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An examination of the glaciomarginal fan of the Odranian glaciation at the Mokrzeszów site, Sudetic Foreland, SW Poland

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Abstract: The article presents the results of research from the Mokrzeszów site in the Sudetic Foreland. Litho-petrographic and sedimentological analyses of sediments from the Middle Polish Glaciations (Early Saalian, Odranian, MIS6) in this area indicate the overrepresentation (90–95%) of large Scandinavian erratics. The deposits, representing a repetitive sequence of Gp-Gms-Sp-Sh/Sr(Dmm) lithofacies, accumulated during at least two episodes of glacial outburst floods and six sedimentary cycles. High-energy flows are estimated for the Gms and Gp facies at about 5 $m \cdot s^{-1}$ and low-energy flows indicate 0.8 $m \cdot s^{-1}$ for the Sp/Sh/Sr facies, to the lack of flow (Fm). The sedimentary sequences confirm the existence of a fan, which may have originated as a subaqueous steep coarse-grained fan in glacial-flow-lake-outburst floods that formed between the ice sheet front and the morphotectonic edge of the Sudetic Marginal Fault line and within the Roztoka-Mokrzeszów Graben, or as an aerial, piedmont fan on the Sudetic Marginal Fault edge. The sediments show discontinuous deformations – gently sloping faults and fractures from glacioisostatic stresses. The fault activity is probably related to the reactivation of the faults due to ice loading during or after the older Saalian glaciation.

Keywords: neotectonics, glacigenic sediments, glacier meltwater flood, subaqueous steep coarse-grained fan, Saalian, Sudetic Marginal Fault (SMF)

INTRODUCTION

Studies on sediments exposed in the Mokrzeszów 1 and 2 quarries (Fig. 1) have a long tradition. These studies were associated indirectly with the aggregate mining carried out intermittently for a period of over a hundred years. It was here that fossils from erratics of Silurian rocks from the Baltic Sea floor were first described (Roemer 1857). Despite the abundance of fossils, researchers were primarily interested in the large accumulations of erratic boulders which are otherwise absent in the region. It should be noted that, until now, the overrepresentation of boulders was not associated with extreme phenomena occurring during ice sheet melting, i.e. with very large increases in the discharge of glacier meltwater streams. Although Łoziński (1909) argued for the glacial origin of the deposits, Cramer et al. (1924), and later Szczepankiewicz (1952), interpreted the boulder-rich deposits from Mokrzeszów as a terminal moraine (Blockpackung). Jahn (1981) interpreted the boulder layers as glaciofluvial (esker) sediments deposited under pressure in a subglacial tunnel at the ice sheet front. Now, the deposits are referred to glaciofluvial Gilbert-deltas, ice-contact deltas (without a delta plain) and subaqueous ice-contact fans (e.g. Lang et al. 2021). Further sedimentological and petrographic studies contributing to this publication on the Pleistocene complex and its bedrock in the Mokrzeszów gravel pits were conducted by Krzyszkowski (1992, 1993a, 2013a), Krzyszkowski & Bowman (1997), Kowalska et al. (2005), Radzevičius et al. (2010), Czubla (2013) and Salamon et al. (2013).

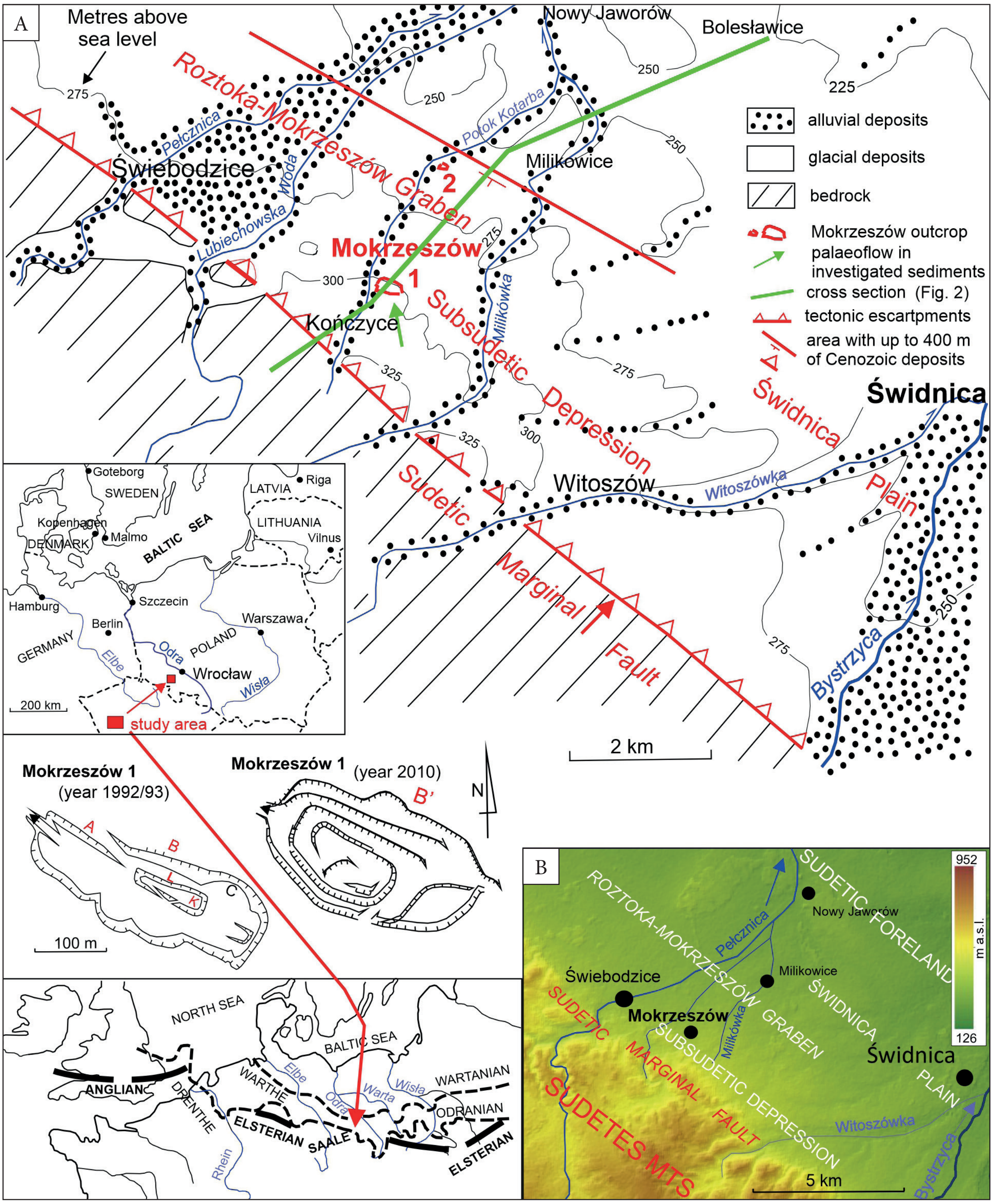

Fig. 1. Location of the Mokrzeszów 1 and 2 gravel pits (A); DEM of the investigated area (B)

This paper focuses on new evidence of the occurrence of glacial lake outburst floods and the formation of proglacial fan deposits under the conditions of:

- a release of significant amounts of water, probably stored under conditions of sudden and massive melting of the Odranian ice sheet (ablation in warm seasons, potentially enhanced by heat supply from the cracked SMF (Sudetic Marginal Fault) basement);
- spatial constraints of hyperconcentrated flow through the transverse SMF barrier (from the SW) because the site is located in the Subsudetic Depression with steep slopes;
- sediment deformation due to neotectonic activity along the SMF and the tectonic Roztoka-Mokrzeszów Graben, and due to stresses in the sediment as a result of advancing ice sheet that crossed the SMF line with steeply inclined slopes.

REGIONAL SETTING

The study area is located at the Sudetic Marginal Fault (SMF) in the Middle Sudeten Mts, south-western Poland (Oberc & Dyjor 1969, Cymerman 1998, Badura et al. 2003a) (Fig. 1A, B). It is a 140 km long, most probably a normal fault, oriented NW-SE. Although the Sudetic marginal zone originated already in the Late Paleozoic epoch (Oberc & Dyjor 1969) the SMF was formed in Late Oligocene-Early Miocene times and reached its maximum vertical separation – up to 1000 m – during the Pliocene (Dyjor 1975, 1983, 1986, Grocholski 1977). The SMF created a clear and often sharp scarp, bordering the Sudetes Mountains in Poland and in the Czech Republic. Neogene graben structures, 100–400 m deep (Dyjor & Kuszell 1977, Dyjor et al. 1978, Ciuk & Piwocki 1979), separate the uplifted Sudetes Mountains from the Sudetic Foreland and the Silesian Lowland which compose the downfaulted north-eastern part of the Bohemian Massif (Danišík et al. 2012).

The issue of SMF netotectonics has been frequently addressed in the literature. For example, Zeuner (1928) highlighted the vertical displacement of fluvial terraces, suggesting the tectonic uplift of the Sowie Mountains (Owl Mts.) along the SMF. Schwarzbach (1942), based on the maximum elevation that Scandinavian erratics were found in the Sudetes Mountains, suggested differential Quaternary uplift with the maxima in the Sowie Mountains. On the other hand, some authors (Dumanowski 1961, Oberc & Dyjor 1969) have suggested that the SMF was inactive during the Quaternary. In any case, the recent literature unanimously demonstrates Pleistocene tectonic activity expressed, among others, by deformed fluvial terraces and piedmont fans along the SMF (Krzyszkowski 1992, 1996, Krzyszkowski & Migoń 1992, Krzyszkowski & Pijet 1993, Krzyszkowski et al. 1995, 2000, Krzyszkowski & Biernat 1998, Krzyszkowski & Olejnik 1998, Krzyszkowski & Stachura 1998a, 1998b, Badura et al. 2003a, 2003b, 2007, Niedzielski & Migoń 2005, Stěpančíková et al. 2008, 2010, 2022, Danišík et al. 2012). The tectonic activity of the area is also evidenced by historical earthquakes recorded sporadically along the SMF (Pagaczewski 1972, Procházková et al. 1978, Ciężkowski & Koszela 1988, Guterch & Lewandowska-Marciniak 2002).

The gravel pits Mokrzeszów 1 (N: 50°50'41.90" E: 16°23'46.43") and Mokrzeszów 2 (N: 50°51'33.50" E: 16°23'31.10") are located in the marginal part of an extensive hillside, immediately east of the village of Mokrzeszów, in the Subsudetic Depression (Richling et al. 2021), approximately 1.6 km away from the Sudetic Marginal Fault, in the area of the Roztoka-Mokrzeszów Graben (Fig. 1A, B) (Dyjor et al. 1995, Dyjor & Kuszell 1997, Grocholski 1997, Badura et al. 2005, Niedzielski & Migoń 2005, Przybylski & Badura 2013). In general, the area slopes to the NE, W and E, forming a distinctly fan-shaped morphological feature (300 m a.s.l.) east of Mokrzeszów. Its deposits have been interpreted as a Gilbert delta (Krzyszkowski 1993a). However, the whole area, with the exception of a narrow zone adjacent to the SMF and to the valleys incised into the "fan", is covered by glacial sediments, mainly tills (Fig. 1B).

The thickness of the Cenozoic deposits in the Roztoka-Mokrzeszów Graben is distinctly greater than in adjacent areas outside the tectonic foredeep (Fig. 2). It applies to both the Quaternary deposits (reaching approx. 40 m in the Mokrzeszów region) and older ones. Within the tectonic foredeep, the Poznań Formation is about 150 m thick. In the study area, the formation is composed of clays (see Figs. 2, 3). They are underlain by sands, clays, and mudflow sediments (about 50 m thick), as well as basalts and basaltic tuffs (about 100 m thick). The top of the clays lies at a depth of about 200 m b.s.l. On the upthrown side, the Ziębice Group and Poznań Formation rocks reach a thickness of ca. 30 m and directly overlie the shales. The Mokrzeszów gravel pit deposits probably represent the Kończyce Formation (Figs. 2, 3) (Krzyszkowski et al. 2019a, 2020, modified).

The data derived from sediments exposed in the Mokrzeszów 1 gravel pit and from boreholes drilled in the region (Dyjor & Kuszell 1977) permit the conclusion that there are two glacial till layers in this area. The older layer represents the South Polish Sanian glaciation (Elsterian till), and the younger one, lying mainly on the surface (Fig. 2), represents the Odranian glaciation (Saalian till) (Badura et al. 1992). The tills are separated by proglacial sediments. The lower till is overlain by gravels and sands; however, outside the foredeep basin, these formations contain only 10% of Scandinavian rocks, which distinguishes them from the glacial formations at Mokrzeszów (90–95% of erratics) (Krzyszkowski & Bowman 1997). In boreholes, pre-glacial sediments have been found under the lower till (Dyjor & Kuszell 1977).

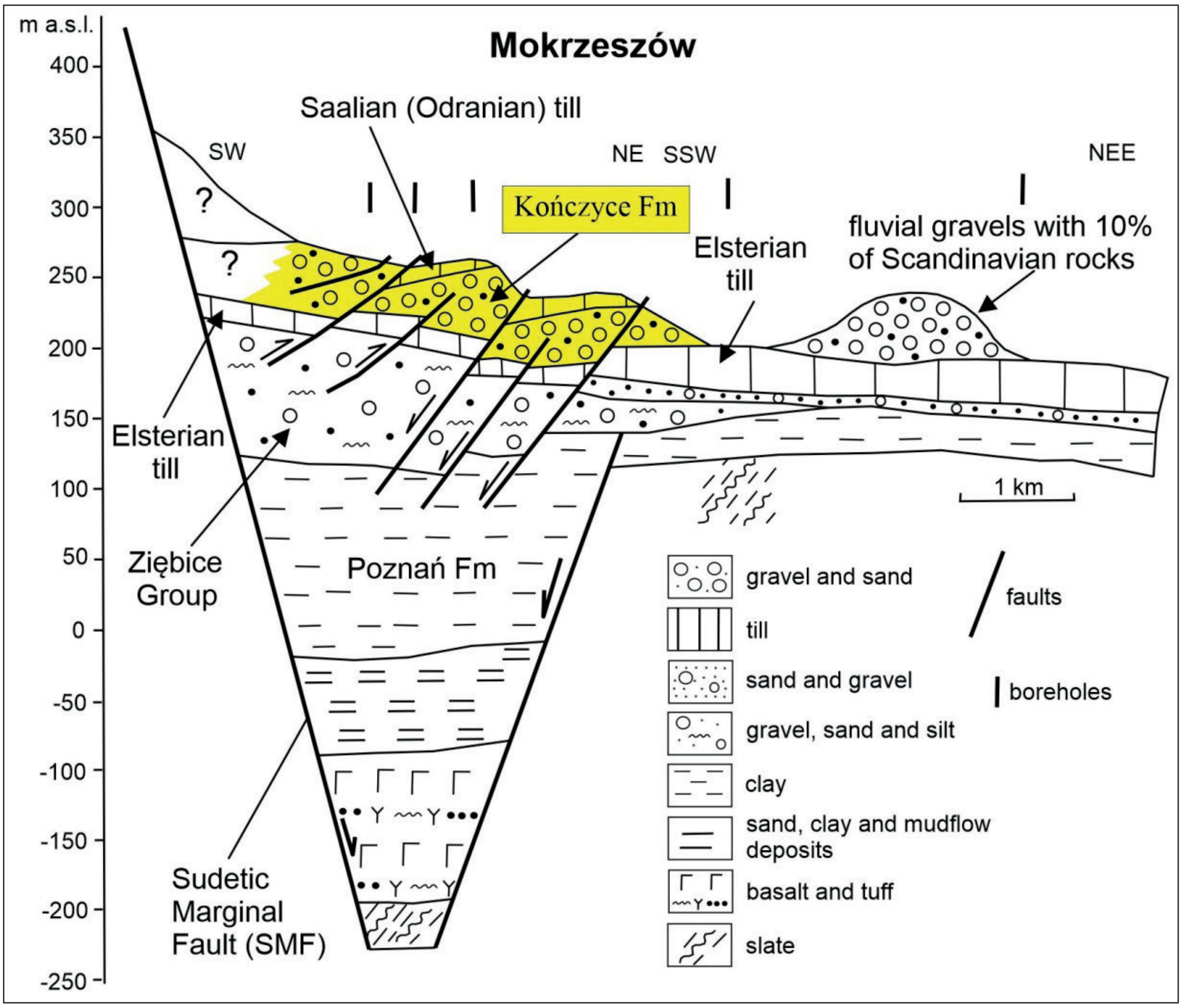

Fig. 2. Geological setting of the study area. Deformation of Cenozoic and Pleistocene glacial sediments in the tectonic zone of Roztoka-Mokrzeszów Graben (after Krzyszkowski 1992, modified). Reverse faulting may be explained by Quaternary compression at the Sudetic Margin Fault (see: Novakova 2015) that was roughly perpendicular to the strike of the fault

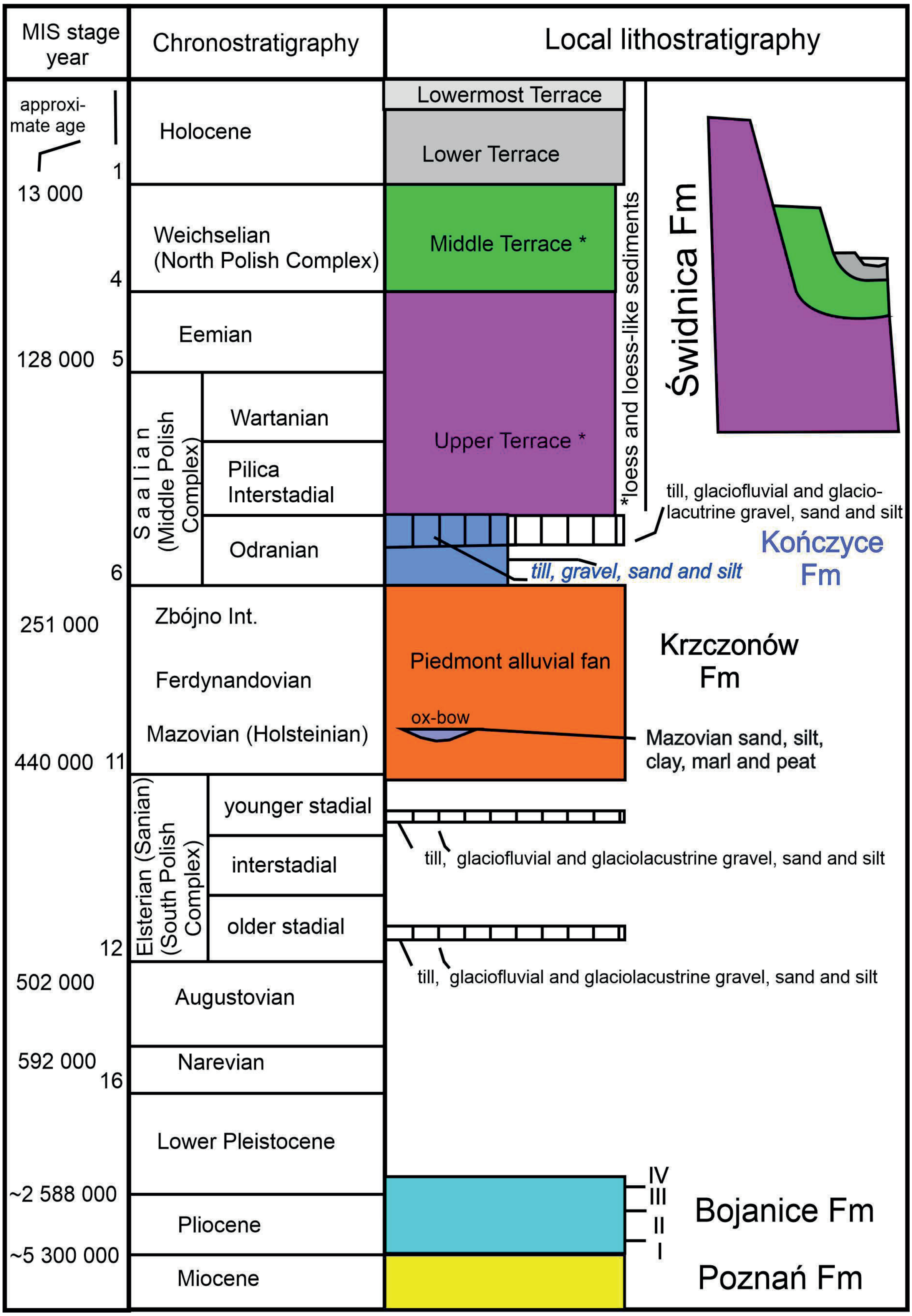

Fig. 3. Chronostratigraphic table acc. to Krzyszkowski et al. (2019a, 2020), modified

MATERIAL AND METHODS

Fieldwork was conducted in the period 1992–1994 in the Mokrzeszów 1 and 2 gravel pits, and again in 2007–2012 in the Mokrzeszów 1 gravel pit, when the Mokrzeszów 2 gravel pit was already completely mined out and revegetated (Fig. 1A).

Lithological studies, especially sedimentological ones, were made on rock samples collected to provide data for paleoenvironmental reconstruction. The identification of sedimentary structures and lithofacies and the determination of depositional conditions enabled the interpretation of sedimentary environments.

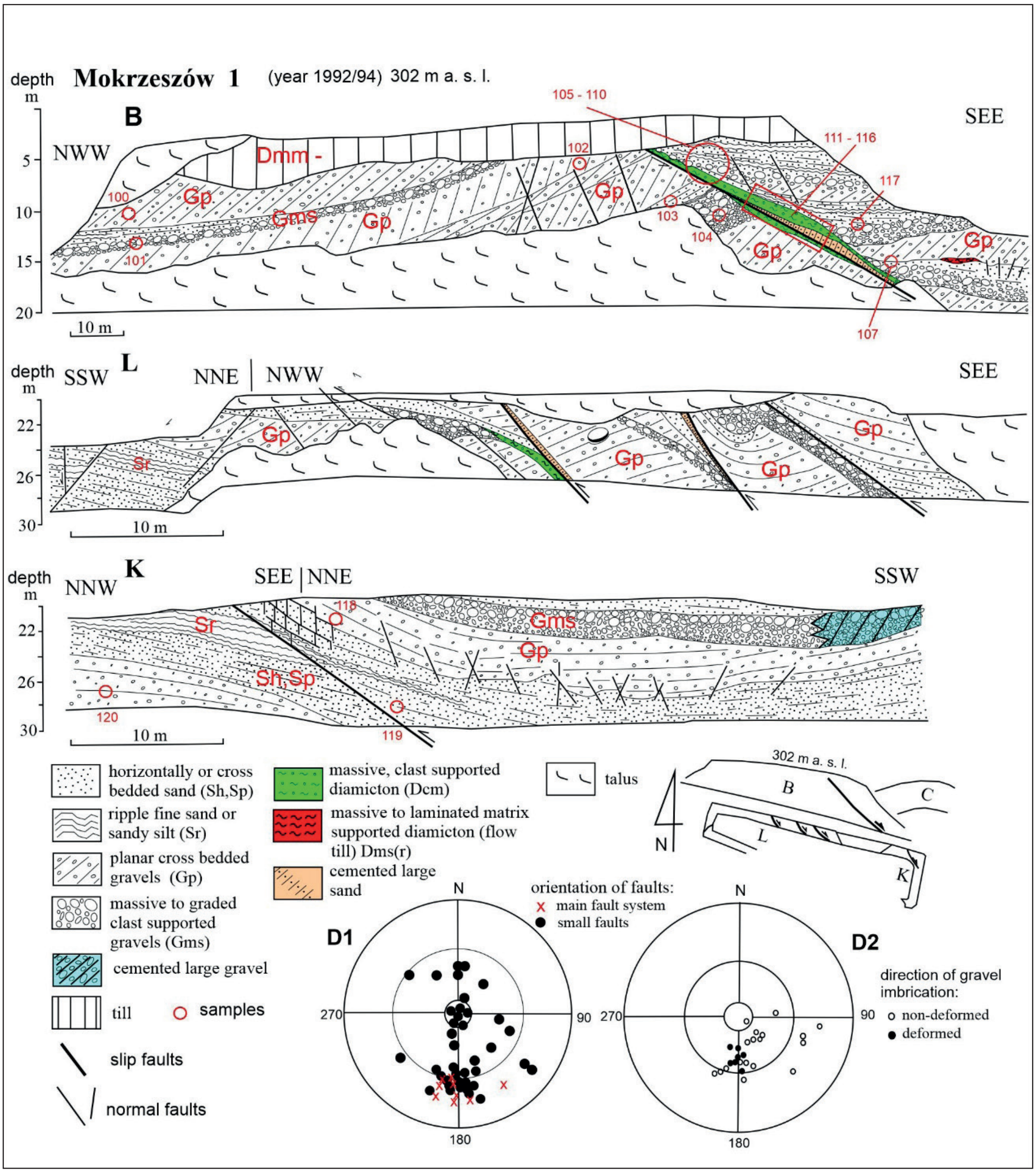

Fig. 4. *Lithology of the exposed Mokrzeszów 1: B, L and K – walls showing coarse-clastic sediments of a glaciolacustrine delta, locally overlain by glacial tills; D1 – diagram of orientation of the faults; D2 – diagram of direction of the gravel imbrication (after Krzyszkowski & Bowman 1997, modified)*

Photographic documentation, showing sediments and landscape forms, sketches of outcrops, and field drawings of pit walls, for which structural (lithofacies) analysis was performed according to Miall (1978) and Krzyszkowski (1993b) (Fig. 3), have also been made.

Litho-petrographic analyses were made in the laboratory of Przedsiębiorstwo Geologiczne PROXIMA S.A. in Wrocław. The studies comprised the identification of heavy minerals and the petrographic properties of gravels, together with the determination of carbonate content. Statistical coefficients (parameters) of grains were determined using the method of Folk & Ward (1957). The results of the lithological and structural studies are presented in Figures 4, 6, 8, 12, 15. Paleoflow directions were determined and directional (paleocurrent) measurements were made in stratified and structurally undisturbed sediments.

To estimate the paleoflood parameters, the average critical flow velocity and the critical shear stress were calculated. The water flow was estimated using the formulae $V_{AV} = 0.18D^{0.487}$ (Costa 1983), where V_{AV} is the average critical flow velocity [$m \cdot s^{-1}$] and D is the mean size of the five largest clasts [mm]. The critical shear stress [Pa] was calculated using the formulae given by Costa (1983) for gravelly bottom – $\tau_{cr} = 0.16D_{MPS}^{1.21}$, where D_{MPS} is the mean size [mm] of the 10 largest clasts.

RESULTS

Characteristics of deposits

Several layers of various lithologies, ranging from silt (Fm) to boulders (Gms) (Tab. 1) were identified (Figs. 4, 6–8) in the glacial sediments exposed at Mokrzeszów (1992/1994). Studies (Krzyszkowski 1992, 1993a, Krzyszkowski & Bowman 1997) have shown the presence of four lithological units in the outcrop: boulders, gravels, sands (including cemented sands) and tills.

The most common facies are large-scale planar cross-stratified gravels (Gp) (Figs. 4, 6, 7A, B, Tab. 1) (Krzyszkowski 1993a) in the main part of the walls. Gravels predominate quantitatively. These three gravel layers occur in different sets (one of the components may be missing) and the individual layers show very different thicknesses. The sediments were deposited from the SSE to the NNW.

The layers of Gms facies – massive matrix supported gravels – boulders, cobbles, pebbles and granules lie in between of the Gp facies layers (Fig. 4 – B and L, Fig. 6) or on the top (Fig. 4 – K). The largest *in situ* boulder was about 66 cm in diameter (Fig. 5B), and the *ex situ* one – more than 100 cm, even 160 cm (Fig. 9B). The matrix in the boulder layers is composed of gravel and coarse sand material. The thickness of the layers ranges from ca. 1 m to several metres. The boulders are usually arranged; imbrication can sometimes be observed in Figure 9. In some layers, a distinct accumulation of the largest boulders (reversed graded bedding) was observed (Fig. 5B).

A	horizontal dispersion of single sets (cm)
Gp	15, 11, 9, 9, 6, 12, 10, 9, 12
Gp	13, 10, 10, 10, 11, 11, 15, 6, 9
Gp	6, 6, 7, 8, 10, 16, 15, 4, 14
Gp	15, 12, 9, 9, 11, 9, 9, 7, 10
Gp	10, 16, 16, 12, 12, 13, 12, 9, 11
B	diameters of large boulders (cm)
Gms	63, 52, 53, 48, 51, 31, 25, 45, 51 58, 47, 50, 23, 22, 41, 31, 26, 42 48, 66
C	the size of individual clasts in the sediments of fine-grained sands (cm)
Sr	2, 0.8, 2.4, 1.3
Sp	1, 2.6
Sh	1.8

Fig. 5. *Horizontal dispersion of single sets (A); diameter of large boulders (B); the size of individual boulders in fine-grained sediments (C)*

Table 1
Lithofacies of the glaciolacustrine suites of Mokrzeszów 1 and 2

Facies code	Facies description	Interpretation
Fm	Massive fine sandy to clayey silt. This forms beds ranging from 0.10 m up to 0.50 m thick. The deposits are commonly truncated	Deposition by suspension fall-out (Allen 1984, Lang et. al 2017)
Sr	Sand or sandy silt with ripple marks. 1–3 m thick. It usually forms lenses within beds of Sh lithofacies. Upslope migrating climbing ripples occur	Deposition from subcritical flows at high rates of suspension fall-out (Ashley et al. 1982, Allen 1984, Winsemann et al. 2007, 2018, Lang et al. 2017)
Sh	Horizontally bedded, medium to coarse sand or sand with rare gravels. This lithofacies forms beds with a thickness of up to 1–3 m and is most often interbedded with lithofacies Gms, Gp	Channel deposition (upper plane bed) between bars of the braided river. Medium to high water discharge (Rust 1972, Smith 1985, Russell & Marren 1999, Krzyszkowski & Łabno 2002, Frydrych & Rdzany 2022)
St	Trough cross bedded sand and gravelly sand. Typically, a 0.2–1.0 m thick layer. Sometimes the sands are mixed with gravel	Channel deposition on slope. Deposition by migrating dunes (Allen 1984, Winsemann et al. 2009, 2018, Lang et al. 2017)
Sp	Small-scale planar cross-stratified poorly sorted sand. There are typically 1–3 m layers of sands or, more rarely, sands with gravels	Channel deposition on slope. Deposition by migrating dunes (Allen 1984, Winsemann et al. 2009, 2018, Lang et al. 2017)
Gp	These are large-scale planar cross-stratified gravels. The thickness of the sets varies from 2 to 8 m; the horizontal spread of single sets in the open pit can exceed 160 cm. A distinct stratification is evident within the Gp assemblages: alternating between coarse gravels (⌀ > 1.0 cm) without matrix (openwork gravels), fine gravels (⌀ = ca. 0.5–1.0 cm) without matrix (openwork gravels), and gravels of varying diameter, generally fine with single boulders up to 10 cm in diameter and with coarse sand matrix (closework gravels)	The deposition occurred from tractional bedload flows in channels on the delta plain or sustained turbidity currents on the delta slope (Lang & Winsemann 2013, Winsemann et al. 2018, Frydrych & Rdzany 2022)
Gms	Massive matrix-supported gravel – boulders, cobbles, pebbles, and granules. There are several boulder layers in the outcrop; these are boulders ranging in diameter from several to ca. 100 cm with a gravelly coarse sand matrix. The thickness of the layers ranges from about 1 m up to several metres. Usually, the boulders are arranged chaotically, while stratification and imbrication can sometimes be observed. In some layers, a clear accumulation of the largest boulders at the top of the layer (reversed graded bedding) is observed	Catastrophic flows. The outbreak of the flood mobilization of large boulders to deliver them to a hyper-concentrated flow of debris; high-energy water discharge sediments (Costa 1984, Nemec & Steel 1984, Maizels 1997, Krzyszkowski 2002, Krzyszkowski & Łabno 2002, Frydrych & Rdzany 2022)
Dms(r)	Massive or laminated diamicton clays with a silty clay matrix and individual gravels and boulders. This diamicton occurs sporadically as lenses up to 0.5 m thick and extending up to several metres. It is most likely a flow till (mud flow deposit) deposited near the glacier head	Mud flow deposition (flow till), partly subcritical flows at high rates of suspension fall-out (Eyles & Miall 1984, Krzyszkowski & Łabno 2002)
Dcm	It is a massive or laminated diamicton dominated by gravels with a sandy-silty matrix. It occurs only in near-fault zones and most likely represents a tectonic breccia that formed by the mixing of Gp gravels and sands along faults	Mud flow deposition within the SMF tectonic zone (Krzyszkowski 2019b)
Dcc	Massive or crudely stratified, clay clast-supported diamicton. This facies comprises a mixture of clay and silt balls, partially interbedded with massive, silty-sandy deposits. The diamicton beds are thin, never reach more than 0.5 m, and always occur within clay-silt rhythmites. The lateral extent of diamicton bodies is rather small, up to 2–3 m. The beds have poorly defined boundaries. They typically form cyclic sequences with rhythmites and Dmm diamictons. The latter is usually the topmost layer, lying on the Dcc facies	Clay deposition near the ice sheet head as a result of tectonic activities? (Krzyszkowski 1993b)
Dmm	Massive, sandy-silty, matrix-supported diamicton with single floating clasts with diameters of up to 0.1 m. This facies occurs as discontinuous layers up to 0.5 m thick, which occur within sandy deposits or rhythmites. The lateral extent varies from 1.0 m up to several metres. Diamicton beds have well-defined lower boundaries, except those with Dcc facies, but the upper boundaries are usually gradational, especially in sands. Locally, Dmm facies occur as a thick set of numerous thin and alternating layers of diamicton and sorted material. Dmm+ – diamicton containing $CaCO_3$ Dmm– – diamicton without $CaCO_3$	Basal till overlap on the deltaic sediments in the glaciotectonic overthrust process (Eyles & Miall 1984, Krzyszkowski 1993b, Krzyszkowski & Łabno 2002)

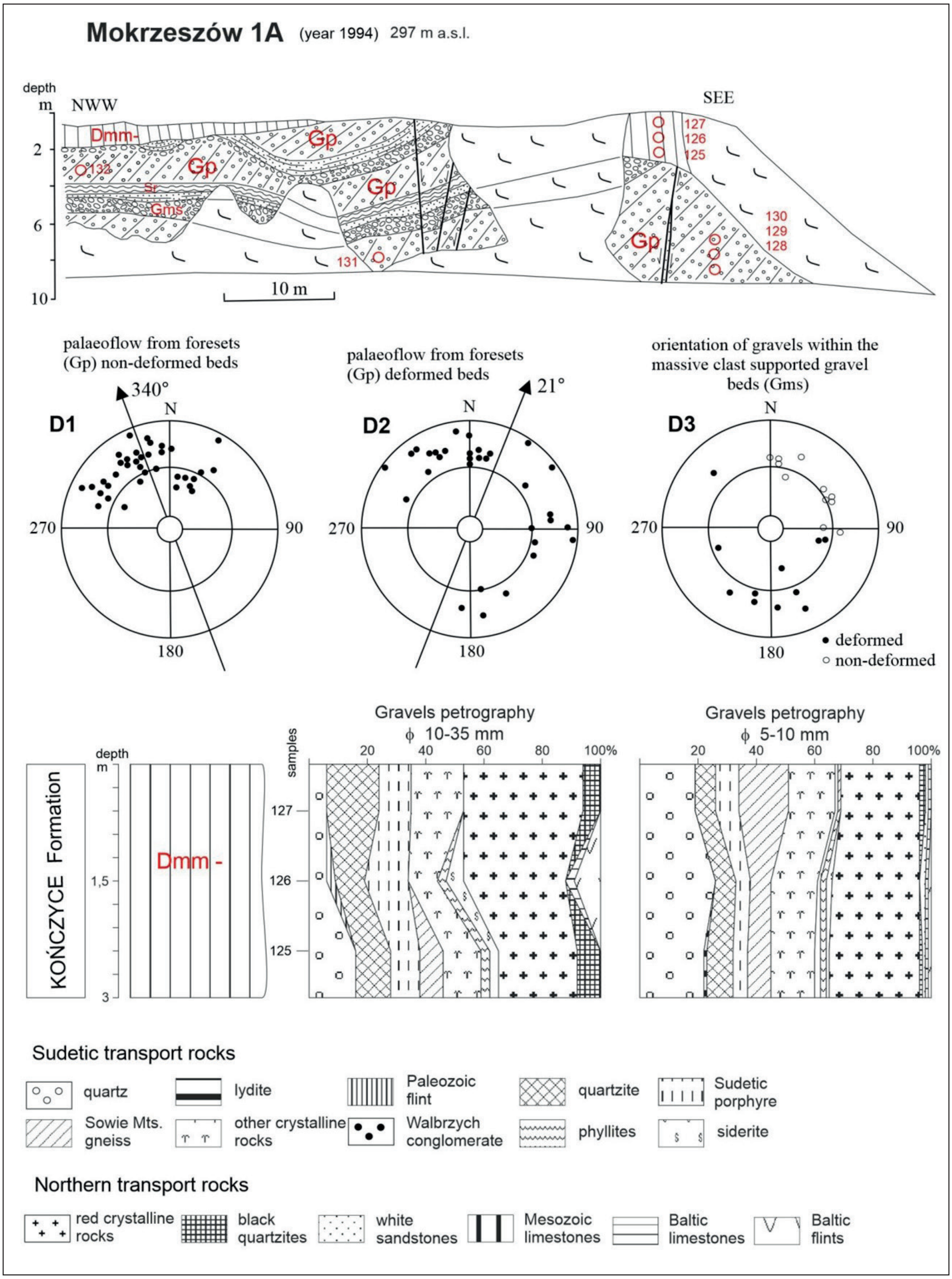

Fig. 6. *Lithology of the exposed Mokrzeszów 1A wall and the results of the analyses of sedimentary structures and the petrographic composition of glacial tills overlying glaciolacustrine delta sediments. For a lithology description see Figure 4: D1 – diagram of paleoflow direction for non-deformed sediments; D2 – diagram of paleoflow direction for deformed sediments; D3 – orientation of the gravels within Gms lithofacies*

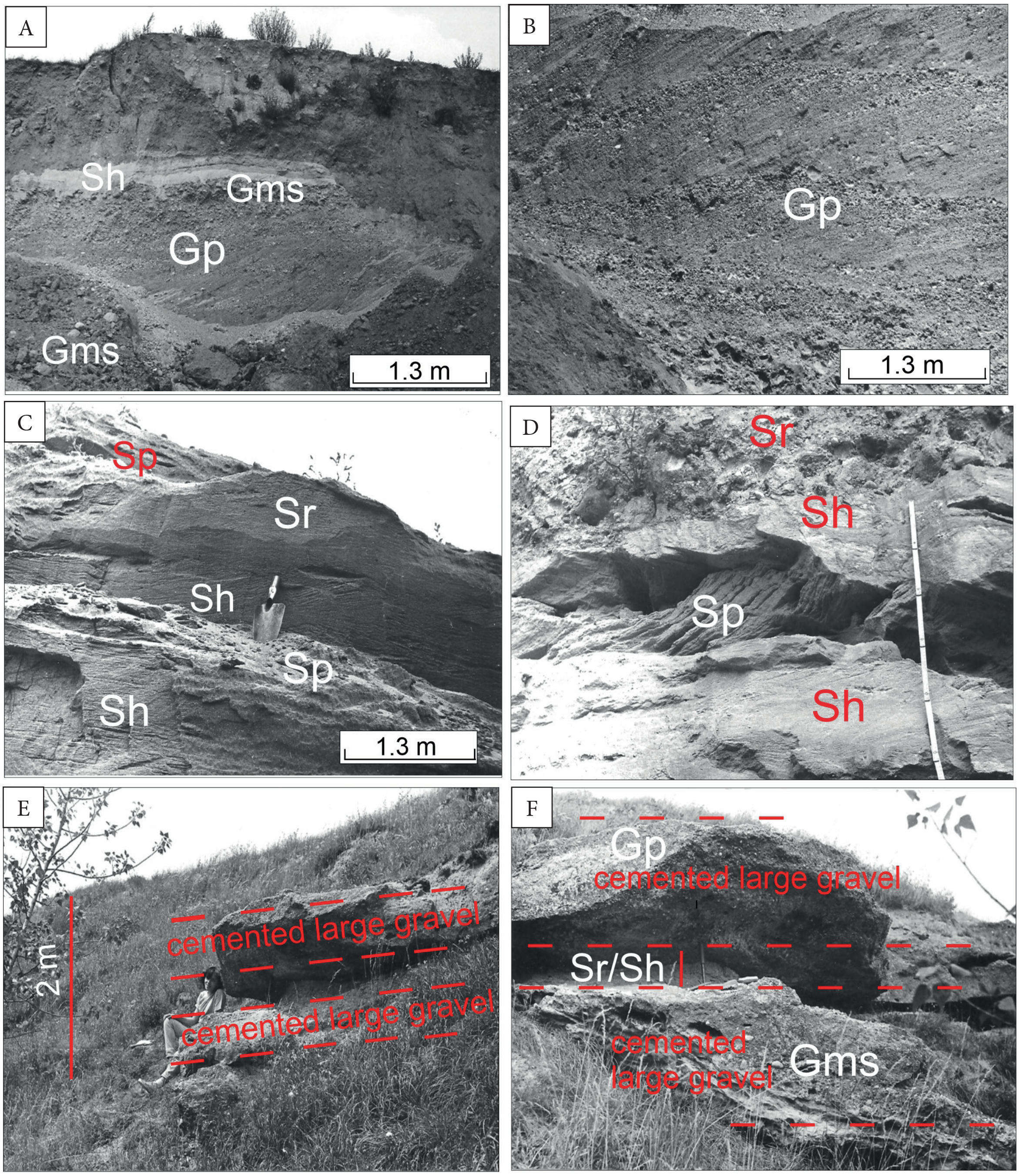

Fig. 7. *Examples of the sediment structure in the Mokrzeszów 1 exposure (A–D): A) and B) coarse-grained, main part of the fan; C) and D) fine-grained top of the fan); view on the Mokrzeszów 1C wall – layers with cemented large gravels separated by fault and horizontally layered sands (E, F) (1992/1993, photo by D. Krzyszkowski)*

On the bottom, between the gravelly facies, sandy facies with small-scale planar cross-stratified (Sp) and trough cross-bedded sand and gravelly sand (St), horizontally bedded sands (Sh), and sand or sandy silt with ripple marks (Sr) are visible (Fig. 4 – L and K, Fig. 7C, D, Tab. 1). Moreover, on the top (see Figs. 6, 8) there were also tills of facies – massive or laminated diamicton – Dms and Dcm (Krzyszkowski 1993a), as well as previously not described tills of massive, sandy-silty, matrix-supported diamicton with single floating clast – Dmm+ and Dmm– facies, represented by two varieties: carbonate (Dmm+) and non-carbonate (Dmm–) (Tab. 1).

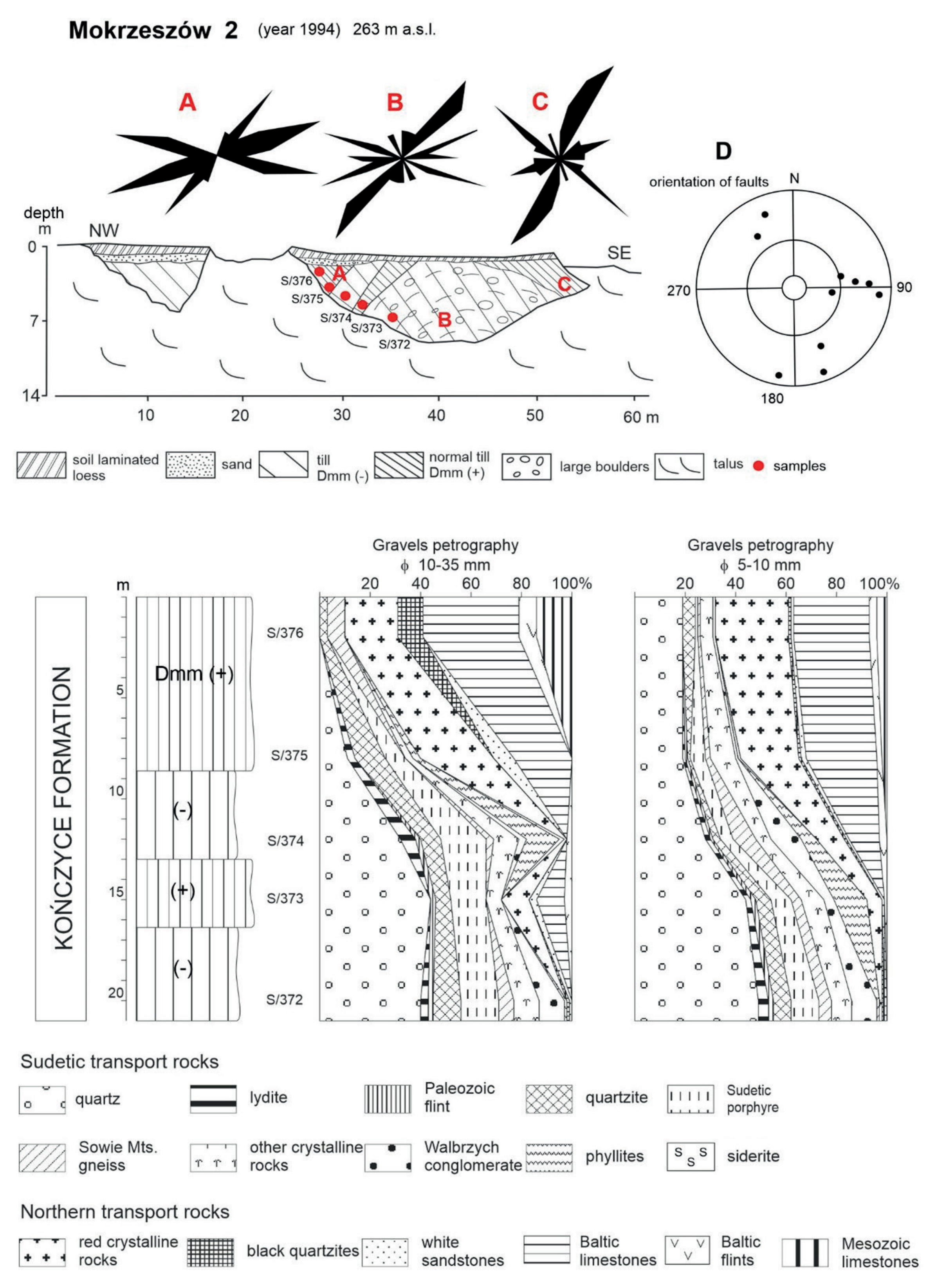

Fig. 8. Lithology of the exposed Mokrzeszów 2 wall (in 1994) and lithological-petrographic features of exposed tills: A, B, C – orientation of the long axes of boulders; D – orientation of the faults

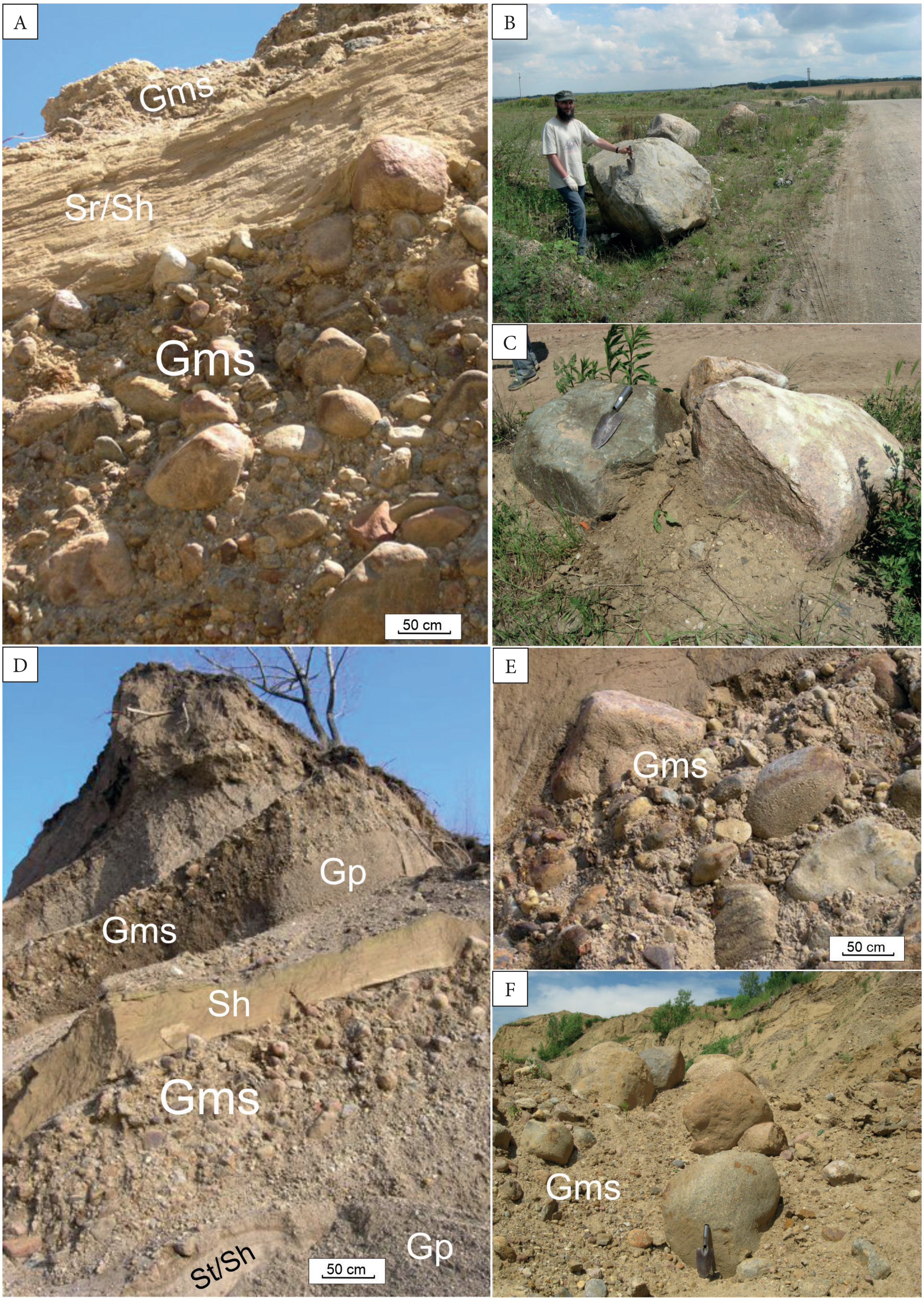

Fig. 9. *Examples of large boulders ex situ (B) and imbrication (A, D, E), suggesting a megaflood episode on the deep slope (D, E, F); A) and D) visible contact between coarse and fine-grained sediments indicating different stages of steep coarse-grained fan development (2008, photos by D. Krzyszkowski, W. Sroka)*

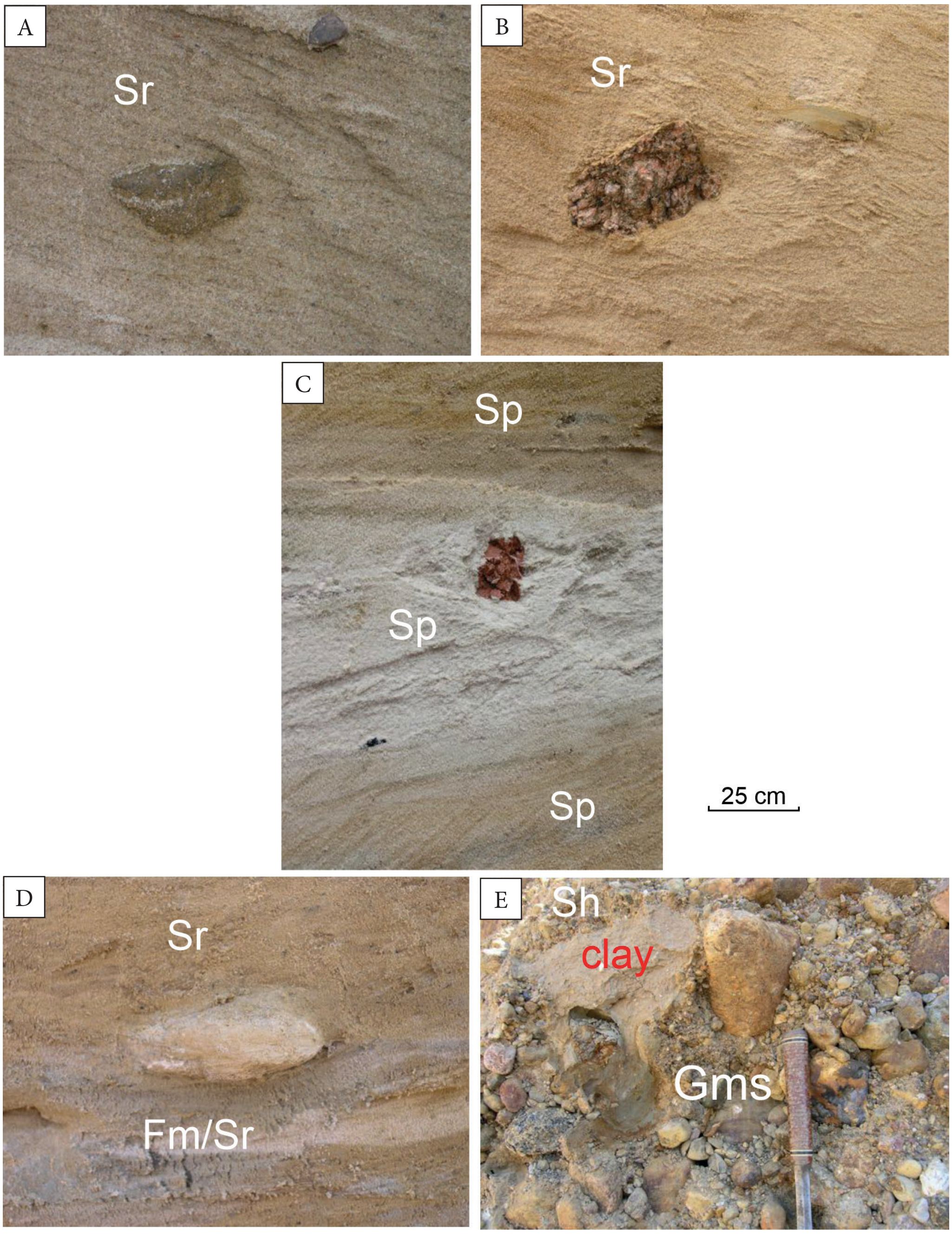

Fig. 10. *Examples of dropstone boulders within the sediments of finer fraction, exposed in the lower part of the gravel pit (A, B, C); example of a single boulder within finer fraction layers (D); example of clayey silt body within a boulder layer (C, D, E). All possibilities of position of dropstones: A) according to flow; B) opposite to flow; C) vertical; D) horizontal; E) mixed (2007, photos by D. Krzyszkowski)*

The 2007–2012 continuous investigations showed significant facies variability (Figs. 9–12): boulders, gravels, sands (including cemented sands) and tills. In the bottom part of the pit, sandy-silty deposits (ca. 5 m thick) were exposed (Figs. 10, 11). The sands have a massive structure and form elongated bodies which are dozens of metres long. The sediments that are more fine-grained are dominated by stratification in the form of climbing ripples (Sr). In places, the sands fill shallow incisions, from several tens of cm to ca. 1 m deep, with a stretch of 5–10 m. Single boulders – dropstones – occur within the sands of this unit (Fig. 10).

At the middle level of the pit, a series composed of three to four sequences of large-scale cross-stratified gravels (Gp) was exposed. Its thickness ranges up to several metres (Fig. 11). The sequences are usually topped with a layer of massive matrix-supported gravels (Gms). The upper part of the pit shows high lithological variability. Within the unit distinguished by Salamon et al. (2013), which is several metres thick, there are thin, alternating layers of massive small-scale planar cross-stratified sands (Sp), trough cross bedded sands St, and sandy silts with ripple marks (Sr) (Fig. 11).

In the uppermost part of the pit there is a massive, sandy-silty, matrix-supported diamicton layer (Dmm), the interpretation of which has not been ultimately confirmed. This is partly due to the strong deformation of sediments at the bottom of the Mokrzeszów gravel pit section. There are also massive or crudely stratified diamicton, clay clast-supported diamicton (Dcc) as flow tills, in the section (Fig. 12, Tab. 1).

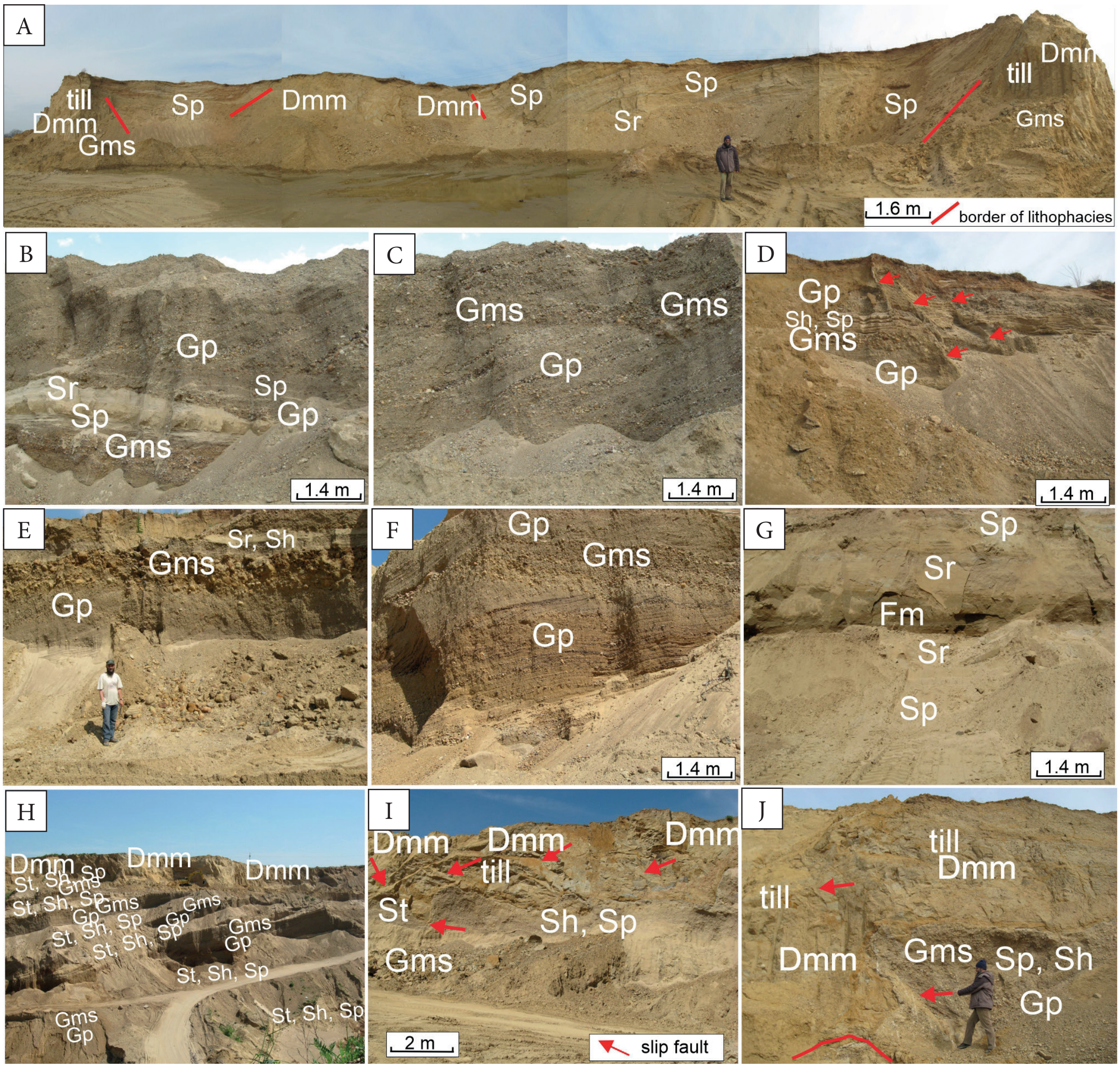

Fig. 11. *Architecture of the subaqueous fan: A) general view of the B' wall (in 2011); B)–F), H), I) samples of the boulder layers (Gms and Gp facies) with large-scale planar or trough-cross-stratified (Gp facies) presenting supply big clasts to the lake system during the second flood episodes (H) on the slope, indicate a higher-energy depositional environment; G) sandy bedforms (Sp facies) separated by sediments of the flood plain (Sr, Fm facies); I), J) main body of the fan (Gms, Gp, Sh, Sp facies) covered by till (Dmm – massive, sandy-silty, matrix-supported diamicton) (2008–2009, photos by D. Krzyszkowski, W. Sroka)*

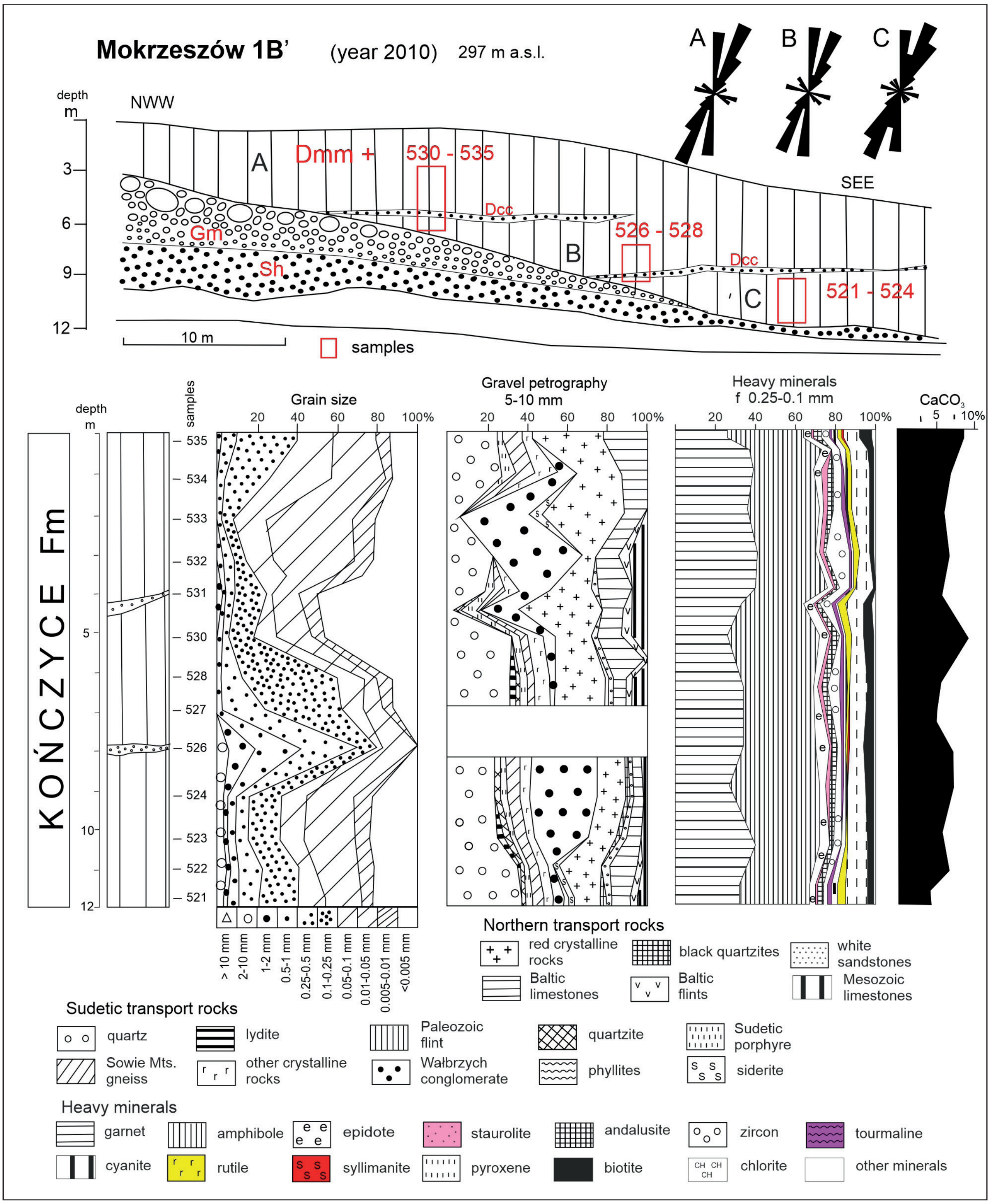

Fig. 12. Lithological-petrographic features of tills found at the top of the Mokrzeszów 1B’ wall (in 2010): A, B, C – orientation of the long axes of boulders. They are similar to those of the 1994 measurements (see Fig. 8), which suggests that the deformation was formed under the influence of equally directed pressure at the same time

Deformation structures

In the main, the sediments of the Mokrzeszów gravel pit lie subhorizontally and are faulted only in places. Two fault systems have been observed: the “main” fault system runs W-E, oblique to the SMF (Figs. 4, 6, 13–15). It is a gently dipping fault (15–30°) which crosses the entire sequence, offsetting the sediments about 20–30 m. Dragged gravels indicate re-orientation, parallel to the fault (Fig. 4). Clast-supported diamicton beds (Dcm facies), 30–60 cm thick, which indicate a tectonic breccia, occur along the fault zone (Fig. 4 – B and L, Tab. 1).

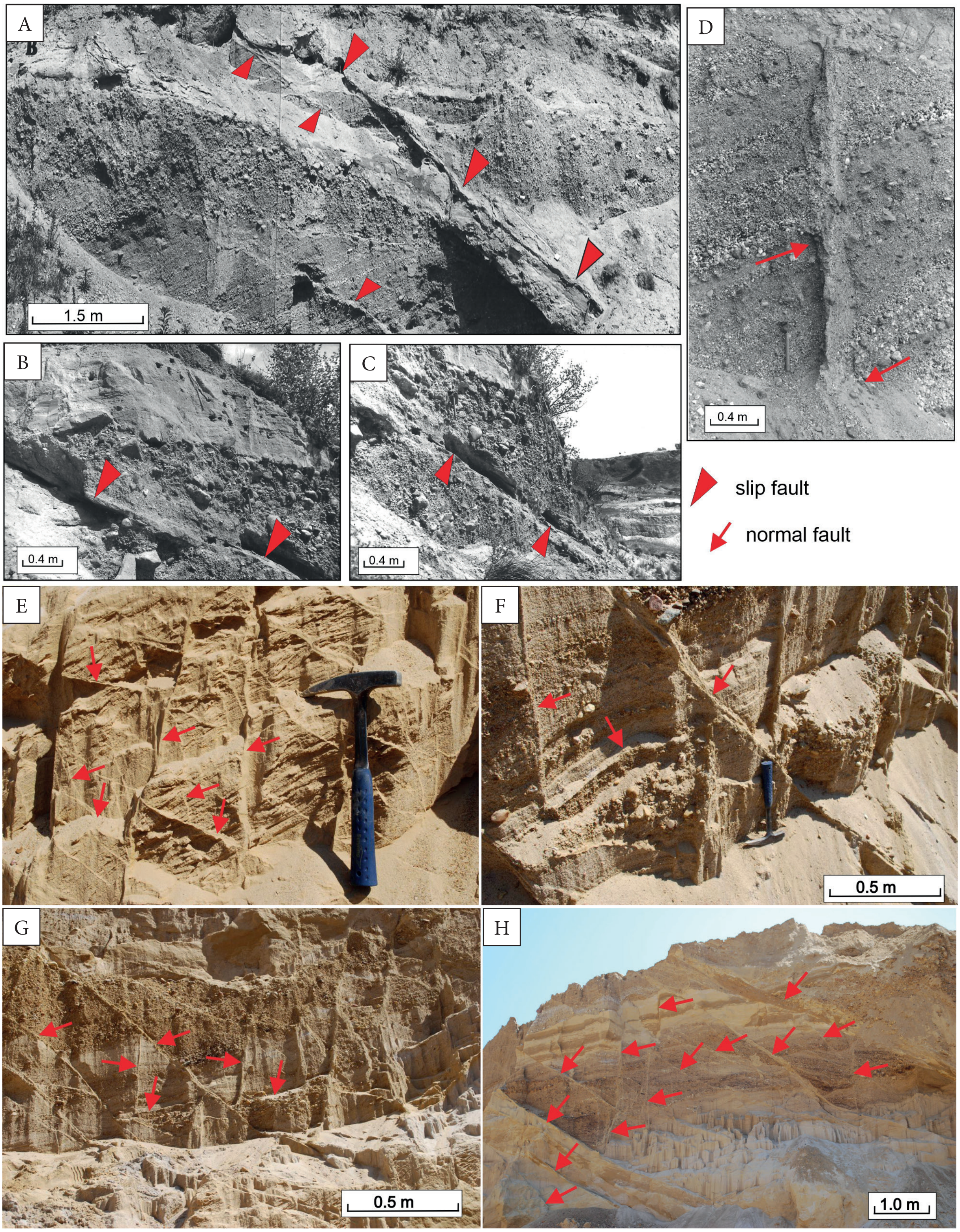

Fig. 13. *Examples of faults visible in the walls of the Mokrzeszów gravel pit: A)–C) disaggregation (deformation) bands; D) subvertical, normal faults (in 1992/93, see Fig. 4); E)–H) disaggregation bands and normal faults visible in the gravel pit, oriented to the south – see Fig. 4 (2008, photos by D. Krzyszkowski, W. Sroka)*

The "main" fault is not a line, but rather a zone composed of many small parallel faults that die out after a short distance. The "small" fault system is represented by numerous subvertical, normal faults, frequently forming conjugate pairs, with displacements of a few centimetres up to 0.5 m and with very variable orientations (Figs. 4, 13, 14). This fault system is exposed within the entire sequence and terminates vertically below the ground surface. Some smaller, gently dipping faults, which only cross part of the sequence, are associated with this system (Figs. 4 – K, 6A, 8, 11, 13). The latter occur only in the upthrown block. At the downthrown block, the sediments are dragged along the fault (Fig. 4), with occasional boudinage structures (Fig. 4 – B). Some small synsedimentary and reverse faults, caused by compaction, have also been observed (Fig. 4 – K).

The Mokrzeszów gravel pit deposits (Krzyszkowski & Bowman 1997) show small, normal, subvertical faults with small displacements and different orientations. These faults are superimposed on older deformations, i.e. on the fractures and on the "main" faults, and thus represent a quite different deformational episode. The dominant normal faulting mode and the unclustered fault orientations suggest an extensional stress regime. The small faults individually account for little extension but, when in large numbers, their cumulative effect may prove substantial (Marrett & Allmendinger 1992). Numerous small faults are also observed in the exposures (Figs. 4, 6, 11, 13, 14). Their orientation is very variable.

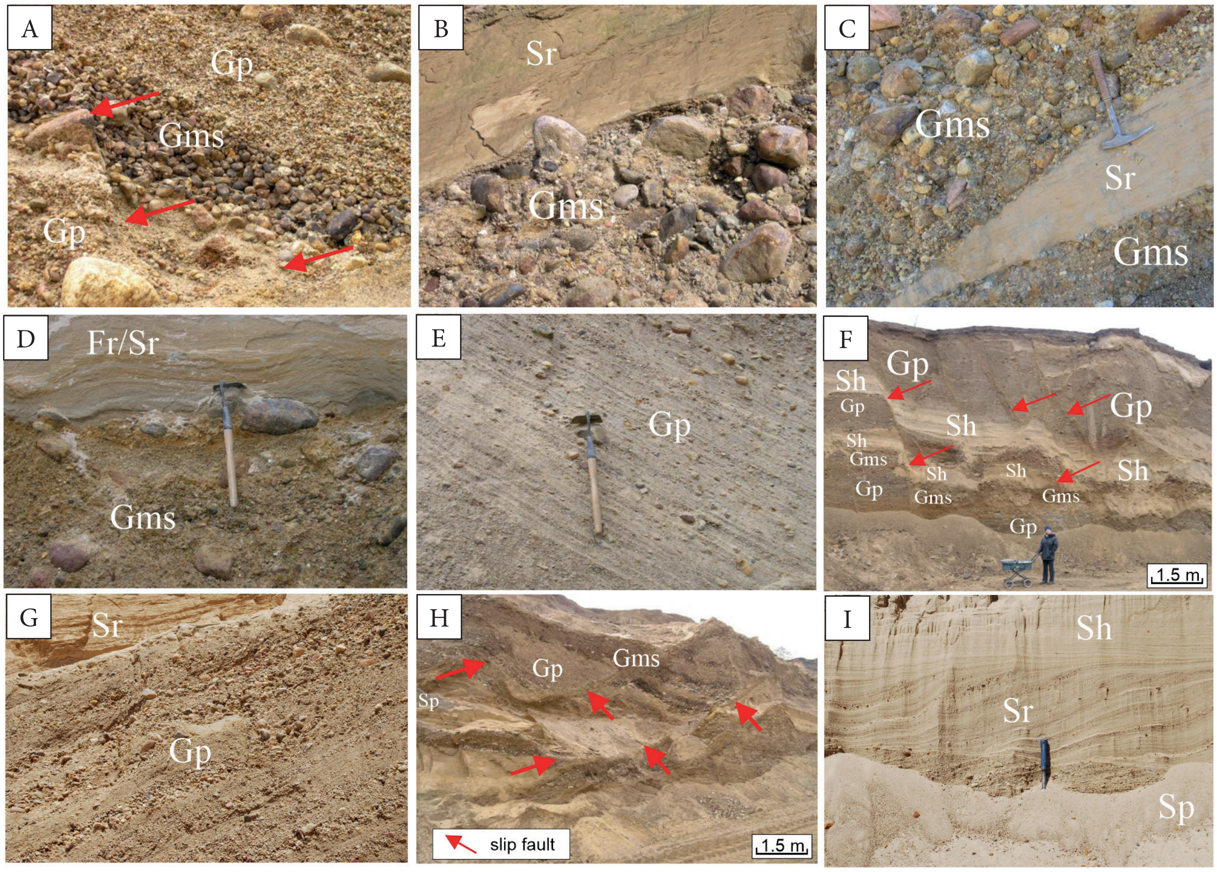

Fig. 14. *Examples of depositional structures and tectonic deformations visible in the walls of the Mokrzeszów 1 gravel pit (2008–2012, photos by D. Krzyszkowski, W. Sroka): A)–E), G), H) main body of the subaqueous/subearial fan: lithofacies differentiation of coarse-grained sediments indicating dissimilar stages of sedimentation on the slope of the deep lake; B), C) visible sharp contact between coarse- and fine-grained sediments, indicating sudden changes in flow energy (B, C, D); F), H) a system of main parallel discharge faults on the slope along the SMF line, oriented towards the south; I) top set of the gentle-slope fan*

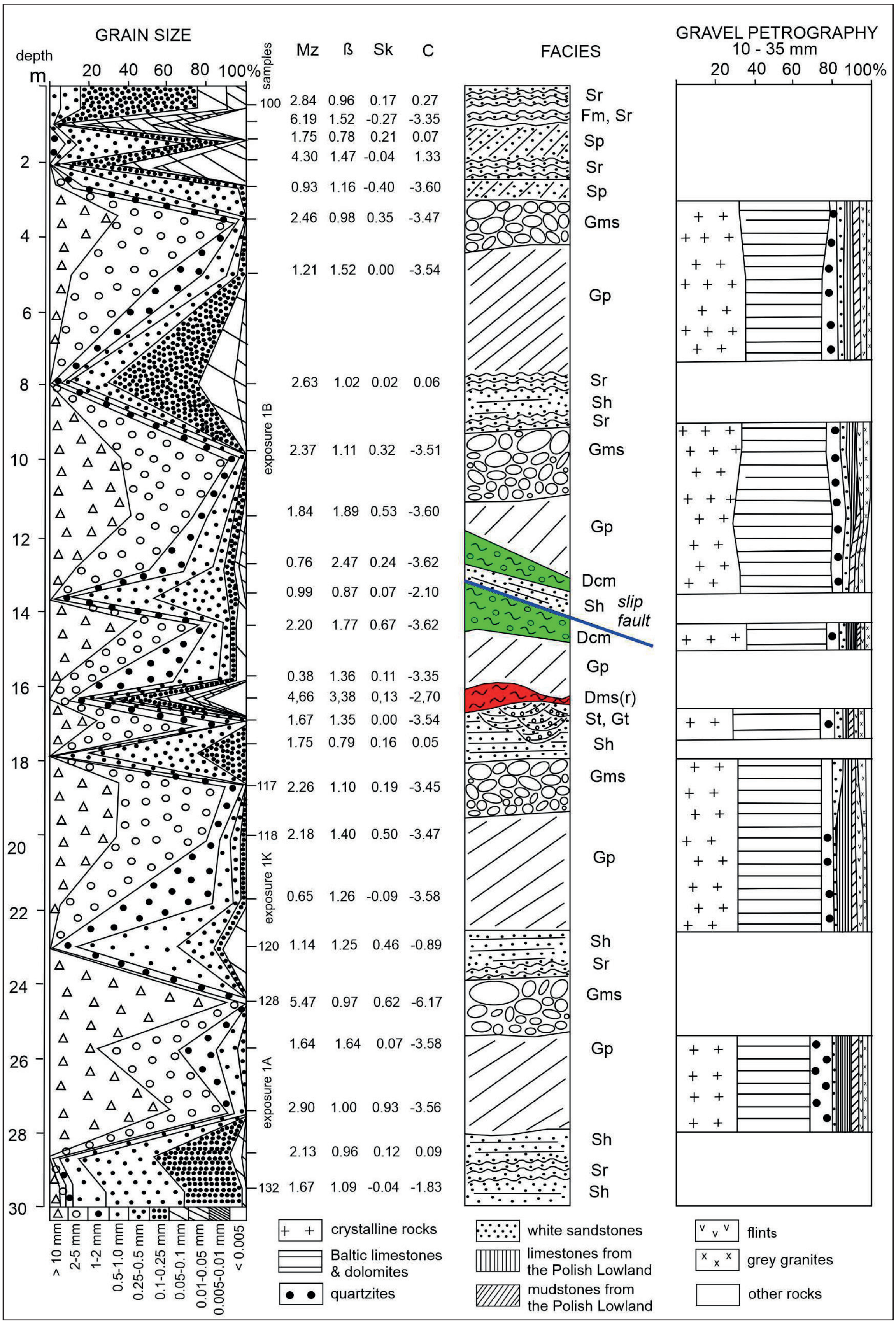

Fig. 15. *Composite lithological log, petrography, and grain size. Exposures: 1B, K (see Fig. 4), A (see Fig. 6). Grain parameters:* M_z, σ, (β), S_k, *C, after Folk & Ward (1957). For lithology symbols see Figure 4*

Petrography

The petrographic composition of the sediments is homogeneous in the Mokrzeszów 1 and 2 sections, despite significant facies variability (Figs. 8, 12, 15).

The gravelly deposits are characterized by the predominance of Baltic limestones (35–45%) and Scandinavian crystalline rocks (32–36%), accompanied by quartzites (4–8%), Mesozoic limestones (3–8%), Mesozoic sandstones (3–5%) and quartz (1–5%) (Figs. 6, 8, 12, 15). Flints and grey (Strzegom?) granites are found in minor amounts. The heavy minerals show a typical glacially derived composition that includes garnet (30–70%), amphibole (20–50%), epidote (1–6%), pyroxene (1–5%), biotite (1–20%) and only a small admixture of tourmaline, zircon, cyanite and andalusite (Fig. 12). Other rock types occur sporadically.

DISCUSSION

Interpretation of sediments

The sedimentation pattern and the sedimentary succession are shown in Figure 16A in relation to the ice sheet advance and the basement tectonics of the SMF. Six to seven sedimentary cycles can be observed in the pit.

Cycle 1 began with a deposition on a steep slope of a lake or SMF edge. The sediment was deposited in the channel by migrating dunes (Gp – see Tab. 1). As a result, the slope became gently inclined. This might have been a trigger of landslides in steeply sloping areas (Eyles & Clague 1987).

Cycle 2 began when the meltwater season started and the delta steepened (Gp) (Fig. 16A). The gravel is clearly organized and may represent large-scale planar cross-stratified (e.g. see examples in Winsemann et al. 2009, 2016 and Frydrych & Rdzany 2022). The deposition occurred from tractional bedload flows in channels on the delta plain or sustained turbidity currents on the delta slope (Tab. 1). The cyclic nature of the deposition may be related to the nature of the proglacial environment, where depositional processes are closely related to climate. Gravels (Gp) and boulder layers (Gms) most probably represent a summer period with relatively constant flows (continuous ice sheet thawing). Considering the Gp (Fig. 5A), the flow velocity and the critical shear stress (Costa 1983) were estimated as ~2 $m \cdot s^{-1}$ and ~66 Pa, respectively. The pulsatility of the flows can be related to a variable inflow of glacial water (warm versus cold days). High-energy and debris flows are associated either with heavy rains and higher temperatures, during which the glacial melting intensifies rapidly, or with other factors allowing large amounts of glacial water to accumulate and later released during spring-summer thawing, surge, or earthquakes (Majzels 1997, Russel & Marren 1998, Russel et al. 2001, 2010, Carrvick et al. 2004, Marren et al. 2009, Winsemann et al. 2009, 2016, Nehyba et al. 2017, Weckwerth 2018, Weckwerth et al. 2019).

The presence of boulder layers and the disordered nature of the deposits indicates that these are cohesive debris flows, possibly associated with hyperconcentrated flows (Majzels 1997, Clark et al. 1999, Marren 2002, Salamon 2009, Russel et al. 2010, Lang et al. 2018, Frydrych & Rdzany 2018, 2022, Winsemann & Lang 2020) that mobilize large boulders supplying them to the delta zone. Following the formulas provided by Costa (1983), the flow velocity and the critical shear stress were estimated as 5 $m \cdot s^{-1}$ and 320 Pa, respectively. It should be mentioned that the estimations were only based on in-situ clasts (Fig. 5B). As a consequence, the results may be underestimated, e.g. the boulders of ca. 1 m in diameter (e.g. Fig. 9B, C) might have been transported at flow velocities of 5 $m \cdot s^{-1}$ (Costa 1983). The availability of the material is also important. It is possible that the flow velocity potentially allowed for the transport of larger boulders that were simply missing in the system.

Cycle 3 is represented by the deposition of Sp, Sh and Sr sands. The upper part of the fan was built by the top set facies (Sp, Sh) and its slope with the Sr facies. Considering the Sr, Sh and Sp facies (Fig. 5C), the flow velocity (Costa 1983) was estimated as ~0.8 $m \cdot s^{-1}$. The critical shear stress (Costa 1983) cannot be estimated due to the limited number of observations. It occurred immediately after flooding on the gentle delta slope (truncated by debris flow) and probably during a period of water scarcity in the glacial system (Frydrych & Rdzany 2018, Krzyszkowski et al. 2019b). During this stage, deposition on the top was predominantly in channels by migrating dunes (Sp) and between bars (Sh) of the braided river. Synchronically, in the steep slope the sands and sandy silts (Sr) were formed from subcritical flows at high rates of suspension fall-out.

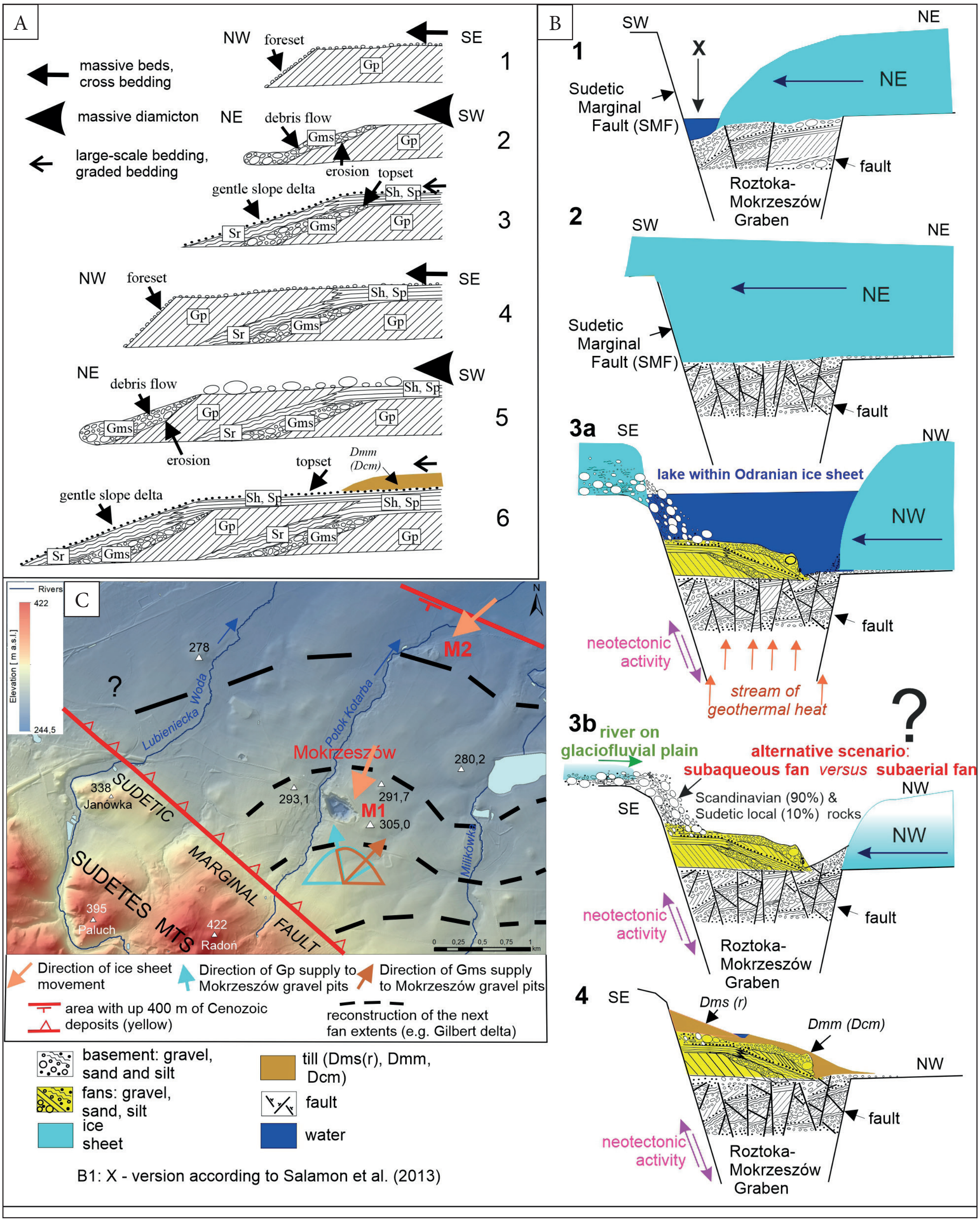

Fig. 16. *Sedimentation model illustrating the development of the fan in the Mokrzeszów 1 gravel pit (after Krzyszkowski 1993a, modified) (A); simplified model showing the pattern of deformations in the Mokrzeszów in the tectonic Roztoka-Mokrzeszów Graben with two scenarios: subaqueous steep coarse-grained delta/fan versus aerial piedmont fan (B); reconstruction of directions of ice sheet advance and of glacial water outflow against the background of modern DEM and tectonic features of the basement (C)*

The deposition of Sp, Sh and Sr sands is a distinctive feature of a subaqueous fan, as described by Winsenann et al. (2004, 2007a, 2007b, 2009, 2018) and Lang et al. (2017). Such a stratification formation may be present in the glaciolacustrine succession (see: Cheel 1990, Gruszka 2001, 2007, Gruszka & Zieliński 2021) formed in the marginal part of a lake (see: Krzyszkowski 1993, Krzyszkowski et al. 2019b). Similar facies are characteristic for the alluvial form, e.g. fan and the terraces on SMF edges (see: Krzyszkowski & Migoń 1992, Krzyszkowski & Biernat 1998, Krzyszkowski & Stachura 1998a, 1998b, Krzyszkowski & Przybylski 2013) or Central Eastern Germany (Krbetschek et al. 2008).

Cycles 4, 5 and 6 are a "repeated scenario" of cycles 1, 2 and 3 (Fig. 16A – 4, 5, 6). The flows that enabled the formation of the foresets (Gp) characteristic of the fan (stage 4) appear again. These are followed by supercritical flows and by the mobilization of cohesive debris flows down the delta slope as a result of glacial flooding, recorded in very coarse-grained (>1 m – see Figs. 5B, 9) and massive sediments, and in flow tills (Cycle 5). In this cycle, the overrepresentation of boulders is slightly greater than in the corresponding second cycle, which would indicate an even greater glacial flood than previously experienced in this lake system.

Cycle 6 corresponds to the flood surge fall, calming the flow until it died out, and to the formation of very fine-grained sediments (Sr) on the slope. During this stage, the upper part of the delta (the top set) was formed, which is composed of sands (Sp, Sh). These three facies of Gp/Sp–St–Sh/Sr form at least six sedimentary cycles that represent a prograding fan delta. The proximity to the ice sheet is confirmed by the occurrence of thin layers of flow till in the form of massive to laminated muddy, matrix-supported diamictons in the coarse deposits (Gms facies).

Cycle 7 should be associated with the direct activity of the ice sheet (oscillation?). The entire sequence of the fan sediments (lacustrine/fluvioglacial?) is topped by a basal till layer (Dmm), which overlaps the sediments in the glaciotectonic overthrust process. (Krzyszkowski & Bowman 1997, Salamon et al. 2013) (Fig. 16A – 6). It may have been thrust over the deposits as a result of glaciotectonic stacking and the subsequent crossing of the SMF barrier (Fig. 16B – 4). Additionally, the presence of tectonic fractures in the bedrock under the advancing ice sheet (SMF, Roztoka-Mokrzeszów Graben) may have led to the release of additional heat (Rdzany 2009, Winsenann et al. 2009, 2018, Lang et al. 2017, 2018), which may have further intensified the supply of water. The basal till is overlain by another till (Dcc and Dcm). This is most likely flow till Dms(r) (mud flow deposits) deposited near the ice sheet front, partly subcritical flows at high rates of suspension fall-out. The occurrence of flow till (Dms(r)) indicates that the fan formed at a short distance from the ice sheet front (Krzyszkowski 1993a).

The sedimentary model of successive depositional cycles and morphological (paleorelief) expression manifested by the fan contradicts the glacial origin of the deposits as representing either a terminal moraine (Blockpackung) according to Łoziński (1909), Cramer et al. (1924) and Szczepankiewicz (1952), or an esker described by Jahn (1981).

Interpretation of the lacustrine sediment deformations

The deposits examined in the Mokrzeszów gravel pit record the existence of a proglacial lake and a proximal outwash plain that formed in the marginal zone of the Odranian ice sheet bounded by a horst to the south, within the Roztoka-Mokrzeszów Graben, as shown in Figure 16B. Cramer et al. (1924b), Szczepankiewicz (1961) and Jahn (1981) interpreted the deformations at Mokrzeszów as glaciotectonic structures. Glaciotectonic structures usually form due to compressive pressures and are most often represented by thrust structures, and inclined, recumbent, or overturned folds, and only rarely by diapir-like structures (Rotnicki 1976, Jaroszewski 1994, Kupetz 2001, Krzyszkowski 2002, Krzyszkowski & Łabno 2002, Urbański 2005, 2009, Aber & Ber 2007, Brandes & Le Heron 2010).

The data from the Mokrzeszów gravel pit (Krzyszkowski 1992, Krzyszkowski & Bowman 1997, Salamon et al. 2013) (Figs. 2, 16B) suggest that the deformed sediments, especially the vertical deposits at the "main" fault zone at Mokrzeszów, indicate flexural zones are within a short distance of several metres, towards a subhorizontal structure. The flexured sediments may be composed of several tilted blocks. According to this model, the cause of flexuring and faulting is the tectonic subsidence of the Roztoka-Mokrzeszów Graben with its maximum thickness of ca. 400 m of trough deposits (Dyjor & Kuszell 1977, Żeleźniewicz 1987). The gravel pit has thus been located within an area of permanent subsidence since the Neogene through to the Pleistocene period.

The "main" fault at the Mokrzeszów gravel pit (Figs. 4B, 15, 17) is oblique to the SMF and most probably forms an antithetic deformation zone, in turn, located in a zone where faults had been observed down into the bedrock (Dyjor & Kuszell 1977, Żelaźniewicz 1987). The unsolved problem is the source of the pressure which caused the gently inclined faults and the flexures. The fault was developing synchronously with the SMF activity, which was revived in the Quaternary (see: Štěpančíková 2022). A comparable situation is described in Müller et al. (2020) at the Harz Boundary Fault in northern Germany, where a large Mesozoic fault was reactivated due to GIA (glacial isostatic adjustment)-related stress field changes at the end of the Weischselian glaciation.

The age of the deformation determines the age of the deformed deposits. The fault activity might be related to the reactivation of the faults due to ice loading during glaciation. The fault most probably developed the expression of syn- or post-Saalian (Odranian) activity along one of a number of basement faults (Brandes & Tanner 2012, Brandes et al. 2018, 2022a, 2022b).

The characteristics of the fault indicate that it is of a brittle deformation. The fault was formed under a thick overburden of sediments. The deformation model is shown in Figure 17. The orientation of the main fault and its location in the tectonic graben very likely indicate rather end deformation/disaggregation bands that developed above a larger, subsurface blind fault (see Brandes et al. 2018, 2022a, 2022b). Minor deformation structures within facies Sr, Sh are similar to those described by Pisarska-Jamroży & Weckwerth (2013). The inverse kinematics of the faults in the upper part may have arisen from Quaternary compression on the SMF line (Novakova 2015) as well as from seismic activity (Štěpančíková 2022).

The orientation of the main fault and its location in the tectonic graben indicate rather an endogenic origin of deformation in the Mokrzeszów open pit (Krzyszkowski 1992, 1993a, Krzyszkowski & Bowman 1997). The small faults as deformation disaggregation bands may have been formed above a larger, subsurface blind fault (see Brandes et al. 2018, 2022a, 2022b).

Glaciotectonic structures occur in series, with repeating stratigraphic sequences and with all types of faults, but the reverse ones are always common (Aber et al. 1989, Gruszka 2001). None of these structural characteristics has been observed in the gravel pit. Thus, it seems that the tectonic trigger, rather than glaciotectonism, better explains the observed deformations.

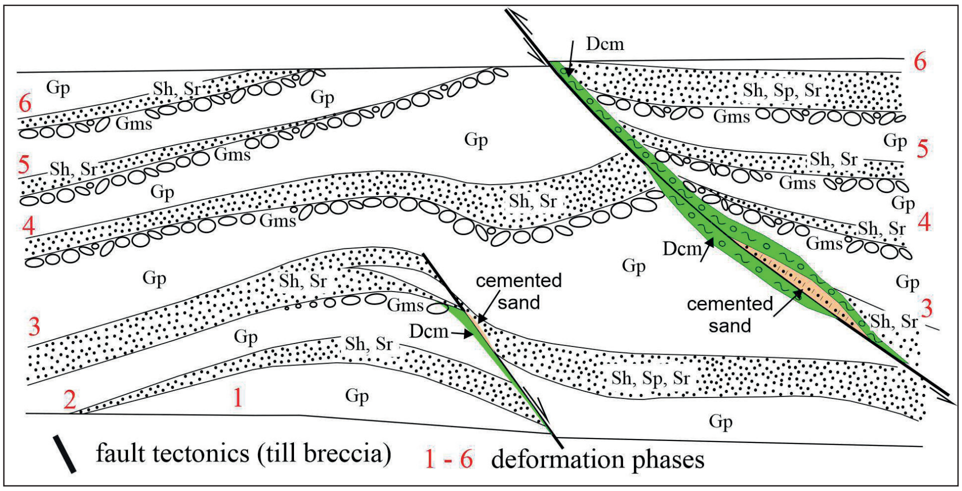

Fig. 17. *Scheme of the interpretation of fault surfaces within the glaciolacustrine delta deposits in the Mokrzeszów 1 pit (after Krzyszkowski 1993a, modified)*

The faults are probably of tectonic origin (Mazur et al. 2010, Štěpančíková et al. 2010, Różycka & Migoń 2017, Stemberk et al. 2019) strengthened by the instability of the sediments on a steep slope. These faults may have been formed by grain rolling and a related reorganization of the grain fabric (see: Brandes et al. 2018, 2022a, 2022b), thus they are disaggregation bands and might indicate neotectonic activity above a branch fault, e.g. of the Sudetic Margin Fault, and in the tectonic Roztoka-Mokrzeszów Graben (Fig. 16B – 3, 4).

Petrographic interpretation

Studies of indicator erratics at the Mokrzeszów gravel pit (Czubla 2013) suggest that the till from the eastern part of the pit may be related to the South Polish glaciations, which is somewhat at odds with the paleogeographic interpretation of the sequences of glacial sediments here (90–95%). The white sandstones (Fig. 15) were interpreted by Jahn (1981) as rocks from the North Sudetic Basin. In a borehole drilled west of Mokrzeszów (Niedzielski & Migoń 2005), directly in the Subsudetic Depression, a 26 m thick till was found to occur down from the surface. The till contains very few local rocks in its petrographic composition of the 5–10 mm fraction, which constitute only several per cent. Among the northern rocks, there is a distinct predominance of Paleozoic limestones (about 40%), allowing the comparison of the till layer with the level correlated with the younger Sanian two glaciation among the South Polish glaciations in the Silesian Lowlands. In the studied fraction (10–35 mm), the percentage of Mesozoic sandstones does not differ from other in the same sandstone in the Saalian deposits of the Polish Lowlands (Górska-Zabielska 2008, Górska-Zabielska & Wachecka-Kotkowska 2014, 2015, Czubla 2015, Górska-Zabielska et al. 2021).

Paleogeographic interpretation

Also worth noting are some difficulties in the paleogeographic interpretation of the Mokrzeszów deposits (Krzyszkowski 1993a). Firstly, the sediments exposed here are unique because there are no exposures with such a large overrepresentation of boulders in the nearest vicinity. In other open pits of proglacial sediments of the same age, only sandy or sandy-gravelly facies (no facies Gp) are exposed (Nowy Jaworów and Jaworzyna Śląska gravel pits, ca. 7–9 km to the NE) (Krzyszkowski & Przybylski 2013). Secondly, in the uppermost part of the exposures (Figs. 4, 6, 12) the overlying basal till Dmm indirectly indicates the Lower Saalian (Odranian, MIS 6) age of the sand and gravel deposits. This closely correlates with the extent of the Middle Polish Odranian glaciation (Czerwonka & Krzyszkowski 1992, Marks 2005, 2011, Krzyszkowski 2013b, Marks et al. 2018) for the area surrounding the Mokrzeszów gravel pit. Thirdly, the geological situation is complicated by a system of faults related to the morphostructural edge of the Sudetes and to the adjacent Roztoka-Mokrzeszów Graben. The fault system indicates the neotectonic deformation of both the bedrock and the studied sediments. Fourthly, the transgression of the last ice sheet that reached the Sudetes borderline resulted in glaciotectonic deformation (Krzyszkowski et al. 1995, Krzyszkowski & Bowman 1997, Salamon et al. 2013). A similar example was described by Fernández & Guerra-Merchán (1996) in a tectonically active zone in Canada.

In the Mokrzeszów exposures, the evolution of the glaciomarginal lake or a river system within the glacial environment can be traced. The ice sheet advanced from north to south and filled the Roztoka-Mokrzeszowa Graben. Over a short period, a lake was formed (Fig. 16B – 1st phase). The sedimentary record from this period was presented by Salamon et al. (2013), showing the succession of a narrow, proglacial lake. A similar situation was described by Krzyszkowski et al. (2019b). The ice sheet then crossed/overcame the SMF barrier (Fig. 16B – 2nd phase). Based on geological studies, the authors presented two alternative scenarios for the formation of the cone as a subaqueous fan (Fig. 16B – 3a) versus an aerial, piedmont fan partly forming by glaciofluvial water (Fig. 16B – 3b).

In the present study, the proposal of two scenarios for the fan formation in different lacustrine and fluvial/glaciofluvial sedimentary environments seems logical. In the first case (Fig. 16 – 3a), when the ice sheet reached far to the south, the area was covered by the ice sheet to the line of the Sudetes Mountains (Czerwonka & Krzyszkowski 1992, Marks 2011), and there was a local break in the ice sheet continuity, and the formation of a lake took place at the study site. Based on litho-petrographic studies, the depositional sequence exposed in the Mokrzeszów pit can be interpreted as the upper part of deltaic sediments accumulated from the south-east to a small ice-dammed lake that formed between the advancing ice sheet and the edge of the Central Sudetes (Salamon et al. 2013, Hanáček et al. 2018, Krzyszkowski et al. 2019b). A similar situation was described by Salamon (2009) for the Polish part of the Eastern Sudetes (see Fig. 16 – B1). The lake was characterized by high hydrological variability and the high energy of depositional processes. This fits into the general paleogeographic picture of glacial drainage in the continental area between the Atlantic Ocean and the Black Sea (Eissmann 2002, Winsemann et al. 2016, Lang et al. 2018). There was a blockage of the north-western outflow of glacial rivers, and this led to the formation of numerous ice-bound lakes in Western and Central Europe (Marks 1996, Panin et al. 2020).

The lake may have formed between ice blocks as a result of their melting caused by geothermal heat, since there are many tectonic discontinuities here, such as the SMF, Mokrzeszów-Roztoka Graben (See Fig. 2). In the lake, a subaqueous fan, oriented SE-NW, was formed on the steep southern slope coinciding with the edge of the SMF, in the opposite direction to the ice sheet advance. The lacustrine subaqueous fan is also supported by the presence of dropstone boulders, shown in Figure 10, as well as structures characteristic of subaqueous debris flows. Unfortunately, this scenario lacks an element characteristic of full lacustrine sedimentation, namely the bottom set, i.e. the lower part of the Gilbert delta, composed of fine sediments, as described by Rust (1972, 1978) and Miall (1977, 1978, 1983).

No delta bottom-set sediments in the form of varved clays are observed at Mokrzeszów, as is the case at many similar sites in the Sudetes (Krzyszkowski et al. 2019b). The analysis of numerous borehole sections from the vicinity of Mokrzeszów, in the Świdnica Plain, and in the Subsudetic Depression (Niedzielski & Migoń 2005, Krzyszkowski et al. 2019a, 2020) permits the conclusion that the ice-dammed lake deposits of bottom facies from the period of the ice sheet advance during the Odranian glaciation are relatively widely distributed in this area. They occur in many places on the ground surface or under a thin layer of glacial tills. At the surface, these sediments predominantly form small occurrences in places where the till cover has been reduced by erosive processes. These are usually laminated muds and fine-grained sands, and locally varved clays. The sediments are greyish yellow or grey in colour and these formations are strongly calcareous.

A distinct chain of occurrences of transgressive ice-dammed lake sediments is visible on a post-glacial plateau between Mokrzeszów and Jaworzyna Śląska. South of Szymanów (approx. 8 km NW of Mokrzeszów), an extensive patch of ice-dammed lake sediments extends to the morphotectonic edge of the SMF (Niedzielski & Migoń 2005). The thickness of fine-grained sediments of the ice-dammed lake in this area does not usually exceed 5 m, reaching at most several metres. However, there is no section in which deltaic sediments are in contact with the bottom facies deposits of the ice-dammed lake. This is due to the local situation of the bedrock. In Mokrzeszów, there are only glacial deposits, i.e. a 25 m thick gravelly series topped with a 1–3 m thick till layer. Perhaps, the rhythmically layered, stratified sediments of the lake bottom, characteristic of the lower part of the Gilbert delta (bottom set delta), are missing, i.e. they have not been formed because the sedimentary basin (proglacial lake) rapidly filled with sediments of successive cohesive flows associated with the subsequent flood (Eyles & Clague 1987).

The second scenario represents an aerial, piedmont fan (Fig. 16B – 3b), formed after the partial deglaciation of the area in a fluvial/glaciofluvial environment. Here, the southern part of the study area was freshly covered by Scandinavian material as a glaciofluvial plain, and the steep slope of the SMF provided an edge for the newly organized fluvial system, over which large clasts could move from south to north, owing to the potential energy converted into kinetic energy. Flood events resulted in supercritical flows (megafloods) (Rdzany & Frydrych 2018) and were followed by flow stabilization and even dying out, as highlighted in cycles 1–3 and 4–6. Such events resulted in the formation of a classic piedmont fan, showing sediment imbrication (Figs. 9, 11) and shaped according to the topography of the area, as shown in Figure 16C.

The fluvial provenance of the fan is supported by the strata pattern characteristic of a piedmont, river rather than a lacustrine environment (Krzyszkowski et al. 2019a). The weakness of this scenario is the multiplicity of deformation structures of different orientations which could theoretically be related to the SMF edge and the ice-sheet wall of the newly formed fan (Salamon 2009) or to neotectonic processes (Štěpančíková et al. 2010, 2022, Novakova 2015). The second element unrelated to the river is the presence of massive tills (Dmm, etc.) that cover the cone in its top part. This indicates the presence of an ice sheet and partly excludes the activity of the river itself, without contact with the melting ice that accumulated the basal and flow tills (Dcm, Dms).

Paleoflow directions were taken into account in both scenarios. The deposition occurred from south to north, in the opposite direction to the advancing ice sheet, as evidenced by the paleocurrent directions and long axes of boulders, shown in Figures 4, 6, 8 and 12. This is a new element in the paleogeography of the area. Salamon et al. (2013) described a fan related to the ice sheet advance direction (X in Figure 16 – B1). In the site, the dominant deposits are gravels (Gp) deposited from the SSE towards the NNW on a steep slope with highly variable flows (Krzyszkowski 1993a, Krzyszkowski et al. 1995, Winsemann et al. 2004, 2007a, 2007b, 2018, Gruszka 2007, Longitano 2008, Pisarska-Jamroży et al. 2010, Krzyszkowski et al. 2019b, Gruszka & Zieliński 2021).

Given the arguments for the existence of a lake close to the ice sheet edge and the river activity, the two scenarios should be combined. The model should depict flooding in a Sudetic river flowing into the ice lake – glacial-flow-lake-outburst floods. It is surprising that the river flowing down from the Sudetes into the lake did not carry much local, Sudetic material, but mostly Scandinavian material (Figs. 12, 15). It also seems interesting that a coarse-grained fan with fan-delta settings (Lang et al. 2017) was formed within the SMF (Krzyszkowski et al. 1995, 2000). A similar situation of glacial lake formation in a tectonically active zone was reported by Longhitano (2008) in the Southern Apennines, and by the team of Brandes & Tanner (2012) and Brandes et al. (2011, 2018, 2022a) in Germany.

Works on glaciomarginal lacustrine deposits formed in an ice-dammed lake in the Sudetic area have shown the classic arrangement of fan deposits, corresponding to the direction of the Saalian ice sheet advance (see: Salamon et al. 2013, Hanáček et al. 2018, Krzyszkowski et al. 2019b). A new aspect of this study is the description of a Saalian subaqueous/areal fan arranged in the opposite direction to the advancing ice sheet, but consistent with the bedrock topography, i.e. the gradient of the river valleys.

CONCLUSIONS

1. The sediments exposed in the Mokrzeszów gravel pit in the central part of the Sudetic Foreland represent an almost complete succession of glacial-flow-lake-outburst floods with a fan composed of gravelly-boulder-sandy sediments. The lake was characterized by high hydrological variability and high energy of depositional processes, ranging from high-energy flows estimated for the Gms and Gp facies at about $5\ \mathrm{m \cdot s^{-1}}$, through flow attenuation to about $0.8\ \mathrm{m \cdot s^{-1}}$ (Sp/Sh/Sr), to the lack of flow (Fm).
2. Sedimentary sequences Gp-Gms-Sh/Sr(Dmm/Dcc) confirm the existence of a fan that formed during at least two separate but successive episodes of glacial floods. Initially, during the ice sheet growth and its subsequent disintegration, Sp/Gp foreset structures were formed at the SMF boundary in a strip of topographic low in the southern slope of the tectonic Roztoka-Mokrzeszów Graben. Then, as a result of rapid ablation and the release of considerable mass of water from the melting ice sheet, cohesive debris flows and the deposition of boulder deposits Gms (>1 m) and flow tills Dcm took place. Rapid glacial and glaciofluvial flooding was followed by flow waning, stabilization of the gentle-slope fan/delta, and aggradation of the top set Sh/Sr – horizontally bedded, medium to coarse sand or sand with rare gravels and sand or sandy silt with ripple marks. The above scenario was repeated, and larger clasts were supplied to the lake system during the last flood episode, which presumably indicates a higher-energy depositional environment. The entire sequence of lacustrine/glaciofluvial

sediments is topped by a basal till (Dmm) that may have been thrust over the deltaic deposits by the process of glaciotectonic stacking and subsequent crossing of the SMF edge barrier by the ice. The presence of tectonic faults in the bedrock could have potentially provided geothermal heat and supplied additional water. The basal till was overlain by a flow till (Dcc) deposited near the head of the ice sheet.

3. The fan deposits, as well as the bedrock sediments filling the Roztoka-Mokrzeszów Graben bounded from the south by the SMF line, were subjected to neotectonic processes during the Pleistocene. The fault activity might be related to reactivation of the faults due to ice loading during glaciation. The lake functioned as a depression between the ice sheet front and the SMF zone, on the border of the Roztoka-Mokrzeszów Graben, and there was an episode when the ice crossed the barrier manifested by the SMF edge. Gently inclined faults and fractures were formed, representing deformational structures not only indicating ductile deformation of sediments but also the possible effects of neotectonics. Reverse faulting was associated with Quaternary compression at the Sudetic Marginal Fault that was roughly perpendicular to the strike of the fault.
4. Lithopetrographic and sedimentological analyses of the bedrock indicate an overrepresentation of great Scandinavian erratics (90–95%). Petrographic studies of the bedrock suggest an Elsterian age. The absence of lodgement-type tills on the ground surface is justified as we consider the location of the study area in the Subsudetic Depression, at the front of the Early Saalian, MIS6 ice sheet. It can therefore be said that the fan sediments (referred to as the Kończyce Formation) were deposited under the glacial conditions of the Odranian glaciation.
5. The presented paleogeographic model of fan sedimentation in relation to bedrock tectonics shows the environment of a glacial lake with a river flowing down to it from the Sudetes that formed between the ice sheet front and the morphotectonic margin of medium-high mountains. The picture presented in this contribution is a case study and adds to the knowledge of many other poorly documented glacial lakes in the piedmont, mountainous areas of Central Europe.

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