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Evolution of the Bystrzyca River valley during Middle Pleistocene Interglacial (Sudetic Foreland, south-western Poland)

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Abstract: The article depicts the problem of river system development during the Middle Pleistocene Interglacial in the Bystrzyca River Valley (Sudetic Foreland, south-western Poland). Ten research sites located within the Świdnica Plain are presented, in which the structural, grain size (granulometry), petrographic, quartz grain morphoscopy, and heavy mineral analyses were carried out. The study results show the formation of piedmont fan deposits 2–8 km to the NE of the Sudetic Marginal Fault. The location of the fluvial deposits between the Sanian and Odranian tills indicates that they were deposited during the Holsteinian Interglacial (Krzczonów Formation, Mazovian; see Table 1). According toxthe lithofacies analysis, vast alluvial plains, composed of angular gravel grains in the south and of sands in the north, were deposited in the Sudetic Foreland in the environment of a very dynamic river. They are covered with a discontinuous layer of Odranian till. The petrographic spectrum shows 90–99% of local rocks, namely, Sudetic porphyry, Sowie Mts Gneiss and milky quartz, and 1–10% of Scandinavian rocks. In the proto-Bystrzyca river system, the existence of an oxbow lake in the distal part of the Krzczonów fan has been proved, which was developing at the end of the Holsteinian Interglacial. The continuity of the alluvial deposits is interrupted in the vicinity of Świdnica due to both the tectonic movements and the formation of the narrow tectonic graben of Roztoka–Mokrzeszów.

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1 Introduction

Most of the mountain forelands are the zones of subsidence and deposition of materials originating from mountain denudation [1–6]. These processes were developing particularly well in the narrow tectonic graben of Roztoka–Mokrzeszów, which marks the Sudetic Marginal Fault (SMF) in its southern sector [7,8]. The scale of such deposition depends on the height of the surrounding mountain massifs, resistance of rocks that compose them, climatic conditions and the subsequent tectonic activity [9,10]. Piedmont fans are often polygenic. They are a valuable source of information about environmental transformations in the Quaternary. Within them, the last glacial–interglacial cycle can easily be distinguished [11]. Complete, older than Vistulian depositional sequences are found less frequently. Research carried out in the Sudetic Foreland enabled the identification of interglacial sequences older than Eemian. Studies of the internal structure of one of the large fluvial landforms – the Bystrzyca Valley within the SMF – made it possible to reconstruct the conditions of sedimentation and formation of fluvial landforms during the Middle Pleistocene.

Multi-year studies of the Pleistocene succession in south-western Poland were based mainly on lithological–petrographic, sedimentological and palaeogeographic analyses [12]. They led to the recognition of fluvial deposits of warm Pleistocene intervals in the Sudetes and Sudetic Foreland [13–16]. However, no interglacial deposits are older than the Eemian Interglacial whose position would be supported by biostratigraphic studies. Palynologically studied Eemian Interglacial deposits are known only from two sites: Imbramowice [17] and Jaworzyna Śląska [7,18], which are located in the

Bystrzyca River Valley system. The latest comprehensive research of deposits from Krzczonów showed the evolution of an oxbow lake that formed on a piedmont fan during the Mazovian Interglacial [19].

This article presents the results of studies of deposits occurring in the central part of the Sudetic Foreland, in the Bystrzyca Valley and Krzczonów Hills, which were exposed close to the surface. These studies were aimed at determining the sedimentary conditions, sources of sediment deposition, role of basement tectonics and climatic constraints. This was to refer to old concepts and create a new model for the development of valleys in the Sudeten Foreland. The palaeogeographic reconstruction of the Bystrzyca Valley in the middle part of the SMF during the Middle Pleistocene is an example of case study research and supplements the extensive research conducted in the foreland of the Central European mountains (Table 1).

2 Regional setting

The study area is located in the Świdnica Plain (which is part of the Sudetic Foreland) at the boundary of the two major geological units: the Sowie Mts Gneiss Complex and the Ślęża Ophiolite Complex (serpentinite; Figure 1a and b) approximately 1.5–8 km from the SMF.

The plain is covered with latitudinal arcuate hills (Figure 1b). The hills, known as the Krzczonów Hills, reach about 25 m in height, and the elevations are up to 275 m a.s.l. Slightly further to the NE are the Kiełczyn Hills. The dominant landform of the relief is the Bystrzyca River Valley. The Bystrzyca is the largest river crossing the central sector of the SMF. In its mountain reach, the river valley is incised 100–150 m into the Sowie Góry Gneisses. The valley is probably of tectonic origin and evolved from the Pliocene to the Quaternary. Dyjor and Kuszell [7] describe it as an Upper Miocene "valley," trending SW-NE and is situated within the Poznań Clays.

The entire Cenozoic succession exceeds ~30–50 m in thickness. These deposits fill a 2 km-wide depression stretching latitudinally south of the Kiełczyn Hills. In the bottom part of this depression, there are regoliths represented by weathered gneisses, which are completely kaolinitised at the top. In this area, they attain a thickness of several metres. The weathering mantle deposits are overlain by Miocene rocks represented by limnic facies. In the lower part, these are quartz sands and muds that pass upwards into blue–grey clays with brown coal/lignite lenses. The Miocene deposits can reach a thickness of 20 m [20,21].

The Miocene and Pliocene succession is overlain by Pleistocene glacial and fluvial deposits. At most, three till layers are observed in the Sudetic Foreland, which have been documented in a superposition near Ząbkowice and Albertów (5 km north of the SMF) and in mine excavations at Jaroszów (20 km north of the SMF) [22–24]. The two lower tills from the older and younger stadials of the South Polish Complex were deposited traditionally from the NW, but the most southerly glacial lobes could locally advance from the N, NE and E. In turn, the Odranian ice sheet of the Middle Polish Complex generally advanced from the NE, although the ice movement direction was locally more diverse [12].

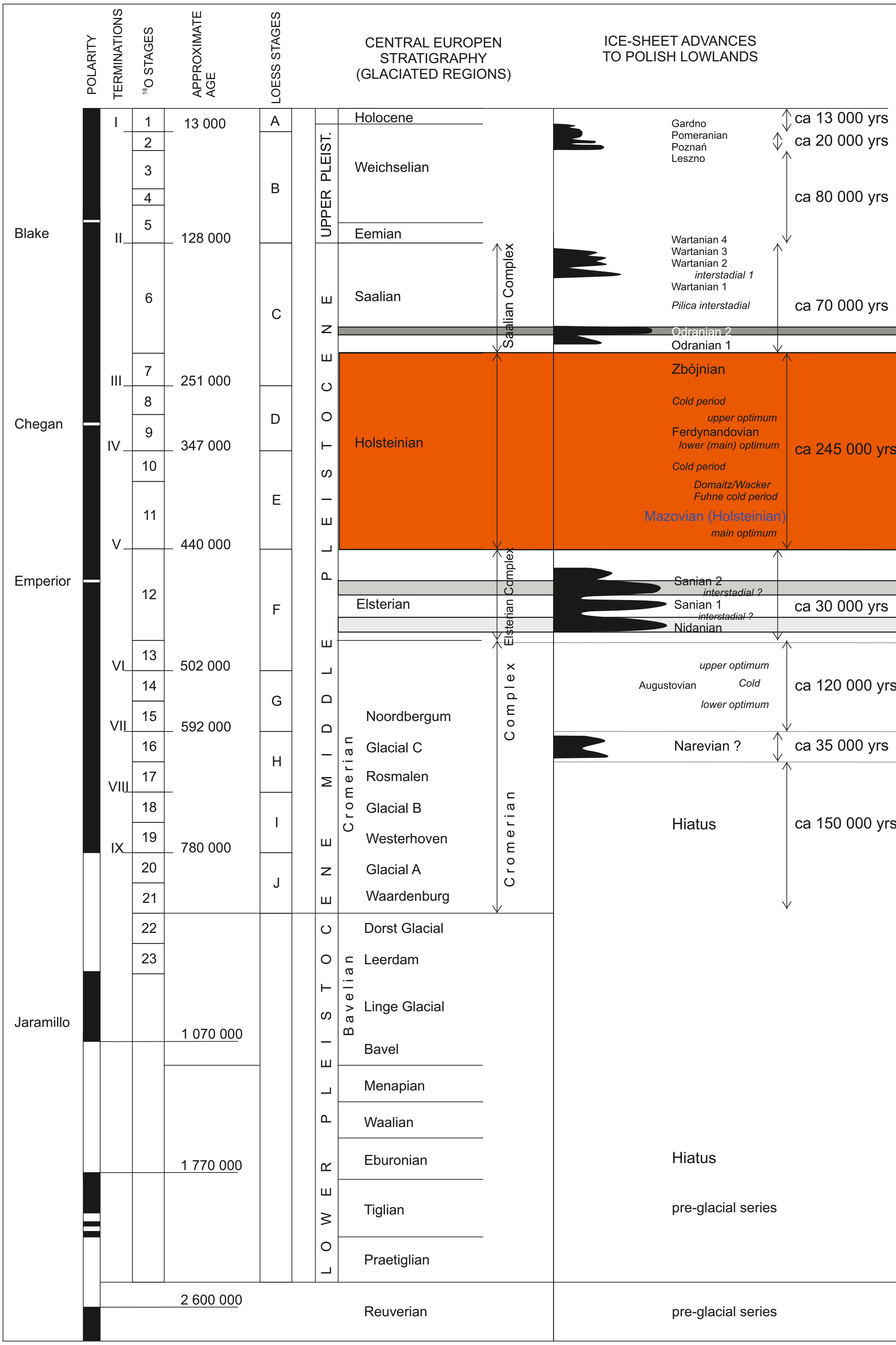
A series of alluvial fans developed along the SMF, with the most extensive system located in the Bystrzyca River basin [15]. Besides the preglacial fans, there is also at least one fan (maybe up to three) formed prior to the Odranian Glaciation. These are stratigraphic equivalents of the upper and middle units [19]. The deposits are partly covered, with the youngest till deposited during the maximum stadial of the Odranian Glaciation (Middle Polish Complex) [13,15]. The youngest deposits in the study area are represented by loess covers.

In the mountain foreland, there are numerous gravel (palaeofans) and fluvial series of the Bystrzyca River from the Pleistocene: the prelacial series (Preglacial Terrace), Middle Pleistocene series (Mazovian (Holsteinian) Interglacial Main Terrace) and three postglacial series (after the Odranian Glaciation) represented by the Upper, Middle and Lower terraces [25]. Between the Preglacial Terrace and the Main Terrace, there are Sanian 1 (Elsterian) Glaciation deposits which are poorly documented in exposures; while above the Terrace, the Odranian Glaciation deposits are represented mainly by a discontinuous cover of tills and proglacial sediments, up to several metres in thickness [26,15].

3 Material and methods

The fieldwork was carried out in 1990–2014 in the 10 open pits (gravel pits): Bojanice 3, Świdnica 1, Makowice 1 and 4, Krzyżowa 1, Boleścin 1 and Krzczonów 1–4 (Figure 1a and b). For lithological and sedimentological studies, 59 samples were taken from outcrop. In the Krzczonów 4 site, many specialist studies were additionally carried out in 2014: palaeobotanical (palynology,

Table 1: Chronostratigraphical table according to Krzyszkowski et al. [19], changed



plant macroremains and fossil woods), palaeozoological (gastropods, ostracods, diatoms, Cladocera and plant dyes), geochemical, isotopic, chemical (including elemental content) and palaeomagnetic [19].

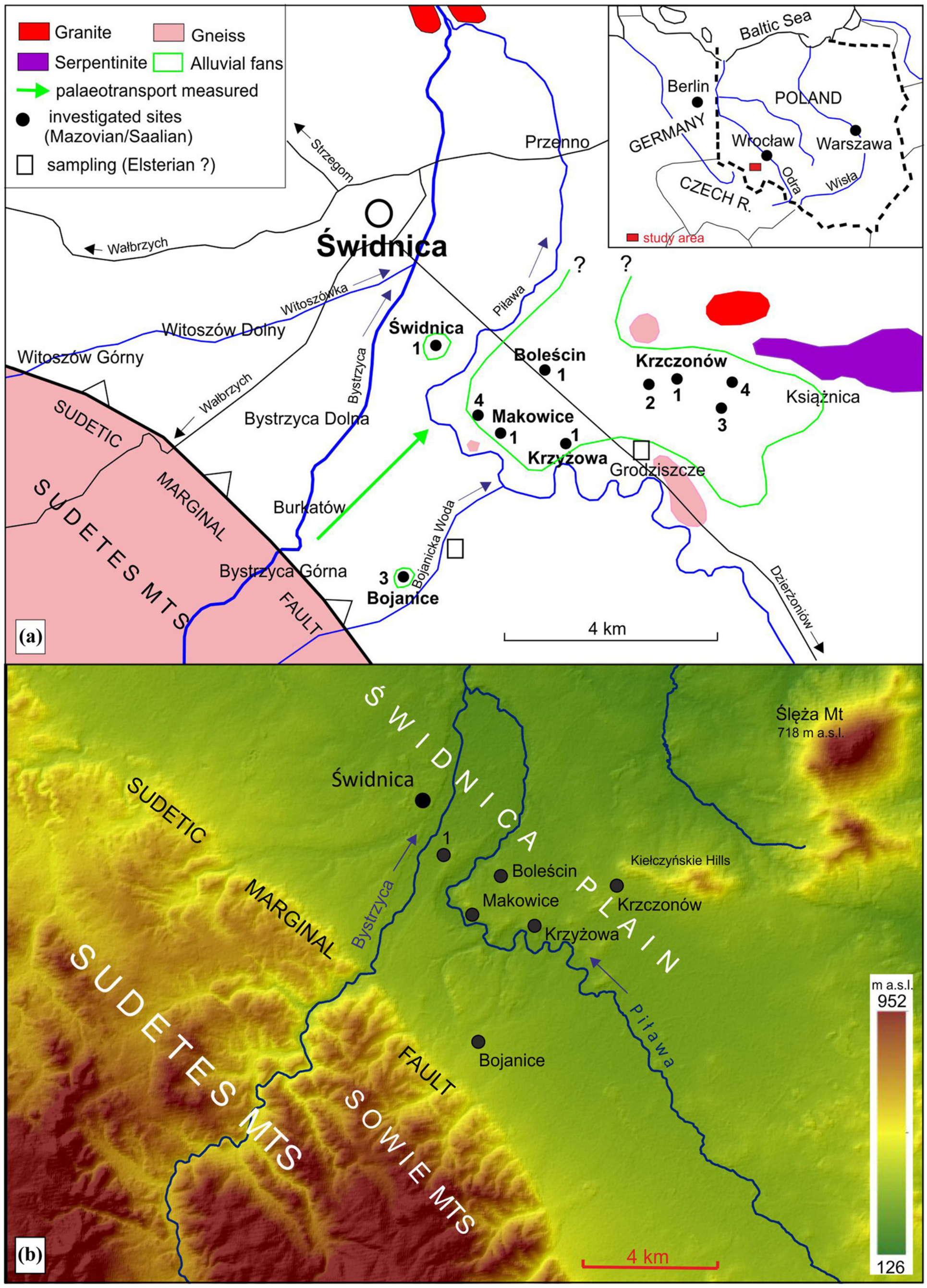


Figure 1: Map of the study area with sites investigated. (a) Map of geological background of the central part of Sudetic Foreland. (b) Surface features of the Świdnica Plain against digital terrain model.

Lithological and especially sedimentological studies have provided data for a palaeoenvironmental reconstruction. Identification of sedimentary structures and lithofacies, as well as determination of depositional conditions, has enabled interpretation of sedimentary environment. Photographic documentation was also made, showing the deposits and landscape forms, sketches of open pits and field drawings of pit walls for which structural (lithofacies) analysis was performed according to Miall [27] and modified by Krzyszkowski [28].

The results of lithological and structural studies are presented in Figures 2–13. Palaeoflow directions were determined, and directional (palaeocurrent) measurements were made in stratified and structurally undisturbed deposits. Sedimentological analysis allowed

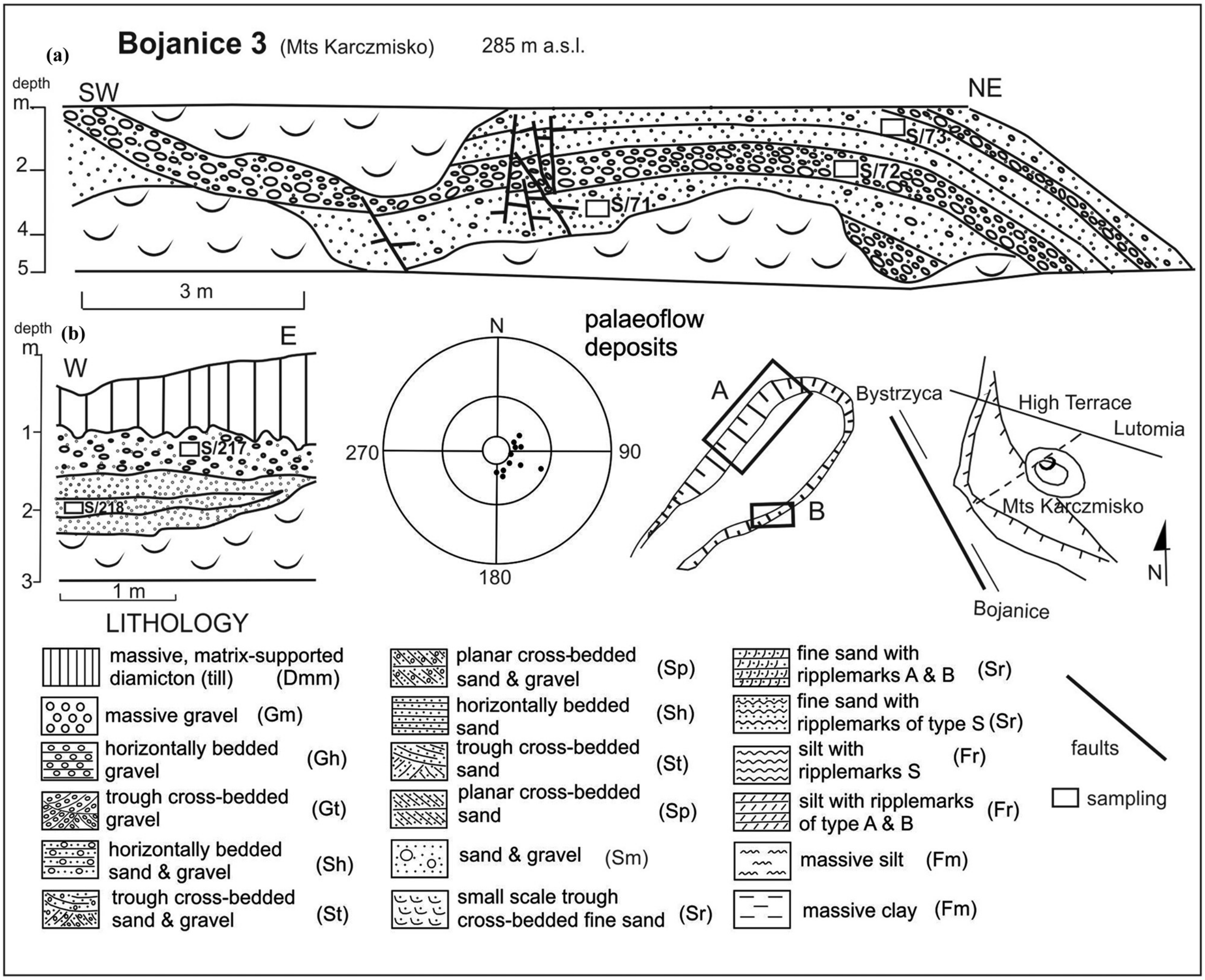


Figure 2: Profile of the fluvial sediments exposure at the Bojanice 3 site. a – as of 1990 and b – as of 2009.

identifying depositional sub-environments for which a mutual spatial relationship was determined, and depth and stratigraphic correlations were made.

Textural features of mineral deposits were investigated based on the grain size and heavy mineral composition and also by morphoscopy, which analyses the shape and roundness of the quartz grain.

The basic grain-size analyses were performed in the laboratories of the Institute of Geology and Geography of the University of Wrocław. Gravel petrography analyses were carried out at Przedsiębiorstwo Geologiczne PROXIMA S.A. in Wrocław on deposits from all research sites. For the analysis of heavy minerals, the “SZERL” software was used, which was written for the ZX-SPEKTRUM microcomputer [29]. For the analysis of quartz grain roundness and character of its surface, the method of determination used was based on Cailleux [30] but with the modification by Goździk [31].

The results of litho-petrographic analyses are presented in Figures 14 and 15.

4 Results

Bojanice 3 open pit is located in the south-eastern part of the foreland tectonic graben of Roztoki–Mokrzeszów [7,8] at an elevation of 285 m a.s.l. (50°46′43.35″N; 16°30′15.67″E), which is approximately 2 km from the morphotectonic edge of the Sudetes (Figures 1 and 2), between the Bojanicka Woda stream and the Bystrzyca River near the Bojanice–Bystrzyca road. The studies were conducted in 1990 (Figure 2a and Figure 15.3a) and in 2009, when only part of the gravel pit was preserved (Figures 2b, 5a, b and Figure 15.3b), because the rest had been reclaimed. Near the village of Bojanice, studies

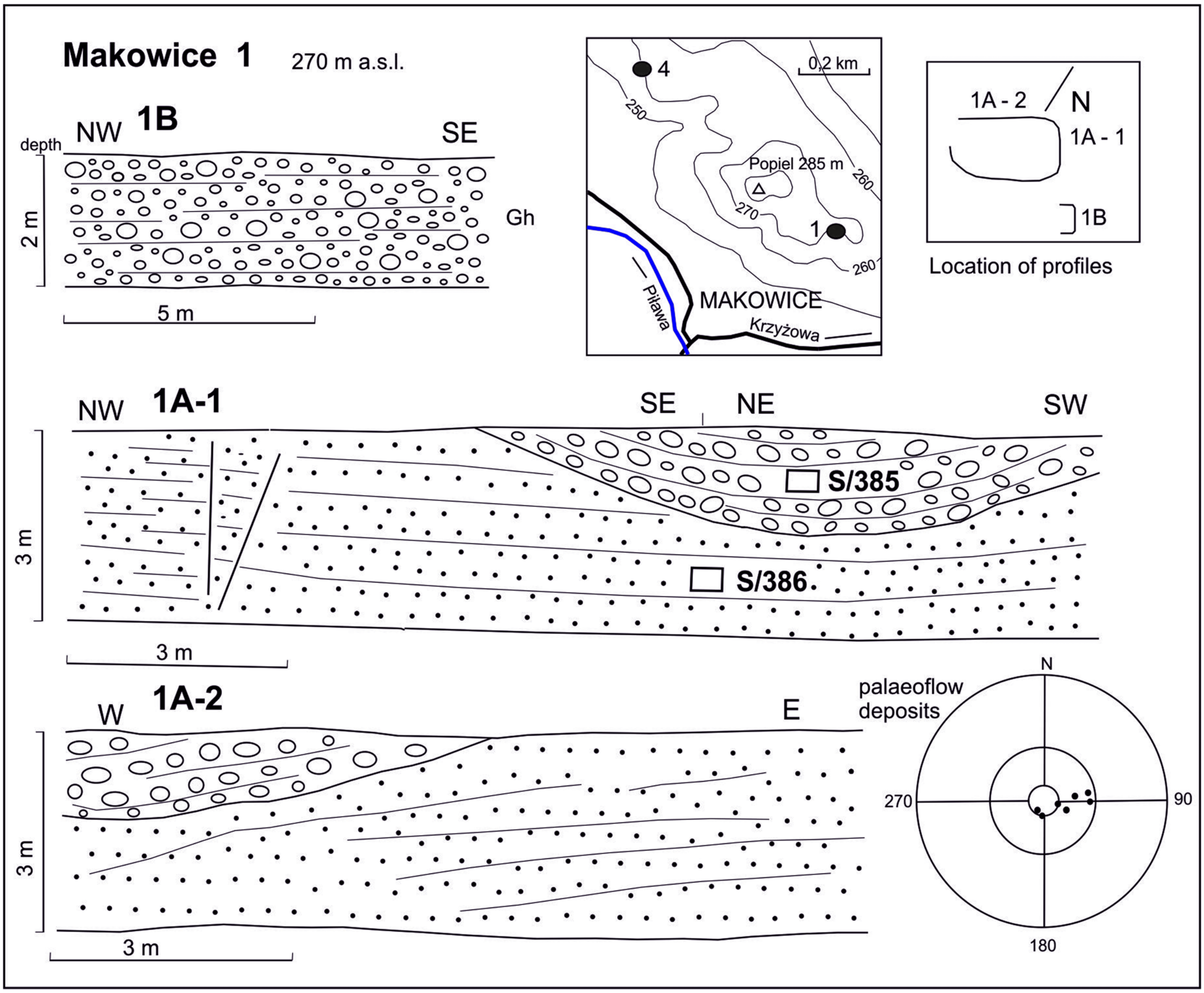


Figure 3: Profile of fluvial sediments exposure at the Makowice 1 site (as of 1995). Explanation of lithology in Figure 2.

were also conducted in other gravel pits (Bojanice 1 and 2) [8,29,33].

Open pit A, which is 5 m deep, exposes horizontally bedded sand (Sh) and gravel (Gh) interbedded with 1 m-thick massive gravel (Gm). The gravel sand and gravel sets are slightly bent (Figure 2a and Figure 15.3A). Locally, there are normal fault sets with the fault slip of about 3 m. On the eastern wall of the open pit B, the sedimentary sequence begins with Sh that passes upwards into 1 m-thick Gm (Figures 2b and 3B). Structural features of the gravel sand deposits indicate high energy of the sedimentary environment within a river channel. The sedimentation took place in an easterly direction (108°; Figure 2) in a gravel-bed-braided river, probably within channel bars. Angular grains account for 90% of the deposit (Figure 15), which indicates a fast and short sediment transport. The gradient change due to the proximity of the SMF explains such large grains in the sediment.

The grain-size percentages are as follows: 5–18% of grains > 10 mm, ca. 10% of grains 2–10 mm and 1–2 mm, and 5–40% of grains 0.25–0.5 mm. Gravel petrography reveals 1% of Scandinavian rocks, dominance of Sudetic porphyry (42–60%), variable contents of milk quartz and lydite (22–41%), and a few percentage of quartzite, Sowie Mts Gneiss, mica schist, sandstone and flint (Figure 15). This indicates a dominance of local rocks (>90%). Analysis of heavy minerals in the deposits of the open pit 3B shows constant contents of moderately weatherable garnet (24%) and amphibole (ca. 10%). Biotite exhibits the greatest content variations, being the least weathering-resistant mineral. Its highest content is found at the base (54%), gradually decreasing towards the top to the level of 22%. Few minerals are resistant to

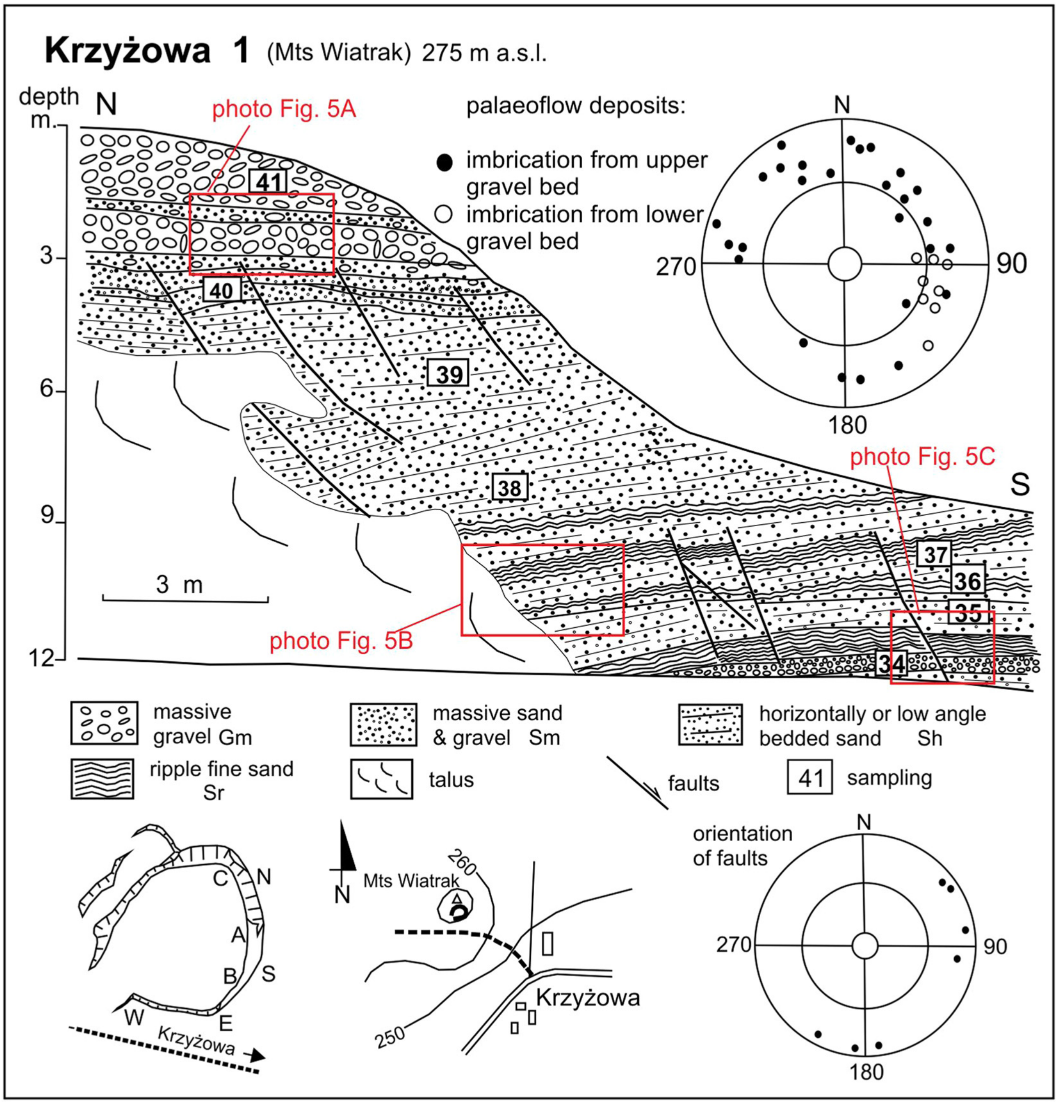


Figure 4: Profile of the fluvial sediments exposure at Krzyżowa 1 site (as of 1993) according to Krzyszkowski [26].

weathering: zircon, and alusite, straurolite and tourmaline. This indicates a short transport route of local rocks that did not manage to undergo the weathering processes.

The whole succession is covered with a thin massive matrix-supported diamicton (till; Dmm; Figure 2b). The till was probably deposited during the last ice-sheet advance in this area at the maximum range of the Odranian ice sheet.

Świdnica 1 open pit is located in the Kraszewice quarter near the Świdnica-Bystrzyca Górna road (Figures 1 and 14) at an elevation of 239 m a.s.l. (50°'12.59″N; 16°29′19.57″E) in the interfluve of the Bystrzyca and Piława rivers (currently reclaimed). There Gm is exposed at a depth of 3.2–4.8 m, which is cut by troughs and filled using cross-bedded gravel (Gt) and Gh. Gravel imbrication is observed. The deposits are coarse and contain pebbles of up 10–50 mm and massive structures, and its sedimentary structures indicate very high flow energy. The braided river probably occupied the entire bottom of the valley, covering older finer deposits.

The petrographic composition is similar to that of the Bojanice 3A site. The dominant component is porphyry (ca. 50%). Milk quartz and lydite account for 22%, while Sowie Mts Gneiss 8% (Figure 14). The deposits contain 4% of quartzite and 4% of other Sudetic rocks. These are local rocks occurring in the Bystrzyca River system. Scandinavian rocks account for approximately 1%.

Makowice 1 and 4 open pits are located about 5 km south of Świdnica in the village of Makowice (Figures 1, 3 and 14) near Popiel Hill (285 m a.s.l). The Makowice 1 open pit (50°48′23.85″N; 16°30′53.05″E) is located at an

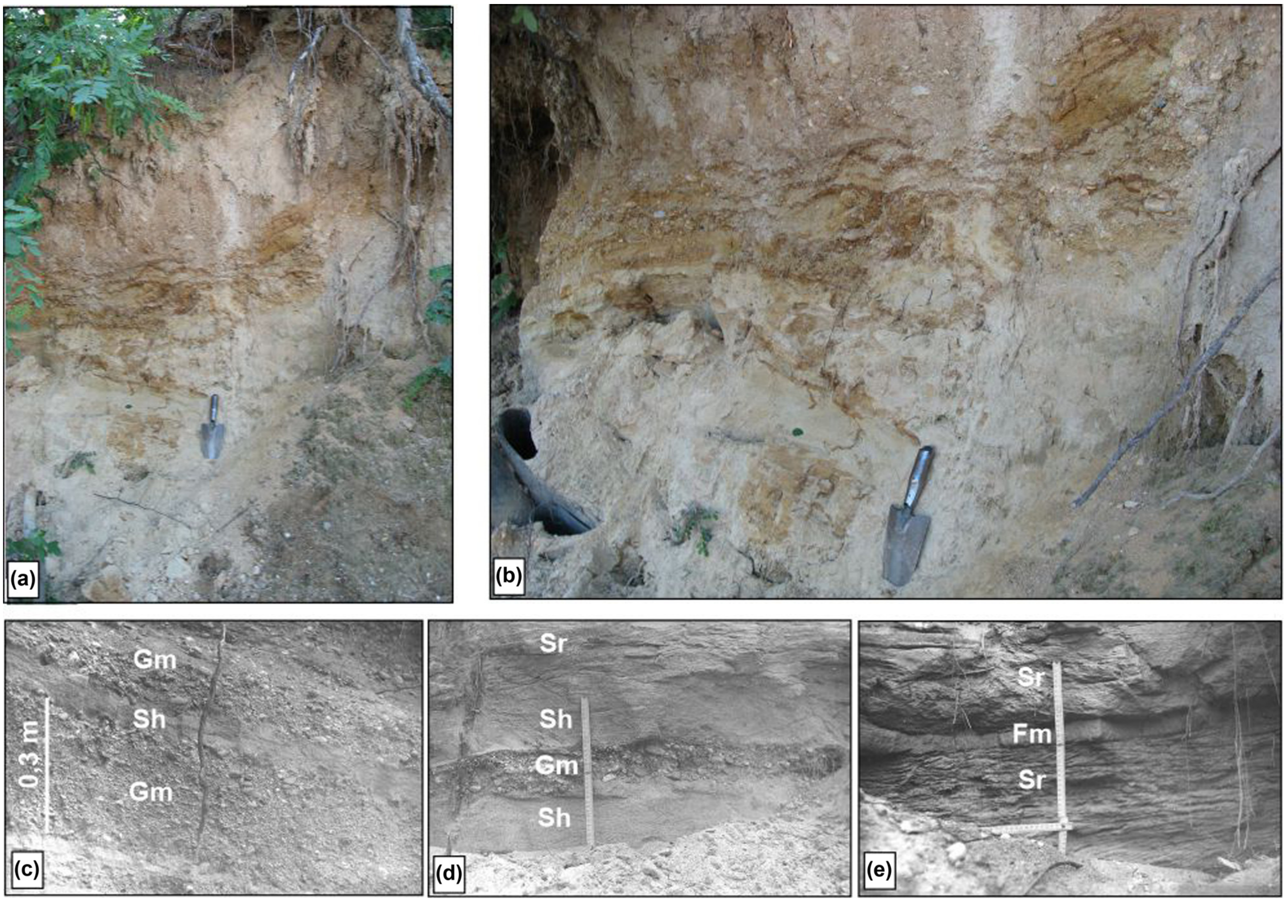


Figure 5: Structural features of fluvial deposits. a and b – at the Bojanice 3 site; c, d and e – at the Krzyżowa 1 site.

elevation of 270.4 m a.s.l., and the Makowice 4 at 263 m a.s.l. (50°48′28.23″N; 16°30′35.52″E).

In the Makowice 1B open pit (Figure 3), Gh is exposed in the south, which is at least 2 m in thickness. It passes into 1.5 m-thick Gt (Figure 3). Similar structures are found in Makowice 4 (Figure 14). The outflow was probably towards the east (ca. 90°; Figure 3).

Coarse-grained deposits are observed only at the top. They are composed predominantly of coarse gravel – from 38% (Makowice 1) to 48% (Makowice 4) – and pebbles of more than 10 mm in size. About 26–38% of the components are represented by 10–20 mm diameter grains. Such features indicate very high flow competence in a gravel-bed river, in which the sedimentation took place in a channel and in the bottom zone of the extensive channels, and on a steep palaeoslope during massive flows.

Petrographic studies of the gravel show its very interesting percentage composition. Over 90% of the components are represented by local rocks. The greatest share is taken by milk quartz and lydite. In Makowce 1, this index is as high as 45%, and in Makowice 4–40%. The second abundant group is porphyry. Its percentage is constant in both open pits and amounts to 21%. The percentage of quartzite, Sowie Mts Gneiss and other Sudetic rocks is about 7–20%. The spectrum also reveals Scandinavian rocks (about 2%), which indicates that the spectrum is typical of the Bystrzyca system.

In Makowice 1, Sh, about 3 m in thickness, is exposed at the base. In the 1A-1 open pit, complementary normal faults are observed, with a fault slip of 2.8 m (Figure 3). Fifty percent of the components are represented by fine-grained sand, 0.1–0.25 mm of grain diameter (Figure 14). Similar proportions in the grain-size distribution can be observed in the lower part of the Boleścin 3 open pit.

Krzyżowa 1 open pit is located at the summit of Wiatrak Hill (275 m a.s.l. (50°48′10.52″N; 16°31′57.93″E); Figures 1 and 4) between the Piława River and the Świdnica–Dzierżoniów road, which is approximately 4 km from the Bystrzyca River. It exposes mainly Sh, ripple sand (Sr), more rarely horizontally bedded or

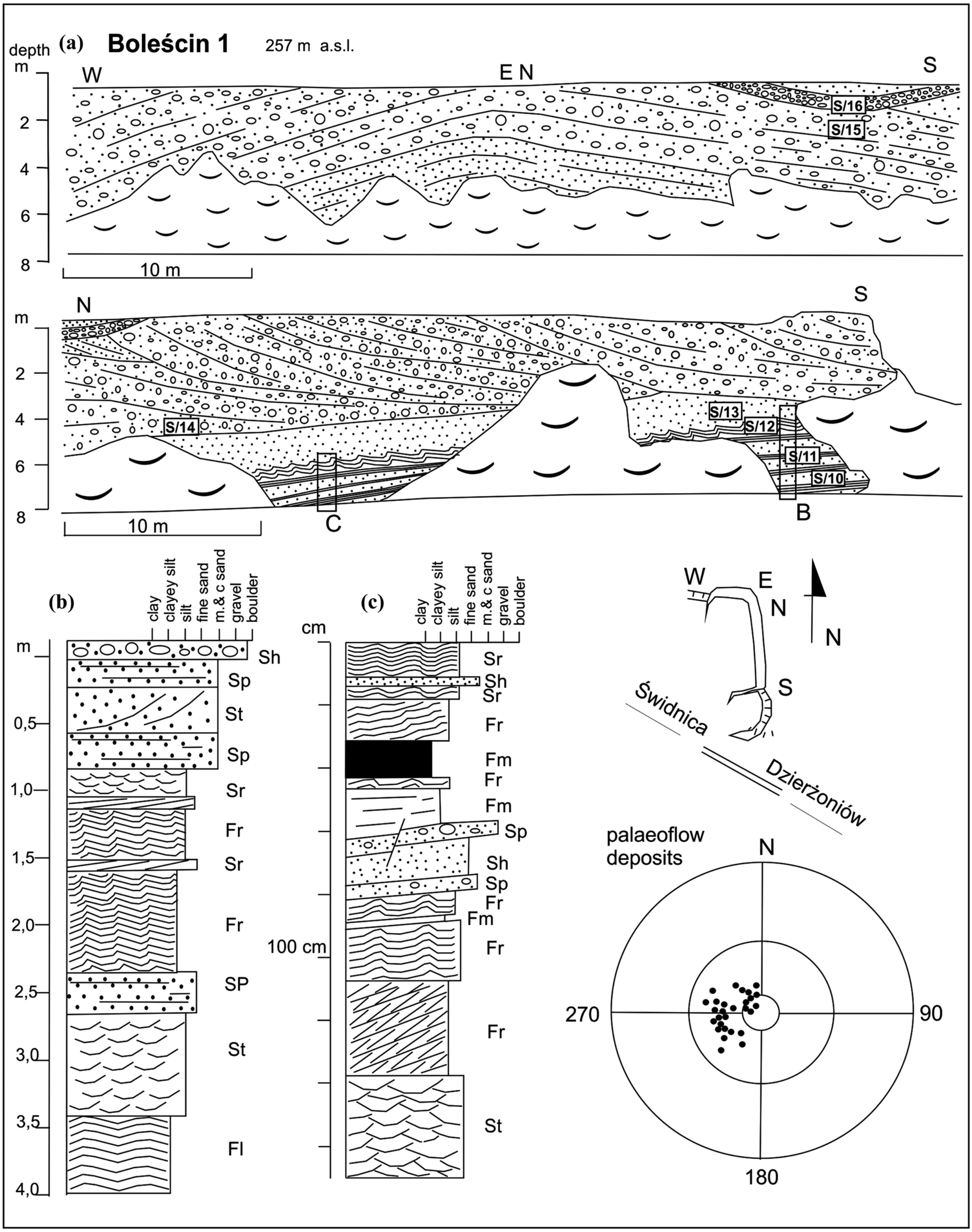


Figure 6: Boleścin 1 site. (a) Profile of fluvial sediments' exposure at the outcrop; (b and c) sedimentological logs (as of 1985). Explanation of lithology in Figure 2.

massive sand (Sm) and Gm. Moreover, two Gm layers are observed: the lower one of several centimetres thick and the upper one on the ground surface of up to 3 m in thickness (Figures 4 and 5). Both gravel layers show

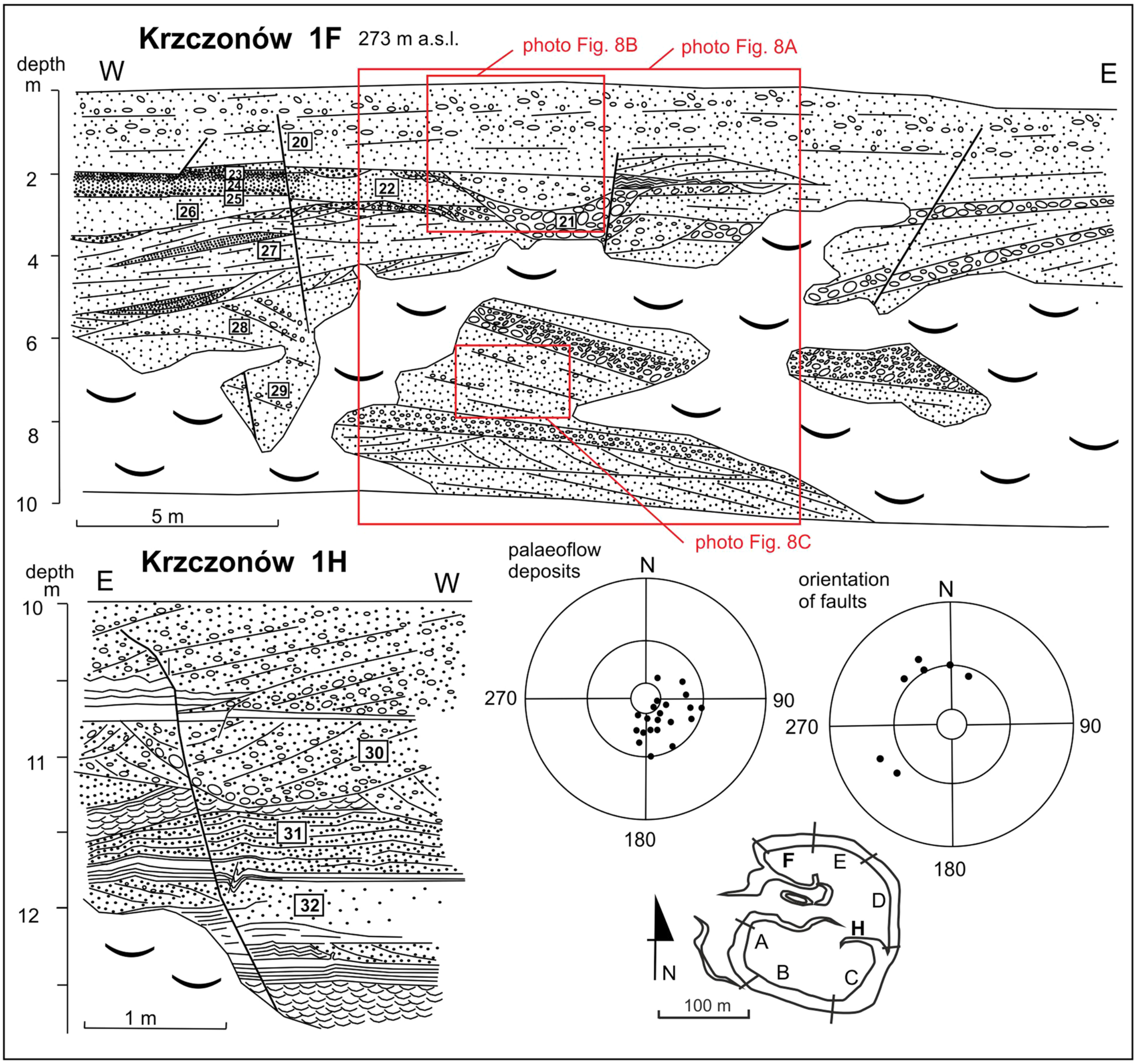


Figure 7: Profile of the fluvial sediments exposure at the Krzczonów 1 site. Explanation of lithology in Figure 2.

imbrication structures, although these are better visible in the upper layer where the pebbles are up to 15 cm in diameter. The gravel layers probably represent longitudinal bars of a braided river. The remaining deposits were perhaps accumulated in a channel at varying flows, with the formation of ripple marks during weak flows or in abandoned channels of meandering river.

This deposit contains only a small admixture of northern rocks (up to 2%) and exclusively erosion-resistant rocks (crystalline rocks, quartzites, sandstones and flints; no Baltic limestones and no Polish Lowlands limestones and mudstones); the remaining 90% of the gravel is represented by local rocks: milk quartz, lydite, porphyry, melaphyre, quartzite, Sowie Mts Gneiss and Palaeozoic silica. Thus, the spectrum is typical of the Bystrzyca system (Figure 14); compared to the Preglacial Series, it contains an increasing amount of less erosion-resistant components: porphyries and Sowie Mts Gneisses as well as some northern rocks. Therefore, the Krzyżowa deposits are undoubtedly of fluvial origin and were accumulated by the Bystrzyca River. The present-day shape of the hill is most likely of erosional-denudational origin [26].

Boleścin 1 open pit (Figures 1, 6, 6a and 14), located in the village of Boleścin near the Świdnica-Dzierżoniów road at the outskirts of the western part of the Krzczonów Hills, has been depleted and reclaimed. It lies at an

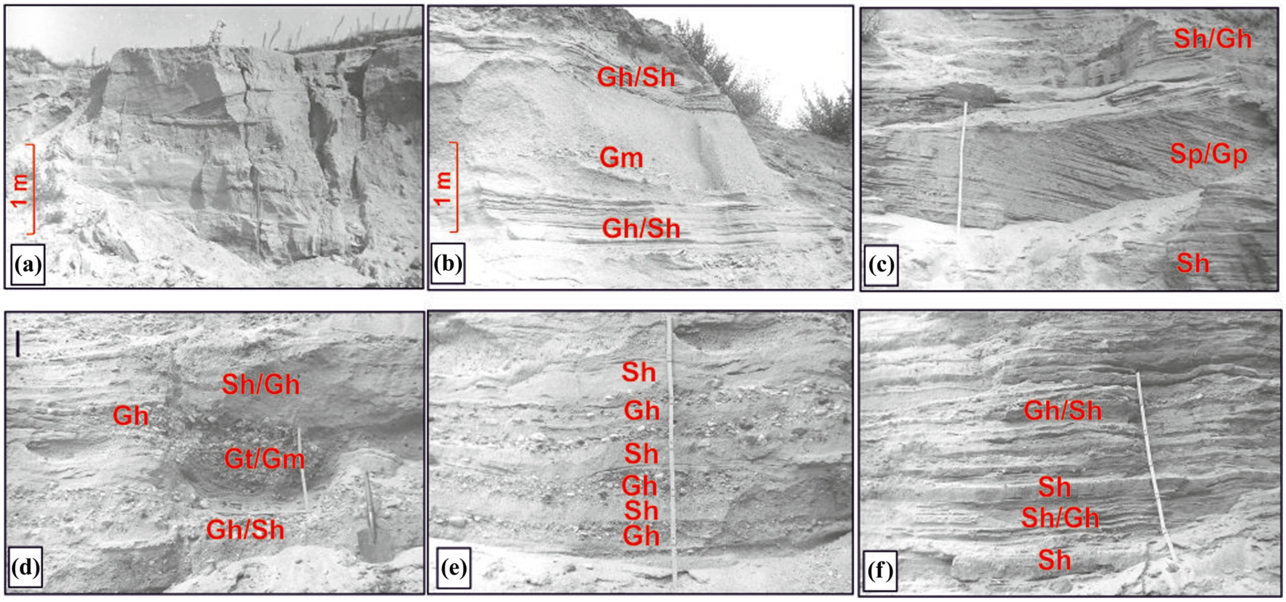


Figure 8: Structural features of fluvial deposits. (a–c) At the Krzczonów 1 site; (d–f) at the Krzczonów 2 site.

elevation of 250.6 m a.s.l. (50°48′54.15″N; 16°31′50.32″E). The open pit walls, 8 m-high, expose silt and sand at the base (Unit 1) and sand and gravel at the top (Unit 2). The high lithological variability is underlined by an erosional boundary at a depth of 4–4.5 m (Figure 6).

At the base of Unit 1 are rhythmically bedded fine-grained deposits (Figure 6). The dominant grain sizes are 0.1–0.25 mm and 0.25–0.5 mm (Figure 14). The sequence starts with trough cross-bedded sand (St) or silt with ripple marks (Sr). Planar cross-bedded sand (Sp) and Sh, 30 cm thick, are separated by thin beds of muds: massive silt and clay (Fm) Sr S or types A and B (Fr) and sand beds: small trough cross-bedded fine sand, fine sand with ripple marks S or types A and B (Sr). At the top of Unit 1, about 1.5 m in thickness, are Sp, Sh and small-scale St. At a depth of approximately 6 m, single small faults appear with a fault slip of 20 cm. These structures indicate deposition in an environment of variable energy. The sand beds were formed in a sand-bed-braided river, as evidenced by the small thicknesses of structures Sh, St and Sp. The remaining deposits were accumulated in a river channel at varying flows, accompanied by the formation of ripple marks during weak flows or in abandoned channels. With time, the flow was waning and the Sr, Fr and Fm structures were formed in an environment of either stagnant water or a weak and even waning flow of meandering river.

The deposits of Unit 2 cut the deposits of Unit 1. They are represented mainly by St and gravel Gt. Sp and Gp are locally observed. The thickness of the Unit 2 deposits reaches 4–6 m. The waters flowed towards the west (Figure 6).

The petrographic composition is similar to that from Bojanice 3B, wherein porphyry accounts for 42%, milk quartz and lydite 35%, quartzite 10-16%, Sowie Mts Gneiss ca. 10% and Scandinavian rocks 1%. Thus, the spectrum shows a relation with the Bystrzyca system.

The Krzczonów 1 (Figures 1 and 7), Krzczonów 2 (Figures 1 and 9) and Krzczonów 3 (Figures 1 and 10) open pits were located about 200–300 m to the south of the Krzczonów–Książnica road. The pits have been depleted and reclaimed. The only open pit currently exploited is Krzczonów 4 (Figures 1, 11 and 13). All of them are located within arcuately extending, longitudinally oriented hills that are known as the "Krzczonów Hills" and reach an elevation of 275 m a.s.l., with a relative height of 25 m.

The Krzczonów 1 open pit (Figures 1, 7 and 14) is located in the western part of the Krzczonów Hills that continue from a sand pit (50°48′46.49″N; 16°35′23.79″E), in a small hill at an elevation of 273 m a.s.l.

The eastern wall of the pit reveals cross-bedded, brown–grey, variously grained sand with a gravel admixture (St and Gt; Figure 8a, c, d and e). In the middle part of the wall are brownish–grey interbeds of argillaceous gravel and sand (Sm). Small lenses of greenish sandy muds were also occasionally observed. Locally, the strata are arranged horizontally (Sh) with no signs of glaciotectonic deformation. At the bottom (Krzczonów 1F – Figure 7), ripple sand (Sr) and Sh

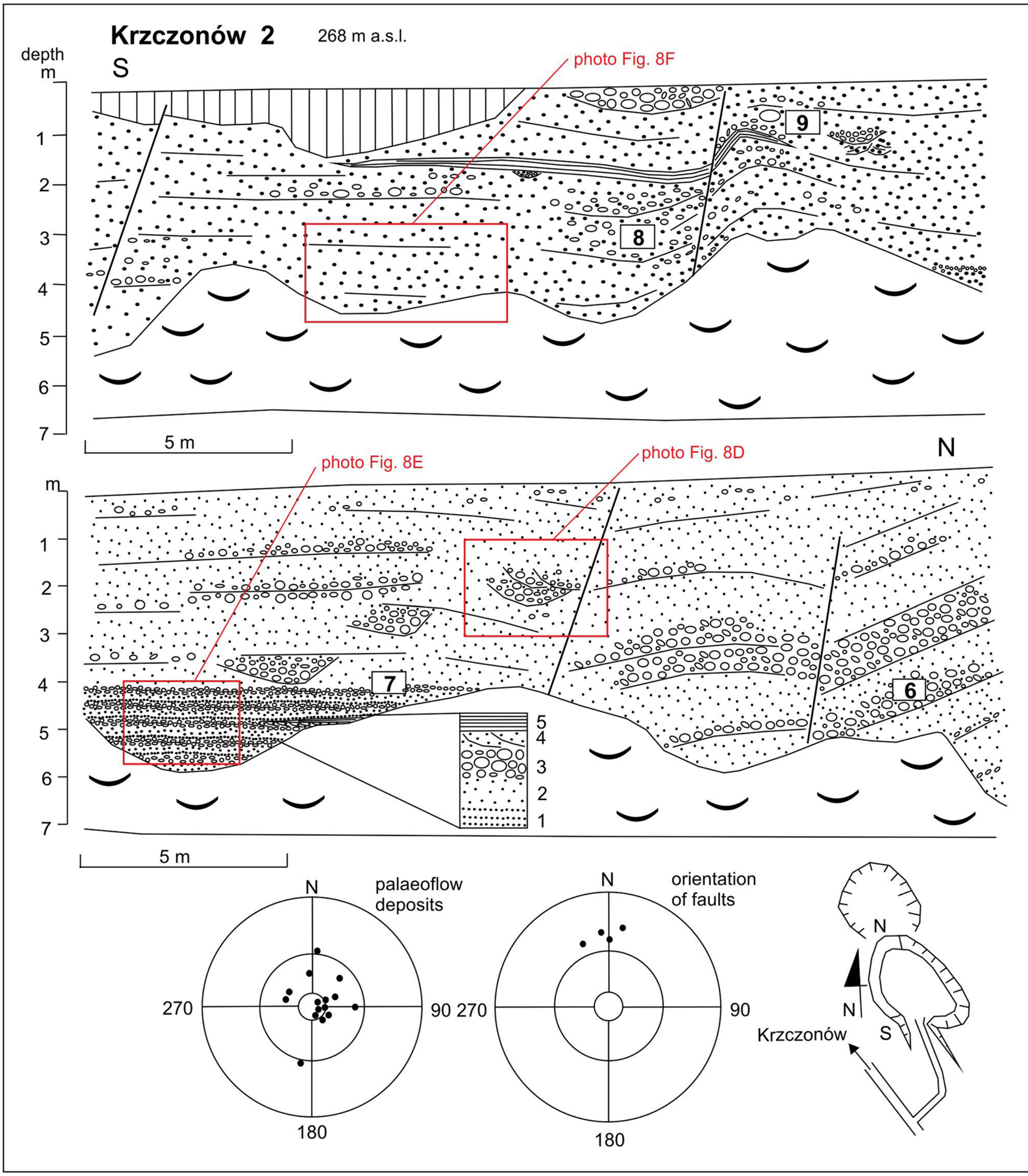


Figure 9: Profile of fluvial sediments' exposure at the Krzczonów 2 site (as of 1993). Explanation of lithology in Figure 2.

(Figure 8b, e and f) appear. Palaeoflow of meandering river directions are determined to be from SE (Figure 7). Normal faults were observed on the wall across the entire scarp. The above structures suggest an overbank or channel-margin environment – first with a very weak flow, until dying out, and then a dynamic change in sedimentation within a channel and the formation of trough structures of a braided river.

The 2.0–5.0 mm gravel fraction is dominated by Sudetic porphyry (over 40%), quartz (about 35%), Sowie Mts Gneiss

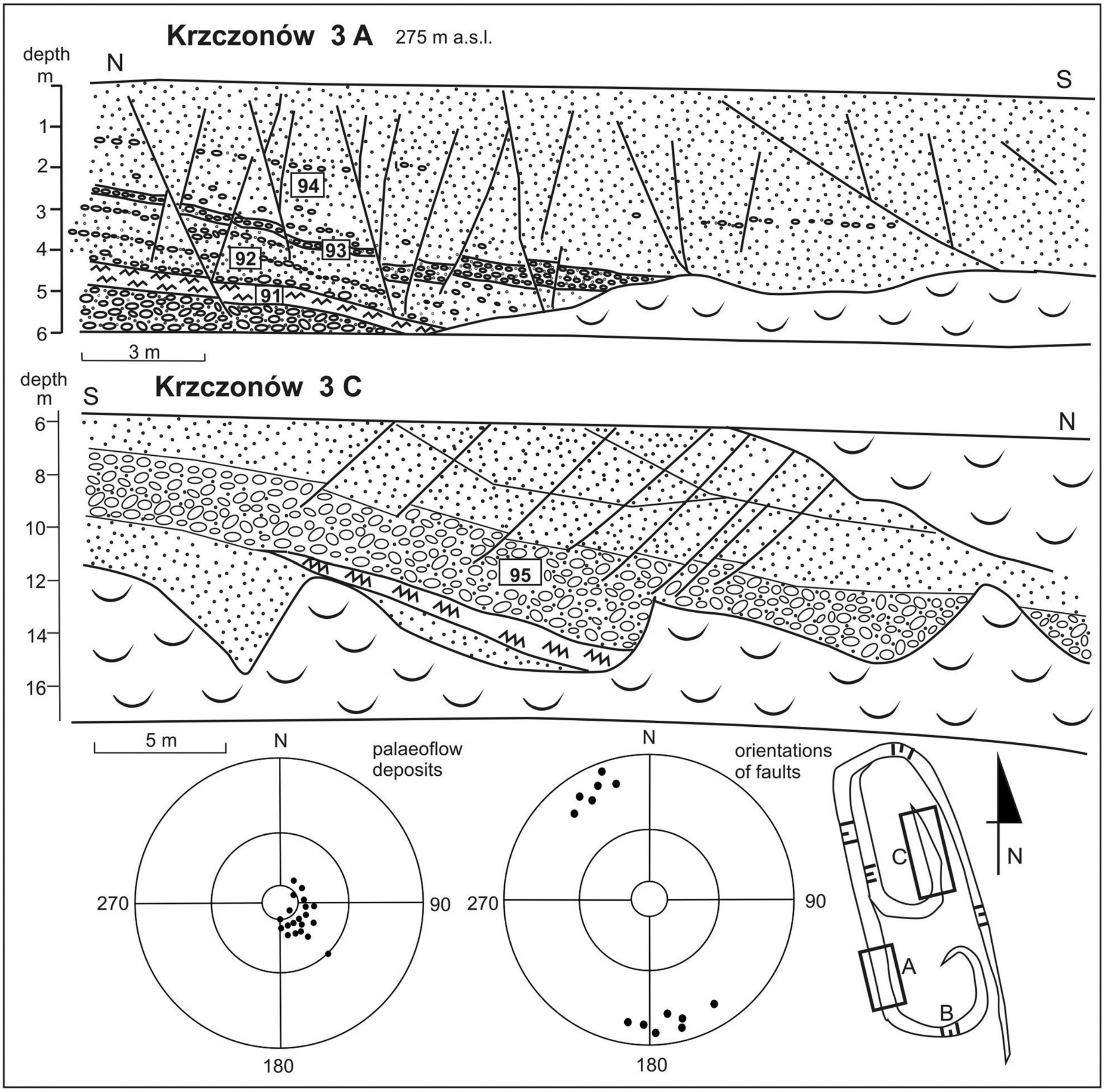


Figure 10: Profile of fluvial sediments' exposure at the Krzczonów 3 site (as of 1993). Explanation of lithology in Figure 2.

(from 10%) and Sudetic quartzite (5%). The content of Scandinavian granites is about 5%. The percentage of other groups of rocks is much smaller (Figure 14).

Krzczonów 2 open pit (Figures 1, 9 and 14) is located SW of the Krzczonów 1 open pit, at an elevation of 259–268.5 m a.s.l. (50°48′40.38″N; 16°35′13.36″E) in another small hill. The lower parts of its 7 m-high walls expose Gh and Sh in several repetitive sequences 1–5 (Sh-SGh-Gh-Sp-Sh; Figure 9). In the upper parts, from a depth of 4.5 m, Sh commonly occur, within which interbeds of gravel (Gh) and Gt appear, which are a few tens of metres thick. The water flow directions are varied: from W through N to E, but the easterly direction dominates. Normal faults were observed on the wall across the entire width of the northward-oriented scarp. As in Bojanice 3 (Figure 2b), the whole is covered by a thin discontinuous layer of Dmm (till; Figure 2b) with a thickness up to 2 m (Figure 9). The till was probably deposited during the last ice-sheet advance in this area at the maximum limit of the Odranian ice sheet.

The gravel fraction 2.0–5.0 mm is represented predominantly by Sudetic porphyry (30–50%), quartz

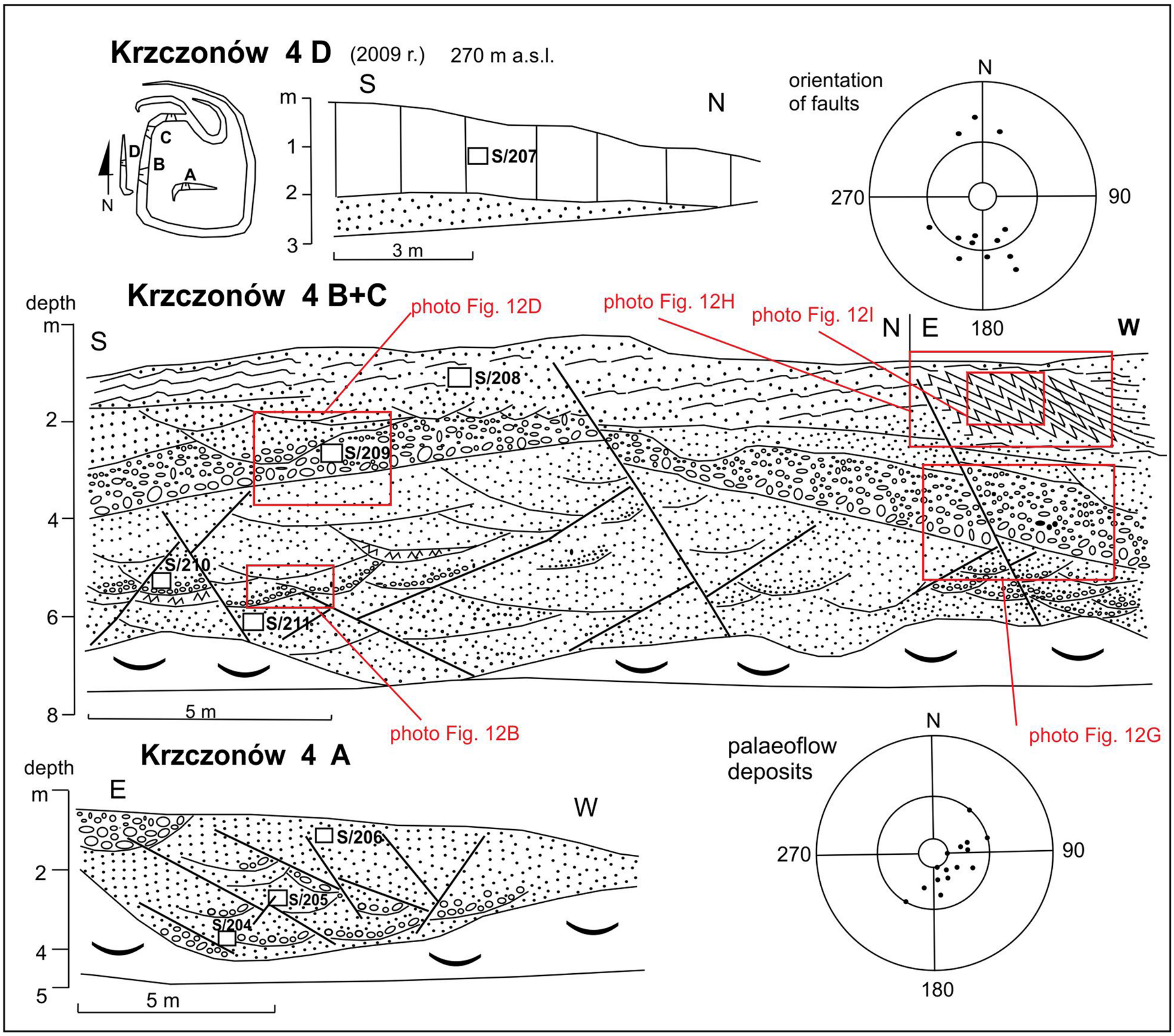


Figure 11: Fluvial sediment exposure profile at the Krzczonów 4A–D site (as of 2009) according to Krzyszkowski and Urbański [37], modified. Explanation of lithology in Figure 2.

(20–45%), Sowie Mts Gneiss (10–15%) and Sudetic quartzite (5%). The content of Scandinavian granites is about 5%. The percentage of other groups of rocks is much smaller (Figure 14).

Krzczonów 3 open pit is located at an elevation of 275 m a.s.l. (50°49′12.59″N; 16°29′19.57″E), south of the Krzczonów Hills (Figures 1, 10 and 14).

To a depth of 15 m, the only practically exposed deposits are the horizontally or low-angle bedded sand and/or gravel (Sh)/(Sl) and Gm with numerous gravel-filled scour and fill structures; sporadic are also ripple sand and sandy mud (Figure 10). Gm surrounded by Sh (Figure 14) is visible at the top. The outflow was towards the E. Normal complementary or parallel faults were observed on the wall across the entire width of the NNW/SSE-oriented scarp (Figure 10). The deposit probably represents the distal part of an alluvial fan with the predominance of sheet-flood deposition and rare channels. Fluvial origin of the deposit is evidenced by its petrographic composition similar to that reported from Krzyżowa 1 (Figure 14). In the 2.0–5.0 mm gravel fraction, the dominant petrographic groups are Sudetic porphyry (40–50%), quartz (30–35%), Sowie Mts Gneiss (10–20%) and Sudetic quartzite (5%). The content of Scandinavian granites is about 3%. The percentage of other groups of rocks is much smaller (Figure 14).

Krzczonów 4 (A–E) open pit is referred to as the “Książnica” Sand Pit (50°48′58.59″N; 16°20′19.57″E). The

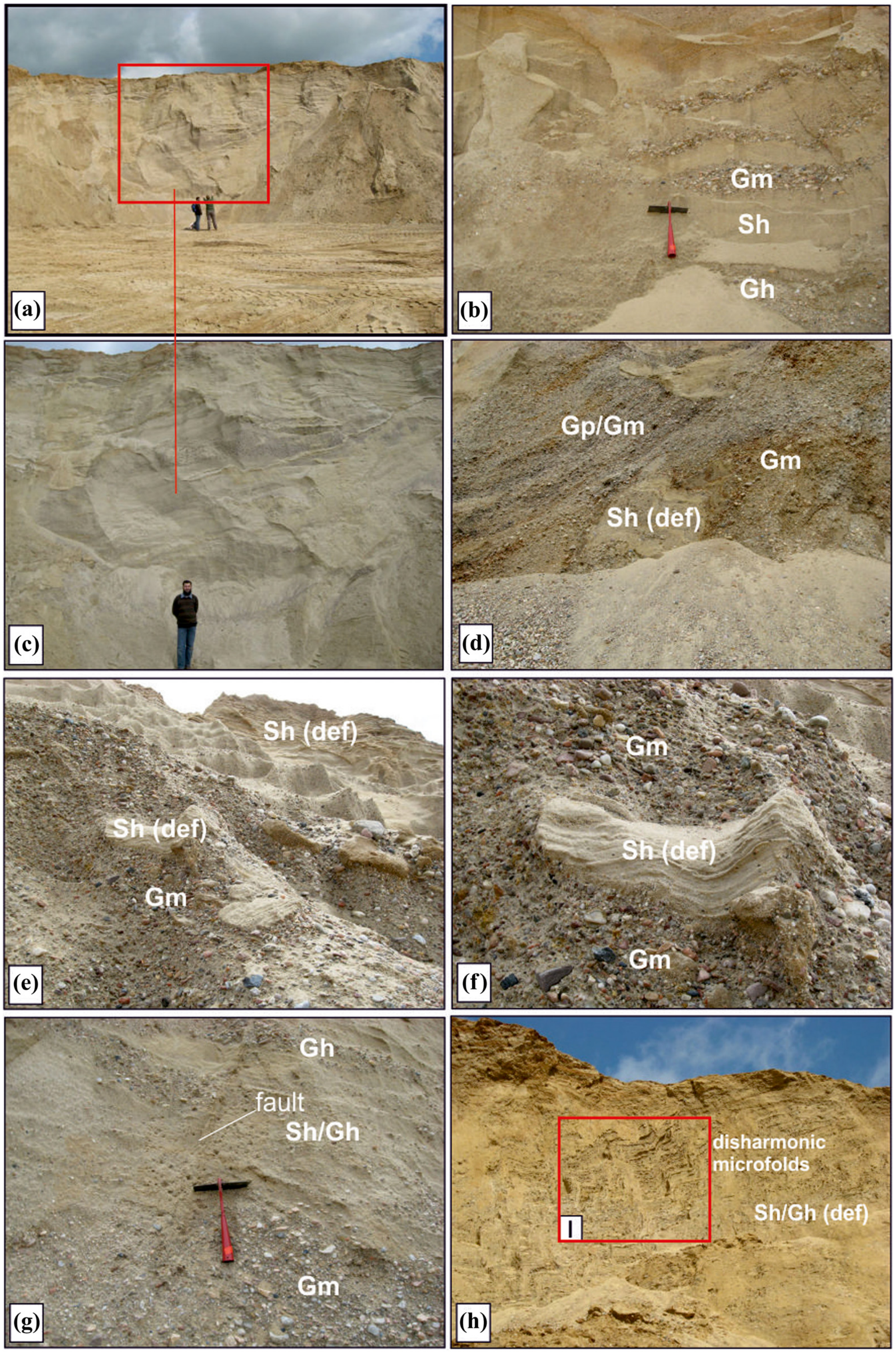


Figure 12: Krzczonów 4 site. (a) general view of the outcrop; (b) interbedding of gravel in the sandy series (see Figure 11); (c) view of the eastern wall of the outcrop; (d) fragment of the channel structure filled with sandy gravel (see Figure 11); (e and f) sand bodies layered in gravel–sand mass; (g) faults in sand and gravel sediments (see Figure 11); (h) general view of the wall with post-sedimentation disorders (see Figure 11); and (i) disharmonious folds within the originally layered fluvial sands.

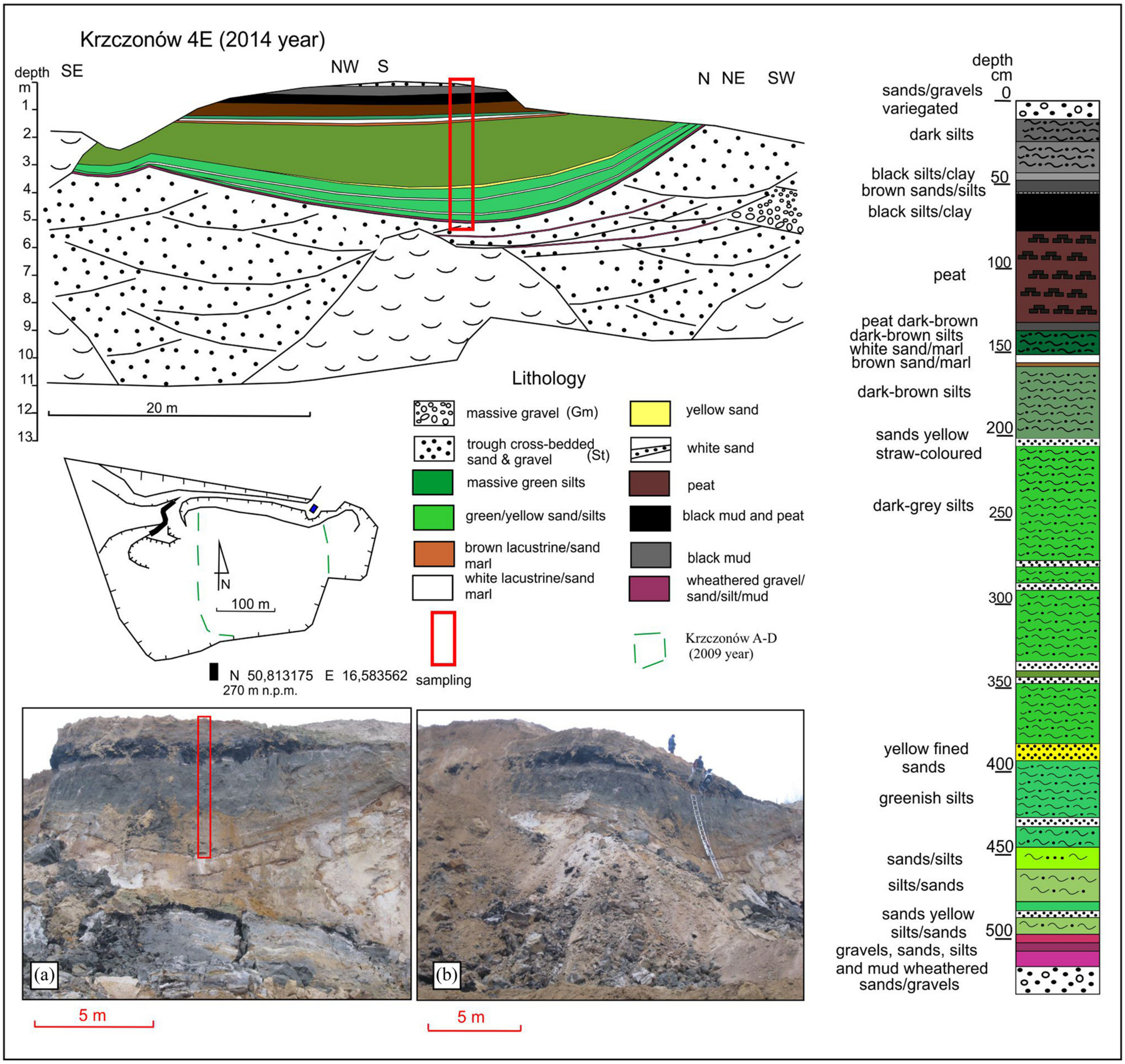


Figure 13: Investigated profile on the right against the background of the geological situation (see profile in NW corner) at the Krzczonów 4E site according to [19], modified; (a and b) view of the exposed fill of the oxbow palaeolake.

exposure was described in 2009. At that time, three mining walls 4A–D were investigated (Figures 1, 11, 12 and 15). The advantage of the site was its interesting geological and geomorphological location in the surroundings of the Bystrzyca River valley in the Sudetic Foreland and south of the Ślęża Massif.

In the western part of the exposure, to the north (wall 4C) and south (wall 4B) of wall 4D and further on in the western slope of an 8 m-high wall (Figures 11 and 12b, d), a sand-gravel series was exposed at that time. In the lower part, it was grey St with an admixture of gravel (GSt; Figure 12). Within minor channel structures, fillings with greenish sandy muds (FSh) were observed, which were several tens of centimetres thick. In the middle part of the western scarp, there is a layer of brown–grey gravel with a thickness of 1–1.5 m (Figures 11 and 12d, g). It is a loamy, secondarily ferruginated deposit. The top part is represented by brown–grey sand with an admixture of the braided channels' planar-bedded gravel. Similar deposits were exposed on the northern slopes (4C, 4A; Figures 11 and 12g–i). At the top of this part, an interesting deformational structure of 3 × 5 m in

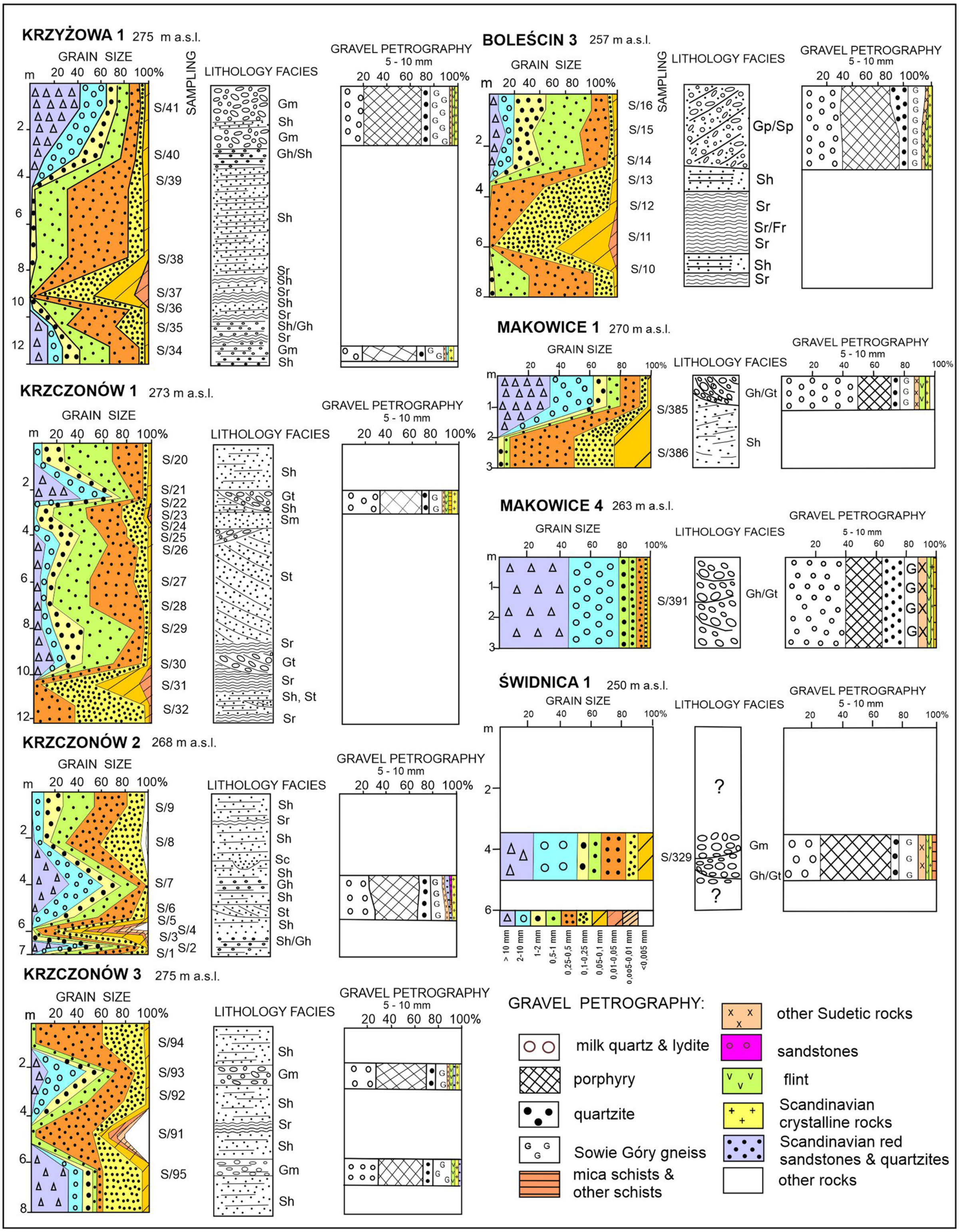


Figure 14: Results of lithopetrographic analysis from the investigated sites: Krzczonów 1, 2, 3; Krzyżowa 1; Boleścin 3; Makowice 1, 4; and Świdnica 1.

size was encountered (Figure 12h). It looks as if the sand, originally horizontally bedded, has been compressed into a harmonica. These are sets of disharmonic microfolds with an amplitude of several centimetres.

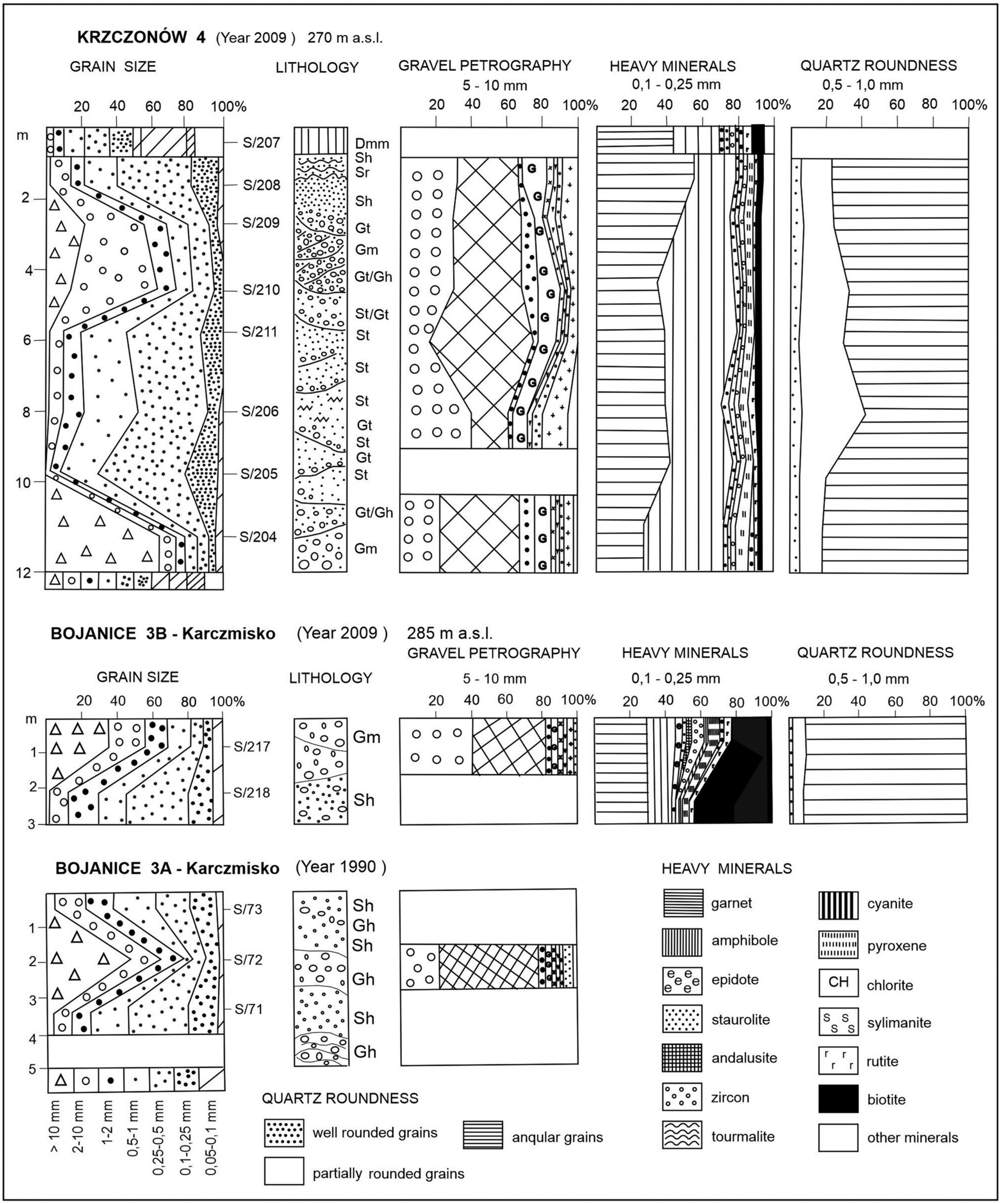


Figure 15: Results of lithopetrographic, heavy minerals and quartz roundness analyses from the investigated sites: Krzczonów 4 (2009): Bojanice 3B (2009) and Bojanice 3A (1990). Explanation of lithology on Figure 2.

The sand–gravel deposits were intersected by a network of normal and reverse faults. The fault planes dip mainly towards the NNW. The channel structures have a greater scatter. The centre of measurement scatter on the Schmitt grid indicates the general flow direction from NW to SE (Figure 11). The petrographic composition of the sand–gravel deposit is dominated by Sudetic porphyry (from 38% to 60%); the percentage of milky quartz and lydite (28–40%) is also high. The contents of Sowie Mts Gneiss (up to 15%) and Scandinavian crystalline rocks do not exceed 20%. In addition, the deposit contains a small admixture of quartzites and flints. The content of northern material ranges from 7 to 20%. Palaeozoic limestones were not at all observed, and the clasts of Scandinavian crystalline rocks are generally weathered. In mineral terms, the deposit consists mainly of garnet (30–58%) and amphibole (15–45%). There are slight admixtures of pyroxene, biotite and staurolite (Figure 15). The grains are better rounded than in the above-described sites. Angular grains account for 60–80%. The content of partially rounded grains is variable: from 20% at the base and top to 40% in the middle part of the wall.

During further mining operations, large sand blocks with disturbed stratification, up to 4 m long, was found in the western part of the sand pit within sand–gravel deposits. This is due to the effect of transporting sand–gravel material along with frozen blocks and sand clasts near the marginal zone (Figure 12e and f). In the north-western wall, organic deposits (peat, mud and sand, filling palaeodepression) became exposed (profile 4E) in 2014 (Figure 13). In a 534 cm-deep research profile located in the central part of the palaeobasin, 267 samples were taken at 2 cm intervals [19].

At the top of the wall, an asymmetric incision became exposed, which was 35-40 m wide and 5.34 m deep and was filled with greenish sandy muds, sands and peat (Figure 13). The investigated profile consists of seven units (from bottom to top), namely, 1 – weathered sand, gravel and silt (3.85–5.94 m) overlain by greenish silt (Fh) and separated by two thin (5–8 cm) yellow, horizontally laminated sand layers (Sh); 2 – yellow, horizontally stratified fine sand (Sh), with dark brown massive silt (Fm; 3.84–1.58 m depth); 3 – brown sand/marl (1.58–1.56 m depth); 4 – white sand/marl (1.56–1.52 m depth); 5 – sand and marl overlain by dark brown silt (1.52–1.37 m depth); 6 – decomposed and compressed peat (C) (0.78–1.37 m depth); and 7 – dark brown silt (Unit 7) covered with Sh and Gh (10 cm; 0–0.78 m depth).

This profile has been comprehensively described and the results of multiproxy research have been published by Krzyszkowski et al. [19]. They indicate that an oxbow lake developed on a piedmont fan in the proto-Bystrzyca valley, in the Krzczonów region, within a fluvial deposit accumulated by a meandering river. Later on, it turned into a valley lake. The lake sediments were deposited under low-energy conditions and the material originated mainly from a close local source. Palynological studies indicate that these deposits are represented by two cycles accumulated over a period of about 800 years, first during the Mazovian Interglacial and then during the advance of the Odranian ice sheet, causing compaction of the upper layers of limnic deposits - marl, brown sand and peat.

Brown–yellow sandy tills, 2 m thick, which were exposed on the upper scarp (wall 4D), were deposited during the Odranian ice-sheet advance (Figure 11). They are underlain by Sm and Sh. Bedded till occurs in the bottom part but massive and structureless (Dmm) in the middle and upper parts. The till found at the top of the gravel series is decalcified and does not contain Palaeozoic limestones. Therefore, it cannot be correlated with any lithopetrographic type in this region.

The gravel fraction of the till is dominated by Sudetic porphyry (28%), quartz (30%), Sowie Mts Gneiss (14%), sands and conglomerates (5%) and Sobótka Massif serpentinite (5%). The total content of the components of Scandinavian provenance is 7% (gneiss, granite, porphyry, quartzite; Figure 15). The most numerous group is garnet (42%). In addition, there are amphiboles (26%) and biotite (8%). The proportion of zircon, epidote, straurolite, cyanite and other minerals is insignificant.

5 Discussion

The deposits studied are exposed on flat and hilly uplands located at an elevation of 238–285 m a.s.l. In all research sites, these deposits show similar lithologies and petrographic compositions. In some exposures, they occur under a cover of decalcified tills that do not provide reliable information on their lithostratigraphic position. Because they are enveloped within the hilly landforms, occurring at the top of the studied profiles and overlying the glaciotectonically undeformed deposits, it can be assumed that this is the youngest till occurring in this region, i.e. from the Odranian Glaciation (Figure 16).

Measurements of sedimentary structures allow determining the palaeotransport direction towards the E and NE. Similar directions were measured in the lower and middle parts of the sections from Krzczonów, Boleścin, Krzyżowa and Bojanice (Figure 16). This

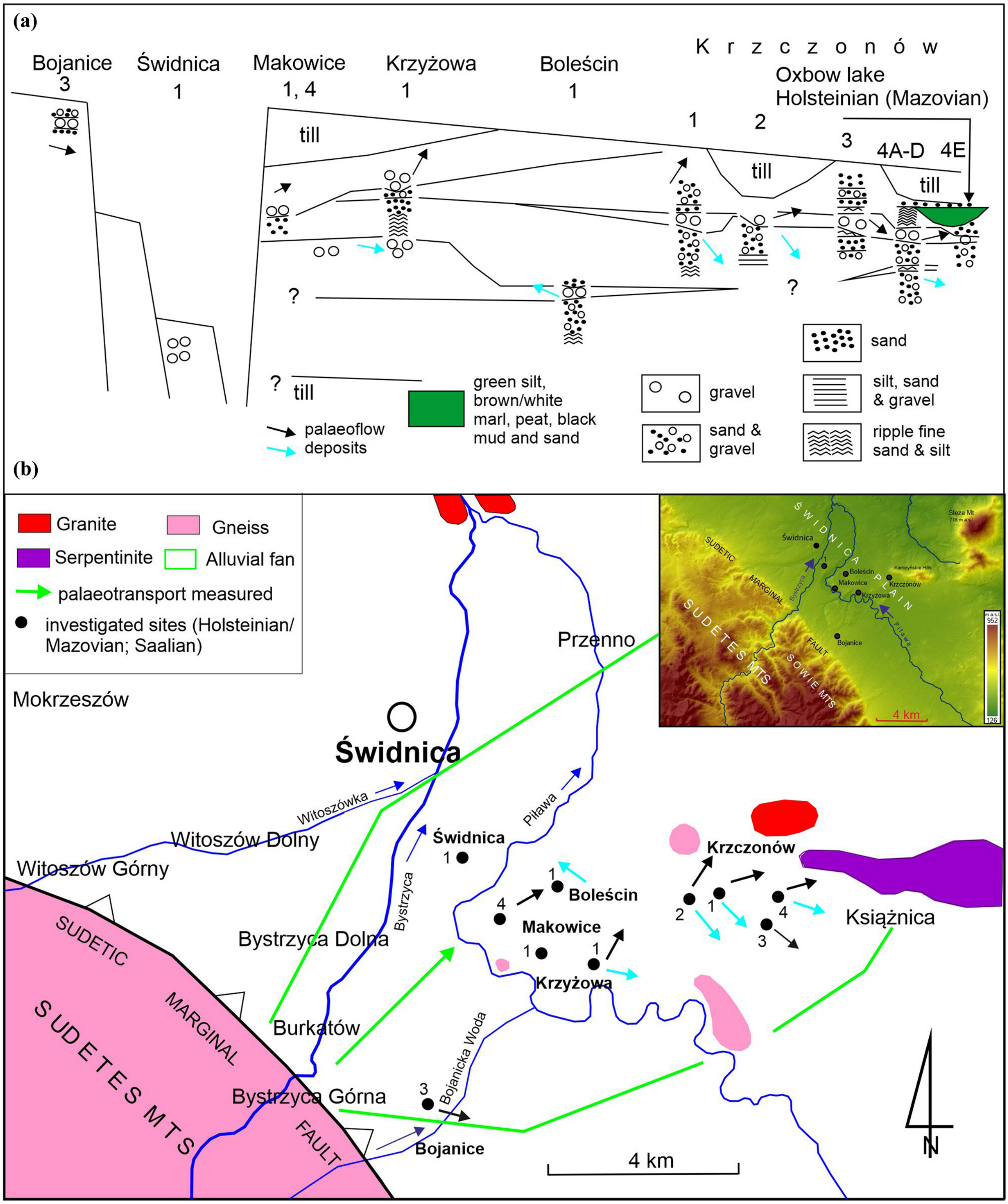
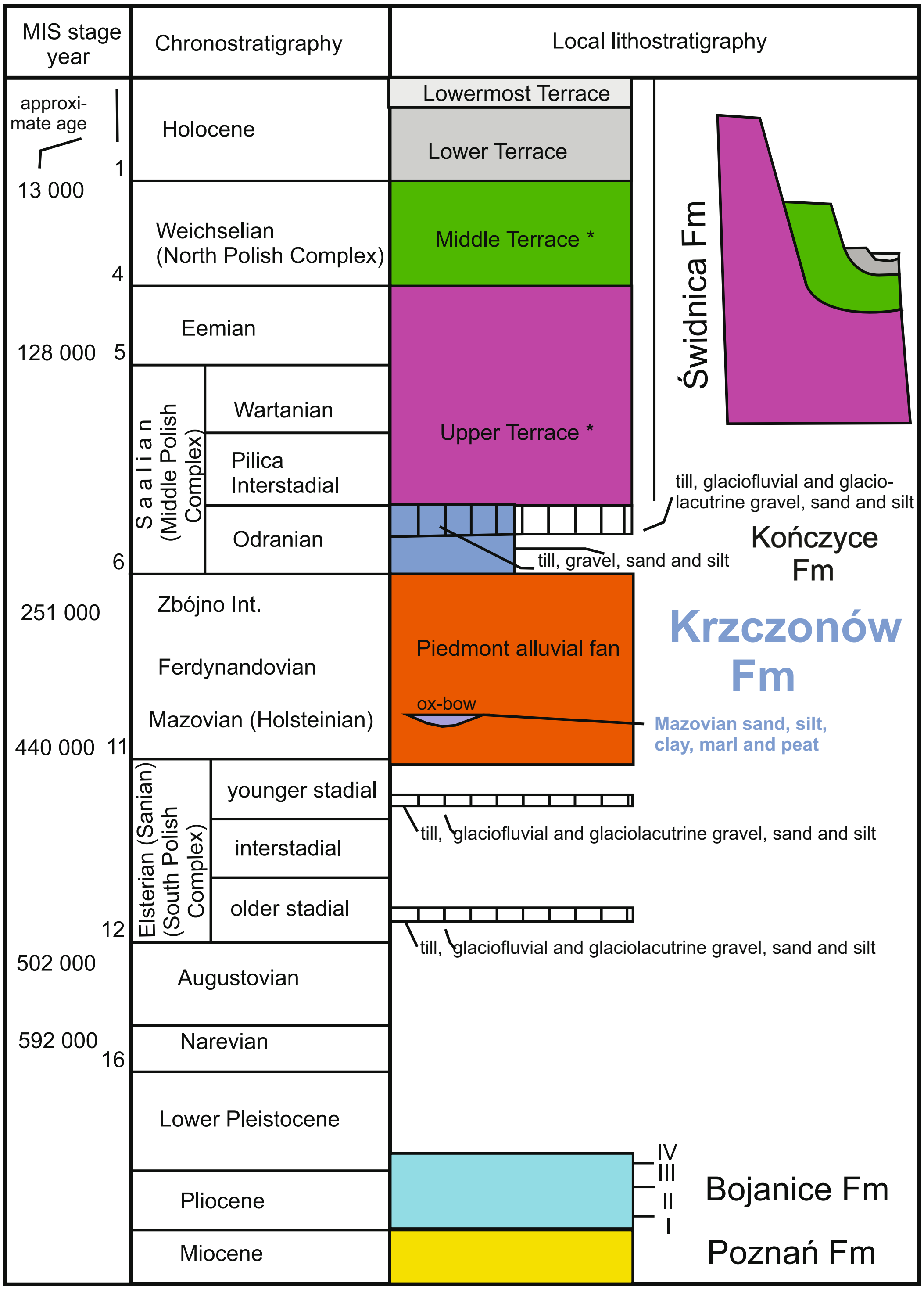


Figure 16: Cross-section with studied profiles (a) and geological sketch (b) illustrating river dispersion gravel–sandy series on the Świdnica Plain according to Krzyszkowski et al. [19], changed.

supports the thesis that these may have been deposits of alluvial fans accumulated in the periglacial period. The situation becomes more complicated in the middle parts of the sections of the Makowice, Krzyżowa and

Table 2: Main relief forms against the chronostratigraphy and local lithostratigraphy (formations) of the Sudetic Foreland



* loess and loess-like sediments

Krzczonów sites (Figure 16). Another transport direction is marked there – from the ESE to SE. It is probably the stage of temporary change in the transport direction during deposition of the alluvial fans [26,15].

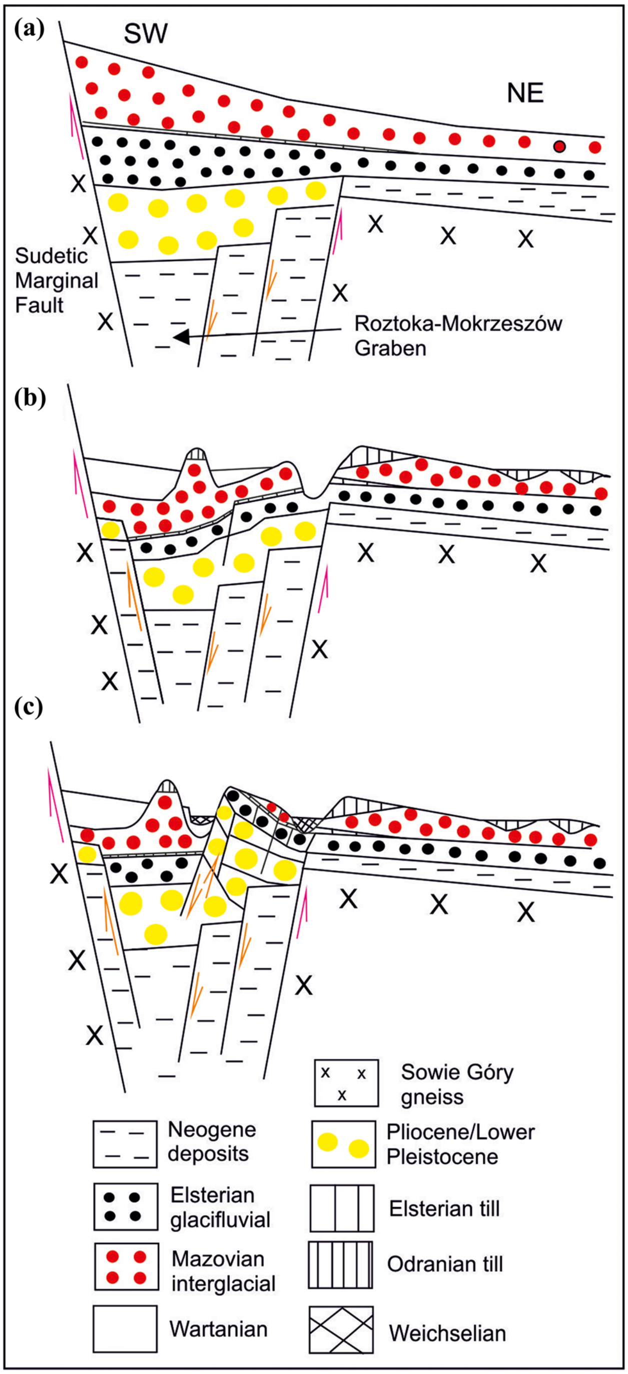


Figure 17: Diagram of the development of the Pleistocene geological structure in the Świdnica Plain from the Masovian Interglacial (a), through the Saalian (b), to the Vistulian Glaciations and Holocene (c).

Based on the structural features of the sediments at the Bojanice, Świdnica, Makowice 4 and Krzczonów 2, only 3 sites were formed by braided rivers. More complicated pictures are at the Makowice 1 and Krzczonów 4, where alluvia were first originated by braided rivers and then by meandering ones. Finally at the Krzczonów 1 site, we have the following order: braided–meandering–braided–meandering rivers.

Based on the petrographic composition determined in the area located east of the Ślęża Massif, where the content of Scandinavian material is up to 20% [33], and taking into account the specificity of the fore-Sudetic region, it has been assumed that these are deposits of the Bystrzyca River alluvial fans. The content of Scandinavian material is 1–10%.

The till exposed on the surface in the nearest research area was classified by Walczak-Augustyniak and Szałamacha [34] as an Odranian Glaciation deposit. The till that occurs in the Makowice 1 and 4, Krzyżowa 1 and Krzczonów 2 and 4 sites can also be associated with the same glaciation. It should be emphasised once again that there is no reliable lithopetrographic evidence due to the high degree of weathering of this deposit. The deposits of the Bystrzyca River alluvial fans, directly overlying the Sanian (Elsterian) Glaciation till, might have formed during the Great Interglacial and the Early Odranian Glaciation prior to the ice-sheet advance in this area (Figure 16a) [13,15].

Lithological studies indicate that an oxbow lake developed within fluvial deposits accumulated by a meandering river in the Sudetic Foreland on the piedmont fan, in the proto-Bystrzyca valley in the Krzczonów area. The lake later turned into a valley lake (Figure 16a). The sedimentation in the lake took place under low-energy conditions. The material originated mainly from a close local source [19]. Palynological studies show that these sediments were accumulated at the end of the Holsteinian Interglacial. The overlying deposits originated during cool periods in the rank of stadials and interstadials [19]. The Krzczonów section provides important data supplementing information about the Mazovian (Holsteinian) Interglacial deposits from the area of western and south-western Poland, as there are extremely few palynological sites of this age compared to other regions of Poland (Table 2). In addition, the Krzczonów section provides valuable data on the vegetation succession during cool intervals at the end of the interglacial.

The deposits exposed in all 10 sites examined, highlighted in green in Figure 1a, are referred to by the authors as the Krzczonów Formation. The alluvial fan deposits can therefore be correlated with the informal lithostratigraphic unit of "lower fluvial complex" established for the area between Nysa Łużycka and Bóbr rivers [35]. Fluvial deposits, underlying the Saale till, are widely known from Brandenburg and included in the Holstein Complex that covers the older Saale [36].

The model presented in Figure 17 depicts three stages of Pleistocene relief evolution in the central part of the Sudetic Foreland:

Stage A involves the formation of alluvial fans in the preglacial period (Preglacial Terrace), which were subsequently covered twice by the Sanian 1 and 2 ice sheets (Elsterian, South Polish Complex), followed by the formation of piedmont fans (Main Terrace) with a meandering system (Krzczonów site – Table 2) at the edge of the Marginal Fault during the Holsteinian, Stage B consists of Odranian ice-sheet advance (Early Saalian, Middle Polish Complex) and the partial covering of the alluvial deposits by a discontinuous till layer; formation of the Bystrzyca valley at the end of the Odranian Glaciation; and formation of the cut-fill Upper Terrace during the Wartanian (Late Saalian, Middle Polish Complex; Table 2). During the Middle Polish Glaciation, the Roztoka–Mokrzeszów graben (Świdnica site) developed due to tectonic movements.

Stage C involves successive phases of erosion and accumulation, and the formation of a system of terraces (Middle Terrace) in the Bystrzyca valley during the Vistulian (Weichselian, North Polish Complex) and of loess covers; and also shaping of the valley bottom during the Holocene (Lower and Lowermost Terrace – see Table 2).

6 Conclusions

Research carried out in ten sites within the Świdnica Plain (south-western Poland) enabled reconstructing the evolution of a piedmont fan that developed in the central part of the Sudetic Foreland.

Alluvial fan deposits – from its proximal (Boleścin and Bojanice sites) to distal (Krzczonów 3 and 4) parts – have been recognised. Within the piedmont fan, the deposits occupy the highest position in the Bojanice site in the SE part of the foreland tectonic graben of Roztoka–Mokrzeszów, about 2 km from the morphotectonic edge of the Sudetes (285 m a.s.l.). At the lowest elevation, they are found in the Roztoka–Mokrzeszów Graben in the Świdnica site, in the interfluve of the Piława and Bystrzyca rivers (238 m a.s.l.). The average elevation of the alluvial landform is 268–275 m a.s.l.

Its fluvial origin is supported by both the grain-size composition and the sedimentary structures. In the south of the area, at the base of the fan, the deposits are generally coarser; and they are Gm, Gh, or trough Gt (Bojanice, Krzyżowa, Makowice, Boleścin). These deposits were accumulated in a dynamic sedimentary environment of a gravel-bed river, often at a gradient change, close to the Marginal Fault. Towards the NE, the deposits become finer and more and more sandy, and locally even pass into gyttjas and peats (Krzczonów 1–4). Beneath the coarser deposits, overbank fine-grained deposits of weak or waning flows (Sh and Sr structures), and even deposits filling an oxbow lake (Krzczonów 4), are often found. The palaeoflow directions determined based on the channel structures also do not provide unequivocal results. Most measurements of sedimentary structures indicate the flow towards the E-SE. However, many structures can as well be interpreted as indicating the direction of material transport to the NE.

On average, the deposit contains about 10% of Scandinavian material, which suggests a fluvial origin. In terms of mineral composition, the deposit shows a considerable proportion of garnets and amphiboles and the absence of other minerals typical of the Sudetes, which is not typical of fluvial origin.

The deposits are underlain by Sanian sands, gravels and tills (Elsterian; South Polish Complex). They are covered with a thin till layer representing the Odranian Glaciation (Early Saalian, Middle Polish Complex). The stratigraphic position of the sands and gravels, occurring between the Sanian and Odranian tills in the sites, as well as the petrographic composition and heavy minerals, indicates that the piedmont fan deposits of the proto-Bystrzyca can be attributed to the Krzczonów Formation, an informal lithostratigraphic unit – "Lower Fluvial Complex" correlated with the latest Holsteinian Interglacial, prior to the Odranian ice-sheet advance.

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