erosional structures (both scour and tool marks). They include flutes (Fig. 16B), groove casts (generated probably as a result of dragging of a plant stalks or stems), prod- and bounce marks. Small-scale, S- to SW-vergent slump folds (Fig. 16C), load casts and flame structures are also present in the bottom parts of beds. The sandstones are predominantly structureless (Bouma T_a), normally and inversely-graded or horizontally-laminated (Bouma T_b). Greenish mudstone intraclasts and plant detritus occur sporadically in the lower parts of beds. The upper parts of beds consist predominantly of ripple-cross laminated sandstones (Bouma T_c). They pass upward into structureless mudstones (Bouma T_e), at tops of the composite beds.

Conglomerates constituting the uppermost part of the quarry are typically clast-supported and contain mainly quartz, gneiss, quartzite, lydite, granite, phyllite and greenstone clasts (Łapot, 1986). The lower contact of the conglomerate exposed in the quarry shows soft-sediment deformation structures, including folded slabs of underlying sandstone and deformed clasts of sandstone incorporated into the conglomerate (Fig. 16D).

The sedimentary succession described here is interpreted as deposit of high-density turbidity currents (sandy lithofacies) and subaqueous sediment gravity flows (gravelly lithofacies). Deposition occurred on slopes of fan-deltas which entered the late Viséan marine basin (embayment? cf. Mastalerz, 1995) from the N and NW.

The sandstones exposed in the quarry contain three conjugate sets of joints designated here as the J_1 to J_3, respectively. Apart from the sets J_1 and J_2 described earlier from the Glinno Graben (Kowalski, 2018), there occur well-defined joints assigned here to set J_3, striking subparallel (N-S) to the graben boundaries (Fig. 16E). In the north-westernmost part of the Kamionki Graben, joints of set J_3 show little evidence of shearing in a dextral strike-slip regime (Fig. 16F).

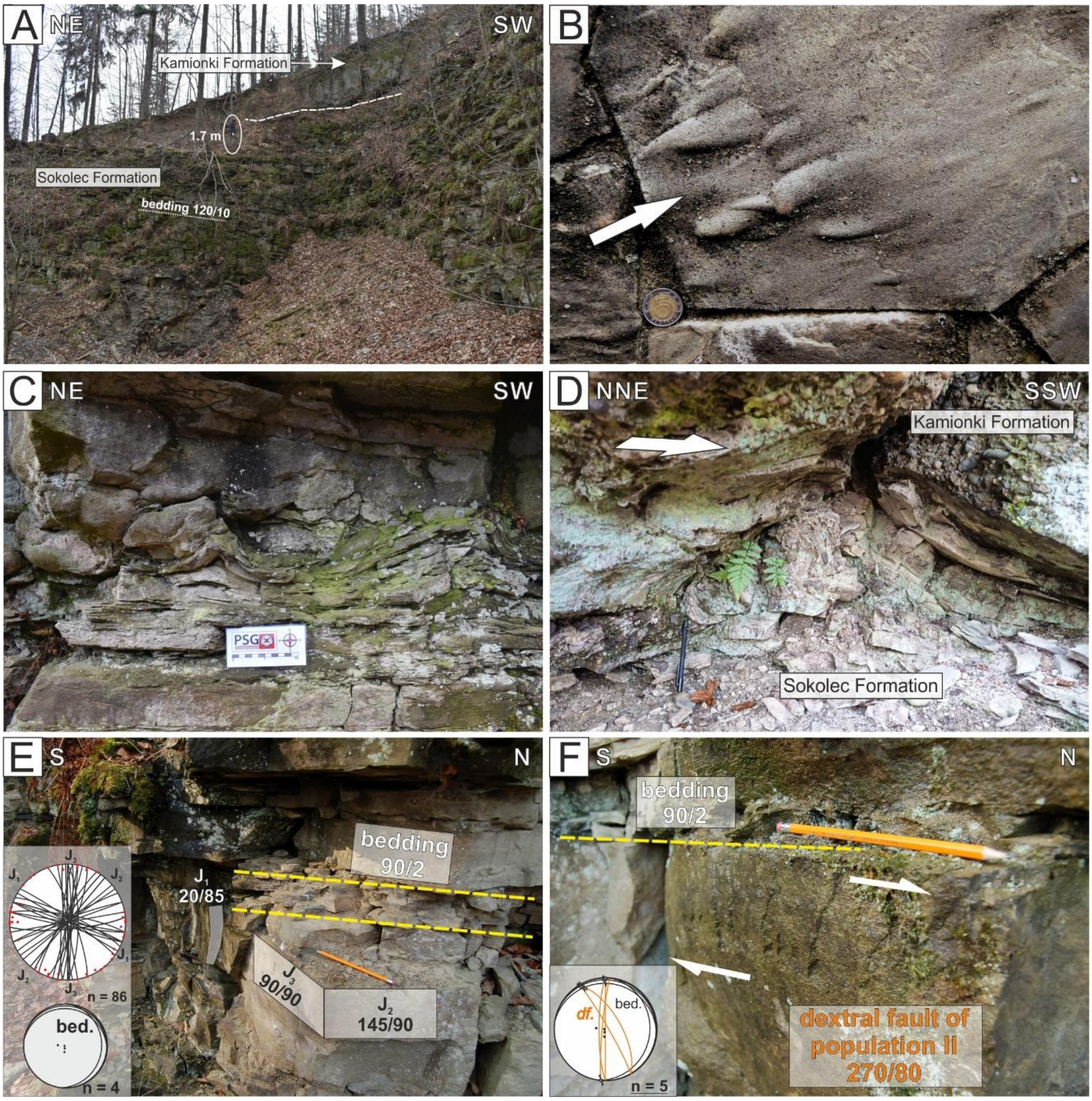


Fig. 16. Main sedimentary and structural features of the Sokolec and Kamionki formations exposed in abandoned quarry (stop 4). A – the south-eastern wall of the quarry with exposure of the uppermost Sokolec Formation and the lowermost Kamionki Formation. B – flute marks on the base of a sandstone bed (slab). The interpreted palaeocurrent direction is marked by arrow. C – small-scale, S- to SW-vergent slump folds within marine sandstone exposed in the quarry. D – folded slab of sandstone of the Sokolec Formation at the base of polymictic conglomerate of the Kamionki Formation. The interpreted palaeocurrent direction is marked by arrow E – three sets of planar, vertical to subvertical bed-confined fractures cutting nearly horizontal sandstones exposed in an abandoned quarry on the footwall of the Western Kamionki Fault. F – Surface of J_3 joint in sandstone, showing evidence of shearing in dextral strike-slip regime (fault population I).

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