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Erosion and accumulation phases during the last glacial-interglacial cycle: a case study of the terrace system of the Odra and Osobłoga rivers (southern Poland)

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In the Odra and Osobłoga River valleys in the vicinity of the town of Krapkowice, a system of morphological levels is present which is exceptionally extensive compared to other such systems in southern Poland. The extent, origins and chronology of these levels have been the subject of many controversies. In the light of current research, the terraces, which are situated on average 14.5–13, 12–10, 8–6, 6–4 and 3–1 metres above the river level, were formed in the post-Wartanian interval. The main factor driving their development was erosion, which compensated for the effects of large-scale aggradation that had occurred during the anaglacial phase of the Odranian Glaciation (MIS 8) dated to 261 ±15 ka. The impact of climatic conditions on the trends towards fluvial erosion or accumulation was only of secondary importance. According to OSL dating, successive phases of vertical stabilisation of the valley floor occurred ~118.8 ±8.3, 87.7 ±5.7 and 42.0 ±2.0 ka. In the meantime, erosion intensified, which resulted in the formation of lower terrace levels. During the climatic minimum of the Upper Plenivistulian (21.5 ±1.5 ka), under conditions of the delivery of sheet-wash-generated sediment, the aggradation of distal reaches of the Odra River valley was locally marked. During the Late Vistulian and Holocene, erosive tendencies continued, which were reflected by the fact that the surfaces of subsequent inset alluvial fills were situated ever lower. In the light of dating results, it can be concluded that during the colder periods correlated with the Rederstall Stadial (MIS 5b) and with the Hasselo Stadial (MIS 3), a braided river was present in the river valleys examined, which was most probably accompanied by permafrost. During the Eemian Interglacial (MIS 5e), during the Late Vistulian Interstadials and in the Holocene, it was a meandering river.

Key words: fluvial processes, river terraces, Late Quaternary, OSL, southern Poland.

INTRODUCTION

Studies of river terrace systems are widely used to reconstruct fluvial processes and also to answer questions related to Quaternary palaeogeography. Among the widely discussed and still unresolved issues are the conditions which determine aggradation/degradation processes in valleys (see Hosfield and Chambers, 2005; Zieliński, 2015). Most of the models which can be found in the literature emphasise the relationship between the evolution of the fluvial system and climate. As a result of many years of research, a number of (frequently contradictory) views have been formulated on this subject:

– interglacial/glacial transition – many authors consider that erosion dominates (i.a., Jahn, 1956; Schumm, 1977; Vandenberghe et al., 1994; Antoine et al., 2000) under conditions of increased flows of rivers which are only lightly burdened by the sediments transported (Gibbard and Lewin, 2002); others point to aggradation, assuming that during the transition between warm and cold periods, a closer connection forms between the slope and channel systems within catchment areas (Bogaart et al., 2003);
– glacials – in the classical approach, accumulation dominates as a result of a combination of increased denudation within the catchment and high water stages (e.g., Church and Gilbert, 1975; Florek, 1997; Fuller et al., 1998), with many authors only associating aggradation with the glaciation's maximum (Jahn, 1956; Schumm, 1977; Vandenberghe et al., 1994; Superson, 1996), and accumulation may be interrupted by erosion phases (Gębica, 2004); according to another approach, the adaptation of rivers to Arctic-Nival type discharge regimes makes river systems essentially stable (Bridgland, 2000);
– late glacial/early interglacial transition – according to the most common view, erosion associated with increased

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flows (the tendency towards an increasingly oceanic climate) dominates, with a decrease in sediment transport and/or a lowering of the rivers' erosion base as the ice sheet retreats (e.g., Jahn, 1956; Vandenberghe et al., 1994); over time, erosion may be supplanted by aggradation in response to a decrease in flow (Maddy et al., 2001);
– interglacials – views diverge considerably here: some think that in warming periods, valleys are degraded as a result of limited denudation within the catchment (e.g., Church and Gilbert, 1975; Florek, 1997; Fuller et al., 1998), some assume that valley channels are vertically stable (e.g., Schumm, 1977; Maizels, 1979; Superson, 1996; Antoine et al., 2000; Maddy et al., 2001), and finally some claim that slight aggradation can be observed, starting with the climatic optimum (e.g., Jahn, 1956; Vandenberghe et al., 1994; Bogaart and Van Balen, 2000).

The various conclusions reached by different authors as a result of their studies of geographically different fluvial systems demonstrate that Late Quaternary tendencies towards valley aggradation/degradation depend to a large extent on local factors. In particular, regional differences in vertical crust movements and the impact of local glaciation should be considered (Bridgland and Westaway, 2014). According to the studies conducted by Rotnicki (1987), transgression/recession of the ice sheet affects the level of the local erosion base, and thus more terraces are formed in a valley reach adjacent to the ice sheet front than in a valley reach which is distant from this front. Additionally, the emergence of freshly deposited glacial sediments within the catchment contributes to accelerating valley aggradation (Maizels, 1979; Bridgland, 1994). The vicinity of Krapkowice is a promising study area for tracing the course of valley aggradation/degradation both in the direct presence of the Scandinavian ice sheet (Odranian = Drenthe glacial stage) and also under conditions where the ice sheet front was farther removed from the study area (175 km during the Main Stadial of the Vistulian).

Our studies examine the extent, origins and age of the individual levels which form the system of terraces of the Odra and Osobłoga rivers near Krapkowice. The results of this work are presented in the context of a broader discussion concerning the factors which determined the succession of fluvial erosion and accumulation phases in the Late Quaternary.

STUDY AREA

The study covered the area of the gorge where the Upper Odra River crosses the Mid-Triassic escarpment which forms the northern boundary of the Racibórz Basin. This region underwent several glaciations, most recently during the maximum extent of the Odranian Glaciation = Drenthe Stage = MIS8 (Fig. 1A). As a result, the surface of inter-valley areas consists mainly of glaciofluvial sands and gravels as well as glacial tills (Wroński and Kościówko, 1982; Trzepla, 1999). In the vicinity of Krapkowice, the thickness of Quaternary strata, which include fluvial deposits (Fig. 1B), is variable and ranges from 0 to ~80 metres (Trzepla, 1999). The substrate includes Mid-Triassic limestones and marls, which form exposures on the right bank of the Odra River. To the south and west of Krapkowice, Miocene clays, muds, sands and gravels from the Poznań series appear in the Quaternary substrate (Fig. 1C). These deposits belong to the northern part of the Carpathian Depression, which was subject to strong subsidence, especially in the Kędzierzyn Trench zone, during the Sarmatian (Dyjor et al., 1977). According to Kotlicka (1981), tectonic movements in the area in question continued in the Quaternary, although their intensity gradually decreased. Glacio-isostatic movements probably played a role here.

The course of fossil river valleys from the Pliocene and from the Early Pleistocene, which only overlaps with the present hydrographic network to a limited extent, indicates that the relatively brief evolution of the Upper Odra River valley started in the Middle Pleistocene (Dyjor et al., 1977; Krzyszkowski et al., 2019). The river system was reshaped as a result of glacial, glaciofluvial and fluvioperiglacial accumulation which accompanied subsequent ice sheet overthrusts in Poland (Fig. 1D). The modern valley network finally developed on the surface formed by the material deposited by the Odranian Glaciation, reflecting the directions of extraglacial outflow (Lewandowski and Kaziuk, 1982).

The modern fluvial landform features in the Krapkowice area are to a large extent the result of the manner in which deglaciation progressed in this area. In the inter-valley zone, flat areas with glaciofluvial origins can be found at 207–206, 197–195, 192–191 and 187–185 m a.s.l. Similarly, in the Odra River valley, culminations of glaciofluvial forms "rising" above the fluvial sedimentary cover reach respectively 207, 193, 189 and 186 m a.s.l. However, the origins (fluvial or glaciofluvial) of the residually preserved sandy and gravelly flat areas with elevations of up to 182 m a.s.l. have not yet been resolved. In particular, the origins of the heavily denuded area with an average elevation of 178.5–177.5 m a.s.l. between the town of Gogolin and the village of Górażdże need to be precisely determined. This level appears to correspond to the flat areas situated 179.5 m a.s.l. on the southern slope of the Osobłoga River valley. These accompany the 186 m a.s.l. culmination consisting of glaciofluvial sands and gravels in the vicinity of the village of Komorniki. However, the lower (and better preserved) morphological levels are undoubtedly of fluvial origin. In the Odra and Osobłoga River valleys near Krapkowice, apart from the 182–179.5 and 179.5–177.5 m a.s.l. levels noted above, there are also morphological levels situated at elevations of around 174.5–173, 172–170, 168–167, 166–165 and 163–161 m a.s.l. Works by Assmann (1934), Walczakówna and Baranowska (1964), Szczepankiewicz (1974), Wroński and Kościówko (1982), Lewandowski (1988), Trzepla (1999) and Waga (1994) have provided extensive data on their locations and structures, but at the same time a number of controversies have arisen resulting from, among other things, the absence of absolute dates of the deposits of which they consist. In particular, the differences of opinion concerned the origins, ages and extents of the individual levels (see Wójcicki et al., 2018). Conversely, we have relatively numerous ^{14}C dating results of Late Vistulian–Holocene deposits in the valley floor (situated at 163–161 m a.s.l.), which was studied by, among others, Klimek (2002), Wójcicki et al. (2010) and Wójcicki and Marynowski (2012).

METHODS

Geomorphological and lithological analyses as well as absolute dating have provided the basis for inferences concerning the evolution of the Odra–Osobłoga fluvial system. The analysis of the extents and heights of the terraces situated on the slopes of the Odra and Osobłoga River valleys was carried out using a digital terrain model and topographic profiles based on LIDAR data with a vertical resolution of up to 0.2 m.

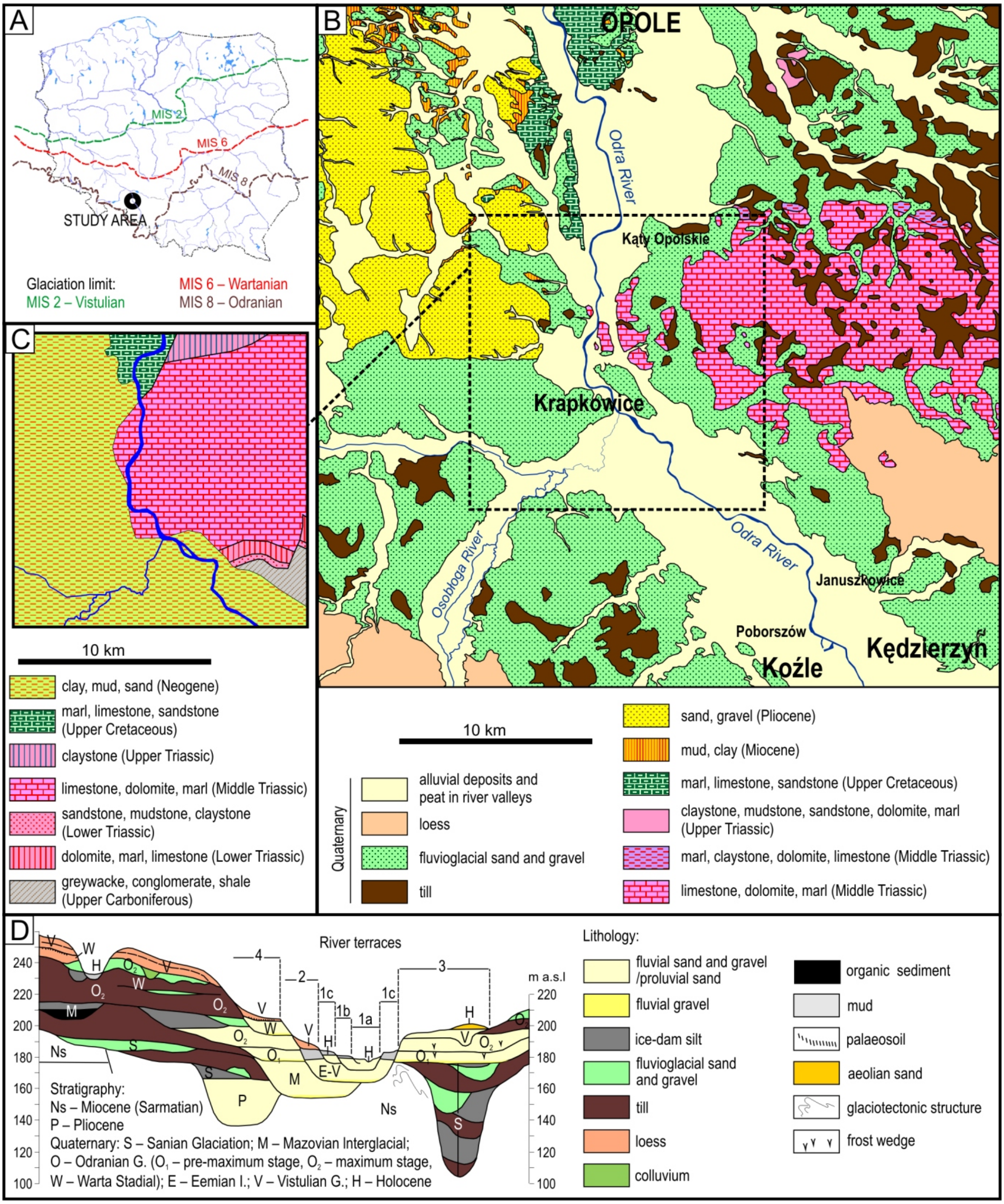

Fig. 1A – location of the study area; B – geological map of the Krapkowice area according to Darski (1986), Trzepla (1993, 1999), Przybylski and Badura (2010), simplified and modified; C – pre-Quaternary geology according to Kotlicki (1977) and Kościówko (1982); D – synthetic lithostratigraphic cross-section of the Odra valley in the Racibórz Basin according to Lewandowski (1988, modified)

Sedimentological profiles were developed for the morphological levels identified in selected exposures. Grain size distribution analysis was by sieving and, for formations which contained fractions finer than sand, by using the so-called combined method proposed by Mycielska-Dowgiałło (1995). First percentile (C) and median (M) values for the grain size distributions obtained were calculated alongside the indices determined according to the Folk and Ward formulae (Folk and Ward, 1957). The composition of organic matter was analysed using the microscopic grid method (Tobolski, 2000) and the results obtained were compiled in the form of Troels-Smith system formulae (Troels-Smith, 1955).

The age of the alluvia was determined using the single-aliquot regenerative-dose optically stimulated luminescence (SAR-OSL) method. The alluvia dated were collected from the upper sections of alluvial bars. It was assumed that the material in question was exposed on the surface between successive flood episodes. Quartz grains belonging to the 90–125 µm fraction were dated. In addition, radiocarbon dating results of the organic matter accumulated in the initial phase of palaeochannel filling in the Late Vistulian and Holocene were used in the work carried out. In this case, it should be assumed that alluvial sedimentation occurred in the period preceding the radiocarbon date obtained. The ^{14}C dates were calibrated using *OxCal 4.3* (Bronk Ramsey, 2009) and the *IntCal13* atmospheric curve (Reimer et al., 2013).

EXTENT AND MORPHOLOGY OF RIVER TERRACES IN THE ODRA AND OSOBŁOGA RIVER VALLEYS

T4 TERRACE (~174.5–173 m a.s.l. = 14.5–13 m a.r.l.)

Small parts of this terrace (in total <3.5 km^2 in area) have been preserved in the marginal zone of the Osobłoga River fan-terrace complex, especially in its southern part (Fig. 2). The upper edge of the terrace exhibits a meander there, which suggests that it could have been formed as a result of the erosive activity of the meandering Odra River channel. The surface of the terrace is partly denuded (Fig. 3), steadily descending towards the valley axis and transitioning into a lower terrace along a slight bend. No remains of this terrace have been identified below the gorge in the Krapkowice area.

T3 TERRACE (~172–170 m a.s.l. = 12–10 m a.r.l.)

This is an extensive (>20 km^2 within Fig. 2) and well-preserved terrace level. The terrace extends beyond the area discussed in this study, both upstream and downstream in the Odra River Valley. Its remains have also been preserved within the contemporary flood plain in the form of isolated cut-off meanders, e.g. around the villages of Nowy Młyn and Pietna in the Osobłoga River valley. A detailed analysis of topographic profiles indicates that this level near Krapkowice was originally established at an elevation slightly >172 m a.s.l. Upstream along the Odra River valley, its highest fragments in the vicinity of Poborszów near Koźle are elevated to ~175 m a.s.l., which translates to a slight downstream gradient of the level analysed amounting to 0.25 m/km between Poborszów and Krapkowice.

T2 TERRACE (~166–165 m a.s.l. = 6–4 m a.r.l.) AND T2+ MORPHOLOGICAL LEVEL (~168–167 m a.s.l. = 8–6 m a.r.l.)

The T2 terrace was exceptionally well-preserved along the Obrowiec–Malnia line on the right bank of the Odra River as one of the Pleistocene routes along which the Odra River crosses the Mid-Triassic escarpment (Walczakówna and Baranowska, 1964). The downstream gradient of the terrace within this reach is ~0.31 m/km. Up the Odra River valley, the T2 terrace gradually disappears, forming (together with the Holocene inset fills) the contemporary valley floor upstream of the village of Stradunia. However, below the Krapkowice gorge, the T2 terrace has been preserved on the right bank of the Odra River in the form of an extensive level rising to an elevation of ~162.5–161.5 m a.s.l. near the village of Kąty Opolskie. In the Osobłoga River valley, a fragment of the T2 terrace has been preserved in the form of a narrow strip (0.09 km^2) to the east of the village of Steblów with traces of braided channels. This fragment lies at an altitude of ~165.5 m a.s.l., i.e. an average of 4 metres above river level.

In the Odra River valley, there are morphological levels similar in elevation to the terrace discussed. Between the village of Obrowiec and the town of Gogolin, in the central section of the Odra River drainage route, a mire is present which is situated at 165.6–166.3 m a.s.l. The marginal zone of the T2 terrace rises steadily towards the valley slopes to reach ~169 m a.s.l. This extensive, gently sloping surface is described as the T2+ morphological level. In the vicinity of the village of Żywocice, a small fragment (0.46 km^2) of a river terrace has been preserved, which lies at an altitude of ~164 m a.s.l., i.e. 3.5 m above river level. It is possible that in terms of age, it is a link between the T2 terrace and the contemporary valley floor.

T1 VALLEY FLOOR (~163–161 m a.s.l. = 3–1 m a.r.l.)

The Odra and Osobłoga River floodplains are the most extensive terrace level in the Krapkowice area, occupying >41 km^2 within Figure 2. They consist of a series of alluvial inset fills of various ages formed by a sinuous river. The boundaries between the alluvial successions originating in the Late Vistulian and in the Early, Middle and Late Holocene are blurred. In the Osobłoga River valley, the oldest fragments of the valley floor around the Nowy Młyn village (T1d terrace) are elevated ~2.8 m above the river level. Near the village of Żywocice, bars of large meanders (T1c level) are located ~2.5 m above the average water stage. The surface of the inset terraces related to the Holocene palaeomeanders (T1b-a levels) is raised 2–0.9 m above the water level of the Osobłoga River. The Osobłoga River floodplain is characterized by a significant gradient (1.34 m/km on average) within the reach from the village of Komorniki to the town of Krapkowice. In the Odra River valley, the highest-lying meander bar surfaces are ~3.6 m above the river level. The largest areas are occupied by parts of the flood plain included in the T1b level, which is located on average 2.2 m above the Odra River water level. Bars of the youngest generation of palaeomeanders (T1a terrace) are elevated from 0.5 to >2 m above river level. The gradient of the Odra River floodplain between the village of Stradunia and the town of Krapkowice is 0.39 m/km, while below the Krapkowice gorge (between the village of Malnia and the city of Opole) it rises to 0.45 m/km.

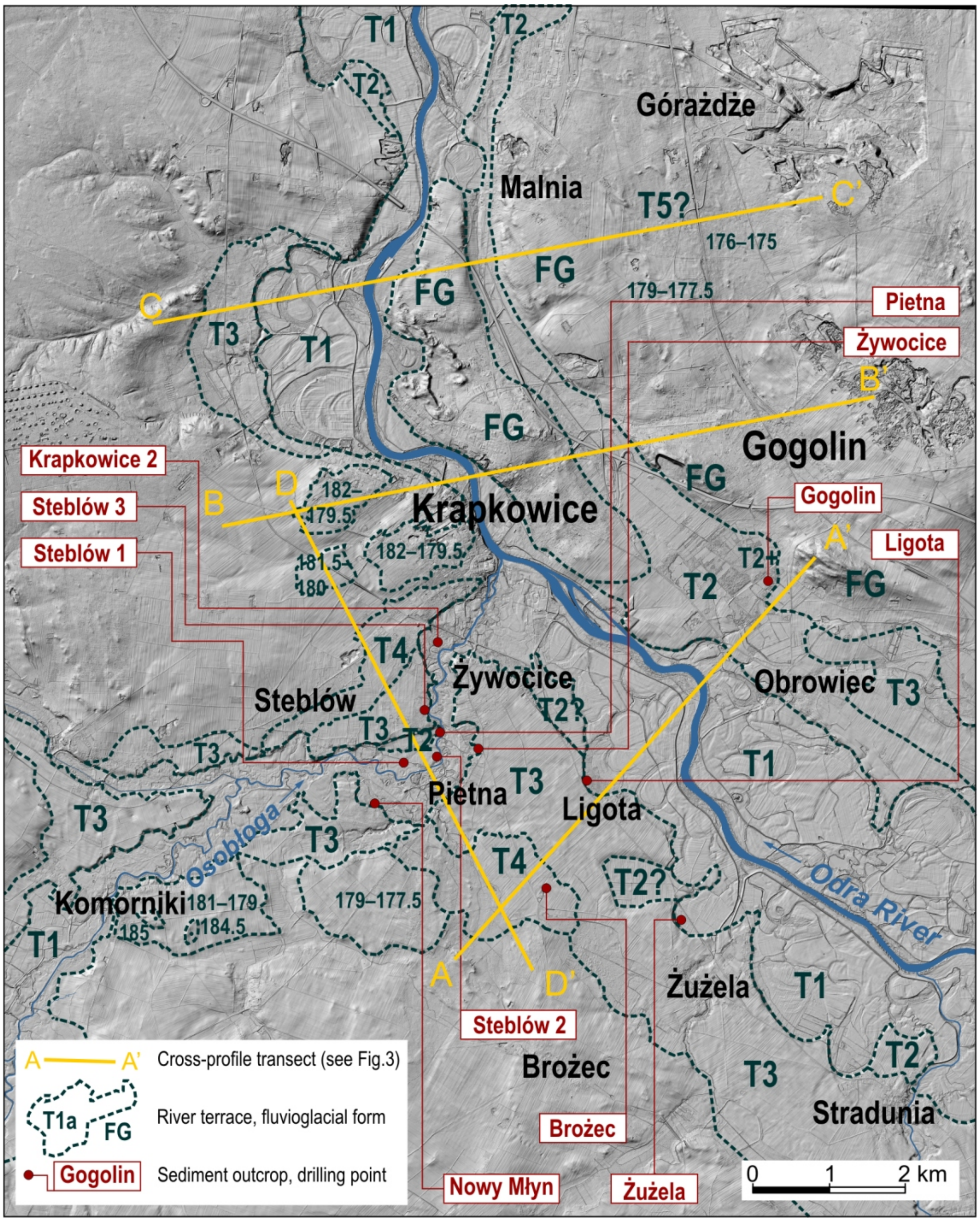

Fig. 2. Shaded relief map of the Odra River Gorge near Krapkowice

DEPOSITS OF THE PLEISTOCENE ODRA AND OSOBŁOGA TERRACES NEAR KRAPKOWICE

T4 TERRACE

Sediment analysis was carried out for the Brożec locality: 50°26'10.6"N, 17°58'47.7"E (see Fig. 2). The analysis was of a section 2 m high (Fig. 4). In its lower section, there is a monostructural lithofacies succession consisting of sandy gravel, gravelly sand and coarse-grained sand (C = 8.5–63.7 mm), which is characterized by trough cross-bedding (GSt, SGt, St; Fig. 5A). The gravels in the Brożec exposure are petrographically diverse and include, among other components, clasts of Fennoscandian rocks. In the upper section of the profile, there is coarse massive sand (Sm), (C = 1.62–1.83 mm), which was modified post-depositionally by soil-forming processes. Illuviation is shown by the presence of the SFm lithofacies above the placic horizon, at a depth of <1 m.

The sandy and gravelly lithofacies succession which exhibits trough cross-bedding (GSt, SGt, St) and is present in the lower part of the section represents a deep channel sediment deposited under conditions of rapid flow during high water stage. Sedimentation took place under conditions of recurring

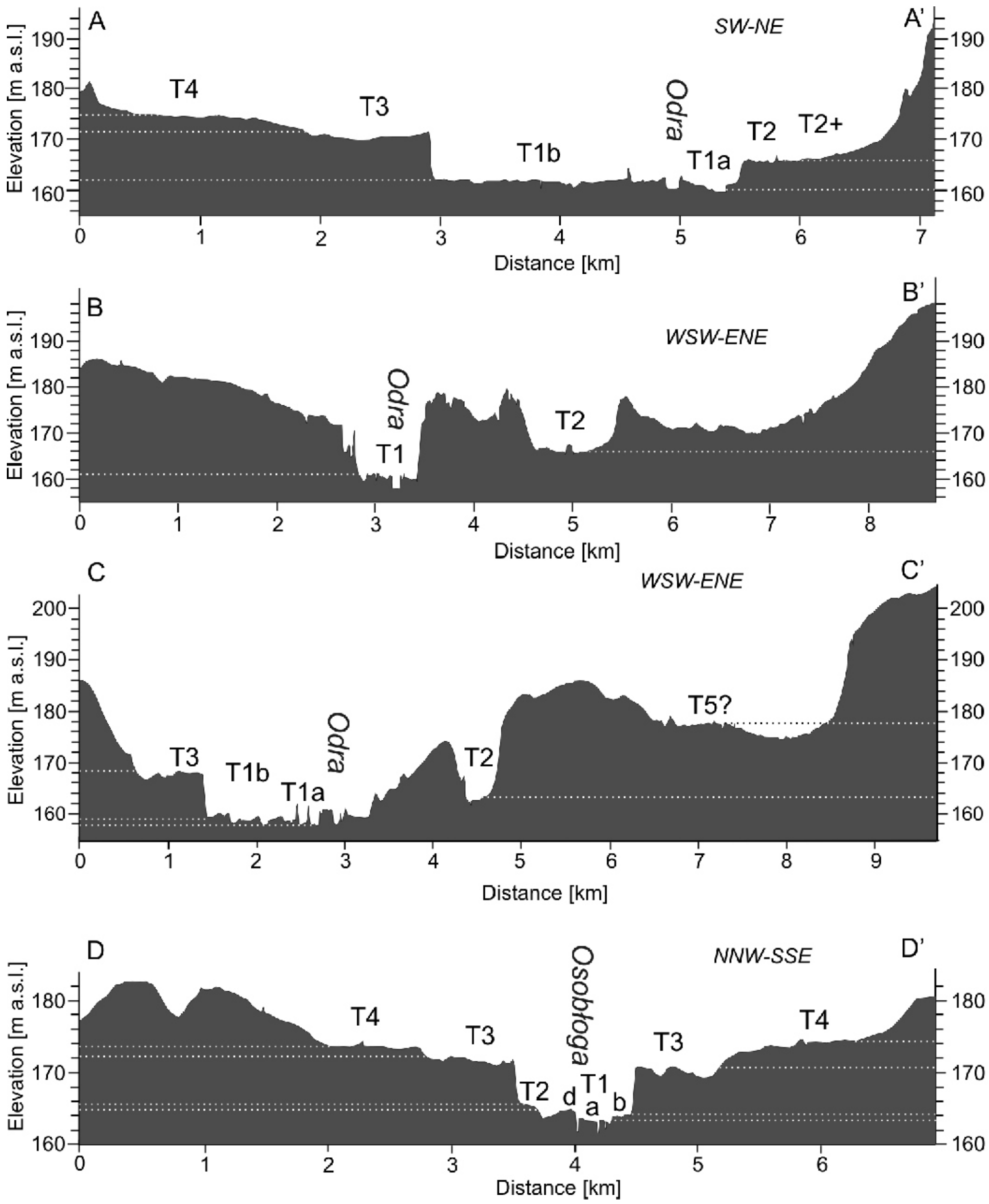

Fig. 3. Cross-profiles of the Odra and Osobłoga valleys (for location of the profiles see Fig. 2)

bottom transport and local erosion that led to the formation of troughs which were subsequently filled with cross-bedded sediment. As a result of these processes, dunes formed at the bottom of the channel. As deposition took place, smaller clasts were selectively removed (negative SkI values). The massive sand (Sm) found in the upper part of the section probably reflects rapid shallow flow under upper plane bed conditions, and also deposition from near-bottom suspension. Better sorted alluvia ($_{I}$ = 1–2.37) most probably accumulated on the slope of the upper bar section during floods which exceeded average water stage. The positive skewness of their grain size distributions suggests that flow became progressively weaker during sedimentation. The presence of a clear, two-part alluvial cycle with normal fractional grain size distribution resembles the sequences typical of meandering rivers with sandy beds (see Zieliński, 2015). The presence of a meandering river is also indicated by the presence of a deep channel, which determines the emergence of dunes.

T3 TERRACE

Sediment analysis was carried out for the Steblów 3 exposure: 50°27'27.0"N, 17°57'27.5"E (see Fig. 2). The analysis concerned a section 6.1 m high (Fig. 6). Two sedimentary successions were identified in this profile, separated at a depth of 1.9 m by a clear erosion surface and imbricated lag deposits. The bottom succession is dominated by sand which exhibits horizontal bedding and low-angle cross-bedding (Sh, Sl), (Fig. 5D). Additionally, lithofacies of horizontally bedded gravelly sand (SGh), massive mud (Fm) and muddy sand with flaser bedding (SFf) are present (Fig. 5E). Within these deposits, deformation load structures (load casts, flame) occur (Fig. 5C). Petrographic analysis demonstrated that this succession only contains monomineral quartz gravel (Wójcicki et al., 2018). The upper succession consists of massive gravels (Gm), sandy gravels (GSm) and horizontally bedded sands (Sh). Within this succession, there is a scour hole (up to 30 cm deep) filled with

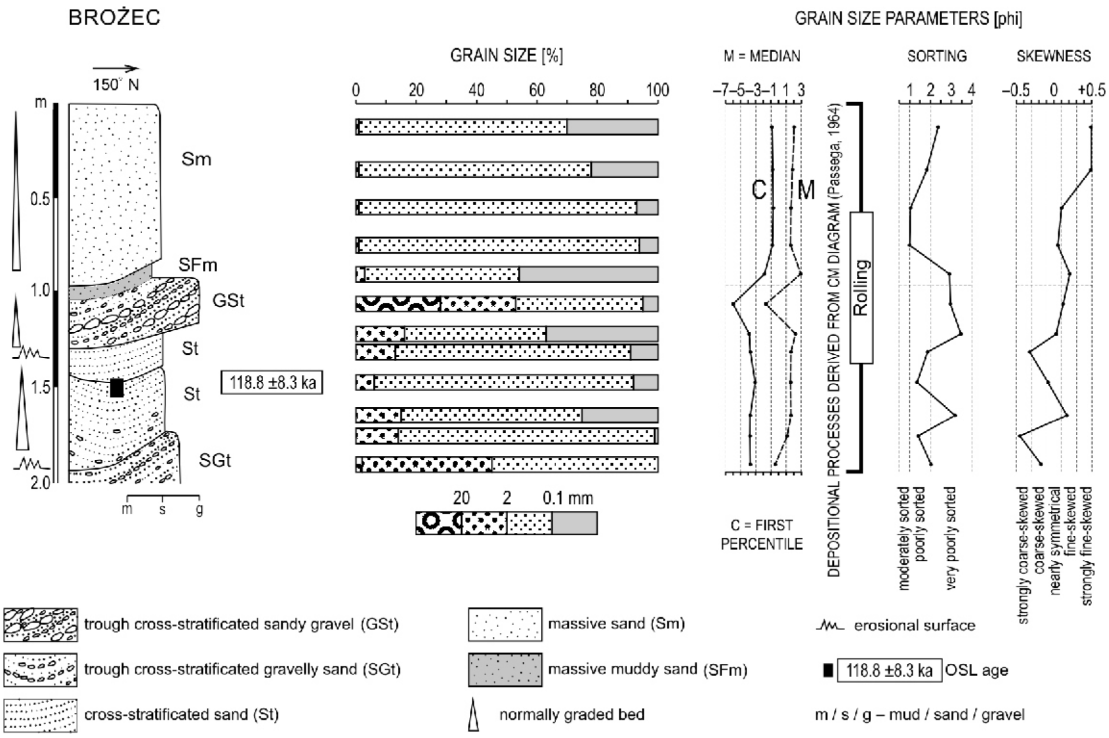

Fig. 4. The deposits of the T4 terrace, Brożec site

gravel and sandy gravel which exhibits flat cross-bedding (Gp, GSp), (Fig. 5B). The gravel present in this succession has a varied petrographic composition, which includes Fennoscandian rocks (Wójcicki et al., 2018).

The lower succession was formed in changing lithodynamic conditions (Mz –0.45–7.1 phi), under a supercritical flow regime (upper plane bed – lithofacies Sh, SGh) and also during transition from the lower to the upper regime (lithofacies Sl). During periods of weaker current, finer material was deposited. Thin insets of fine sand and massive mud (Sh, SFf, Fm) reflect inhibition of flow and the slow deposition of fine suspensions from still water (C = 0.37–0.85; M = 0.002–0.005 mm). Muddy sand with flaser bedding (SFf) was the result of successive periods of weak flow and water stagnation (see Martin, 2000). This succession probably represents shallow-bed alluvia, and shallow beds are typical of braided rivers in which aggradation is strong. This is indicated by the presence of the Sh, SGm and Sl lithofacies which are present in the form of thin shoals (see Zieliński, 2015). Fine-grained layers (Sh/Fm) formed under stagnant flow conditions during low water stages are also often found in the alluvia of shallow, aggrading braided rivers (e.g., Therrien, 2006). The deformation structures (load casts, flame) present in these deposits are considered to be typical for strongly aggrading sedimentation in shallow braided rivers (Tunbridge, 1981). The petrographic composition of the gravel (monomineral quartz gravel) indicates the deposition of sediment which was previously subject to long-term chemical weathering (Wójcicki et al., 2018).

The upper succession (lithofacies Gm, GSm, Sh) was formed in high-energy flow conditions in a gravel-bedded river, probably within an interbar channel. This is indicated by the succession of gravelly and sandy sediments, the presence of an erosion surface with lag deposits and the presence of a scour hole filled with gravel (Gp). The formation of lag deposits is considered to be typical of intense re-deposition of alluvia in interbar channels, most frequently in the rising flood phase (Zieliński, 2015). Scour holes/large-scale troughs are eroded during the maximum water stage, often in the zone where two interbar channels meet and subsequently, as the flood wave recedes, they are filled with material which is transported near the bottom (Salter, 1993). The petrographic composition of the gravel (the presence of Fennoscandian rocks) reflects the fluvial redeposition of glacigenic sediments.

T2 TERRACE

Sediment analysis was carried out for the Pietna locality: 50°27'17.5"N, 17°57'35.8"E (see Fig. 2). The analysis concerned a profile with a thickness of 2 m (Fig. 7). Here, tabular lithosomes are present with a thickness of up to 80 cm. In the lower section of the profile, there is massive sand (Sm) and massive sandy gravel (GSm) with thin interbeds of coarse sand (Mz = from –0.81 to –2.97 phi; C = 48.38–69.68 mm at a depth of 1.0–1.8 m). In the upper section of the profile, there is coarse massive sand (Sm) with dispersed gravel (C = 8.92–14.04 mm). The structure of this deposit was obliterated during the development of brown soil epipedons. The gravels in the Pietna exposure are petrographically diverse and include, among other components, clasts of Fennoscandian rocks.

These deposits were formed in a high-energy environment, under conditions of variable and relatively shallow flow – upper plane bed. Periodically, the transport became less dynamic (sandy layer at a depth of 1.0–0.8 m), but gravel is present even in the upper section of the succession. These features indicate the environment of a braided river, traces of whose palaeochannels can be seen on the surface of the terrace. The enrichment of sandy-gravelly deposits with finer fractions at a depth of up to 0.6 m is interpreted as the effect of near-surface weathering which accompanied soil-forming processes.

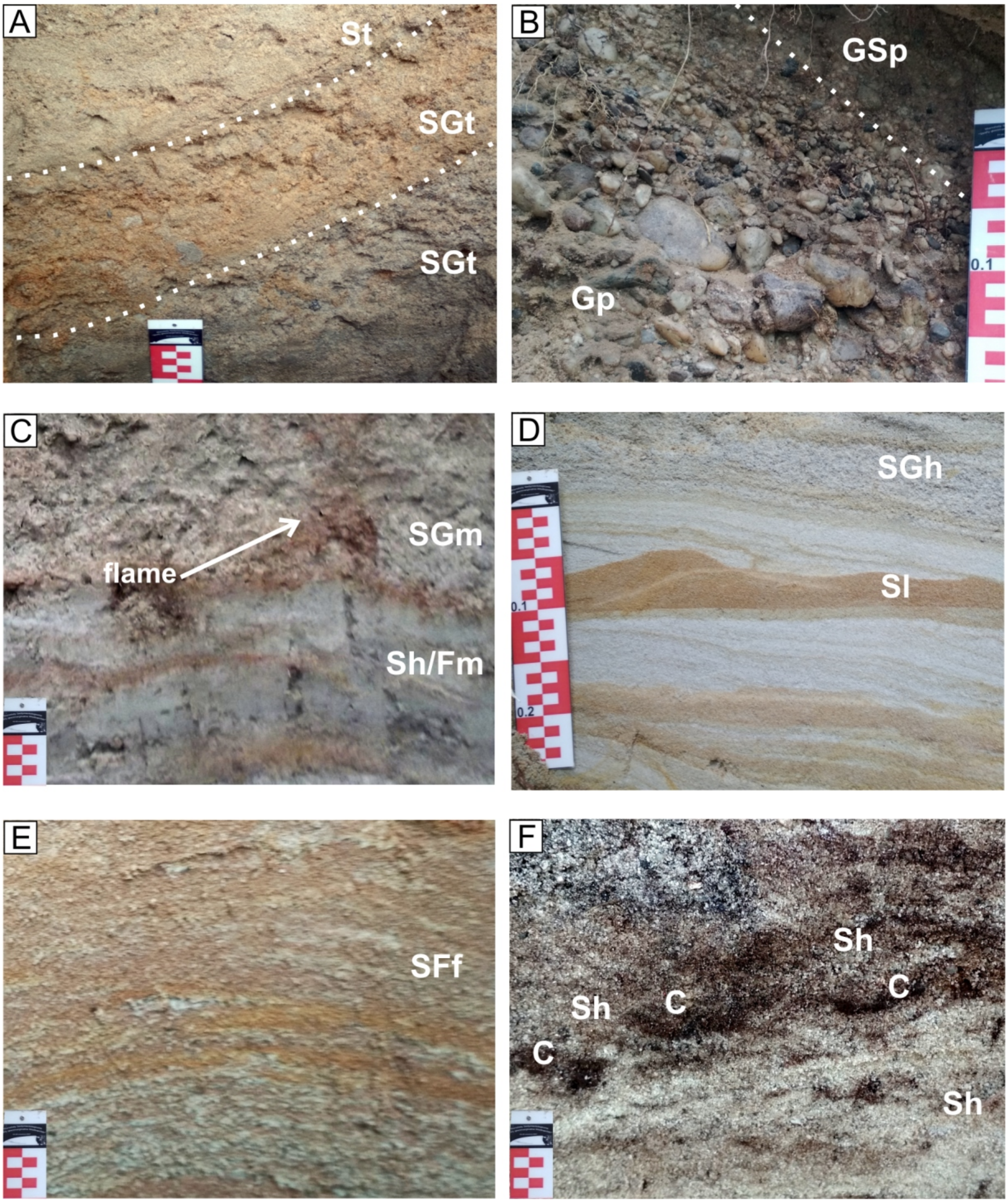

Fig. 5. Examples of lithofacies

A – lithofacies succession with trough cross-bedding (SGt, St); **B** – cross-bedded gravel (Gp, Gsp) filling the scour hole; **C** – flame-type deformation structures; **D** – sand lithofacies with low-angle cross-bedding (Sl); **E** – muddy sand with flaser bedding (SFf); **F** – deposits comprising peat fragments (C) and sand with horizontal bedding (Sh)

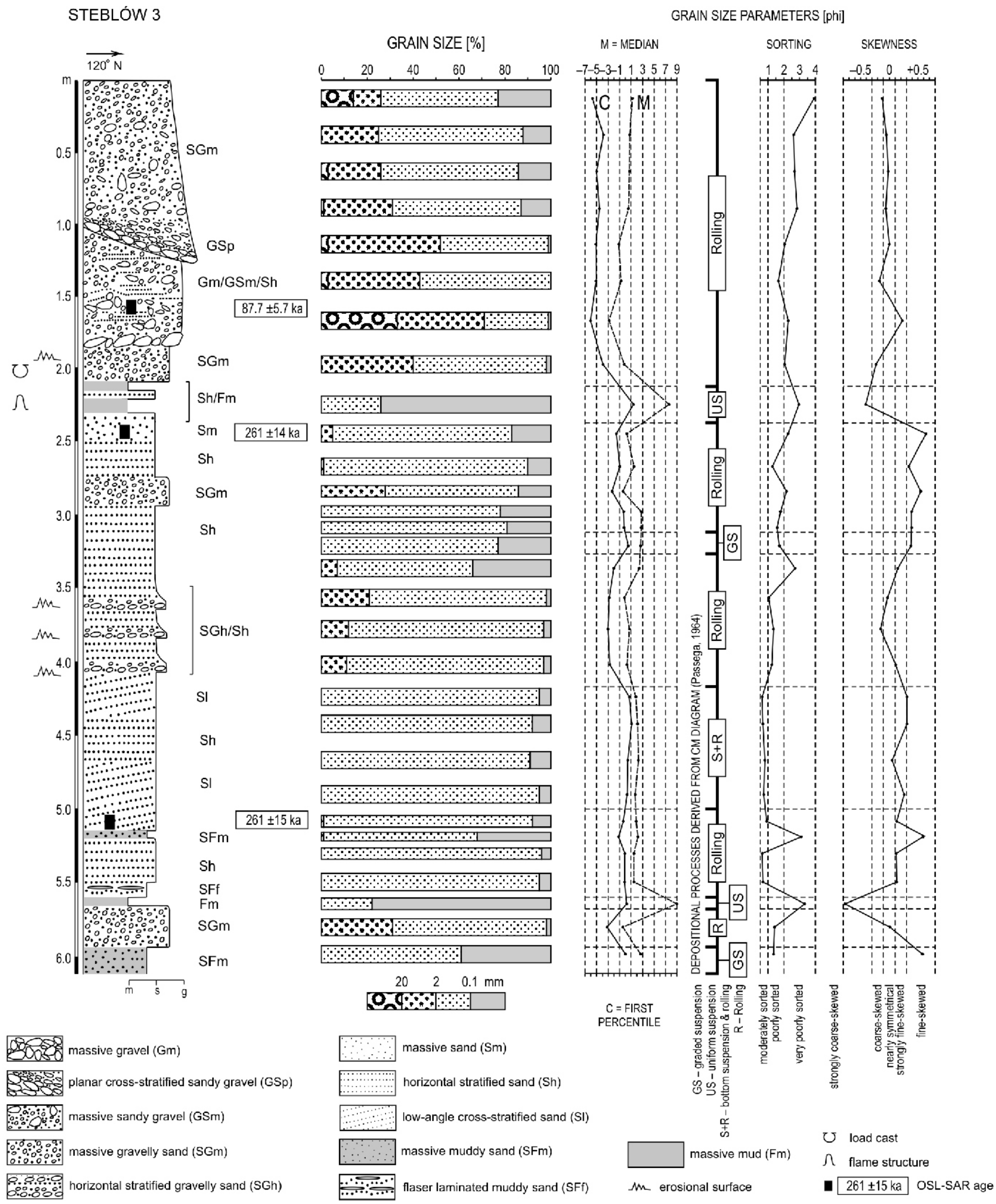

Fig. 6. The deposits of the T3 terrace, Steblów 3 site

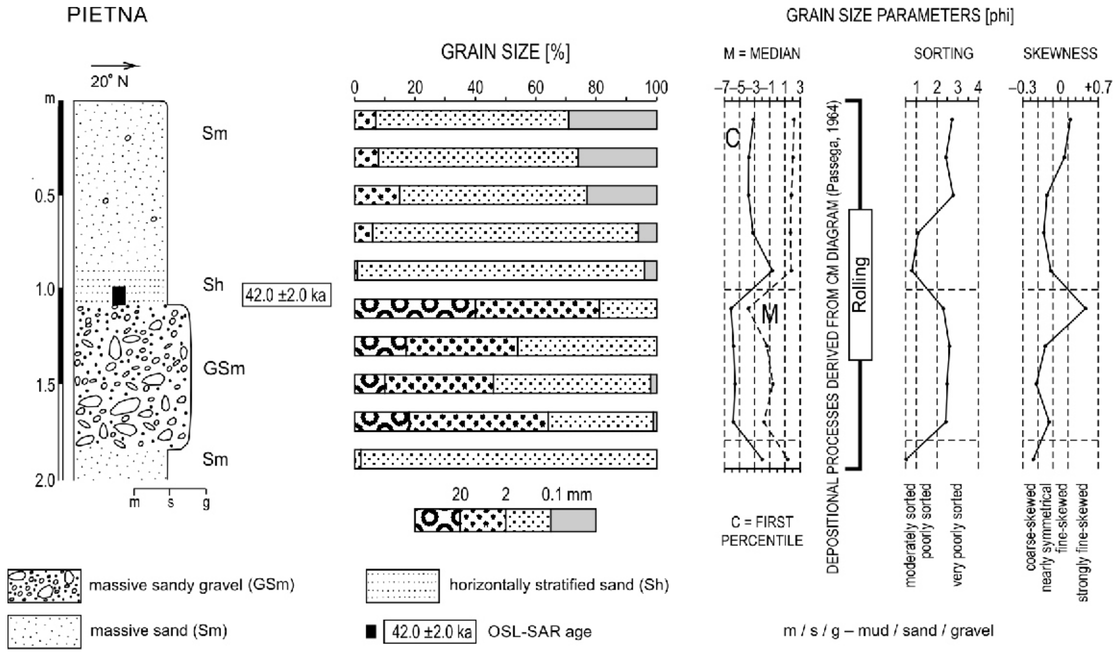

Fig. 7. The deposits of the T2 terrace: Pietna site

T2+ MORPHOLOGICAL LEVEL

Sediment analysis was carried out for the Gogolin locality: 50°28'21.9"N, 18°01'17.0"E (see Fig. 2). The analysis concerned a section 2 m high (Fig. 8). Here, clastic and organic deposits are present (in the upper part of the section). At a depth of >1.0 m, there is sand with a few pebbles, with a massive structure (Sm). Above, there is a tabular lithofacies composed of horizontally bedded sand (Sh). Normal fractional grain size distribution is visible in places. The layers are inclined at an angle of ~4° towards the SW. This gradient is in line with the local slope gradient in this area. Clastic deposits within the Gogolin profile are characterized by a relatively good sorting ($_1$ usually <1.0) and in many cases by the negative skewness of their grain size distribution. The organic component (C) comprises strongly decomposed peat in which there have been preserved the following: (1) at a depth of 0.42–0.30 m – mainly brown mosses and *Sphagnum* sp. as well as *Phragmites australis* remains (Bryalo-Parvocaricioni peat); (2) at a depth of 0.30–0.18 m – mainly bark (wood peat); (3) at a depth of 0.18–0 m – mainly small sedge roots (Magnocaricioni peat). In the transitional layer between clastic and organic deposits (at a depth of ~0.5 m), angular lumps of peat and horizontally bedded sand (Sh) are present (Fig. 5F).

The massive sand lithofacies (Sm) is probably a channel sediment deposited under conditions of rapid shallow flow. The horizontally bedded sand lithofacies (Sh), consisting of layers inclined downslope, is the result of slope-related sheetwash/sheet flood deposits. The Odra River valley near Gogolin was filled with peat as a result of paludification (without bioindicators of an aquatic environment). Initially, the mire was dominated by sedge-moss fens on which no forest grew. During the forest phase of mire development, processes of sand supply from the slope were halted. In the youngest phase, which was most probably connected with man-made deforestation in a similar fashion to that at adjacent sites (Wójcicki and Marynowski, 2012), denudation processes intensified again. During its development, the mire was subject to periodical drying, which led to recession of peat. The presence of peat and sand (Sh/C) in one layer reflects the fragmentation of the deposit with the formation of desiccation cracks.

DEPOSITIONAL AGE

The dating of Pleistocene morphological levels was based on direct age determinations of the deposits using the OSL method. The age of deposits in the Brożec exposure (see Fig. 4), which was determined at 118.8 ±8.3 ka (Table 1), indicates that the T4 level can most probably be associated with the Eemian Interglacial (MIS 5e) or possibly the Herning Stadial (MIS 5d) at the beginning of the Vistulian. The oldest deposits were found in the Steblów 3 exposure, where they were dated at 261 ±15 ka and 261 ±14 ka at depths of ~560 cm and 240 cm, respectively (see Fig. 6). Thus, these can be associated with the maximum stadial of the Odranian Glaciation = Drenthe glacial stage (MIS 8). In the postglacial interval, these deposits were incised and overlain by younger alluvia due to lateral erosion of the riverbed. The T3 level alluvia, which are separated by a clear erosion surface, were dated to 87.7 ±5.7 ka. In the light of this, they originate from the Early Vistulian, most likely from a period correlated with the Rederstall Stadial (MIS 5b) or the beginnings of the Odderade Interstadial (MIS 5a; Wohlfarth, 2013). The age of T2 terrace deposits in the Pietna exposure was determined at 42.0 ±2.0 ka (see Fig. 7), and thus they were most probably deposited in the Middle Plenivistulian, in an interval correlated with the Hasselo Stadial between the Moershoofd (~46–44 ka) and Hengelo Interstadials (~39–36 ka). The age of clastic deposits in the Gogolin exposure was determined at 21.5 ±1.5 ka (see Fig. 8) and this indicates that they may be of MIS 2 age, which corresponds to the maximum extent of the Vistulian ice sheet (Leszno/Poznań phase).

In the case of the flood terrace, age determinations are based on ^{14}C dating of organic deposits accumulated in oxbow lakes. Therefore, the river channel alluvia associated with them should be considered older. The palaeochannel situated within

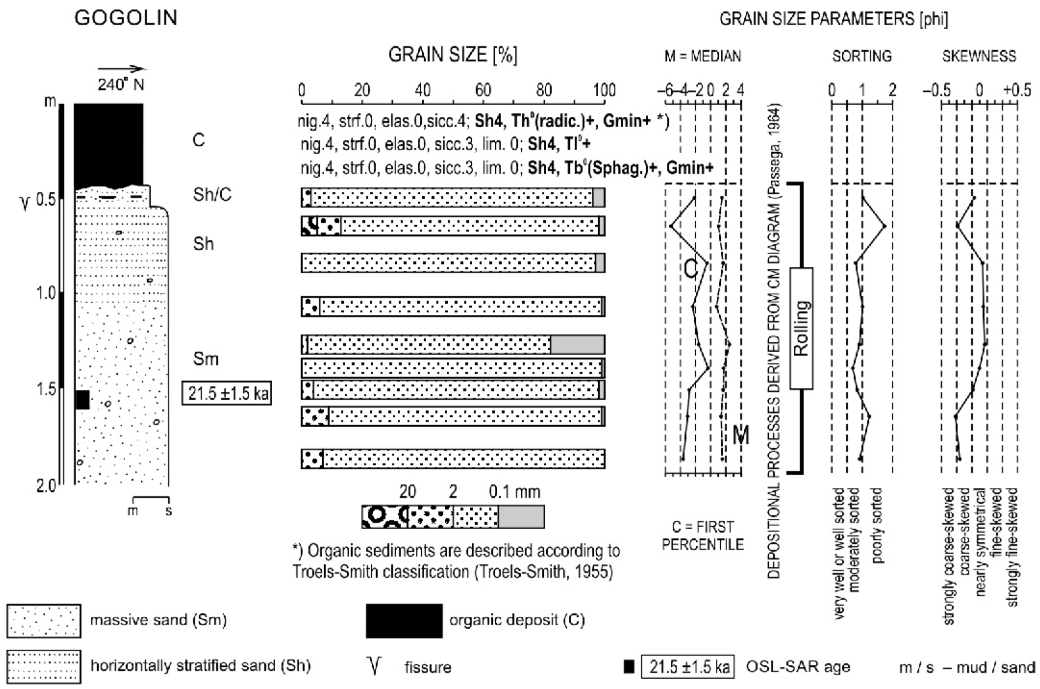

Fig. 8. The deposits of the T2+ morphological level: Gogolin site

the highest part of the floor of the Osobłoga Valley (T1d level) is filled with deposits whose organic contents in the lower part of the section have been radiocarbon dated (Table 2) to the beginnings of the Allerød (Wójcicki and Marynowski, 2012). The large palaeomeander in the Żywocice area (T1c level) probably originates from the Late Vistulian/Holocene. The surface of the terraces of the T1b-a inset levels within the Osobłoga River flood plain is related to late Holocene palaeomeanders (Klimek, 2002; Wójcicki and Marynowski, 2012). The two palaeomeanders associated with the T1b level in the Odra River valley near Krapkowice originate from the Middle Holocene (Wójcicki et al., 2010).

EVOLUTION AND DRIVERS OF FLUVIAL AGGRADATION AND DEGRADATION OF THE ODRA AND OSOBŁOGA RIVERS IN THE LAST GLACIAL-INTERGLACIAL CYCLE

The overall structure of the terrace sequence along the Odra and Osobłoga rivers in the Krapkowice area indicates that the evolution of the lower Osobłoga valley was closely related to trends appearing in the Odra valley. The impact of the local erosion base is observed up to 10 km upstream of the Osobłoga River mouth. As a result, a uniform fan-terrace complex of the Odra and the lower Osobłoga rivers evolved in this area in the late Quaternary.

The results of dating (261 ±15 ka and 261 ±14 ka) of alluvia within the Osobłoga River terrace outcrop south of the town of Krapkowice indicate that the valley was subject to strong aggradation during the maximum stadial of the Middle Polish Glaciation (Odranian = Drenthe glacial stage = MIS 8). The succession of monomineral (quartz) sediments deposited at that time, which does not contain any admixtures of Fennoscandian rock clasts, additionally suggests that this could have taken place in the anaglacial phase of that glaciation. In the light of sedimentological analyses, the marked raising of the valley floor was the work of a braided river, which was overloaded with debris and had a shallow channel which was prone to avulsion. At that time, an extensive alluvial fan formed at the mouth of the Osobłoga River in the place where it enters the Odra River valley. This probably occurred when the outflow of extraglacial waters in the northern direction was inhibited by the overthrusting Odranian ice sheet. The aggradation of the surface of the fan-terrace complex of the Odra and Osobłoga rivers in the Krapkowice area may have reached a maximum elevation of 179.5–182 m a.s.l. The altitude of the Odra/Osobłoga valley bottom was raised by not less than 14 m in relation to the layer dated to 261 ±15 ka in the Steblów 3 exposure. Floodplain aggradation can be favoured by glacioisostatic downpressing (see Krzyszkowski et al., 2019). Evidence of the rivers' strong reaction to the close proximity of the ice sheet front has been provided, *inter alia*, by the studies conducted in the Prosna River valley, which demonstrated that when the ice sheet stopped, rapid aggradation occurred and during its recession, intense erosion followed (Rotnicki, 1987). However, the impact of fluctuations of the erosion base on fluvial erosion and accumulation in the Prosna River valley completely waned after ~150 km. Study results from the Warta River valley in the Uniejów Basin indicate that the influence of the ice sheet on fluvial processes was already significantly reduced at a distance of 30 km from the ice sheet front (Petera, 2002). Therefore, it cannot be ruled out that the dating of the rapid aggradation phase in the Odra River valley simultaneously indicates the age of the Odranian ice sheet overthrust.

In the post-glacial interval, a prolonged tendency to river incision was initiated. It is possible that this was related to inversion in vertical crustal movement under the influence of glacial isostatic adjustment (see Bridgland and Westaway, 2014; Krzyszkowski et al., 2019). The elevation of the valley bottoms was reduced by at least 5 m from the end of deglaciation to the Eemian Interglacial. A poorly preserved morphological level (terrace T5?) at 179.5–177.5 m a.s.l. shows that a fluvial phase with equally balanced erosion and accumulation was active dur-

Table 1

Radioisotope concentrations with final dose rate and OSL dating of Pleistocene morphological levels in the Odra and Osobłoga valleys

Laboratory code	Outcrop	Sampling depth [cm]	Th [Bq/kg]	U [Bq/kg]	K Bq/kg]	Dose rate [Gy/ka]	OSL Age [ka]
GdTL-3130	Gogolin	155	6.1 ±0.1	5.1 ±0.1	236 ±6	1.01 ±0.04	21.5 ±1.5
GdTL-3133	Pietna	110	14.2 ±0.2	10.1 ±0.2	266 ±7	1.31 ±0.05	42.0 ±2.0
GdTL-3134	Brożec	170	7.1 ±0.2	5.1 ±0.1	232 ±6	1.01 ±0.04	118.8 ±8.3
GdTL-2820	Steblów 3	150	7.4 ±0.2	5.1 ±0.1	236 ±6	1.01 ±0.04	87.7 ±5.7
GdTL-3131	Steblów 3	240	13.4 ±0.2	10.0 ±0.2	200 ±6	1.08 ±0.04	261 ±14
GdTL-3132	Steblów 3	560	12.0 ±0.2	8.1 ±0.2	265 ±7	1.17 ±0.05	261 ±15

ing this period. It may perhaps be correlated with the climatic deterioration of the Wartanian Stadial (MIS 6).

In the light of the studies conducted, all the better-preserved morphological levels of fluvial origin (levels <174.5 m a.s.l.) were formed in the post-Wartanian interval (Fig. 9). The dating of T4 terrace deposits suggests that this level was most probably formed in the Eemian Interglacial. This is indirectly supported by geomorphological arguments and lithological analyses which suggest that the terrace was formed by a meandering river. The transition from the Eemian interglacial to the Vistulian was not marked by any rapid changes in the fluvial environment (Petera, 2002). Studies of the middle terrace of the Vistula River valley in Kraków indicate that meandering rivers may have continued to function in southern Poland when boreal coniferous forests dominated during the Early Vistulian interstadials (Sokołowski et al., 2014). During the Brørup Interstadial, forest growth limited the activity of denudation processes and intensified the deepening of riverbeds in the Carpathians and the Sub-Carpathian basins (Starkel, 1980).

The results of dating the alluvia present in the T3 terrace suggest that the surface of the fan-terrace complex was dissected from ~174.5 m a.s.l. to 172 m a.s.l. before the period correlated with the Rederstall Stadial (MIS 5b). The structural and textural characteristics of the alluvia dated to 87.7 ±5.7 ka indicate (GdTL-2820) that they accumulated in a cool climate, in the high-energy environment of a braided river. This could have been caused by the rapidly deteriorating climatic conditions. According to the chronology based on oxygen isotope measurements in deep-sea deposits, that glacial substage peaked at 87 ka (Lisiecki and Raymo, 2005). As a result of this cooling, shrub tundra appeared in Poland with extensive areas occupied by herbaceous plants with steppe elements (Mamakowa, 1989). At the same time, multiannual permafrost emerged in the Polish lowlands for the first time in the Vistulian (Kozarski et al., 1980). Evidence of its presence have also been found in the Odra River area, in outcrops of the T3 terrace in the Januszkowice village near the town of Zdzieszowice (Czerwiński, 1968). As a result, the river channel system may have been transformed and braided rivers may have appeared at that time, as documented by Superson (1996) in the Wieprz River catchment. In the Odra and Osobłoga River valleys, fluvial processes developed on a large scale, as T3 is the most extensive Pleistocene terrace in the Upper Odra River valley. Taking into account the large extent of this terrace, it should be assumed that its development was

Table 2

Results of ^{14}C dating of the deposits filling the Odra and Osobłoga rivers palaeochannels

Laboratory code	Core Location	Sampling depth [cm]	Dated material	Conventional ^{14}C age [yr BP]	95.4% cal age (Median age) [cal yr BP]
Ki-7162	Nowy Młyn Osobłoga v. – T1d	114–120	mainly tree detritus; periderm and wood remains	11780 120	13940–13360 (13610)
Ki-7163	Żywocice Osobłoga v. – T1c	195–200	mainly tree detritus, remains of *Phragmites australis* and *Carex* sp.	10200 ±75	12350–11410 (11890)
Ki-13088	Ligota Odra valley – T1b	216–224	mainly tree detritus, remains of *Nymphaeaceae* and *P. australis*	6420 ±80	7470–7170 (7350)
Ki-14899	Żużela Odra valley – T1b	233–237	mainly tree detritus, remains of aquatic plants and *P. australis*	6340 ±80	7430–7030 (7270)
Ki-15888	Steblów 1 Osobłoga v. – T1ba	230–235	mainly aquatic plant debris, remains of *Carex* sp. and *P. australis*	3540 ±60	3980–3640 (3820)
Ki-15880	Steblów 2 Osobłoga v. – T1ba	138–142	mainly brown moss, remains of *Carex* sp. and *P. australis*	2040 ±90	2310–1820 (2010)
Ki-7160	Krapkowice 2 Osobłoga v. – T1a	146–150	mainly tree detritus	1920 50	1990–1730 (1870)

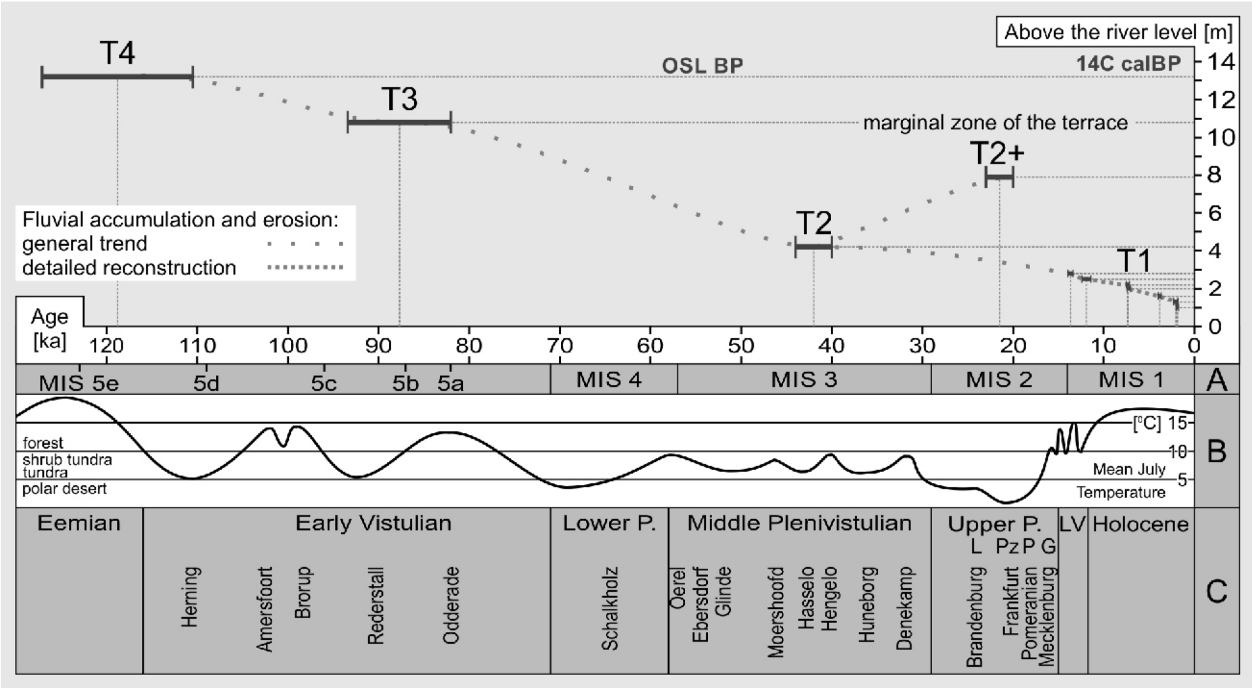

Fig. 9. Changes in the elevation of river terraces of the Odra and Osobłoga rivers in the last glacial-interglacial cycle

A – marine isotope stages (MIS) according to Lisiecki and Raymo (2005); **B** – temperature curve according to Roman et al. (2014); **C** – stratigraphy of the last glacial stage in Poland and its correlation with Western Europe according to Marks et al. (2016): Lower P. – Lower Plenivistulian; Upper P. – Upper Plenivistulian; L – Leszno; Pz – Poznań, P – Pomeranian; G – Gardno; LV – Late Vistulian

associated with the long-term vertical stabilisation of the valley floor. However, no aggradation followed and the alluvial cycle of the braided river at the Steblów 3 site is <2 m thick.

After a period of valley floor stabilisation, which was at least partly associated with the Rederstall Stadial (MIS 5b), a long-term trend towards erosion emerged in the vicinity of Krapkowice, which essentially consisted in the sediments being removed without the valleys being extended in a lateral direction. Between the end of the Early Vistulian and the Middle Plenivistulian, the surface of the flood plain moved downwards by ~6 m – from 172 to 166 m a.s.l. It should be stressed that the development direction of fluvial processes in the Lower and Middle Plenivistulian was ambiguous. The results obtained in the Odra River valley are consistent with the observations from central Poland, where in many valleys a trend towards erosion was observed from the end of the Early Vistulian through the Early and also partly Middle Plenivistulian (Petera, 2002). On the other hand, some fluvial systems have been identified where a trend to aggradation prevailed, as in the Wieprz River catchment at the end of the Early and at the beginning of the Middle Plenivistulian (Superson, 1996). In the vicinity of Krapkowice, vertical stabilisation of the floor of the Odra River valley occurred and the T2 terrace developed in the Middle Plenivistulian (MIS 3) ~42.0 ±2.0 ka (GdTL-3133), i.e. in the period correlated with the Hasselo Stadial. The lithological characteristics of the alluvia indicate that they were deposited in a cold climate (no organic intercalations are present), in the highly energetic environment of a braided river (whose traces have been preserved on the surface of the T2 terrace below Steblów). This trend of fluvial processes was probably favoured by climate deterioration. At that time, forest areas in southern Poland were replaced by tundra communities with steppe and photophilous vegetation (Środoń, 1972). Much evidence points to the development of permafrost – traces of its presence were recorded within the T2 terrace both in the suburbs of the city of Opole (Jahn and Piasecki, 1952) and in Obrowiec village, where the fissure structures present were considered synsedimentary (Czerwiński, 1968). In the Sub-Carpathian basins, this period was marked by the predominance of aggradation (Gębica, 2004), while the most significant erosion phase took place before the maximum extent of the Vistulian ice sheet (Starkel et al., 2007; Gębica et al., 2015).

When the ice sheet in the Polish Lowlands reached its maximum extent, the upper Odra River catchment was located in the Arctic-Alpine vegetation zone with tundra and steppe vegetation admixtures (Środoń, 1972). In the river valleys of the Carpathian foreland, braided rivers functioned between 23 and 15 ka (Gębica, 2004; Starkel et al., 2007; Gębica et al., 2015). However, in the light of the analysis of the sedimentary succession from the Pietna site, there was no aggradation of the Osobłoga River valley floor during the Vistulian climatic minimum. Only marginal fragments of the Odra River depression along the Obrowiec–Malnia line were supplemented by sandy sediments dated to 21.5 ±1.5 ka (GdTL-3130), which were redeposited from the slope. The mechanism by which surfaces of this type were formed was identified with respect to deposits of the Middle Plenivistulian in the river valleys of central Poland (see Turkowska, 1988). The sediments were delivered from the valley slopes as a result of transverse processes (sheetwash), and only then could they be redeposited as a result of longitudinal fluvial processes. The conditions for the development of transverse processes were the presence of slopes with a sufficient gradient, which at the same time could supply the sediments deposited in the valley (Petera, 2002). Owing to these conditions, the aggradation of the Odra River valley in the Upper Plenivistulian only had a local dimension. In the depression of the Plenivistulian drainage route of the Odra River, as a result of paludification, a mire developed whose individual development phases are probably associated with the Holocene. In the youngest phase, which was most probably related to anthropogenic deforestation (see Wójcicki and Marynowski, 2012), slope processes intensified again.

Along with the retreat of the ice sheet from the current territory of Poland, lateral erosion accelerated in the valleys of the Odra and Osobłoga rivers, which resulted in the reduction in lateral extent of the T2 terrace. As a result, in many reaches the flood plain now borders directly on the edge of the T3 terrace. In the light of radiocarbon dating results, a sinuous river appeared in the Osobłoga River valley no later than at the beginning of the Allerød. Despite the spread of forest cover in the Late Vistulian and in the Holocene, valley floor degradation processes continued. In Allerød–Mid-Atlantic times it is estimated that the incision rate of the Odra and Osobłoga river channels was ~0.96 mm/year. In the Mid-Atlantic–Older Subatlantic times (1st century CE), the average channel incision rate accelerated to ~1.85 mm/year, most likely due to the deforestation and economic development of the river valleys studied (Wójcicki and Marynowski, 2012).

CONCLUSIONS

1. Large-scale aggradation of the Odra and Osobłoga River valleys near the town of Krapkowice occurred during the anaglacial phase of the Odranian Glaciation (MIS 8). The lithological characteristics and similar dating results of samples representing an alluvial succession >3 m in thickness (261 ±15 and 261 ±14 ka) suggest that the vertical growth of sediments was rapid, most probably due to the outflow being inhibited by an overthrusting ice sheet.

2. In the Late Pleistocene and in the Holocene, alluvia removal processes dominated, interrupted by periods of vertical stabilisation dated to ~118.8 ±8.3, 87.7 ±5.7 and 42.0 ±2.0 ka. Even during the climatic minimum of the Upper Plenivistulian, no widespread trends towards aggradation were identified in the T2 terrace, except for its marginal fragments being supplemented by transverse processes (occurring on valley slopes) dated to 21.5 ±1.5 ka. In this context, there are no reasons for pointing to Late Quaternary climatic fluctuations as the main factor determining the course of fluvial processes in the Odra and Osobłoga River valleys. Rather, the results obtained indicate that the main driver of the development of the fluvial system analysed was erosion which compensated for the effects of large-scale aggradation during the Odranian ice sheet transgression.

3. The study results appear to support the relationship between climatic conditions and the channel development pattern. In the light of dating results, it can be concluded that during the colder periods correlated with the Rederstall Stadial (MIS 5b) and with the Hasselo Stadial (MIS 3), a high-energy braided river system was present in the river valleys examined, which was most probably accompanied by permafrost. During the Eemian Interglacial (MIS 5e), during Late Vistulian interstadials and in the Holocene (MIS 1), the flood plain was shaped by a meandering river.

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