Substratum sedimentology and topography of two riparian peat bogs in the Bieszczady Mountains (Carpathians)

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SUMMARY

The valley of the upper course of the San River in the Bieszczady Wysokie mountain range is, after the Orawa-Nowy Targ Basin, the area with the largest number of peat bogs in the Polish Carpathians. This study combined a levelling survey with data from dense networks of boreholes on two riparian bogs (Łokieć and Dźwiniacz) in the Bieszczady Mountains (East Carpathians) to characterise the morphology of the two peatlands, create a digital elevation model (DEM) for Łokieć, and describe the underlying sediments. Previous radiocarbon dating of basal peat samples has indicated that both peat bogs began to grow during the younger part of the Holocene, but not at the same time. The results of the coring undertaken in our study demonstrated that both bogs fill 0.5–1.5 m deep troughs cut into a fluvial terrace situated 4–6 m above the level of the San River. The bog domes are asymmetrical, more than 2 m high, and their summits lie directly above the deepest parts of the troughs. The troughs are lined by sediments of mainly fluvial origin (silt, sand, fine gravel), and in their deepest parts the peat lies directly on clays originating from weathering of shales in the terrace base. On this basis, the troughs are interpreted as palaeochannels (infilled oxbows) representing fragments of the ancient San River channel, cut off by erosion and situated at the former level of the valley bottom. Raised bogs seldom occur in mountain valleys, where reworking of floodplain deposits proceeds at a higher rate and peatlands are frequently eroded by fluvial action. The two bogs that we studied in the Bieszczady Mountains are exceptional in that they are set in preserved palaeochannels.

KEY WORDS: digital elevation model (DEM), lithology, oxbow lakes, peatlands, Polish Outer Carpathians

INTRODUCTION

Investigations on most peat bogs in Poland have concentrated on peat properties, ecology and economic value (e.g. Denisiuk 1977, Żurek 1987, Tobolski 2003, Ralska-Jasiewiczowa *et al.* 2006, Glina *et al.* 2018). Studies on the relief of the mineral substratum beneath peat and its role in bog formation are less frequent, although literature strongly emphasises the importance of landscape, relief, hydrology and substratum in the initiation and further development of peat (e.g. Carling 1986, Żurek 1990, Cooper & McCaan 1995, Rhodes & Stevenson 1997, Bragg & Tallis 2001, Tobolski 2003, Dykes & Warburton 2007, Łajczak 2009, 2013, 2014; Edvardsson *et al*. 2012, Forysiak *et al.* 2014). The locations of bogs in mountains in relation to local relief, nature of the mineral substratum and groundwater outflow requires more detailed investigation (Łajczak 2014, Krąpiec *et al.* 2016, Drewnik *et al.* 2017, Stivrins *et al.* 2017).

After the Orawa-Nowy Targ Basin, the valley of the upper course of the San River in the Bieszczady Wysokie mountain range is the area with the largest number of bogs in the Polish Carpathians, extending over approximately 80 hectares. The bogs here are peculiar in being located on fluvial terraces in the bottoms of mountain valleys. Most have already been studied by botanists (Deniusiuk 1977, Kalemba *et al*. 2004, Kucharzyk & Szary 2016) and the stratigraphy, palynology and ash content of their peat have been described (Marek & Pałczyński 1964, Ralska-Jasiewiczowa 1972, 1980; Ralska-Jasiewiczowa *et al.* 2006, Malec 2009). Samples from three of these bogs have been dated using the traditional method (the Conventional Radiocarbon Age) (Ralska-Jasiewiczowa 1972, 1980; Haczewski *et al.* 2016). Also, comprehensive investigations of peat sections have provided data on the Late Glacial and Holocene history of change in the natural environment of the Bieszczady; especially on the history of vegetation (Ralska-Jasiewiczowa 1972, 1980), changes in hydrography, and the dynamics of fluvial processes in river channels (Ralska-Jasiewiczowa & Starkel 1988, Starkel *et al.* 1996, 2006). On the other hand, the relief and sedimentology of the substrata of these bogs are not well characterised. This topic requires attention because many peat bogs in the Bieszczady formed on mineral sediments composed mainly of alluvial conglomerates and silt, which might be expected to favour underground drainage that would hamper the formation of peatlands.

The present study investigates how the locations of two riparian peat bogs in the Bieszczady Mountains are related to the lithology and relief of the underlying substrata. Our first goal was to study the types and origins of mineral sediments directly beneath the peat, which may provide clues not only about their origin, but also to their role in establishing the bogs. Our second goal was to study the relief of the basal surface of the peat and its relationship to the surface topography of the peatland.

METHODS

Study area

The segment of the San River valley containing the studied peat bogs extends along the NE side of the Połoniny Range - the highest part of the Bieszczady Wysokie mountains (Tarnica 1346 m a.s.l.). This is also the easternmost fragment of the Carpathians in Poland (Figure 1a). In this area the river channel marks the national border between Poland and Ukraine. The longitudinal gradient of the river is low (5.5 ‰) and the depth of the channel increases downstream from 1 to 3 metres. The present-day capacity of the channel is sufficient to contain the

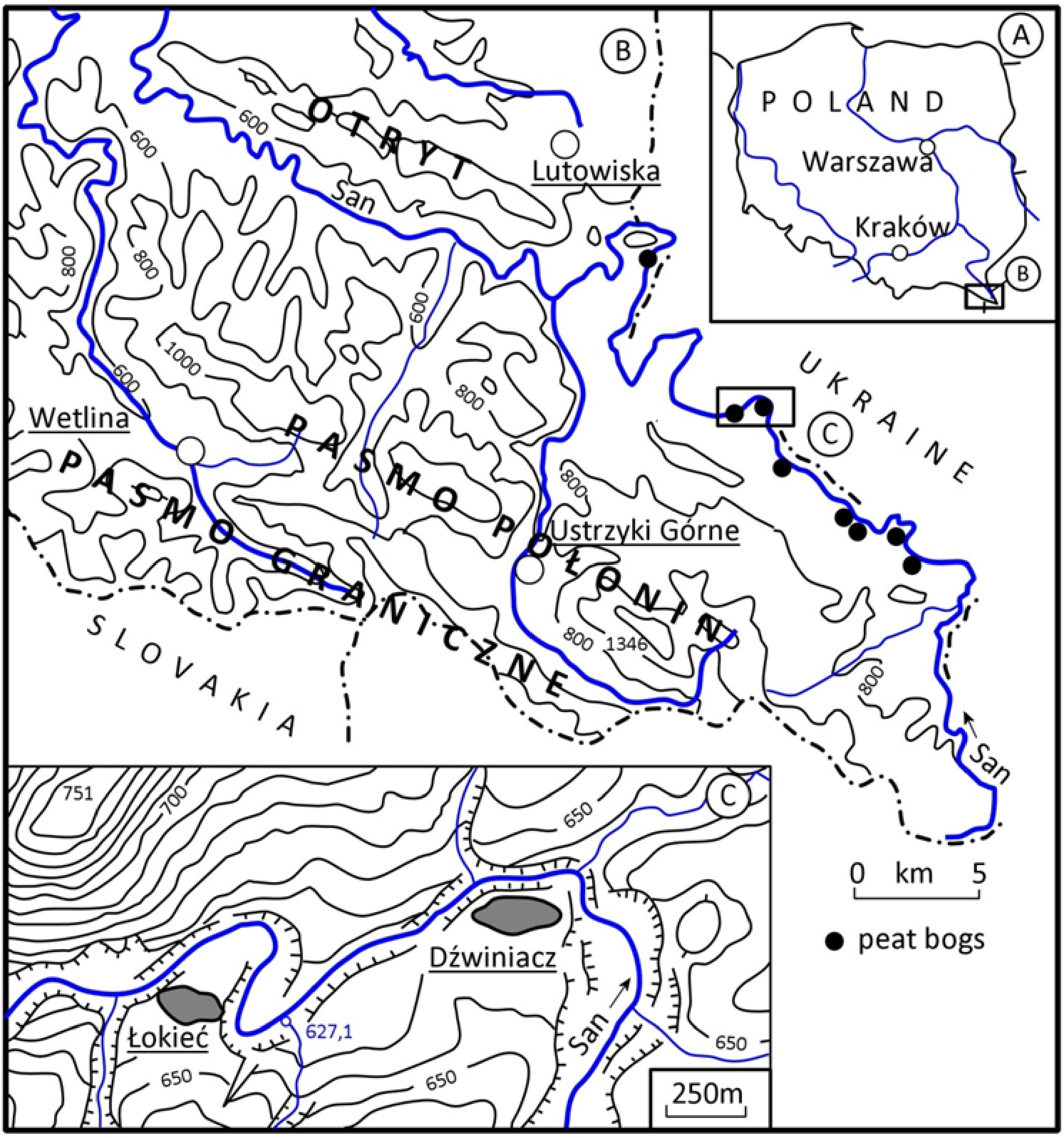

Figure 1. Location of the study area (A) in Poland, (B) in the Bieszczady Mountains, and (C) in the San River valley.

flow even during floods. Oscillations in the river's water level are small, moderated by extensive woodland cover on adjacent slopes. Mean annual of precipitation ranges from 1000 to 1200 mm, and mean summer and winter air temperatures are 16 °C and -4 °C, respectively (Nowosad 1995). A surplus of rainfall over evaporation is characteristic of the growing season (May through August) in this region (Kowanetz 1998).

There are ten bogs in the widened segment of the San River valley between the tenth and twentieth kilometres of its course (Figure 1b). They are situated on elevated fluvial terraces dating from the Late Glacial and Early Holocene. The surface areas of the bogs range from 1 to 9 ha, and peat thickness from 1 to 6 m (Haczewski *et al*. 2007, 2016). In the largest, Tarnawa Wyżna bog, the peat layer is up to 7 m thick (Marek & Pałczyński 1964, Ralska-Jasiewiczowa 1972, 1980). The peat domes are elongated and rise 1.5–3.0 m above the edge of the bog. The thickness of peat in some of the bogs is greater than the relative heights of their domes, meaning that they must fill depressions in the surfaces of the underlying fluvial terraces.

The bogs (Dźwiniacz and Łokieć) that we studied are situated on the left bank of the San River approximately 20 km from its source. The Dźwiniacz bog (49° 09′ 20″ N, 22° 47′ 09″ E) has a surface area of around 8 ha and the Łokieć bog (49° 09′ 12.5″ N, 22° 46′ 14″ E) covers about 4 ha (Figure 1c).

The Dźwiniacz bog developed on a fluvial terrace which is now elevated 4–6 m above the river level, on the convex side of a river bend, at altitude 638–640 m a.s.l. The terrace is nearly 300 m wide and is separated from the river channel by a narrow (5–15 m) ledge of the terrace which lies 3–4 m above the current river level. The bog lies between the foot of the valley slope to the south and the river channel, at distances of 5–10 m from the former and 50–60 m from the latter. The bog is ellipsoidal in shape, with its long axis oriented E–W. This long axis is gently arched with convexity to the south, in accordance with the curvature of the base of the valley slope. The peat dome is low (1–1.5 m) and elongated with the more gentle slope on the northern side. The axial part of the bog has a layer of ponded surface water a few tens of centimetres thick, especially on its southern side. A periodically inundated marsh lies between the base of the valley slope and the edge of the peat dome, and the nearby part of the bog is covered by a thin (5–10 cm) layer of loam washed down from the slope. This part of the bog is fed with groundwater seeping from the regolith on the nearby slope. On its northern and western sides, the bog is drained by shallow trough-like depressions. The northern margin of the bog relatively dry, with water table some 50 cm below the top surface of the peat, and overgrown with spruce.

The Łokieć bog is situated on a fluvial terrace at 634–632 m a.s.l., 4–5 m above and 80–20 m away from the river. It is domed, but peat extends far across the terrace from the dome, even encroaching locally on the lower (4 m) terrace level. The plan outline of the bog is ellipsoidal with gentle bowing toward the valley slope. It is separated from the slope base by a shallow depression, 20–30 m wide, with standing water which is deepest (10–20 cm) in its NW part. The depression is fed with water from argillaceous regolith on the valley slope. The peat dome is 1 m high on its valleyward side, but on the San River side its height exceeds 2 m, especially in the NE part. The bog's margin is driest, and overgrown with brush and isolated birch trees, on the SE side. The San River undercuts the terrace near the SE corner of the bog, exposing the structure of the mineral substratum. A layer of alluvial gravel and sand about 1 m thick overlies the flysch bedrock, which is nearly 4 m thick and represented by groups of sandstone beds alternating with packages of shale beds. The beds dip at 30–40° SW, i.e. away from the river channel.

Field survey

We studied mineral and organic sediments, especially those from the zone of the contact between the peat and underlying mineral material. Peat thickness, its lateral variations and the shape of the peat base were established by drilling 43 boreholes in both studied peat bogs, 1–4.5 m deep, using a Russian peat corer (chamber length 50 cm, diameter 5 cm). Results from four similar boreholes made for the Detailed Geological Map of Poland, sheet Dźwiniacz Górny (Haczewski *et al*. 2016) were also taken into account. Nine additional boreholes were drilled on the outer margins of the bogs, beyond the extent of peat, where mineral sediments reach the surface. The dense network of boreholes (Figure 2) penetrated the peat layer (up to 4 m thick) and continued 0.2–1.3 m into the mineral substratum. At Dźwiniacz there were 16 boreholes up to 3.1 m deep, situated along four transects; and at Łokieć there were 31 boreholes up to 4.3 m deep, arranged along three transects. Drilling through the mineral substratum reached the layer of medium and coarse gravel; deeper penetration was not possible with a hand corer. The total of 55 samples of mineral material from the boreholes comprised 20 samples from Dźwiniacz and 35 from Łokieć. The particle size distribution of mineral sediments was determined by the sieve-areometric method after Mycielska-Dowgiałło (1998), and texture was determined using the FAO-USDA scale.

The relative ages of ancient courses of the San River channel were established by analysis of the relief of ancient fluvial terraces. The traces of ancient river channels are preserved as erosional undercuttings of convex segments of the channels and as locally cross-cutting or merging bowed depressions with marshy bottoms. Successively younger channel traces are less and less elevated relative to the present-day channel. Moreover, erosional undercutting of the 4–6 m high terrace just before the Dźwiniacz bog has exposed a fossil trough whose direction and elevation above the modern channel correspond to the position of the studied peat bog.

Levelling was undertaken for each borehole site, providing a basis for characterisation of the bog dome surface. For the Łokieć bog dome, a detailed levelling survey was also performed, relative to a benchmark established in its central part. Input data for reconstruction of the base and top surfaces of the peat layer were obtained by levelling of dispersed points with a total station theodolite (Dahlta 010A, Karl Zeiss Jena). The points were arranged in a dense network with 48 nodes (spacing 3–5 m) covering the bog at uniform density (Figure 2).

The top and base surfaces of peat were presented as a digital elevation model (DEM). The model was constructed using geostatistical analysis and interpolation by ordinary point kriging. Evaluations of ordinary kriging were also taken into account (Wackernagel 2003, Namysłowska-Wilczyńska 2006). Geometry of elementary network and parameters of the point search area were established before performing the final interpolation of absolute elevation of the peat basal surface. The process of creating the DEM was finalised with evaluation of the cartographic correctness of the contour image of the bog surface and the peat base.

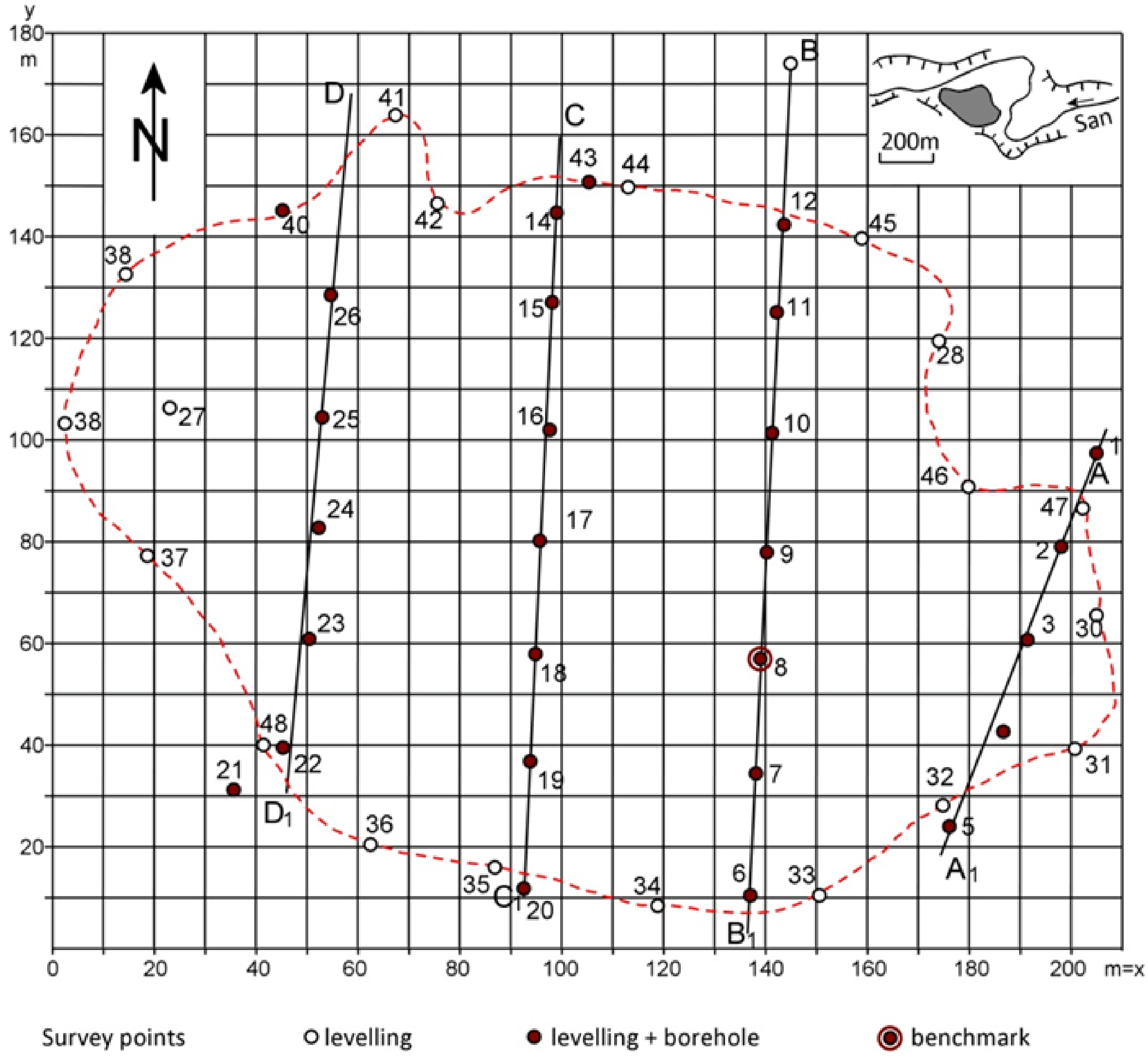

Figure 2. Network of levelling points and boreholes at the Łokieć bog.

Construction of the digital elevation model (DEM)
The DEM was constructed according to the general scheme used in geostatistics (Wackernagel 2003, Namysłowska-Wilczyńska 2006). Parameters of the statistical distribution of the dataset were determined before the geostatistical analyses: extreme values, mean, median, standard deviation, variance and the coefficients of variation, skewness and kurtosis. Statistical distributions of the peat surface elevation and the depth of peat base departed markedly from normal distributions, which was unfavourable for geostatistical analysis. Kurtosis of data distribution for the top of a layer was 2.32 while data distribution for a layer's floor was 1.58.

The analysis involved the following stages: calculation of empirical isotropic semivariogram, fitting of theoretical semivariogram, calculation of anisotropic semivariogram, and cross validation. The second stage of the geostatistical analysis consisted of determining geostatistical models of elevation variability of the bog dome and of peat depth. The theoretical semivariogram that best approximated the empirical model was chosen for this purpose. The many approximation trials used various standard theoretical models and their combinations (spherical, power, linear, exponential, nugget effect). The best geostatistical model was chosen on the basis of the results of cross validation, following evaluation of parameters of the theoretical models and of the results of elevation and depth estimates using successive models. In both studied cases, the linear model was chosen for use in kriging estimation. This choice was supported by the results of cross-validation - the root mean square error (RMSE) was closer to 0 than for all other models. For the top of the peat layer RMSE was 0.436, while for its floor RMSE was 0.4653.

RESULTS

The Łokieć peat bog as described by the DEM
The model of the bog dome (Figure 3a) shows that it is elongated and more than 220 m long. The axis of the dome crest delineates a broad arc which is gently concave on the side facing the valley slope to the south. The elevation of the dome is greatest (>2 m) in the middle of its long axis (sections B–B$_1$, C–C$_1$). Its

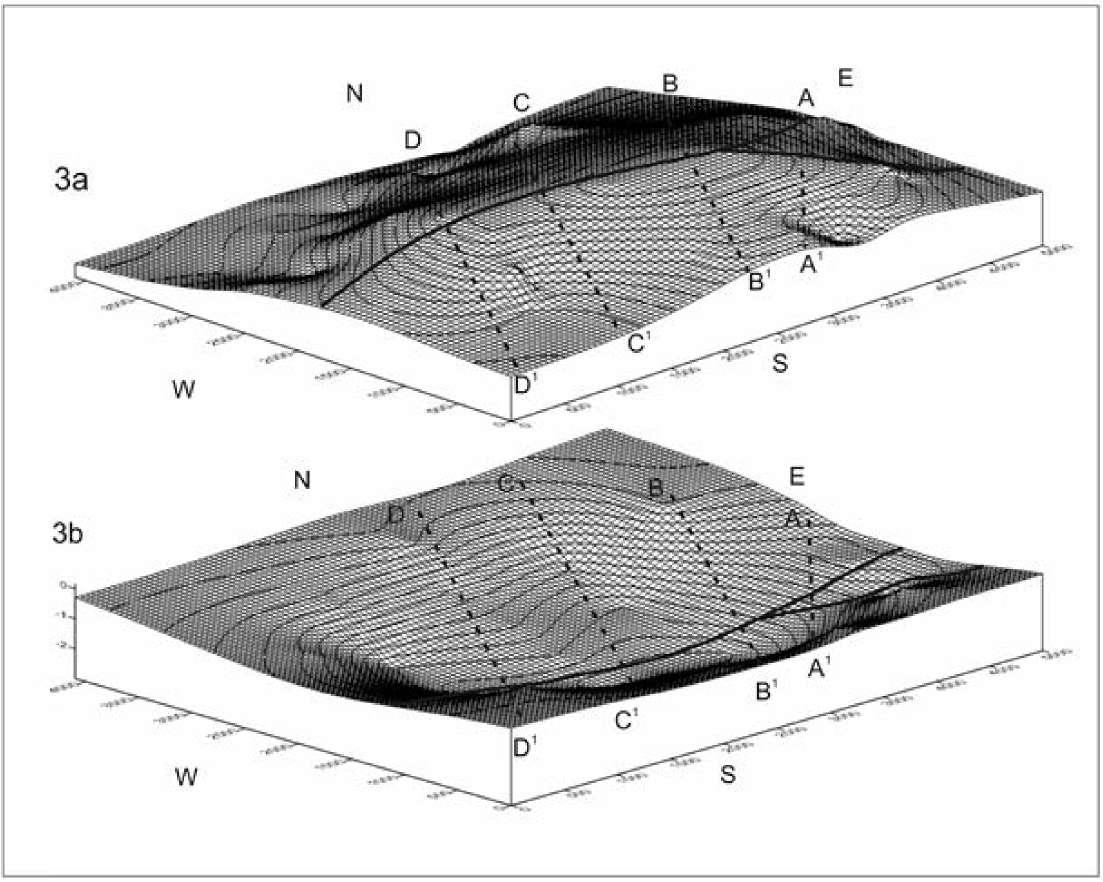

Figure 3. The digital elevation models (DEMs) produced for the surface of the Łokieć bog dome (3a), and for its base (3b).

surface gradually descends westward (section D–D_1). The dome is widest in the middle of its axis length (140 m). The average width of the dome is 80–100 m and its width decreases to 40 m near the ends of the arc. The slopes of the dome are asymmetrical and steeper on the southern side. The other slope of the dome is more irregular, and has two distinct concavities with marshy depressions at their bases.

The DEM of the base of the bog (Figure 3b) presents a negative of the dome in most of its morphometric characteristics. The basal surface of the peatland is a trough-like depression whose axis is elongated similarly to the dome axis (east–west). Its course is also concave on the valley slope side (south) and convex on the San River side. The length of the depression (~ 240 m) is somewhat longer than that of the dome, as is its maximum width (100 m). The lengthwise slope of the bottom is low, toward the west. On this side the bottom of the depression is closed with a barrier higher than that on the east. Two shallow hollows separated by a low threshold lie along its long axis and two lateral embayments with their own erosional pans, not exceeding the depth of the main depression, are present on the northern side. The depression is deepest (0.8–1.1 m) in the mid-western part of its course (behind the threshold). The eastern part of the depression is shallower (0.2–0.4 m) than the western part (0.3–0.6 m). The slopes of this depression are asymmetrical, similarly to the dome surface. The southern slope is steeper, higher, and concave in cross section.

Geological structure of the mineral substratum

The position of both studied peat bogs on the alluvial terrace of the San River is determined by the nature of the mineral substratum beneath the peat, which is mainly composed of alluvium although this has not been proven beneath the deepest part of the Łokieć bog. The structure of both bearing terraces is typical of terraces in mountain valleys, with a base of solid rock overlain by alluvium of variable grain size; although the alluvial cover is heterogeneous with respect to grain size, thickness and structure.

Drilling revealed a distinct erosional trough in the gravels underlying the Dźwiniacz bog. The trough has an arcuate course and fine-textured sediments which are thickest in the bottom of the trough, where the base of the overlying peat base is also deepest. Interpolation of data from 16 boreholes in 4 transverse sections on this bog showed that the trough cut in gravels is up to 1.5 m deep and 10–25 m wide (Figure 4). The depth at which fine-textured

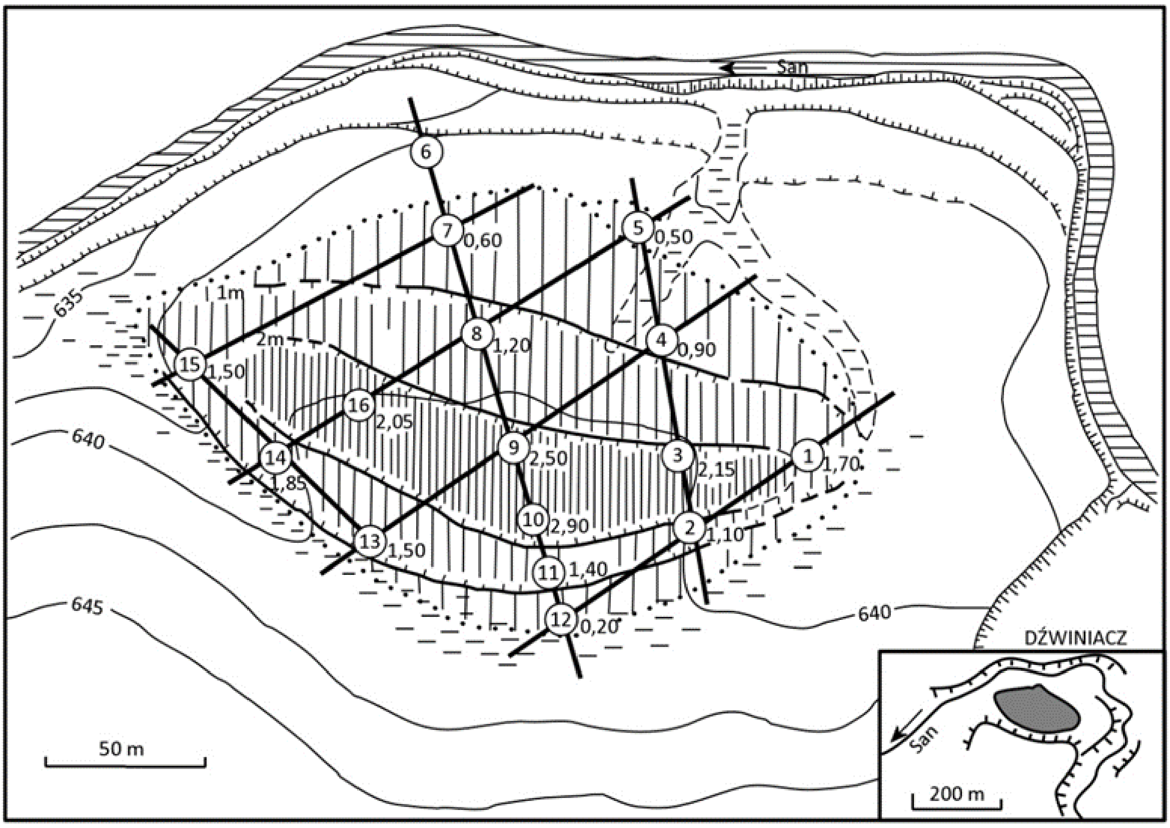

Figure 4. Network of boreholes (1–15) on the Dźwiniacz bog with interpolated depth of the peat base (contours: 1 m, 2 m).

sediments appear in the borehole profiles indicates that the axis of the trough buried beneath the peat differs in orientation from the present-day San channel, being situated close to the base of the valley slope and running parallel to it.

The gravel in the bottom of this buried trough is overlain by a thin (5–10 cm) layer of sand with silt, changing upwards to silt (layer up to 20 cm thick) then gradually to peat-rich silt and peat (up to 2.9 m thick). The gravel was not penetrated by drilling. The opinion that their thickness is reduced is based on observations of a nearby (to SE) undercut margin of the terrace in the bank of the San (Figure 5) where peat, reaching to the top of the terrace, is 2.2 m thick. Assuming that the maximum peat thickness is about 3 m and it forms a dome 1–1.5 m high, only a thin layer of gravel (0.5–0.7 m) should be present beneath the bottom of the trough. Gravel exposed in the river banks is poorly consolidated, dominated by flat sandstone cobbles 6–12 cm in size (*b* axis) chaotically embedded in finer pebbles and coarse sand. Only the upper part of the gravel layer contains clearly more sand and is covered by a thin veneer (10–15 cm) of sandy clay.

Silts in the substratum of the Dźwiniacz bog are overlain by peat up to 2.9 m thick. The greatest values of peat thickness are grouped within the arcuate depression incised into the gravel. Peat not only fills the depression but also spreads over silty sands on its northern margin, thinning from 0.6 m to 0.2 m over a distance of 90 m.

Three horizons could be distinguished in the vertical section of the peat layer. The lower horizon, 0.4–0.5 m thick, consists of well decomposed dark peat. It has been radiocarbon dated at 4290 ± 80 BP by Haczewski *et al*. (2016), at depth 2.4–2.6 m. It is overlain by a 0.3–0.4 m thick horizon of peat rich in wood debris. The uppermost horizon is up to 2.2 m thick and consists of weakly decomposed water-soaked peat, poor in wood debris. A sample taken near the contact with the lower horizon, at depth 2.0–2.2 m, was radiocarbon dated at 1320 ± 70 BP (Figure 5).

Mineral sediments beneath the Łokieć bog were studied in more detail. Four transverse cross sections through this bog, running through 27 borehole sites, revealed the presence of a trough-like depression in the gravel layer similar in width and depth (up to 1.5 m) to the trough at Dźwiniacz (cross section B–B_1 in Figure 6). The trough gradually shallows and bifurcates westward (cross section D-D_1). It is steeper on the southern side, facing the valley slope, than on the northern side. The boreholes made it possible to determine the grain size of the sediments but not their sedimentary structures. The trough is filled with sands, silts and clays, locally up to 1 m thick in total.

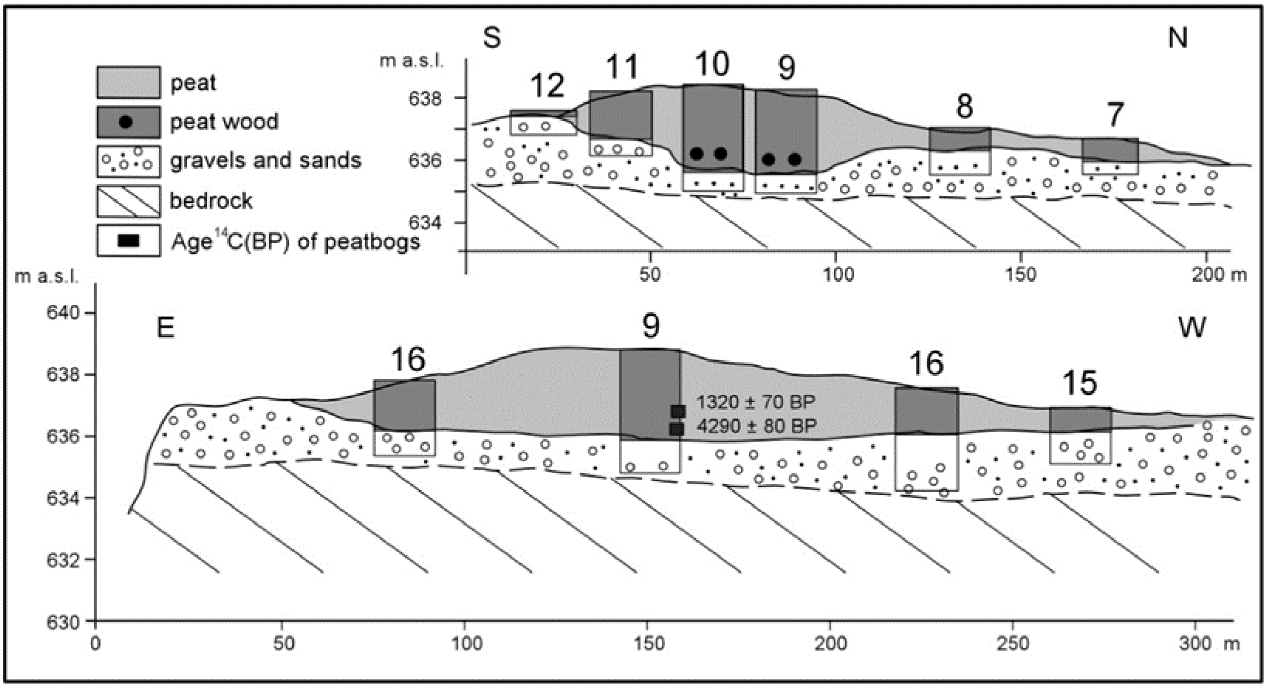

Figure 5. Longitudinal (S–N) and transverse (E–W) cross sections through the Dźwiniacz bog.

Their vertical sequence varies between individual drilling sites. Normal grading from sand to silt or clay is absent in most sections; clays often lie directly on sands (Figure 6). A thin (up to 0.1 m) layer of sand is directly overlain by a 0.6 m thick layer of silt without a clay top (section A–A_1) in the inlet part of the trough. Farther west, in the deepest part of the trough, fine sand lies directly on clay (section B–B_1). It is likely that the clays here are weathered shales belonging to the flysch series in the terrace base. Silts in the next borehole to the west lie on clays underlain by sand (sections C–C_1, D–D_1). On the southern side facing the valley slope, admixtures of sandstone debris and clay are present within the trough and on its margin.

The distributions and proportions of mineral sediment texture classes in the borehole profiles are shown in detail in Figure 7. Samples of sediments underlying the peat were selected along sections A–A_1 (20 samples) and C–C_1 (15 samples). Lateral continuity of the lithological horizons is best expressed in the eastern part of the trough (section A–A_1) and less clear farther to the west (section C–C_1). The vertical sequence displays inversed grain-size grading in the eastern part, and normal grading in the western part. The predominance of clay and silt in the deepest part of the trough is notable, especially on the (south) side facing the valley slope. Sand predominates in the basal part of the trough fill, but its proportion decreases upwards in favour of fine-grained sediments indicative of slackwater deposition. In a few locations the proportion of sand fraction increases upwards, suggesting increasing energy of flow in the trough. In general, the borehole sections indicate that the peat is directly underlain by silts and clays, even when it is as thin as 0.2–0.4 m. The fine-textured sediments are thickest in the deepest parts of the basal surface of the peat layer, which represent potential sites of peat initiation.

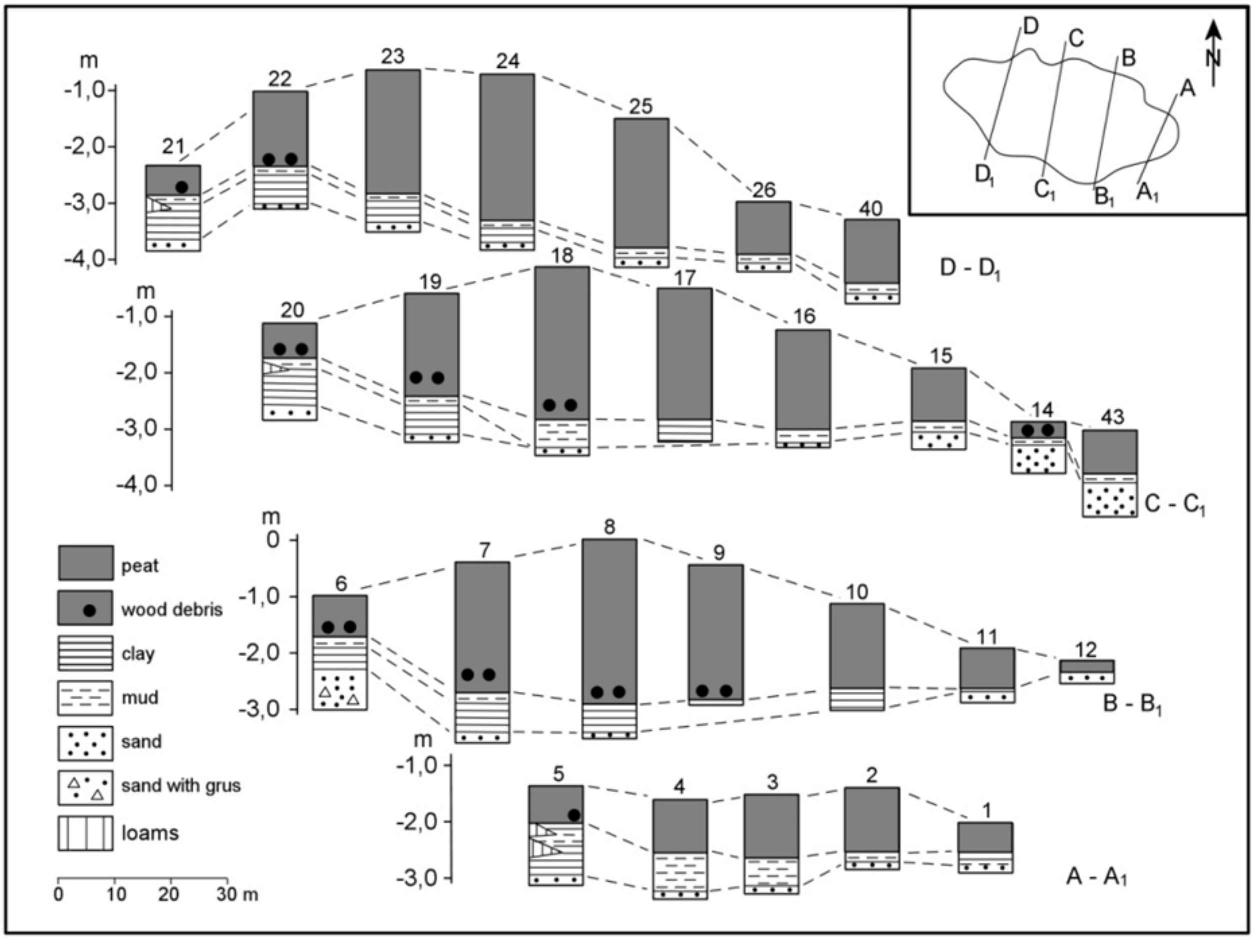

Figure 6. Lithology of alluvium in the substrate of the Łokieć bog along four transverse sections. Locations of cross-section lines and borehole numbers as in Figure 2.

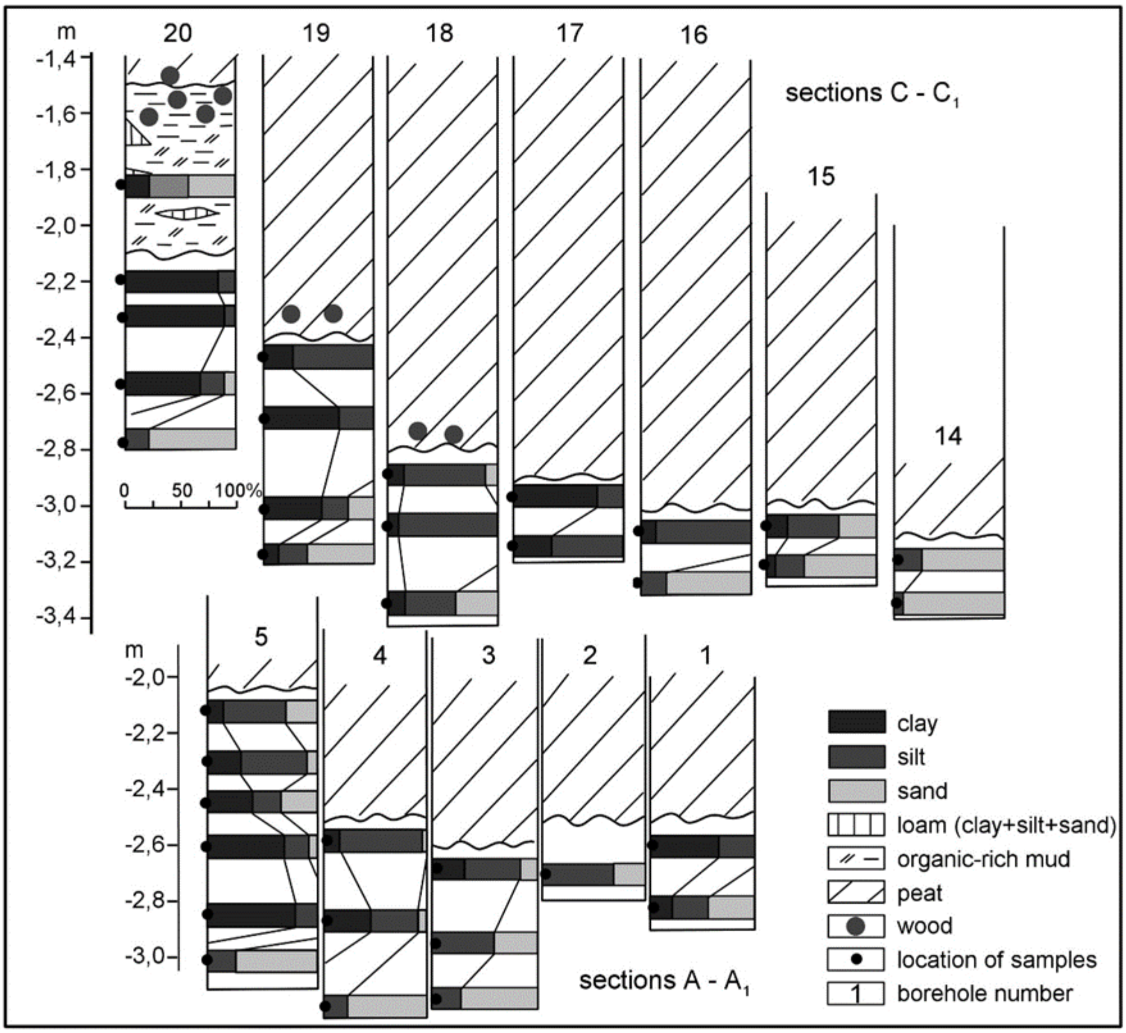

Figure 7. Grain-size distribution beneath the Łokieć bog. Numbers of cross sections and boreholes as in Figure 2.

DISCUSSION

The results of drilling combined with the results of a levelling survey of the peat dome surface clearly demonstrate that the Łokieć bog occupies an elongated depression incised into gravels of the San River terrace. The arcuate course of the depression, its extension along the base of the valley slope and the westward inclination of its floor, all strongly suggest that the depression was carved by erosion and that it is a palaeochannel, i.e. a remnant of the Late Glacial San River. A similar origin seems most likely for the depression beneath the Dźwiniacz bog. The bent courses of both palaeochannels and their similar elevations above the bottom of the present-day river channel indicate that they belong to the same stage of the ancient course of the San River (Figure 8), corresponding to the present-day fluvial terrace elevated 4–6 m above the channel bed. At this stage the San River channel was sinuous and the segments that are now filled with peat bogs are remaining fragments of this channel (‘oldest’ in Figure 8).

The modern surface of the terrace around the peat bogs is smooth and does not bear any clear traces of the ancient fluvial channel. Also, the undercut margins of the terrace in the bank of the San River do not reveal any erosional trough. This is possibly because the gravel filling it looks the same as the surrounding gravel. When the San River channel shifted (by turning to the north; see Figure 8) and deepened, the abandoned segment of the former channel became an oxbow lake which was only periodically active. Both ends of the oxbow filled up with overbank natural levée sediments, and occasionally even channel sediments, during floods. Fine-grained sediments (sand, silt, clay) could be laid down only between the two levées, within the oxbow lake impounded by them. The presence of these

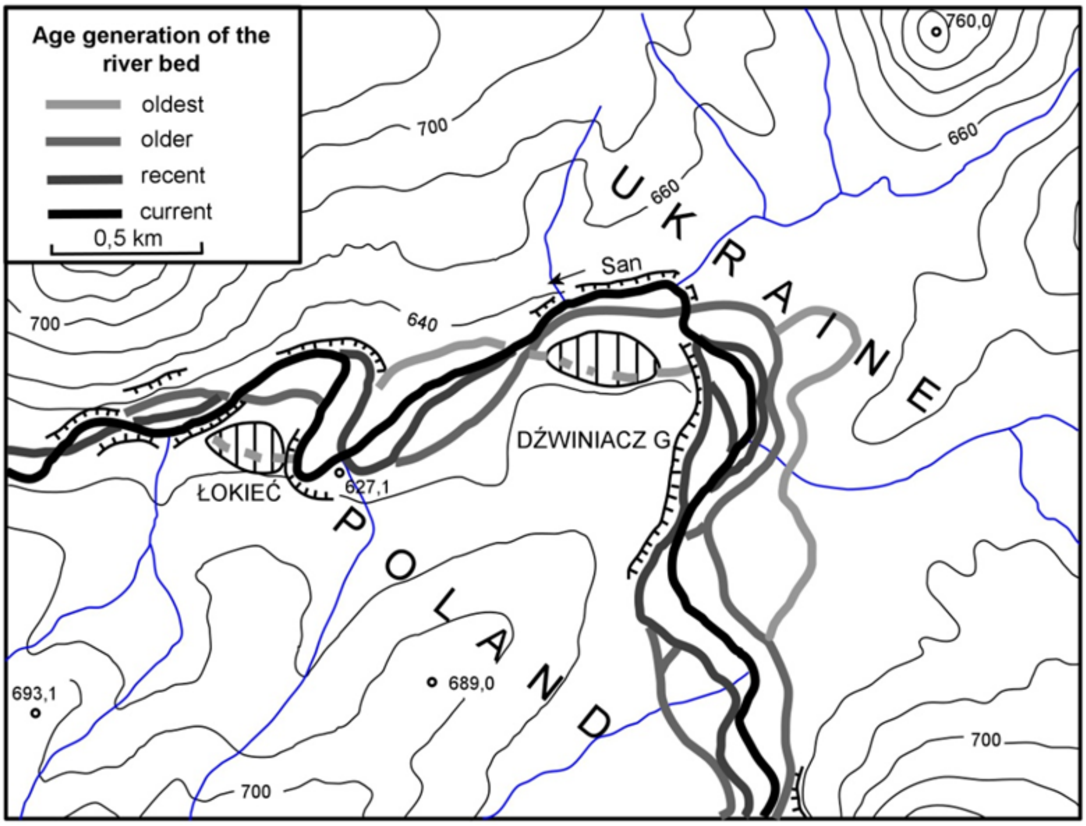

Fig. 8. Locations of the Dźwiniacz and Łokieć bogs relative to the shifting course of the San River during the late Holocene.

sediments and their maximum thickness along the axis of the oxbow are clear evidence of sedimentation of overbank sediments in slack or stagnant water (Teisseyre 1985, Zieliński 1998, Falkowski 2007, Szmańda 2011). The dissected channel segment beneath the Łokieć bog could have been periodically active, as two borehole profiles on the southern side show an upward increase in the proportion of sand, suggesting that flow may have been more energetic at certain points in time. The additional presence of loam and sandstone debris in the fine-grained sediments on this side (Figure 6, Figure 7) confirms that material from the valley-side slope was occasionally supplied to the river channel.

The DEM of the basal surface of the peat layer indicates that the palaeochannel was much shallower (up to 1.5 m) and wider than the present-day San River channel, which is only 8–15 m wide. The palaeochannel now occupied by the Łokieć bog had an uneven bottom with hollows, a threshold and embayments in its right (northern) bank. Its southern bank was higher, and the deeper part of its bottom was covered mainly with clays and silts.

The cover of silts and clays on the bottoms of the detached and occasionally flooded elevated segments of the ancient river channel fostered the growth of peat bogs. The fine-textured sediments prevented effective infiltration of water into the underlying gravel and supplies of water were guaranteed by periodic flooding of the river and lateral seepage of groundwater from the nearby valley side (Łajczak 2014). The borehole data demonstrate that the peat layer is now thickest directly above the palaeochannel bottoms and the belt of thickest peat follows the curvature of the palaeochannels (Figure 4). Peat is thickest in the axial parts of the peat domes, and the bog surfaces rise highest over the deepest parts of the palaeochannels.

According to basal radiocarbon dates (Haczewski *et al*. 2016), peat accumulation started during the humid climate stages approximately 4300–3500 BP. The San River was active in the channel segments now occupied by the two peatlands (‘oldest’ in Figure 8) until the river changed course and incised new segments of channel (‘older’, ‘recent’ and ‘current’ in Figure 8). Suspension of the segments that nowadays contain peat bogs, and blocking of their ends with alluvium, could have taken place during one of two phases of increased fluvial activity in the Carpathians dated at 6500–6000 BP and 5000–4400 BP by Starkel *et al*. (2006). In its early stages, peat accumulation was often interrupted, as indicated by the siliciclastic intercalations in the lowermost layer of the Łokieć bog (cross section C–C_1 in Figure 6) which reflect repeated flooding of the terrace with silt deposition on the initialising peat bogs. Similar intercalations have been found in bog peat at another location in the San River valley, 6–8 km upstream (Ralska-Jasiewiczowa 1980).

The formation of both of our study bogs on the terrace of the San River that is elevated 4–6 m above the present-day channel bottom is undoubtedly related to the relief of the terrace and the type of alluvium laid down on its surface. This terrace is crossed by the courses of suspended cut-off fragments of palaeochannels cut into gravels of the contemporary level of the valley bottom. The presence of ancient channel segments beneath the peat bogs is confirmed by the DEMs based on borehole and levelling data from both peatlands; as well as by the thickness of peat, which exceeds the heights of the bog domes, and by the elongated shapes of both domes. The borehole data indicate that both bogs are directly underlain by mostly fine-grained fluvial sediments with the characteristics of overbank sediments, and especially those of oxbows. They were laid down in occasionally flooded basins abandoned by the San River following the incision of a new channel. The silt and clays are thickest in the oxbows. The presence of these sediments would inhibit drainage and create natural water reservoirs in the abandoned oxbows, thus helping to initiate peat accumulation. We also hypothesise that continued peat accumulation in both bogs would be assisted by groundwater seepage at the bases of valley slopes supplementing the water supplied as rainfall (Łajczak 2014).

The growth of biogenic sediments (especially peat) in oxbows is common in lowlands and in the valleys of great meandering rivers (e.g. Żurek 1975, 1990; Andersson & Schoning 2010, Kaiser *et al.* 2012, Forysiak *et al*. 2014, Okupny *et al*. 2014, Lipka & Zając 2018). Abandoned channels of sinuous rivers are favourable for the growth of oxbow peat bogs (Starkel 2001, Hughes & Barber 2003, Edvardsson *et al.* 2012). In the areas of Poland covered by the Middle Polish and Vistulian glaciations, such sites are among the most common locations of biogenic accumulation (Żurek 1987, Kloss 1993, Wójcicki 2014). Raised bogs seldom occur in mountain valleys, where reworking of floodplain deposits proceeds actively and peatlands are frequently eroded by fluvial action (Starkel 2014). Thus, both of the peat bogs that we studied in the Bieszczady Mountains are exceptional in being set in preserved palaeochannels.

AUTHOR CONTRIBUTIONS

JK conducted drilling on both peat bogs, analysed the samples of mineral sediments from beneath the peat, made geomorphological maps of the bogs and their environs, made the drawings (except for Figure 3), and wrote most of the text. MS conducted the levelling survey of the Łokieć peat bog dome, constructed the numerical models of the dome and substratum surfaces (Figure 3), and wrote the remainder of the text.

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