Geomorphology 108 (2009) 58–70

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Alluvial fans as an effect of long-term man–landscape interactions and moist climatic conditions: A case study from the Glubczyce Plateau, SW Poland

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ARTICLE INFO

Article history:
Accepted 15 August 2007
Available online 5 February 2009

Keywords:
Alluvial fans
Deforestation
Prehistoric settlement
Land-use changes
Sudeten
Poland

ABSTRACT

At the mouth of periodically drained valleys in the loess Glubczyce Plateau (SW Poland), favorable conditions for deposition of alluvial fan sediments occur, so these forms are very common in the investigated area. The origin of the forms analyzed is related to long-term human–landscape interactions, because deforestation and land-use changes started in the Neolithic, ca. 5.5 ka BC, causing intensification of soil erosion processes. Willful and continuous interference by man into natural environment began at that time. Thus, human impact is responsible for acceleration of runoff and mobilization of sediment which formed alluvial fans at the mouths of episodically drained valleys. The objectives of this study are (1) to measure the morphological and topographical characteristics of the fans, (2) to describe and analyze the inner structures of the alluvial fans analyzed and (3) to date the alluvial fan deposition.

The alluvial fans are mainly formed of silty–clayey massive sediments. The gravel–sand layers occurring in two exposures indicate the incision of the valleys in the older Pleistocene sediments underlying the loess upland deposits and intensive phases of erosion in the course of which coarser material could have been transported.

Radiocarbon dating of the peat filling the bottoms of the valleys and underlying the mineral deposits of the fans indicates that sediment transfer from cultivated valley slopes and its deposition at the mouth of the valleys was recorded in alluvial fan sediments by the Neolithic (6895 ± 140 BP). During this period, erosion was probably intensified by a moister climate. Radiocarbon dating of organic layers, which were discovered inside the sediments of two fans, show that the youngest dated stage of intensified erosion took place in Early Medieval Times, when the Glubczyce Plateau was colonized again by Slavs after the “settlement depression” during the Migration Period.

1. Introduction

Alluvial fan deposits form part of fluvial sediment cascades and are widely researched to record changes in sedimentation and catchment condition. Numerous studies are concerned with inner structure, morphology and hydrology of alluvial fans (e.g., Blissenbach, 1954; Rachocki, 1981; Harvey, 1988; Blair and McPherson, 1992; Calvache et al., 1997; Blair and McPherson, 1998). To date, the majority of investigations of alluvial fans were conducted in mountain and fore-mountain areas, where forms built of coarse-grained sediments, often derived partly from debris flows, were analyzed (Bull, 1977; Brazier, 1987; Chamyal et al., 1997; Gómez-Villar and Garcia-Ruiz, 1997; Sorriso-Valvo et al., 1998; Harvey et al., 1999a; Webb et al., 1999; Gómez-Villar and Garcia-Ruiz, 2000; Anderson et al., 2000; Zanchetta et al., 2004). It is assumed that particularly four factors control the evolution of alluvial fans: intrinsic controls (e.g., Patton and Schumm, 1975; Scott and Erskine, 1994), changes of base level (Miall, 1992; Harvey et al., 1999a), climatic variations (Wasson, 1977; Starkel, 1991; Chamyal et al., 1997; Harvey et al., 1999b; Larue, 2002), land use changes (Teisseyre, 1995; Coulthard, 2001; Coulthard et al., 2002; Larue, 2002; Klimek, 2003; Zygmunt, 2004; De Moor and Verstraeten, 2008), or the relative roles of climate or human activities (Ballantyne, 1991; Chiverrell et al., 2007, 2008).

It seems as if alluvial fans received particular attention where they form distinctive landforms. However, more subdued alluvial fans in low-relief settings and humid regions carry a similar potential for the study of past environmental change (e.g., Faulkner, 2002; Chiverrell et al., 2007; De Moor and Verstraeten, 2008; Panin et al., 2009-this issue). This holds true especially for the study of longer-term human impact on catchment condition and fan development because settlement activities often have been concentrated in humid basinal and piedmont areas. In Poland, the Glubczyce Plateau (upper Odra basin, Fig. 1) provides such a suitable study area because it has been one the most attractive agricultural areas for millennia owing to its favorable soil and climatic conditions. Here, long-term human–landscape interactions resulted in the nearly complete clearing of pristine forests. Prehistoric settlement concentrated mainly on the edges of

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doi:10.1016/j.geomorph.2007.08.021

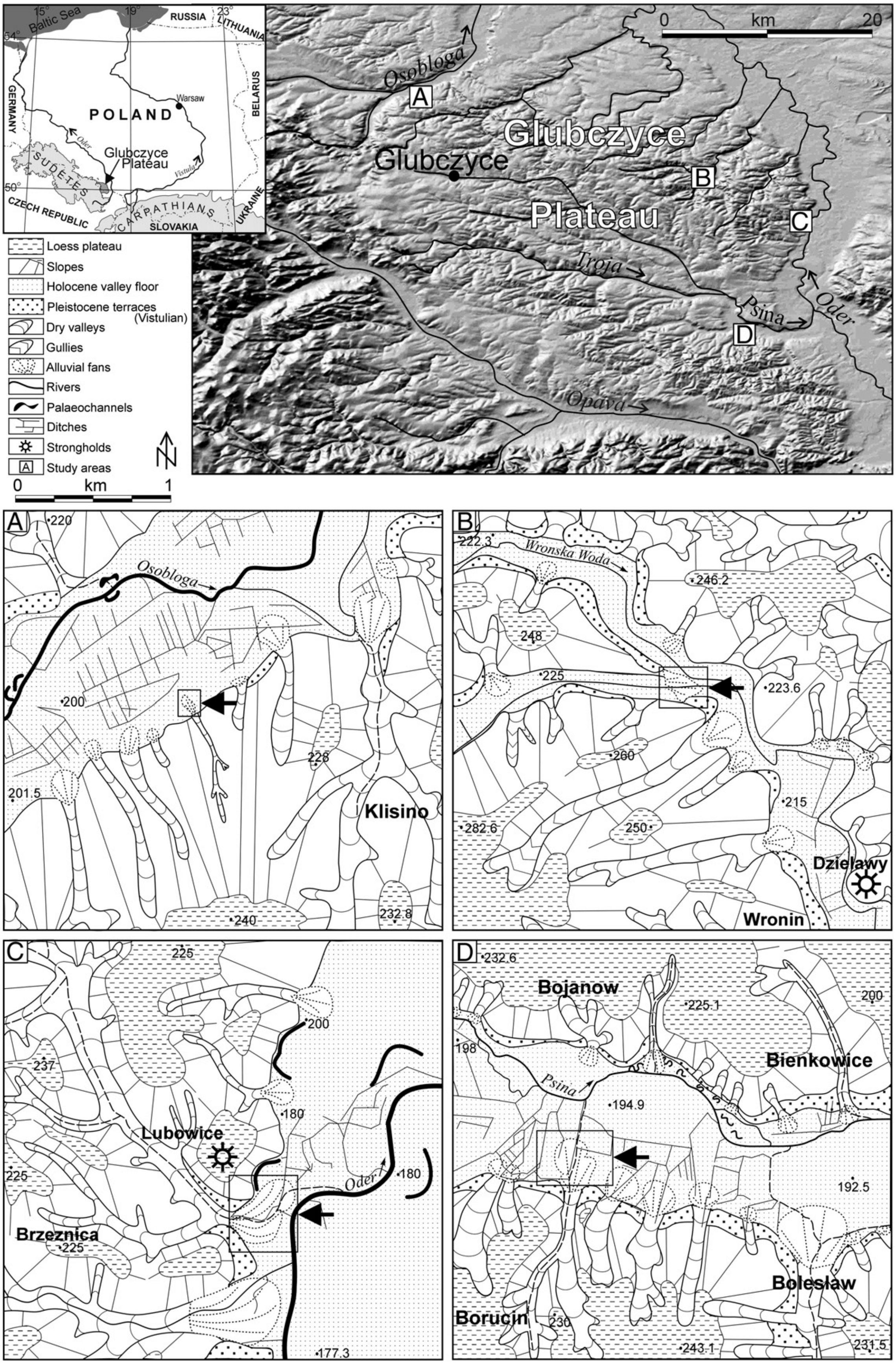

Fig. 1. Location and geomorphological maps of the study areas (A— Klisino, B— Wronin, C— Lubowice, D— Borucin).

river terraces, in subslope zones and close to main and side river valleys. This ensured constant access to water and protection against the wind. The removal of the forest cover affected the stability of valley slopes resulting in intensified soil erosion, particularly during heavy rainfall and snow-melt floods. The material eroded from deforested, cultivated slopes was transported to valley floors and then partly deposited at valley mouths in the form of alluvial fans. In this study the reconstruction of landscape evolution is attempted on the basis of small alluvial fans deposited at the mouth of four small valleys in the loess Glubczyce Plateau, south-western Poland (Figs. 1, 2). Periods of variable fan evolution are compared to the timing of colonization and variable land-use intensity in the surveyed catchments as well as to climate change during the Holocene.

2. Study area

The research was carried out on the loess Glubczyce Plateau (520 km^2) in the Upper Odra Basin (Fig. 1). The study area is delimited to the south and west by the Eastern Sudeten Mountains and the Carpathians. In the east and the north, it borders on the Silesian Upland.

The area under review lies within the Silesian–Moravian structure consisting of Precambrian and Paleozoic rocks (Stupnicka, 1989). In the south-western part of the plateau, there is a zone formed by Lower Carboniferous sedimentary flysch rocks (graywackes, sandstones and mudstones). In the remaining part of the area, Tertiary sediments of the Sudeten Foreland and the Carpathian Depression (mainly Miocene clay) are found. The bedrock is covered by Vistulian loess.

The Glubczyce Plateau is an undulating denudation plain, dissected by erosion in numerous places. It gently descends from the Sudeten foothills towards the east and northeast, from 320 m a.s.l. to 220 m a.s.l. The area is largely drained by river systems flowing into the Osobloga, Psina and Troja rivers which flow parallel to the edge of the Sudeten Mountains towards the east and northeast, and by the systems that flow directly into the Odra. The plateau is dissected in many places by episodically drained valleys, which accounts for its hilly relief. At some places, relief reaches 40 to 50 m. In subslope zones, alluvial fans accumulating on dry valley floors are common (Zygmunt, 2004). The modern topography of this region is largely the result of erosion and denudation transformations of the area formed during the Middle Polish glaciation (Riss) and influenced by the bedrock structure (Gilewska, 1999). The present morphology of the plateau is the result of processes that occurred mainly during the Pleistocene and Holocene. During the North Polish glaciation (Würm), the Glubczyce Plateau lay in the periglacial zone where severe conditions prevailed. In this period, a loess cover up to 9 m thick was formed as a result of aeolian dust deposition (Jersak, 1991).

The average rainfall in the area ranges from 600 to 700 mm, of which 200 to 250 mm occur in the winter half-year and 350 to 450 mm in the summer half-year. Most rainfall is recorded in July (100 to 120 mm in the northern part of the area and 80 to 100 mm in its southern part). The least precipitation occurs in January (30 mm). As in other areas of Poland, rivers in this region are characterized by a nivo-pluvial regime. The highest water stages are observed in early spring (snow-melt floods) and in summer, when they are caused by torrential rains.

Owing to the loess cover, local soils are among the most valued agricultural lands in Poland. In the loess parent material, Chernozems as well as brown earths and loessive soils developed. The Chernozems are now largely degraded. In the bottoms of smaller and larger river valleys, alluvial soils formed (Bednarek and Prusinkiewicz, 1999). On postglacial sediment and Carboniferous outcrops where the loess cover was stripped, pseudo-podzolic and rusty soils can be found. In some areas, regosols of limited agricultural value prevail, which are usually covered by forests. However, due to favorable soil conditions this region has very few forests and is mostly agricultural. Both cereals and root plants are cultivated here: primarily wheat, sugar beet, rape and barley. The length of the frost-free period is around 260 days.

The expansion of agriculture varied in space and time so that the scale and tempo of long-term human–landscape interactions is different in various regions of Poland. One of the first colonized Polish areas by Neolithic farmers was the Glubczyce Plateau (SW Poland) as it attracted the prehistoric tribes to settle there and utilize the land (Kulczycka-Leciejewiczowa, 2004). One of the attractive factors was the good soil developed upon the loess and loess-like sediments. Because of the dense network of surface streams, this area also had a good water supply. Very crucial to choosing the Glubczyce Plateau was the close proximity to the Moravian Gate (tectonic depression between The Sudeten Mountains and The Carpathians) which was used by Neolithic communities moving to the north. Very careful choice of the settlement sites and cultivated areas is evidence of the knowledge of the early tribes about the natural environment. Because of deforestation and changes of terrain utilization by the Neolithic agricultural tribes in the Atlantic Period (ca. 6–5 ka BC), intensification

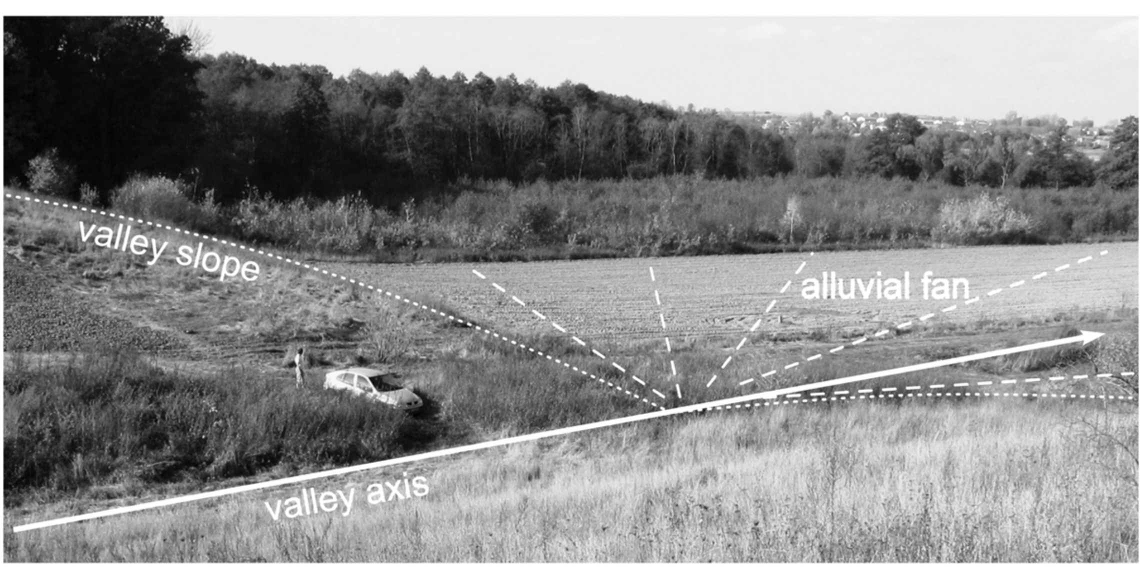

Fig. 2. The example of the Klisino alluvial fan (cf., Fig. 5) which was deposited at the mouth of episodically drained valley on the loess Glubczyce Plateau.

of the erosional processes began. Since that time intentional and continuous interference of humans with the natural environment began. The Neolithic tribes were able to establish their permanent settlements and cultivate areas adjoining the occupied territories, leading to the degradation of the environment. A decrease of soil infiltration capacities by human activity caused a significant increase of sheet flow and acceleration of slope dissection and soil erosion. These processes were exceptionally intense on the loess areas of the Glubczyce Plateau so that the current relief of the area is partly the result of its anthropogenic transformation, started in the Neolithic times. Eroded material from deforested and cultivated slopes of the valleys was deposited in the bottoms of the small valleys, and partly at their mouths as alluvial fans. Thus, the inner structure of the fans contains an important record of landscape evolution which was controlled by agro-colonization of the loess plateau. However, anthropogenic denudation cannot be analyzed without regard to Holocene climatic changes. The periods of wetter climate, or heavy rainfall episodes and intensive snow melts, could have intensified the effects of human-induced erosion. The research conducted in the loess areas shows that a single storm is able to deposit sediment layers several centimeters in thickness (Fig. 3).

3. Materials and methods

To map alluvial fan landforms morphometric field-note taking and precise leveling were carried out. Backhoe trenches and augering (mechanized bucket auger, peat auger for retrieving sediment or peat cores, respectively) served to study the internal sedimentary structures and the stratigraphic context of underlying bedrock or floodplain deposits (Fig. 4; see Fig. 5 for locations). Lithostratigraphic recording followed the lithofacial coding of Miall (1978) and Zielinski (1998). Here, lithofacies letters "I" (silts) and "L" (clays) were added in order to adapt to subdued lithologic differences in a largely fine-grained depositional environment (for a conceptual background cf. Houben, 2007). Geophysical resistivity measurements using multi-electrode equipment (Lund Imaging System®; Dalin, 1996) were performed to estimate the thickness of peat underlying minerogenic alluvial deposits. These measurements were used to trace changes of physical parameters occurring in shallow layers (up to 10 m). Samples collected during the field work were subjected to laboratory analyses. In the case of mineral samples, grain-size analyses (by the sieve and aerometric methods using a hydrometer) were performed.

The chronostratigraphy of depositional events was established by combining lithostratigraphy and radiometric data. To extract suitable dating materials and thus preclude age offset effect because of 'old' carbon, plant macrofossils of organic samples were determined at the Museum of Silesia in Katowice, Poland. Radiometric dating by the ^{14}C method was performed at the Kyiv Radiocarbon Laboratory, Ukraine. For interpretation and comparison with other temporal information, radiocarbon ages were calibrated using INTCAL04 (Reimer et al., 2004; Fairbanks et al., 2005). Calibrated calendar dates are given as BC/AD. Deriving a chronology of alluvial fan deposits with radiocarbon dating of interbedded or underlying organic matter, however, further requires paying attention to the specific sample age-context relations. In brief, radiocarbon measurements yield a *terminus ante quem* age of a stratum underlying the radiocarbon-sampled layer, but a *terminus post quem* age of the sampled or overlying stratum (e.g., Bowman, 1990). These issues have recently been discussed by Chiverrell et al. (2007) who take particular account of radiocarbon-derived chronostratigraphic evidence of alluvial fan deposition. The stratigraphy of fan development can be compared to archeological data on settlement and farming periods on the Glubczyce Plateau. Archeological information was provided by local archeologists and 1:25,000 AZP maps (Archeologiczne Zdjecie Polski – Archeological Photographs of Poland). These maps contain information about artifacts found during surface research and excavations. Thus, the palaeogeographic

Fig. 3. Sediment layer with a thickness of 9 cm deposited during one rainstorm in July 2004 (research site: Borucin).

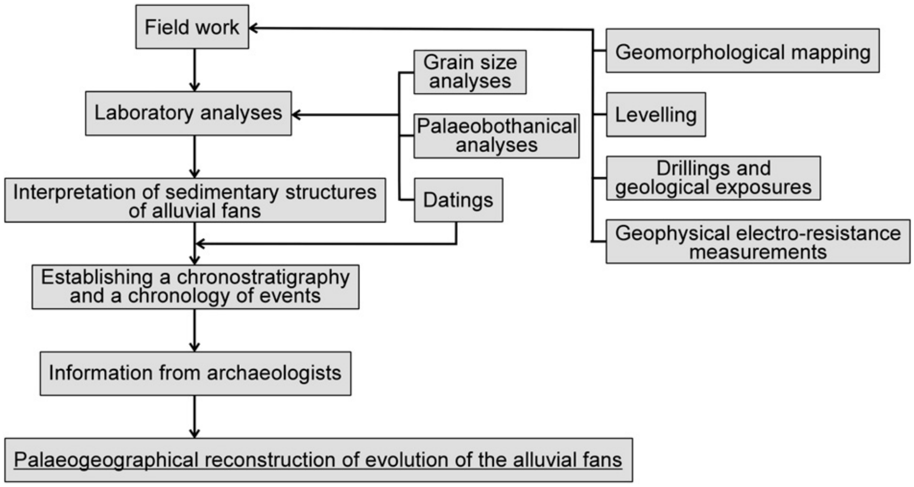

Fig. 4. Scheme of the research methods which were used to analyze the alluvial fans.

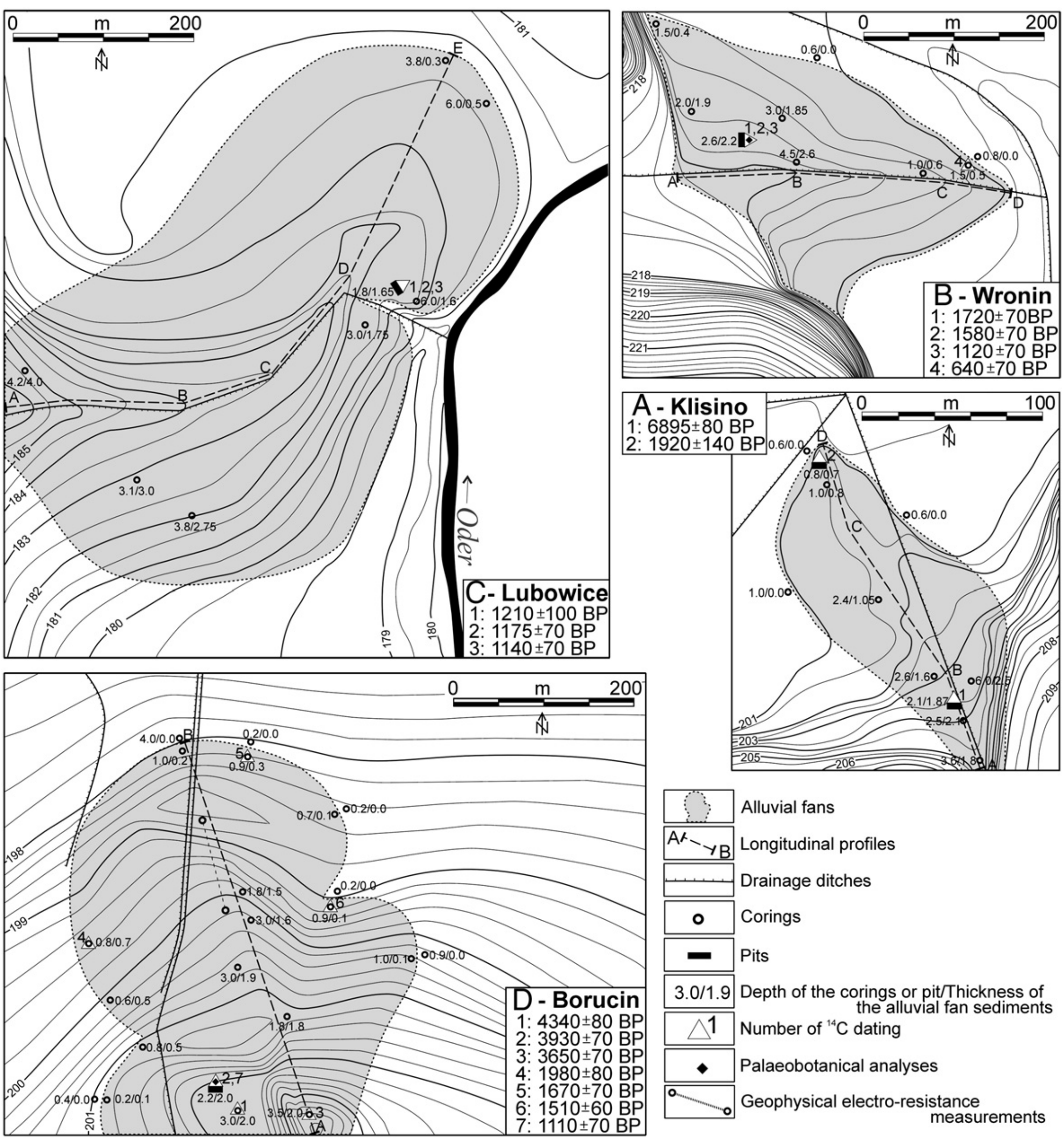

Fig. 5. Location of field researches within the alluvial fans.

Table 1
Morphological and topographical characteristics of the alluvial fans and their drainage basins.

Study area		A: Klisino	B: Wronin	C: Lubowice	D: Borucin
Catchment area [km^2]		0.32	9.39	5.95	3.01
Alluvial fan area [km^2]		0.012	0.061	0.180	0.130
Fan/catchment area [%]		3.75	0.65	3.03	4.94
Valley gradient [m/m]		0.0334	0.0046	0.0132	0.0167
Alluvial fan gradient [m/m]	Complete	0.0202 (100%)	0.0041 (100%)	0.0086 (100%)	0.0128 (100%)
	Proximal part	0.0348 (172%)	0.0033 (80.49%)	0.0110 (127.91%)	0.0181 (141.41%)
	Medial part	0.0136 (63.33%)	0.0037 (90.24%)	0.0069 (80.23%)	0.0105 (82.03%)
	Distal part	0.0121 (59.90%)	0.0053 (129.27%)	0.0079 (91.86%)	0.0098 (76.56%)
Length of the valley [km]		0.86	7.50	4.00	3.39
Length of the alluvial fan [km]		0.196	0.406	0.735	0.457
Maximal width of the valley [km]		0.38	2.00	1.80	1.30
Maximal width of the alluvial fan [km]		0.11	0.37	0.40	0.39
Capacity of the alluvial fan [m^3]		13 271	86 304	405 143	191 706
Density of the valley network [m/km^2]		4 375	3 662	3 086	4 527

reconstruction of alluvial fan evolution is based on a synthesis of sedimentological and archeological data.

4. Results

4.1. Morphological and topographical characteristics of the fans

The analyzed fans occupy surface areas from 0.012 km^2 (research site Klisino) to 0.18 km^2 (research site Lubowice), and their drainage areas range from 0.32 km^2 (research site Klisino) to 9.39 km^2 (research site Wronin; Table 1). The drainage areas are elongated and rather symmetrical (Fig. 6). Valley lengths range from 0.86 km (research site Klisino) to 7.5 km (research site Wronin) and their gradients range from 0.0046 m/m (research site Wronin) to 0.0334 m/m (research site Klisino). The fan at Klisino exhibits the highest gradient (0.0202 m/m) despite the fact that it has the smallest area and volume. The lowest gradients were observed on the Wronin fan. The gradients of the fans reach maximum values in their proximal parts (Klisino: 0.0348 m/m, Borucin: 0.0181 m/m, Lubowice: 0.0110 m/m; Fig. 7). The Wronin fan is an exception since its gradient is highest in its distal part (0.0053 m/m). Fan area is an indirect indicator of volume. Catchment area has no significant impact on fan size and volume. On the other hand, the density of the river network within individual catchments affects morphometric properties. Where episodically drained valleys

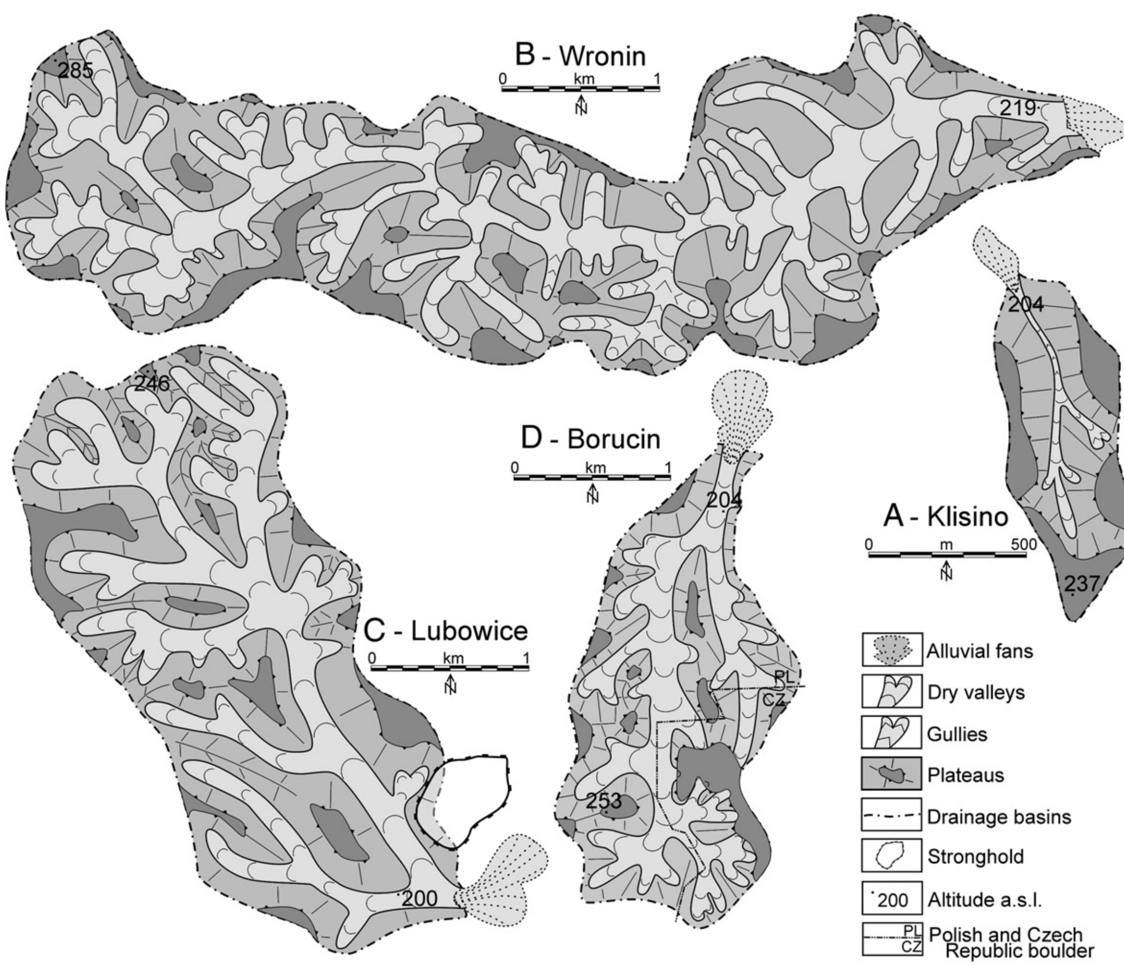

Fig. 6. Morphological map of the drainage basins of the analyzed alluvial fans.

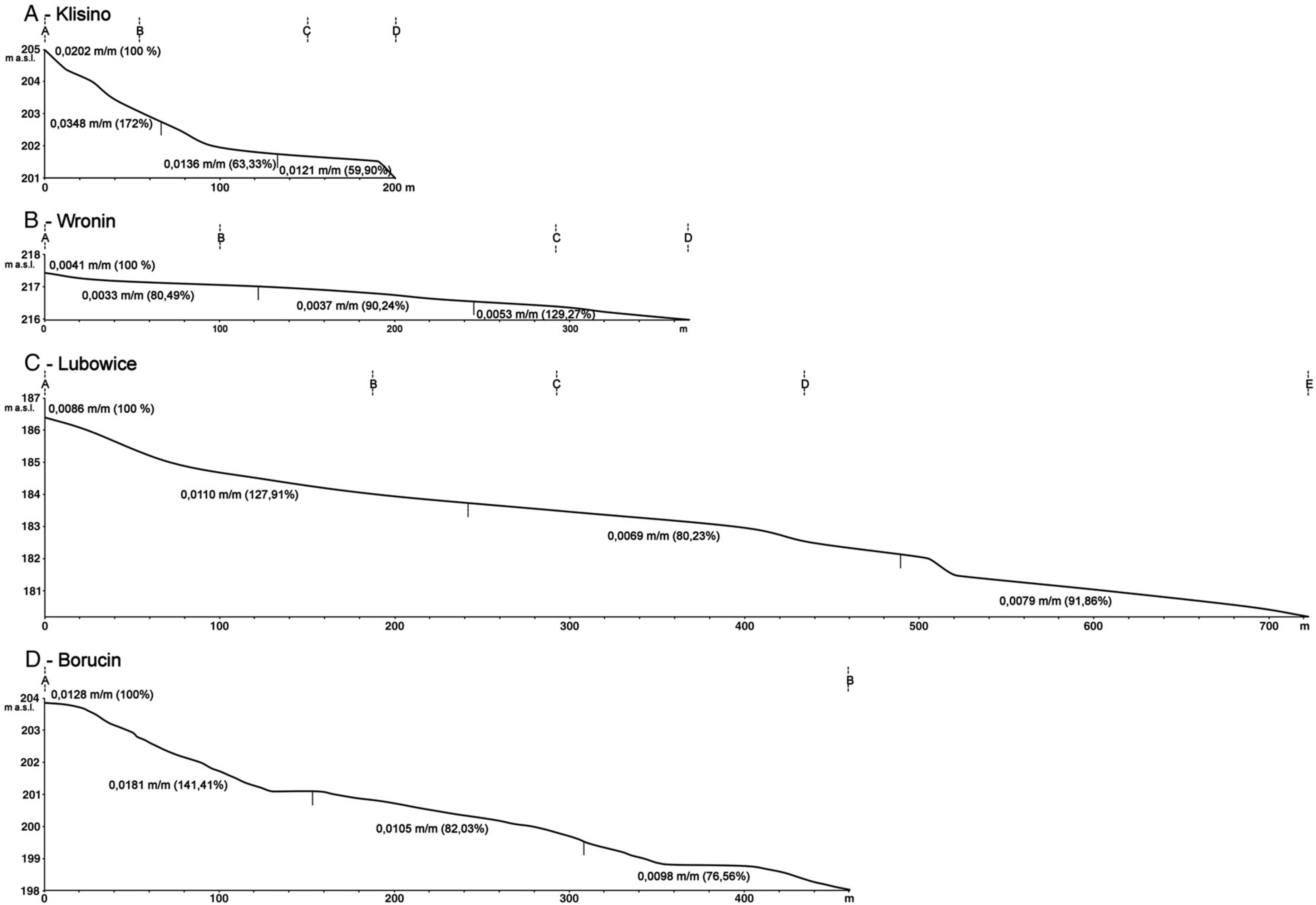

Fig. 7. Longitudinal profiles of the fans and their gradients.

are denser, "internal fans" form at the mouths of smaller tributary valleys. Therefore, a significant amount of eroded sediment is retained within the catchment. Conversely, less dense river networks supply sediments to main valleys at higher rates and create larger alluvial fans. For example, the fan at Lubowice, where the valley network within the catchment is the least dense (3086 m/km^2), exhibits the largest volume (405,143 m^3) and the second largest area (0.18 km^2; Table 1).

4.2. Inner structures of the alluvial fan sediments

4.2.1. Klisino fan

Palaeobotanical analyses of peat, which underlies the mineral sediments of the fan in Klisino, showed that the Osobloga valley was colonized by typical plants connected with meadow swamps (*Carex*) before fan formation started. The typical backswamp peat found here is known as Bryalo–Parvicaricioni (Zygmunt, 2007). The Klisino fan is the least thick and thickness of the alluvial fan sediments decreases to the NW. The fan is formed mainly by fine-grained sediments (Fig. 8A) and organic matter content ranges from 2.6% to 3.7%. The sedimentary structure shows five horizontal layers varying in grain size and color. In the lowermost layer 10 cm of dark-gray, massive silty-sandy clays occur. Directly above this layer there are 20–25 cm of massive sandy–clayey silts. Textural and structural features of these sediments indicate very low energy conditions. Above these sediments two layers of laminated clayey-sandy silts are visible which are 40 and 30 cm thick. These layers have the same granulometric fabric but colors are different. The lower sediments are more rust-white in color and have more oxidized rootlets. The color of upper layers becomes grayer and darker with depth. In these layers, isolated charcoal

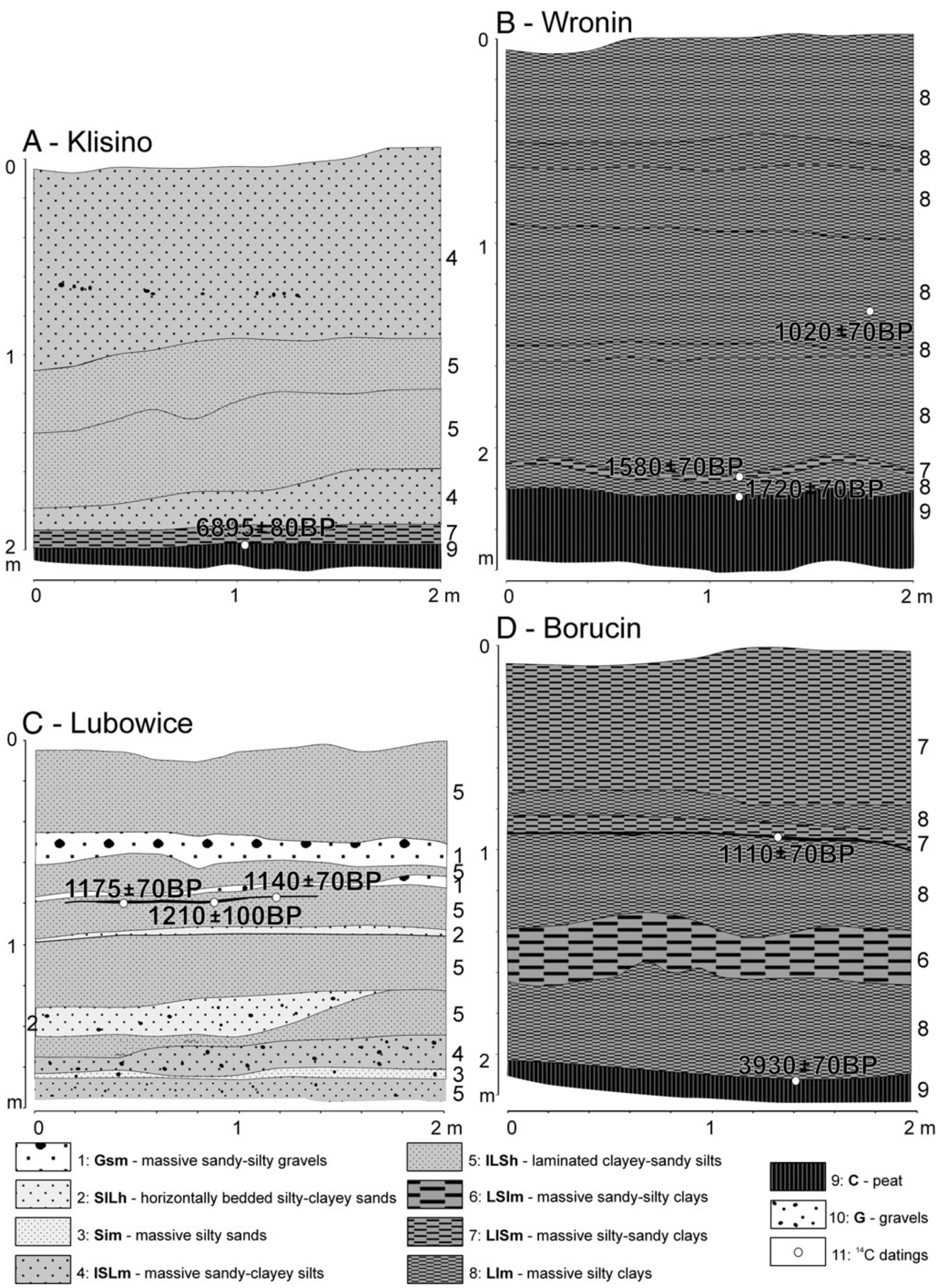

Fig. 8. Internal structure of the fans.

fragments can be observed, but due to their small number it has not been possible to date them by the ^{14}C method. These two layers indicate an increase of energy in the depositional fan environment. Traces of buried roots of water plants indicate rapid sedimentation. The surface layer of the alluvial fan is of massive sandy–clayey silts (1 m). Some quartz gravels, which give bleached horizontal layers (about 3 cm), occur in 70 cm depth. The maximum clast diameter of these gravels is 3 cm. Larger gravels (up to 9 cm) are visible only on the fan surface. The presence of these gravels indicates higher stream velocities.

4.2.2. Wronin fan

The maximum thickness of the Wronin fan is 2.4 m. Organic matter content within its sediments ranges from 4.1% to 89.9%. Most organic matter is present in clays that border the underlying peat (Fig. 8B). The presence of buried pieces of tree, found in the bottom of the fan sediments, probably shows a very early use of fire for forest clearing. Sediments eroded from the slopes were deposited in the depression where peat plants were developed (mainly *Carex*). In these conditions Magnocaricioni peat was developed (Zygmunt, 2007). The massive silty-clayey grain-size distribution of the alluvial fan, which prograded on the peat, is almost homogeneous. At 2.05 m depth a 4 cm horizon of massive silty-sandy clays is visible. Organic matter content in this horizon is 18.7% and indicates a sudden high energy flow. At 1.32 m depth, some charcoal is visible. Thickness of the mineral sediments (silty clays with variable color) decreases to the East. The Wronin fan does not contain finer gravel and sand sediments. Sandy gravels, which are derived from Pleistocene terraces, were introduced to the fluvial system only in the upper and middle parts of the catchments. The low valley gradient does not permit transportation of these coarse sediments into lower parts of the catchment where only fine grained sediments are visible.

4.2.3. Lubowice fan

The Lubowice fan shows the greatest thickness (4 m). It prograded onto the alluvium of the Odra, represented by clayey-sandy silts (Fig. 8C). These planar cross-stratified sediments form a point-bar. Isolated gravels of 5 to 6 cm in diameter were also present in those sediments. Thus, the alluvial fan was developed very close to the Oder River channel and its progradation probably caused the channel to shift to the East. The alluvial fan consists of fine sediments and organic matter content less than 1.5%. Laminated silts as well as silty and sandy deposits with a massive structure prevail within the fan deposits. Gravel additions of up to 5 cm in diameter are also common (Fig. 9). Additionally, sandy and silty gravels with a massive structure form two continuous layers (with a thickness of 15 cm and 4 cm, respectively) that interbed into the laminated clayey-sandy silts. Some gravels forming those two layers exceed 10 cm in diameter (cobbles). The gravels consist mostly of local Sudeten gravel. Scandinavian material (Rapakivi granite) is also represented here. This kind of petrographic composition is typical for older Pleistocene terrace sediments which occur on the edge of the Oder valley. Their presence inside the alluvial fan indicates very intensive erosion in the valley and a high-energy depositional area. Transport of gravels was possible because of the higher valley gradient (Table 1). At the depth of 80 cm, a thin organic horizon can be observed which enabled the dating of the deposition of sediments that lie above it.

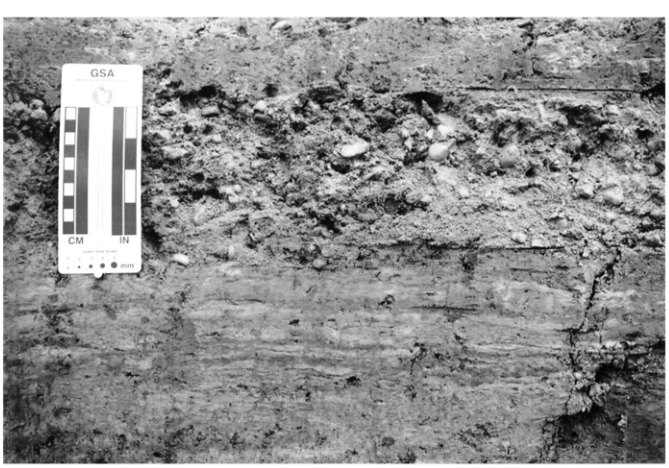

Fig. 9. Layer of sandy–silty gravels in the alluvial fan sediments (research site Lubowice).

4.2.4. Borucin fan

The alluvial fan at Borucin prograded on the Alnioni peat which was developed in a swamp with *Alnus glutinosae* (Psina valley, cf. Zygmunt et al., 2006). During floods this depression was a backswamp where peats developed. After deforestation soil erosion was more intense so the alluvial fan started prograding onto the peat. Geophysical analyses have demonstrated that the thickness of the peat underlying the mineral deposits of the fan is around 4 m. The maximum thickness of the Borucin fan is 2.1 m. Organic matter content reaches 8.3%. The fan is composed of seven layers which can be linked to periods of different soil erosion intensity. Directly on the peat lies dark gray massive silty clays (80–90 cm; Fig. 8D). On these sediments there are about 50 cm gray-rust massive sandy-silty clays. The next layer (0.9–1.0 m) upward is composed by light-gray-brown massive silty clays. Above, a 2 cm layer of very dark organic material with small charcoals is found. It is buried by white silty–sandy clays, and the white color is being connected with pedological processes (eluviation). These sediments are covered by massive silty clays (15 cm) and massive silty-sandy clays (about 1.2 m).

4.3. Dating results

4.3.1. Klisino fan

The radiocarbon dates yielded by the uppermost layer of the peat filling the floor of the Osobloga valley (which is around 1 km wide) and underlying the mineral deposits of the Klisino fan suggest that this fan was the first of the four fans to form. The accumulation of peat at the base of the fan was interrupted at the very beginning of the Neolithic Age, at 6895 ± 140 BP (Fig. 8A). The maximum range of the sediments deposited in the distal part of the fan was dated to the Roman period at 1920 ± 80 BP (Fig. 5A). Numerous artifacts left by subsequent farming and herding tribes demonstrate that settlement in this area was continuous (Table 2).

4.3.2. Wronin fan

The Wronin fan is the youngest formation analyzed. In the proximal part of the fan, its deposits buried the peat some time after 1720 ± 70 BP (Fig. 8B), while in the distal part this occurred after 640 ± 70 BP (Fig. 4B). Radiocarbon dating results confirm the archeological data pointing to intensive Medieval settlement in the Osobloga valley. Among the evidence for intensive settlement in this area in the Middle Ages are the remains of a big Early Medieval stronghold measuring 200 by 240 m (Fig. 1B). This stronghold is located 1.5 km to the southeast of the fan analyzed. The relatively low density of the permanent stream network limited opportunities for extended human presence and the foundation of permanent settlements in the area. Archeological data provide evidence for settlement in prehistoric times, but they only point to a temporary human presence. The catchments bordering on the ones analyzed from the north and the south were settled by larger numbers of humans and in a more permanent manner. Within the fan catchment, close to its southern border, two flint workshops existed, but the catchment adjacent to the south was colonized more permanently. It is supposed that Bronze Age human activities have been recorded in small within-

Table 2
Results of radiocarbon datings, their calibration and correlation with the archaeological past.

Research site	Number	Age ^{14}C (BP)	Calibrated age (BC/AD)		Age/period	Culture
			1σ	2σ		
Klisino	1 (Ki 13115)	6895 ± 80 BP	5878–5854 cal BC (0,105879) 5850–5714 cal BC (0, 894121)	5976–5949 cal BC (0,041686) 5919–5643 cal BC (0,958314)	Neolithic	Band pottery
	2 (Ki 13114)	1920 ± 140 BP	92–67 cal BC (0,049219) 63 cal BC–254 cal AD (0,950781)	351–298 cal BC (0,022438) 228–222 cal BC (0,001694) 210 cal BC–416 cal AD (0,975868)	Iron /Roman	Przeworsk
Wronin	1 (Ki 13112)	1720 ± 70 BP	243–402 cal AD (1,)	130–438 cal AD (0,965936) 487–531 cal AD (0,034064)	Iron/Roman	Przeworsk
	2 (Ki 13111)	1580 ± 70 BP	412–555 cal AD (1,)	264–275 cal AD (0,008041) 333–623 cal AD (0,991217) 630–630 cal AD (0,000742)	Iron/Roman	Przeworsk
	3 (Ki 13110)	1020 ± 70 BP	899–918 c l AD (0,092484) 963–1049 cal AD (0,63325) 1084–1124 cal AD (0,20698) 1137–1151 cal AD (0,067285)	880–1187 al AD (0,99652) 1199–1206 cal AD (0,00348)	Iron/Early Medieval, Medieval	Slavs
	4 (Ki 13113)	640 ± 70 BP	1285–1326 cal AD (0,441828) 1343–1394 cal AD (0,558172)	1262–1424 cal AD (1,)	Medieval	Slavs
Lubowice	1 (Ki 11897)	1210 ± 100 BP	688–754 cal AD (0,294788) 757–894 cal AD (0,677902) 927–934 cal AD (0,02731)	654–998 cal AD (0,990508) 1003–1013 cal AD (0,009492)	Iron/Early Medieval	Slavs
	2 (Ki 11899)	1175 ± 70 BP	774–900 cal AD (0,765988) 918–964 cal AD (0,234012)	687–989 cal AD (1,)	Medieval	Slavs
	3 (Ki 11898)	1140 ± 70 BP	782–789 cal AD (0,031345) 811–845 cal AD (0,178553) 856–981 cal AD (0,790102)	695–698 al AD (0,003587) 708–747 cal AD (0,049798) 765–1021 cal AD (0,946615)	Medieval	Slavs
Borucin	1	4340 ± 80 BP	3090–3044 cal BC (0,175984) 3035–2888 cal BC (0,824016)	3335–3210 cal BC (0,118158) 3192–3151 cal BC (0,026819) 3138–2861 cal BC (0,816103) 2808–2756 cal BC (0,031916) 2719–2705 cal BC (0,007003)	Eneolithic	Corded ware
	2 (Ki 11892)	3930 ± 70 BP	2558–2554 cal BC (0,011504) 2550–2537 cal BC (0,057192) 2491–2333 cal BC (0,82497) 2325–2300 cal BC (0,106334)	2618–2609 cal BC (0,005006) 2598–2594 cal BC (0,001538) 2583–2202 cal BC (0,993455)	Bronze	Bell Beaker
	3	3650 ± 70 BP	2135–2069 cal BC (0,316462) 2064–1938 cal BC (0,683538)	2273–2257 cal BC (0,007753) 2207–1875 cal BC (0,967119) 1843–1817 cal BC (0,014734) 1798–1779 cal BC (0,010395)	Bronze	Bell Beaker, New Cerekwia
	4	1980 ± 80 BP	88–76 cal BC (0,046159) 56 cal BC–93 cal AD (0,848015) 97–125 cal AD (0,105826)	179 cal BC–220 cal AD (1,)	Iron/La Tene, Roman	Celtic, Przeworsk
	5	1670 ± 70 BP	256–303 cal AD (0,221591) 315–433 cal AD (0,729964) 494–505 cal AD (0,041148) 523–526 cal AD (0,007297)	218–553 cal AD (1,)	Iron/Roman, Migration	Przeworsk
	6	1510 ± 60 BP	439–487 cal AD (0,292278 531–615 cal AD (0,707722)	427–644 cal AD (1,)	Iron/Migration	–
	7 (Ki 11891)	1110 ± 70 BP	832–836 al AD (0,012355) 869–1017 cal AD (0,987645)	712–745 al AD (0,022479) 767–1038 cal AD (0,977521)	Medieval	Slavs

catchment fans. Only in the Middle Ages did human activities lead to the deposition of a more pronounced alluvial fan at the mouth of the main valley.

4.3.3. Lubowice fan

Absolute radiocarbon dating of the Lubowice fan was not possible because of low organic matter content and its progradation onto minerogenic alluvium of the Odra river (Fig. 8C). Based on archeological data, it may also be supposed that the Lubowice fan started to prograde during the Neolithic Age. Numerous artifacts and settlement traces found within the fan catchment and dated to the Neolithic also provide evidence for settlement in this area and the deforestation of the fan catchment. Those data have been collected using the AZP maps. Additionally, the presence of an organic horizon at a depth of around 0.8 m made it possible to determine the time when accumulation last occurred within the fan. The erosion stage during which the uppermost layer of the fan was deposited took place in the Early Middle Ages (1210 ± 100 BP, 1175 ± 70 BP, 1140 ± 70 BP, Fig. 8C). An indirect method of dating of the long term man–landscape interactions is the occurrence of (1) strongholds (area fortified with wooden palisades) and (2) archeological artifacts, which indicate a longer presence of humans within the fan drainage area and nearby.

To summarize, based on archeological finds it can be concluded that the exceptionally intensive deforestation of the fan drainage area at Lubowice occurred during the Bronze Age. This is confirmed by the stronghold of Lusitian culture (VIII/IX BC), which is situated near the alluvial fan (Figs. 1C, 6C). The preserved wooden stronghold (fort) embankments are about 1.5 km in length which is seen to be indicative of widespread deforestation at that time.

4.3.4. Borucin fan

The Borucin fan also prograded onto the peat filling the bottom of the Psina valley (Fig. 8D). The fact that this research site yielded the most radiocarbon dates allowed the probable fan accumulation stages to be determined (Fig. 10). The fan started prograding in the Late Neolithic (4340 ± 80 BP; Fig. 10A). The oldest dated stage of its development dates back to 3930 ± 70 BP (Fig. 10B). The next stage dates to the Neolithic and the beginning of the Bronze Age (3650 ± 70

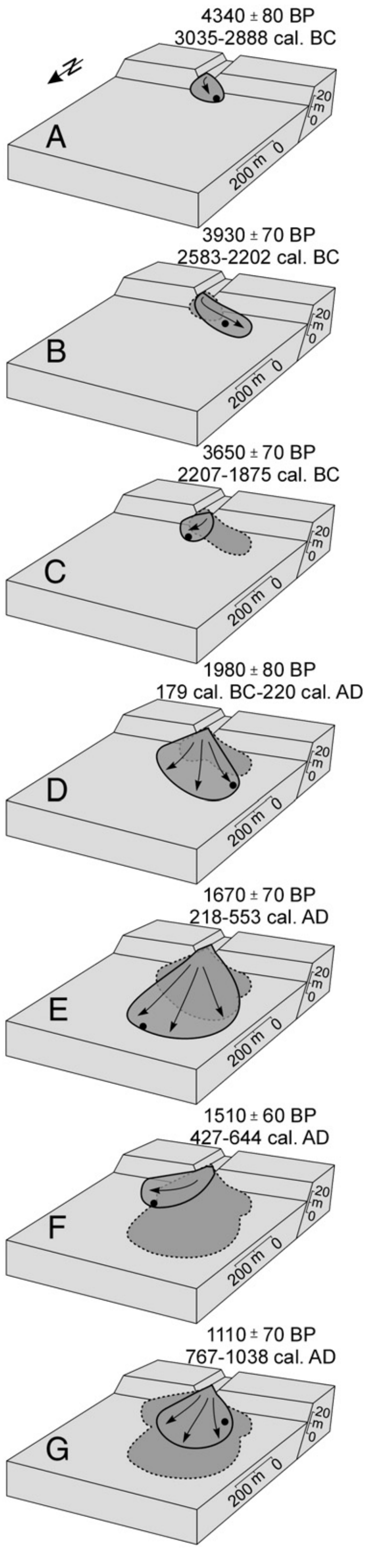

Fig. 10. Phases of the alluvial fan progradation in Borucin (A–G: explanation in the text).

BP; Fig. 10C). Initially, the fan developed in a north-westerly direction and along the valley axis (1980 ± 80 BP; Fig. 10D). Its maximum progradation occurred during the Late Roman Period (1670 ± 70 BP; Fig. 10E). Due to an increase in the level of deposition in the axial zone, the fan started to prograde in a north-easterly direction (1510 ± 60 BP; Fig. 10F). The last dated stage of fan accumulation can be described as a convex deposit. The stage at which this accumulation took place was determined on the basis of the dating of the organic layer underlying the clayey sediment forming this accretion (Fig. 8D); it was dated to the Early Middle Ages (1110 ± 70 BP; Fig. 10G). This accumulation was related to the renewed agricultural colonization of the area by Slavs in the Early Medieval period (Fig. 11).

5. Conclusions

Detailed research carried out in the four alluvial fans and the analysis of archival data show that the processes of intensive deforestation and land cultivation on the loess Glubczyce Plateau started in the Early Neolithic. Deforestation of the undulating plateau increased the surface runoff (Wasson, 1996; Ayala and French, 2003; Lang et al., 2003). Acceleration of soil erosion processes and alluvial fan progradation seem to have been triggered mainly by the intensity of land use. The environmental effects of land cultivation were superimposed on the changes induced by climate (especially wet periods). Heavy local rainstorms could have accelerated accretion of the alluvial fans too.

The Glubczyce Plateau was colonized by farmers from the south very early so human-induced soil erosion started earlier than in the other loess regions in Poland. The first farmers, which colonized this area, belonged to the Bandkeramik culture. A first phase of permanent settlements was also visible on the Sudeten and Carpathian foreland (Kaczanowski and Kozlowski, 1998). All of these areas are covered by loess and thus favorable for agriculture. Thus, much of the depositional stratigraphy of the downstream alluvial fans consists of relatively fine-grained alluvium because of human-induced erosion of loess-derived soils on catchment hillslopes. Accordingly, different than alluvial fans in steeper catchments with coarser-grained subsurface lithologies (e.g., Harvey, 1992; Chiverrell et al., 2008), it is reasonable to assume that vertical accretion from suspension flows during flood events significantly contributed to alluvial-fan formation. This may also be the reason for the relatively subdued landform of some of the investigated alluvial fans (cf., Borucin fan, Fig. 5D).

The earliest evidence of human-induced soil erosion on the Glubczyce Plateau can be dated to 6895 ± 80 BP (the Klisino fan). Early soil erosion on this area was also described by Klimek et al. (2006). Organic material which underlies colluvium in Biala is dated to at least 6650 ± 90 BP. Anthropogenic denudation of the southeastern Polish loess is mainly connected with activity of Globular Amphora Culture (Kruk, 1981; Snieszko, 1995; Kruk et al., 1996). This phase of soil erosion was probably connected with a phase of precipitation increase (Starkel, 1988, 1989). Within the northern foreland of Carpathians valley alluviation caused by deforestation did not begin until the Early Medieval Times (Klimek et al., 2006). An increase of human impact on the loess areas in Poland was also visible in X–XI and XI–VVII centuries AD (Snieszko, 1985, 1995). Kukulak (2003) described rapid changes in alluviation of the mid-mountain San catchment (SE Poland) which was connected with the XV–XVI centuries phase of colonization. Intensive deforestation and cultivated deforested areas caused gully erosion in the area (Buraczynski, 1997; Schmitt et al., 2006). The first phase of gully development was at the turn of XV/XVI centuries and the second one in the beginning of XX century.

Among the fans analyzed three prograded onto peats that filled valley bottoms (research sites Borucin, Lubowice, Wronin). The Lubowice fan prograded onto Odra river alluvium. The radiocarbon dating of the peat filling the bottoms of the valleys and underlying the fan sediments attests that the analyzed fans started to cover the organic sediments in the Neolithic, 6895 ± 140 BP (research site Klisino; Fig. 11). The increasingly wet climate which occurred in Europe in the mid-Atlantic period probably contributed to the development of this formation (Macklin et al., 2006). At the same time, a phase of increased fluvial activity of Polish rivers could also be observed (Starkel et al., 2006). The Borucin fan started to accumulate in the Neolithic as well (4340 ± 80 BP). Indirect conclusions may be

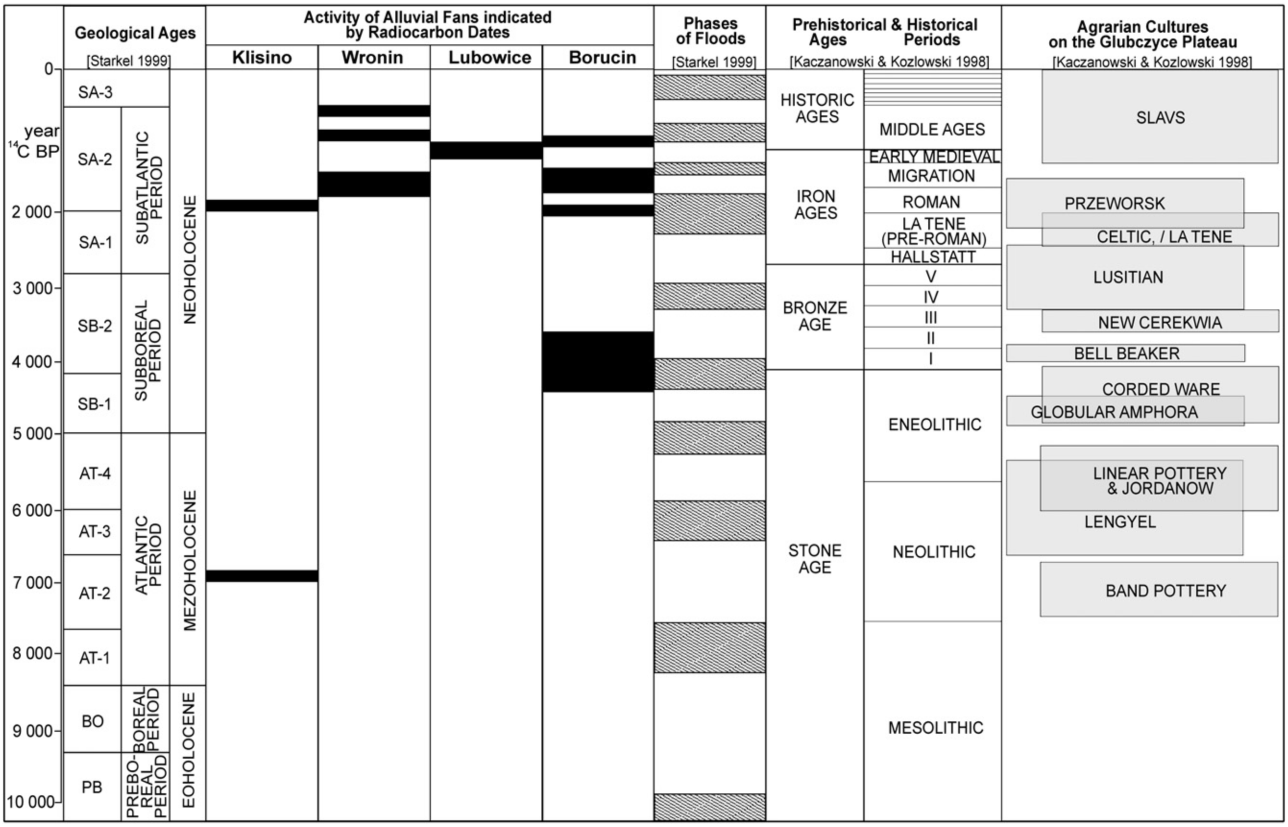

Fig. 11. Time of the alluvial fan development in context of the historical and geological chronology of events on the Glubczyce Plateau.

drawn that the Lubowice fan also started to develop at the time when the Glubczyce Plateau was initially colonized by farming and herding tribes. This is evidenced by numerous artifacts and settlement traces found in the catchment of the valley that supplied the sediment forming the fan. However, the absence of organic matter prevents direct dating of this formation. The Wronin fan is the youngest among the formations analyzed. It only started to prograde in the Middle Ages (1720 ± 70 BP). The intensive erosion phase in the Early Middle Ages is reflected by the sediments forming three of the fans analyzed. At this time, the accumulation can be discerned in the shape of two fans as a convex deposit (research site Borucin: 1110 ± 70 BP; research site Lubowice: 1210 ± 100 BP, 1175 ± 70 BP, 1140 ± 70 BP).

The findings of alluvial fan analysis confirm archeological results. Continuous settlement has been present on the Glubczyce Plateau since the Neolithic Age. During the Migration Period, the area was depopulated and the forest cover partly regenerated; this stage lasted for about 200 years (Kaczanowski and Kozlowski, 1998). In the Early Middle Ages, intensive Slav settlement and cultivation took place in the area. Since archeological research is still incomplete in many areas, the reconstruction of long-term man–landscape interactions based on the analysis of alluvial fan sediments may provide a helpful complement. The dating of the progradation of fans may also be used to validate archeological data concerning the time when individual areas were settled by farming and herding communities.

Acknowledgements

This research has been funded by grant No. KBN PB-508/NoZ/2003 from the State Committee for Scientific Research. The author wishes to thank the supervisor of her doctoral thesis, Professor K. Klimek, for his cooperation in the work related to the grant as well as the warmth and trust shown. I would also like to thank P. Owczarek, Ph. D. for his support and assistance in field work provided. Thanks go to J. Herget and A. Lang for helpful comments, and P. Houben for assistance with the manuscript. Special thanks go to S.W. Trimble for proofreading.

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