Annales Societatis Geologorum Poloniae (2021), vol. 91: 347–362 doi: https://doi.org/10.14241/asgp.2021.18

"GHOST STRUCTURES" IN ALKALINE FEN MICRORELIEF AS A CONSEQUENCE OF LATE GLACIAL PERIGLACIAL ACTIVITY IN CHALKLANDS – A CASE STUDY FROM THE CHEŁM HILLS (EAST POLAND)

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Dobrowolski, R., 2021. "Ghost structures" in alkaline fen microrelief as a consequence of Late Glacial periglacial activity in chalklands – a case study from the Chełm Hills (East Poland). *Annales Societatis Geologorum Poloniae*, 91: 347–362.

Abstract: On the basis of high-resolution LiDAR data, collected at the surface of alkaline fens in the Chełm Hills area (Lublin chalkland, East Poland), structures deviating from the natural paludification processes related to the development of fens ("ghost structures") were identified. At each of the sites analysed, field verification by means of drillhole cores indicates an indirect relationship between the modern topography of the peatlands and the morphology of their substratum, related to periglacial processes. Three categories of periglacial structure were recognized in the chalk bedrock: (1) solifluction sheets, lobes and terraces; (2) pingo-type structures (ramparted depressions, lithalsas); and (3) relict cryogenic mounds. A conceptual model of the development of slope and peatland relief in the Lublin chalkland during the Late Glacial and Holocene was prepared on the basis of the results obtained. The results indicate the role of the periglacially transformed chalk substratum in the development of alkaline fens in the chalklands, which rarely was considered in previous studies.

Key words: Alkaline peatlands, solifluction structures, relict cryogenic mounds, LiDAR.

Manuscript received 20 May 2021, accepted 7 October 2021

INTRODUCTION

Chalklands, which occur in Europe in several areas, including SE England, Normandy in France, Belgium, eastern Poland, southern Belarus and northwestern Ukraine (Fig. 1A), represent a special type of landscape that was the consequence of a specific geological structure, dominated by fissured Maastrichtian chalk and morphodynamic processes of various origins and ages. Soft carbonate rocks, such as chalk and chalky limestones, are very susceptible to both chemical solution and mechanical deformation, especially as a result of frost activity, with a tendency to postdepositional transformation (Murton and Ballantyne, 2017). As a consequence, the chalklands are characterized by the co-occurrence of: (1) a chalk karst complex, distinguished from the classic one by a different register of surface forms and the limited occurrence or lack of underground forms (Maruszczak, 1966; Rodet, 1991; Dobrowolski, 1998; Dobrowolski *et al.*, 2000; Maurice *et al.*, 2006), and (2) a complex of gentle denudational landforms, including convex forms, slightly inclined slopes, levelled foothills. Both complexes of forms were largely shaped/modified in the periglacial environment. The preservation of primary Pleistocene periglacial structures, especially their morphological manifestation in the modern landscapes of chalklands, is extremely rare, owing to the lithological features of chalk.

Periglacial environments, forming in the foreland of ice sheets, are characterized by a cold climate and significant ground freezing. The growth and melting of ground ice lead to ground deformation and drive the periglacial debris system. During climate warming at the end of the Pleistocene glacial periods, the ice-rich rock layer of the European chalklands thawed, creating deformation of the top parts of chalk grounds, and enhanced mass movements, especially solifluction (Murton *et al.*, 2003). In the long term, solifluction is considered to be the dominant mechanism of slope modification in periglacial environments, in spite of its slow rate and relatively long duration (Åkerman, 1996). It significantly contributes to the evolution of periglacial landscapes (Matsuoka, 2001), especially those of chalklands (Murton, 2021). Unfortunately, searching for a clear periglacial imprint on the present-day chalkland topography is often not

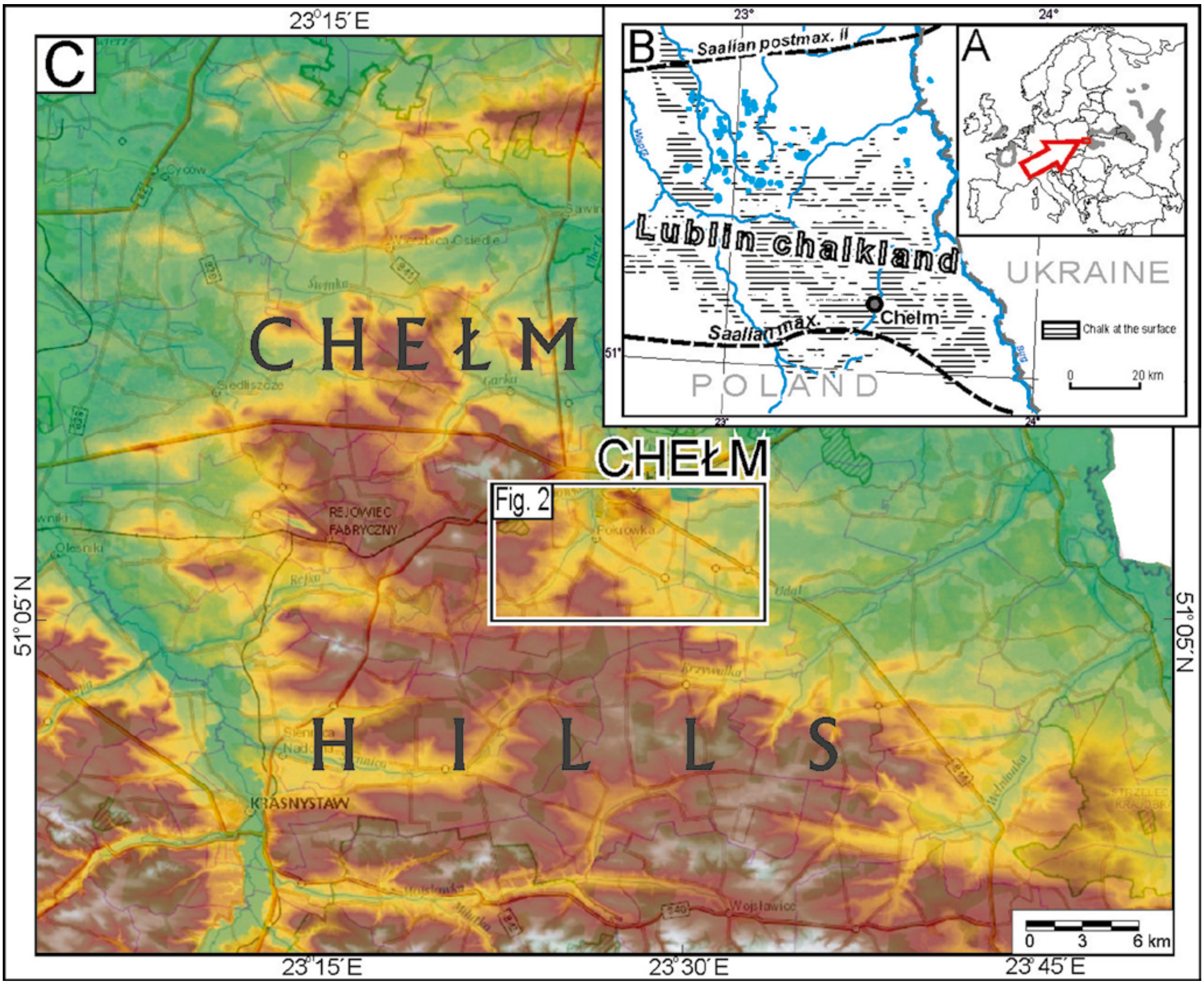

Fig. 1. Study area. **A.** Location in relation to the European chalklands. **B.** Location in relation to Lublin chalkland with the extent of the Saalian ice-sheet. **C.** Hypsometry of the Chełm Hills (after Geoportal 2, 2015); the range of Figure 2 is marked with a rectangle.

simple because of the masking role of Holocene denudation and accumulation processes, which completely blurred the history of the relief. Accordingly, the assessment of the scale of periglacial transformation in chalklands and clear-cut identification of landforms may be difficult, especially in strongly karstified and peat-covered areas. The detailed analysis of high-resolution LiDAR data for these areas may provide qualitatively new information on the periglacial fossil slope forms, which are hidden and well preserved below the peat cover of large peatland complexes, also recorded as "ghost structures" in peatland microrelief.

In this paper, probably for the first time, the origin and age of these phenomena are discussed. Well-preserved "near-surface periglacial relics" beneath ploughed soil have been identified by many authors on aerial photographs on the basis of different soil moisture conditions and patterns of land use (e.g., Williams, 1964; Heyse and Ghysels, 2003; Bateman *et al.*, 2014; Van Vliet- Lanoë *et al.*, 2017; Fabijańska and Dąbski, 2019). However, mainly polygons could be identified, owing to lithofacial differences in the infilling of structures and in the host rocks. Other Pleistocene periglacial structures generally were not identified in contemporary chalkland relief. Moreover, the duplication of periglacial substratum structures in the micromorphology of fens (as 'ghost structures') so far has not been of particular interest to researchers, either in the geomorphological (morphogenetic reconstruction) or telmatological (analysis of peat-forming plant successions) contexts. Thus, the term "ghost structures" used in this article refers to those deposits and palaeoforms of peatland basement, which are reflected in the micromorphology of the mire. This kind of preservation of old structures under an overlayer of organic deposits and their clear manifestation in the modern topography of fens is a consequence of the properties of paludic accumulation, the aggradation of peat determined by relief of the substratum.

The main goals of this research are (1) identification y of relict slope forms recorded under Holocene peat at the foot of chalk hills, on the basis of the analysis of high-resolution aerial images, (2) verification of the assumed periglacial origin of these forms by means of the lithofacies analysis of sediments from drillhole cores, and (3) creation of a conceptual model of the development of slope relief in chalklands during the Late Glacial and Holocene, which takes into account the peatland succession governed by the relief of the substratum.

MATERIAL AND METHODS

The main source of information about "ghost structures" underneath the Holocene peats in the Chełm Hills in the Lublin chalkland (East Poland) was a survey of aerial images from the High Resolution Orthophotomap for Poland with terrain pixel size 25 cm (Geoportal 2, 2015). Further detailed spatial analysis of four selected sites (Strupin, Krzywice, Kamień, and Zawadówka; Fig. 1) was conducted on the basis of LiDAR data using Airborne Laser Scanning (ALS). This resulted in the creation of a Digital Terrain Model (DTM) with a horizontal accuracy of 1 m and vertical accuracy <0.15 m. The DTM was created by converting ASCII files directly to raster in ArcMap (ESRI). Analysis of aerial photographs in the final stage was coupled with verification fieldwork, based on numerous geological drillholes along geodetic transects and lithofacies analysis of the bottom parts of cores, comprising the transformed chalk basement.

Some of these sites had been the subjects of previous field research in the context of the development of the chalk karst landforms in relation to the tectonic structures of the Late Cretaceous massif (Harasimiuk, 1975; Dobrowolski, 1998; Dobrowolski *et al.*, 2015) and/or the evolution of spring-fed fens (Dobrowolski *et al.*, 2002, 2005; Pazdur *et al.*, 2002; Pietruczuk *et al.*, 2018).

New field studies were performed to extend the previous observations to cover the influence of the periglacial environment on the carbonate basement. In selected locations, corresponding to the opposite parts of the "ghost structures", i.e., depressions *vs*. ridges/ribs, cores with an undisturbed internal structure of the sediments were collected. Each core was analysed macroscopically and described using the non-genetic Troels-Smith formula (Troels-Smith, 1955), modified by Dobrowolski (2011).

STUDY AREA

Geological and hydrogeological background

The bedrock of the area analysed is dominated by the Late Cretaceous rock complex with the Upper Maastrichtian formation at the top and represented mainly by chalk and chalky limestone facies (Wyrwicka, 1980). The carbonate rock complex (ca. 300–400 m thick), dipping monoclinally to the SW, was affected by disjunctive tectonic movements, related to the Laramide and Young Alpine orogenic phases (Harasimiuk, 1980). Consequently, it is strongly fissured by two systems of orthogonal joints and numerous mesofaults (Dobrowolski, 1995; Dobrowolski *et al.*, 2014). The Paleogene and Neogene deposits occur as the infillings of the post-Sarmatian grabens (Harasimiuk and Henkiel, 1979) and as cover material on isolated chalk hills (Harasimiuk 1975). Their thickness varies from several decimetres in the northern part of the Chełm Hills to over 30 m in the tectonic grabens in the southern part of the area (Harasimiuk, 1975).

This area was glaciated three times (Marks, 2005) and was within the range of pro- and/or extraglacial permafrost four times (Dobrowolski, 2006). The Pleistocene deposits of various ages and lithologies occur as thin, strongly denuded patches. These are mainly Saalian glacial and glaciofluvial sands and glacial tills, as well as Weichselian fluvial or lacustrine silts and sands (Fig. 2). Diluvial sands and silts (chalk diamicton *sensu* Murton and Ballantyne, 2017), related to the periglacial environment, commonly occur at the foot of the chalk hills. Periglacial conditions played an important role in the transformation of the Neogene and Pleistocene relief of the area (Dobrowolski, 2006). They also had a significant influence on Holocene morphogenesis (Dobrowolski *et al.*, 2014). Holocene deposits, mainly peats and peat alluvia, fill the bottoms of river valleys, extensive depressions outside the valleys, and numerous closed depressions (Fig. 2).

The shallowest aquifer is in the Late Cretaceous rocks. The aquifer is generally unconfined, although in places, mainly in the slope-foot zone, it is slightly confined owing to the occurrence of chalk residue and/or chalk diamicton, which can result in the rise of groundwater. The development of the hydrological conditions of the area has been strongly affected by the occurrence of tectonic joints in the Late Cretaceous complex. Because of the low permeability of the chalk, tectonic faults are the main zones of groundwater flow.

Site description

The Chełm Hills mesoregion is a core area of the Lublin chalkland (eastern Poland), located in the borderland of the Lublin Upland and the Western Polesie Lowland (Solon *et al.*, 2018). All sites are situated in the contact zone between the foot of the high elevated chalk hills and large polygenetic depressions filled with Holocene peats (Fig. 2).

Strupin site (51°05'08"–51°05'29"N; 23°28'59"–23°29'41"E)

It is a vast, NW–SE elongated basin, ca. 2 km^2 in area, 2 km long, and 0.5–1 km wide, the location of which was controlled by tectonic factors (Dobrowolski, 1998). In the southwest, it is closed by an isolated chalk hill rising to 232.0 m a.s.l. To the north, south and east, the basin borders on low (up to 197.5 m a.s.l.) chalk ridges, in places covered by thin patches of Saalian glacigenic sands or Weichselian fluvial and lacustrine sands and silts. The basin bottom, covered by biogenic deposits (gyttjas and peats), is flat and rises from 192.0 m a.s.l. in the southeast part to 195.0 m a.s.l. in the northwestern part. The basement relief, reconstructed on the basis of about 120 geological drillholes (Dobrowolski, 1998), is variable and distinctly asymmetric.

Krzywice site (51°04'45"–51°05'00"N; 23°30'00"–23°30'33"E)

The site is located in the headwaters part of the Udal River catchment, to the south of the chalk ridge separating it from the Strupin site. The studied fragment is a small, SW–NE elongated, basin-shaped depression, about 0.15 km^2 in area, 0.8 km long and 0.25 km wide. Its bottom,

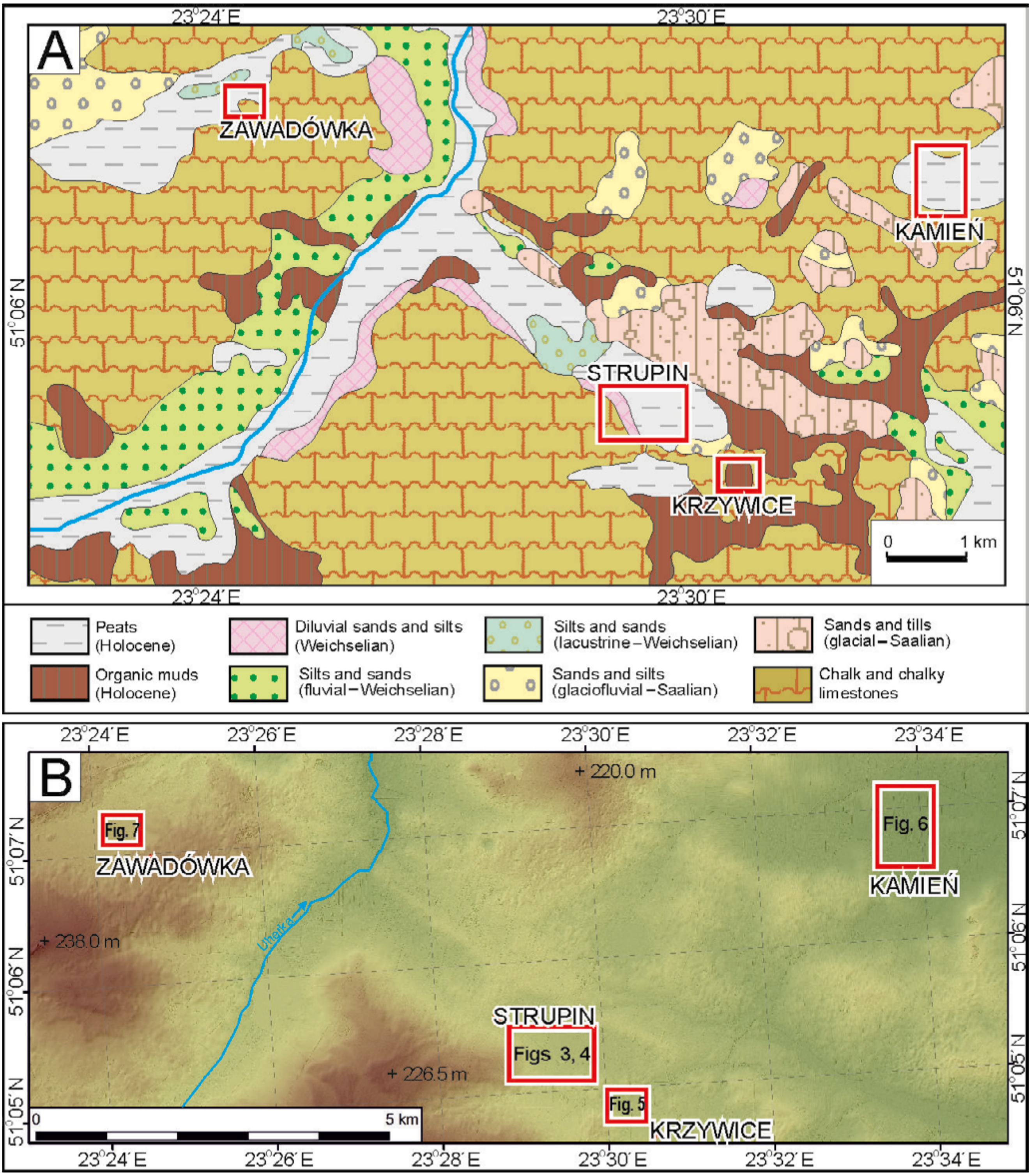

Fig. 2. Location of the research sites. **A.** Geological map (surface deposits) of the study area (after Harasimiuk *et al.*, 2006a, b). **B**. Digital Terrain Model (after Geoportal 2, 2015); the ranges of Figures 3–7 are marked with rectangles.

covered by peats and organic muds, rises from 191 m a.s.l. in the northeast to 192 m a.s.l. in the southwest. To the west, it borders on hills composed of chalky limestones (202 m a.s.l.). Slightly lower ridges (195 m a.s.l.), forming the northern and partially southern margins, are covered in places by a thin layer (<1 m) of Pleistocene sands. The thickness of peat deposits at the bottom of the depression does not exceed 2.5 m.

Kamień site (51°06'40"–51°07'02"N; 23°33'25"–23°34'00"E)

This is the western, peripheral part of a large, polygenetic depression, clearly visible in the surface of the karstified chalk area. The part of the depression studied is about 3.5 km^2 in area; the length of the sublatitudinally oriented long axis is 2.5 km and of the transverse axis is 1.5 km. The bottom of the form (182–180 m a.s.l.), drained by the Kacap River, slopes to the east. Chalk is exposed in the immediate vicinity of the entire basin. To the west, the depression borders on an isolated chalk hill (223 m a.s.l.), nowadays almost completely mined out by an open-cut chalk mine. Chalk ridges (195 m a.s.l.), which are in places covered by patches of Saalian tills and glacigenic sands and/or Vistulian periglacial sands, form the northern and southern boundaries of the basin (Fig. 2). The thickness of organogenic deposits in the study area does not exceed 1.5 m.

Zawadówka site (51°07'03"–51°07'20"N; 23°24'11"–23°24'35"E)

This is a spindle-shaped basin (ca. 3 km^2 in area, 3.5 km long, 0.5–1 km wide) with a SW–NE orientation, distinctly distinguishable among the surrounding isolated chalk hills, rising to 268-270 m a.s.l. in the north and west and to 220–248 m a.s.l. in the south and southeast. The basin bottom, covered by Holocene alkaline peats with a maximum thickness of ca. 6 m, slopes to the northeast (from 209 to 201 m a.s.l.). Late Cretaceous carbonate rocks are exposed in the entire area. In the immediate vicinity of the depression to the north, they are covered by Saalian glaciofluvial sands (Fig. 2). In the central part of the study area, ascending springs occur, feeding the cupolas of spring-fed fens (Dobrowolski *et al.*, 2005).

RESULTS

Strupin site

Spatial analysis. The analysis of high-resolution aerial images of this site indicates the occurrence of two types of structure (both with a height difference of ca. 15–30 cm) in the microtopography of the peatland, which are reflections of the structures in the basement, beneath the peat (Fig. 3). The set of structures includes: (1) a complex of relatively narrow humps/banks (2–10 m wide) with a lobate or tortuous pattern, generally with a NW–SE orientation, parallel to the peatland axis; and (2) annular mesoforms (5–25 m in diameter; width of the ramparts is ca. 1–5 m), concentrated close to the marginal part of the chalk hill, at the contact with the fen depression.

Geological survey/verification. The Strupin peatland has geological documentation with a detailed description of the organic deposit sequence and a reconstruction of the configuration of the chalk basement (Dobrowolski, 1998). The maximum thickness of the organic deposits in the entire depression is ca. 9 m, but in the analysed part of the fen it does not exceed 3 m. The palaeorelief of the fen basin is asymmetric and indicates the presence of a relatively flat southwestern slope and a steep northeastern one (Fig. 4). Geological cross-sections, transverse to the depression,

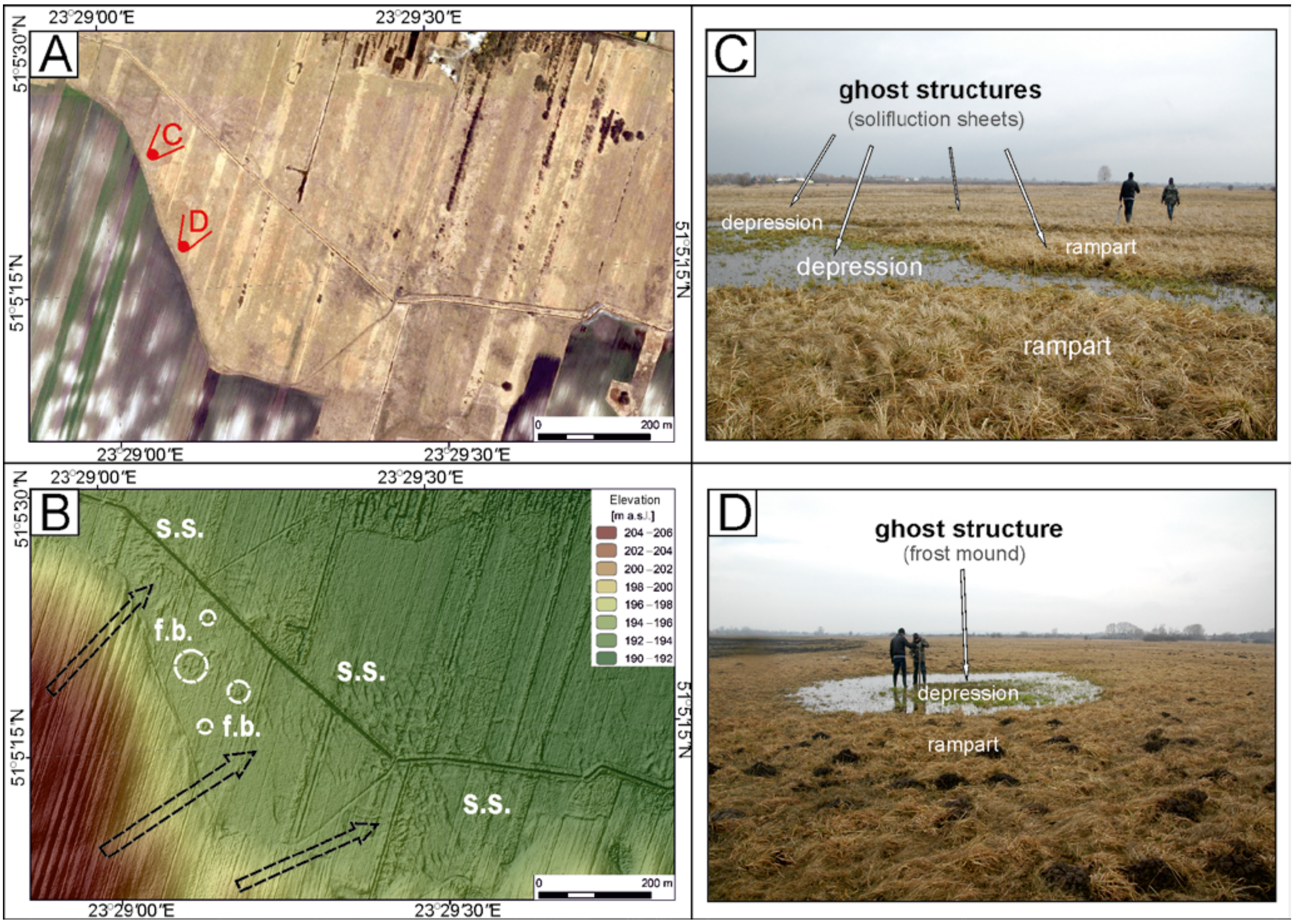

Fig. 3. Strupin site (source – Geoportal 2, 2015). **A.** Aerial photograph with the location of places where the terrestrial photos were taken (C, D). **B**. Digital Terrain Model (DTM) with the distribution of ghost structures: s.s. – solifluction sheet, f.m. – frost mound; the assumed directions of solifluction movements are marked with arrows. **C, D.** Terrestrial photos of ghost structures (location of the photograhs in A).

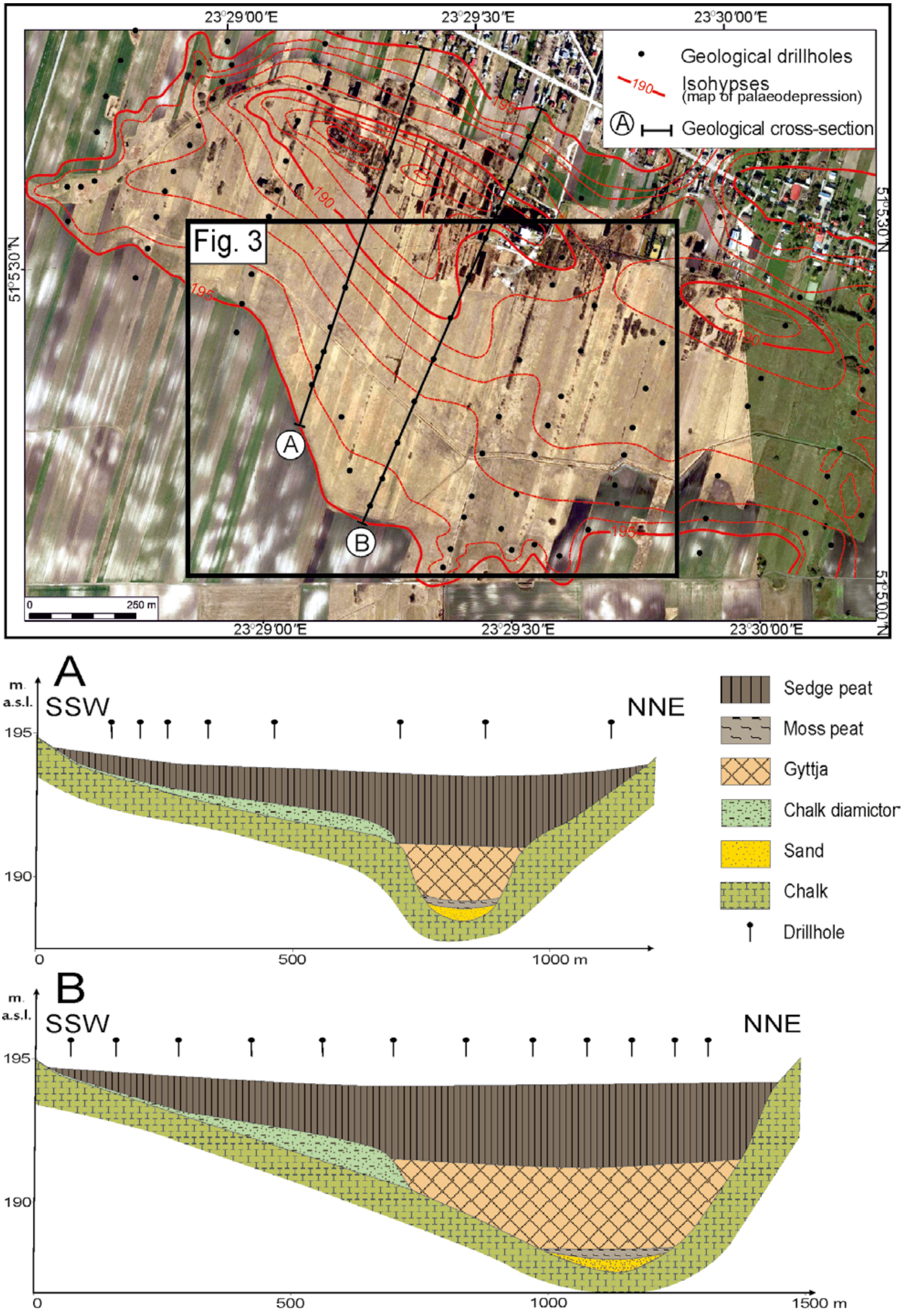

Fig. 4. Strupin site – map of the alkaline fen substratum in relation to the DTM, with the location of geological drillings (after Dobrowolski, 1998). **A**, **B**. Geological cross-sections.

indicate the presence in the bedrock of the southwestern part of the depression of a redeposited, weathered chalk layer (regolith) with a thickness of 0.5–2.0 m, forming distinct terrace steps (Fig. 4). These forms, which resulted from periglacial activity, extend approximately 300–500 m from the escarpment and have overall slope gradients of approximately 5–7°. Renewed geological drilling within the "ghost structures", with the recovery of cores with non-disturbed deposits, allowed the author to carry out a lithofacies analysis of: (1) the chalk basement and (2) the biogenic deposits. The sequence of major lithofacies in the cores includes two segments in both cases, in the "ghost depressions" and above the "ghost humps": (A) mineral and (B) biogenic. Their description is presented in Table 1.

As a result of a previous geological survey in the southwestern part of the depression, a complex of 10 pipes, described as karst pipes, was found under the peat cover (1–1.5 m thick) in the chalk basement. The horizontal dimensions of the pipes are 0.4–0.6 m in diameter and the depth without the peat overlayer is 2–3.5 m (Dobrowolski, 1998). Three types of such forms have been distinguished, differing in the nature of infillings and the degree of sediment consolidation, indicating possible development stages: (1) without infillings, contemporarily supplied by ascending groundwater, (2) filled with unconsolidated, hydrated calcareous gyttja, and (3) filled with consolidated, compact calcareous and/or detrital calcareous gyttjas, slightly laminated (Dobrowolski, 1998).

Krzywice site

Spatial analysis. An aerial image of the site shows the set of linear structures on and beneath the peat cover (ghost structures). They are mainly parallel to each other, in some parts slightly contorted in relation to the depression axis, and their orientation follows the edge of a local chalk hill. The differences in height of these microstructures on the surface of the peatland are ca. 15–20 cm. The width of the single ramparts is 2–4 m and the distance between them is from 1 to 25 m (Fig. 5).

Geological survey. The thickness of the organic deposit cover in the headwaters part of the Udal River catchment does not exceed 2 m. The depression is filled with organic muds and sedge peats. Below the organic deposits, there is a 1–1.5 m-thick layer of weathered, redeposited chalk. Three categories of lithofacies were found in this chalk bedrock: (1) coarse- and medium-grained, sharply angular clasts of chalk in a silty matrix, (2) massive chalky diamicton, and (3) organic silt in a chalky matrix.

Kamień site

Spatial analysis. A very frequent type of "ghost structure" was distinguished as a result of detailed DTM analysis of the site. It is represented by a set of dense, very narrow humps/ribs. Several dozens of such forms occur over a distance of approx. 0.5 km, strongly undulating in plan view,

Table 1

Description of the deposits from the Strupin site according to Troels-Smith (1955) and Dobrowolski (2011).

Segment	**Unit**	**Presence within the "ghost structure"**		**Description**	**T-S formula**
		depression	**rampart**		
A – mineral basement (bedrock)	1	-	+	coarse, sharply angular clasts of chalk in a silty matrix	Gmaj.3, As1, Ag+, nig.0, sicc.2, elas.0, strf.0
	2	+	+	massive chalky diamicton, in some parts with inserts of silts and sands, with ductile microdeformities	Gmin.2, As1, Ag1, nig.0, sicc.2, elas.0, strf.0
	3	+	+	massive chalky silt with inserts of sands and/or single fine clasts of chalk	As3, Ag1, Gmaj.++, nig.0, sicc.2, elas.0, strf.0
	4	+	+	organic silt in the chalky matrix	As3, Sh1, nig.3, sicc.2, elas.0, strf.0
B – organic deposits	1	+	-	detritus-calcareous gyttja with malacofauna	Ld2, Lc2, Sh+, test (moll.), nig.1-2, sicc.1, elas.0, strf.0
	2	+	-	sedge-moss peat, medium and well decomposed with dispersed amorphous calcium carbonate and malacofauna	Th$^{3-4}$2(Car.), Tb$^{2-3}$1, As+, test (moll.), nig.3-4, sicc.2, elas.0, strf.0
	3	+	+	sedge peat, medium and well decomposed, silty, with dispersed amorphous calcium carbonate	Th$^{3-4}$3(Car.), As1, Cp(min.)+, nig.2-3, sicc.2, elas.1, strf.0
	4	+	+	sedge-reed peat, slightly decomposed, with malacofauna	Th$^{1-2}$3(Car.), Th$^{1-2}$1(Phr.), Cp(min.)+, test (moll.), nig.4, sicc.2, elas.2, strf.0
	5	-	+	calcareous tufa, medium- and coarse-grained	Cm(maj.)2, Cm(min.)2, nig.1,sicc.2, elas.0, strf.0

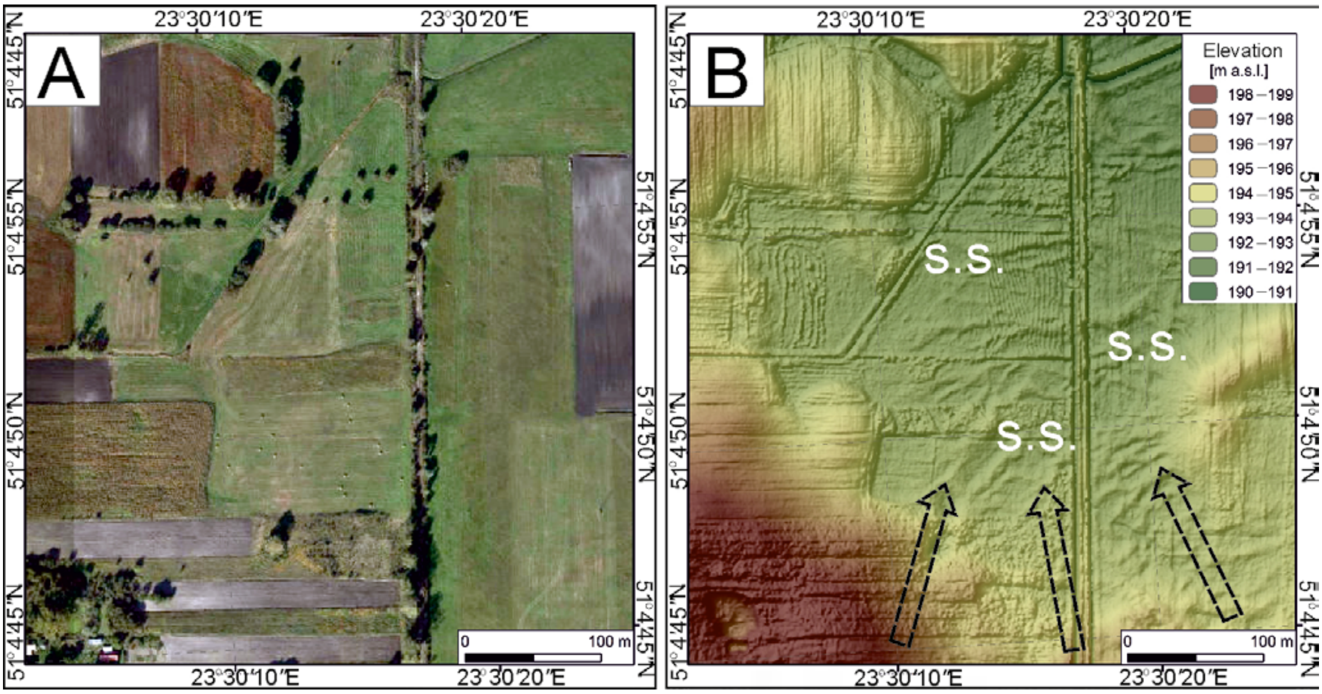

Fig. 5. Krzywice site (source – Geoportal 2, 2015). **A**. Aerial photograph. **B**. Digital Terrain Model (DTM) with the distribution of ghost structures: s.s. – solifluction sheet; the assumed directions of solifluction movements are marked with arrows.

and longitudinally oriented, perpendicular to a high, local chalk hill. The structures are arranged in the form of an inverted, anastomosing pattern (Fig. 6). The length of individual ribs is 1–1.5 km, the width is 1–5 m, and the distance between them is usually 2–10 m.

Geological survey. The organic cover of the depression is very thin. In the western part, it is composed of organic muds, which pass into sedge peats, less than 2 m thick, in the eastern part. The mineral segment, including chalk bedrock, consists of 4 main units: (1) coarse- and medium-grained chalk clasts in a silty matrix, occurring only in embankments in the bedrock; (2) massive chalky diamicton, in some parts with inserts of silts and sands; (3) silty sands with medium-grained chalk clusters; and (4) organic silt in a chalky matrix.

Zawadówka site

Spatial analysis. The detailed DTM analysis (LiDAR data) allowed the author to distinguish two types of "ghost structure" with height differences of 15–30 cm in the surface image: (1) a set of linear ridges/ribs, arched in places, up to 500 m long and 2–5 m wide, following the edge of a local chalk hill; and (2) elliptical or oval ring structures with an area of 1500–5000 m^2 and axis dimensions of 40–80 m, located on the edge of the depression, on the border with the foot of a chalk hill (Fig. 7).

Geological survey. The Zawadówka peatland has detailed geological documentation (Dobrowolski *et al.*, 2005). The maximum thickness of the organic deposits in the entire large depression is ca. 6 m, but in the analysed part of the fen it is relatively small and does not exceed 3 m. The organic cover is composed mainly of sedge and sedge-reed peats, in some parts lined by calcareous gyttja. The chalk basement beneath the peats consists of 3 main units: (1) brecciated chalk (disaggregated and comminuted chalk) in a silty matrix, (2) massive chalky diamicton with single fine clasts of chalk, and (3) organic silt in a chalky matrix.

DISCUSSION

The results of the investigations, a combination of spatial analysis and geological surveys, particularly the textural features of the redeposited chalk basement, indicate that the structures analysed represent three categories of periglacial form, connected with the processes of: (1) solifluction and slopewash forming solifluction sheets, lobes and terraces, (2) degradation of segregated ice in pingo-type structures (ramparted depressions, lithalsas), and (3) degradation of intrusive ice, forming relict cryogenic mounds.

Solifluction structures

Solifluction is the term used to describe a combination of two slow geomorphological processes related to the periglacial environment, namely (1) soil creep (frost-heave followed by thaw-settlement) and (2) gelifluction, which is the slow thaw-induced, saturated flow of soil (Ballantyne and Harris, 1994). Such phenomena, the most widespread slope-deforming processes in the periglacial environment, are strictly dependent on the geological substratum. They are very common in areas, where rock outcrops are susceptible to frost activity. Chalk is a special example of such rocks (Murton, 1996, 2018). Although solifluction rates in such areas are generally limited to a few centimetres per year,

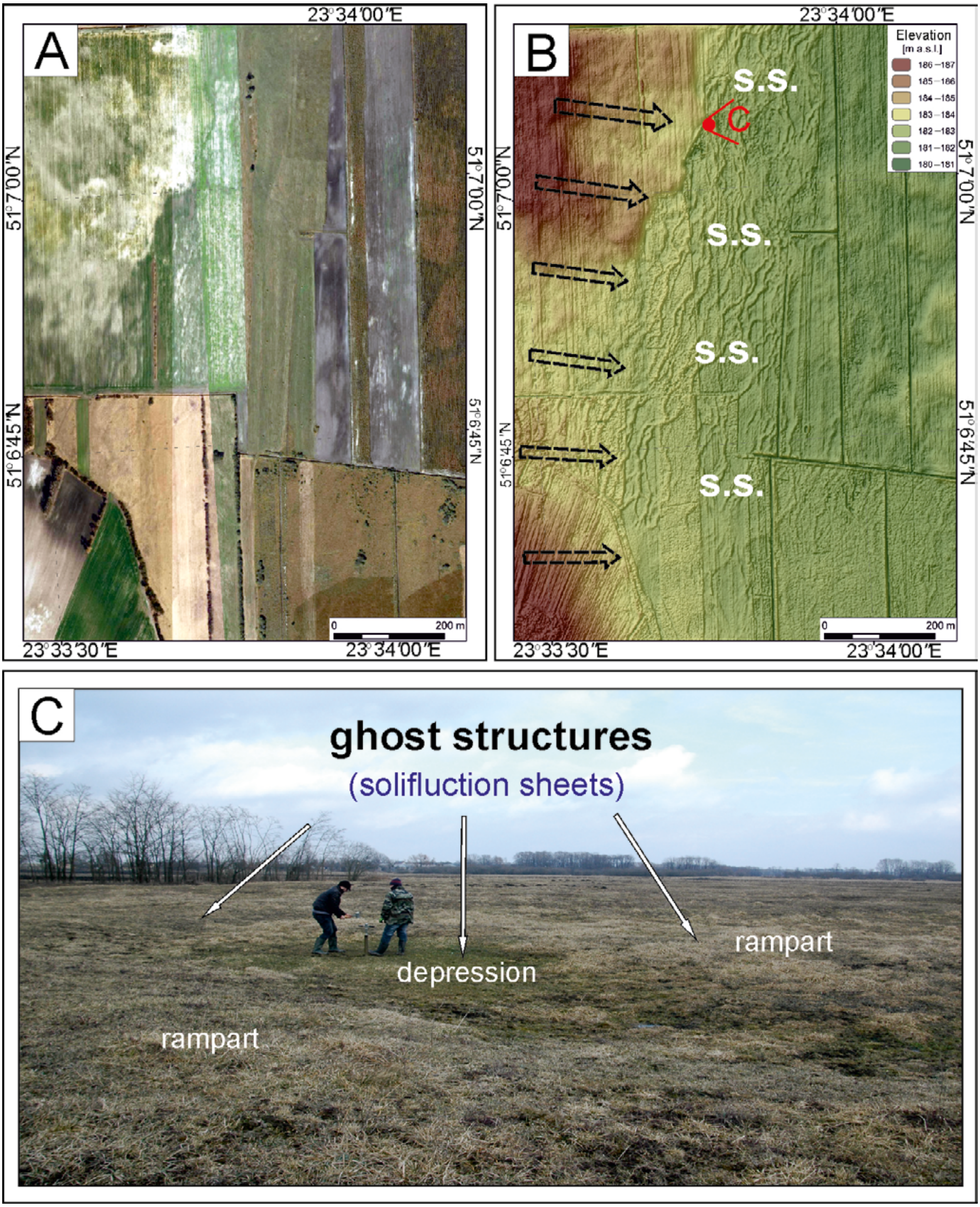

Fig. 6. Kamień site (source – Geoportal 2, 2015). **A**. Aerial photo with the location of the place where the terrestrial photo was taken (C). **B**. Digital Terrain Model (DTM) with the distribution of ghost structures: s.s. – solifluction sheet; the assumed directions of solifluction movements are marked with arrows. **C**. Terrestrial photo of ghost structures (location of the photograph in A).

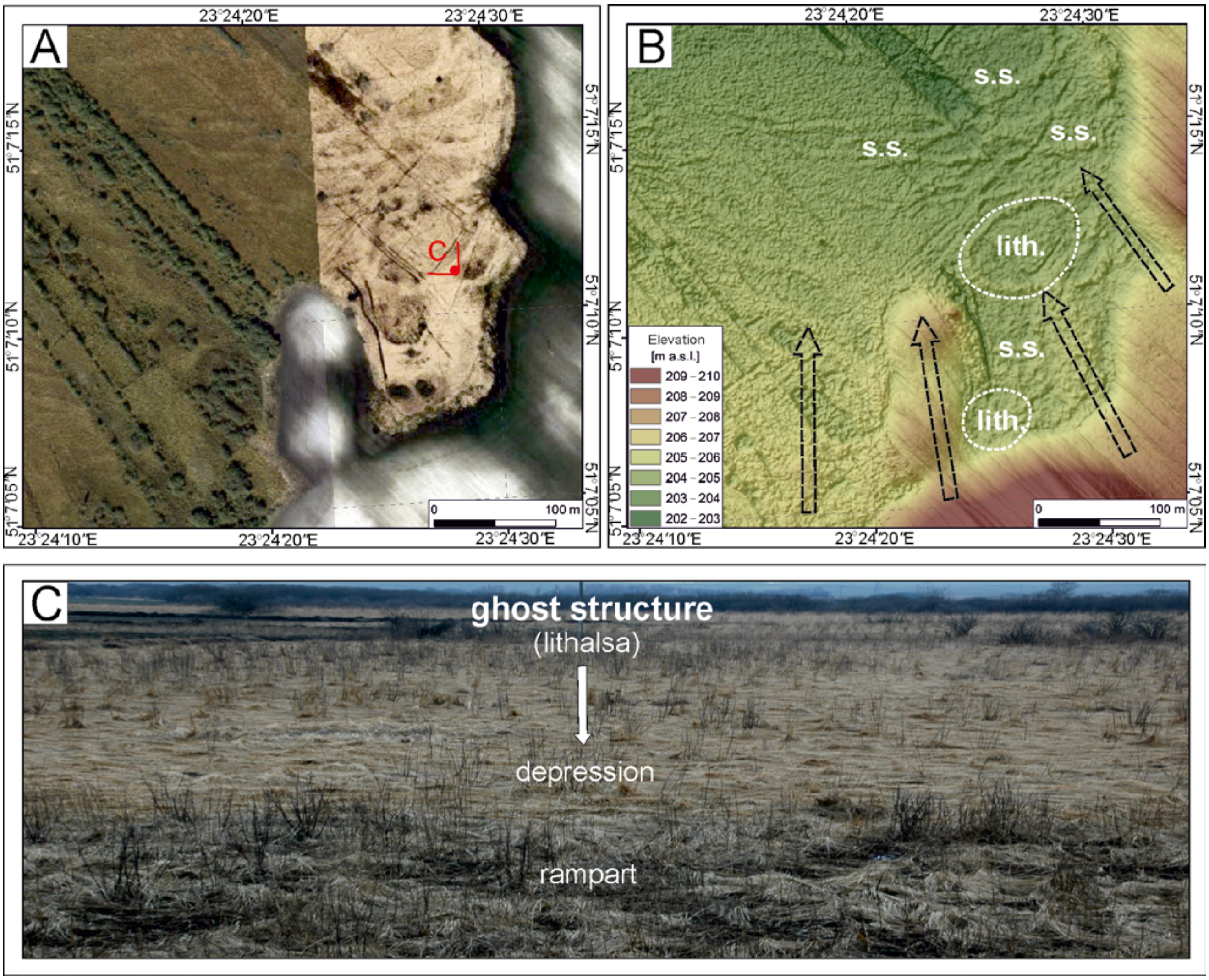

Fig. 7. Zawadówka site (source – Geoportal 2, 2015). **A**. Aerial photo with the location of the place where the terrestrial photo was taken (C). **B**. Digital Terrain Model (DTM) with the distribution of ghost structures: s.s. – solifluction sheet, lith. – lithalsa; the assumed directions of solifluction movements are marked with arrows. **C**. Terrestrial photo of ghost structures (location of the photograph in A).

they are the dominant periglacial mechanism of slope modification in the long term (Åkerman, 1996). Accordingly, the periglacial Pleistocene transformation, especially by way of solifluction processes, had a significant impact on changes to the primary landscapes of chalklands (Bateman *et al.*, 2014; Murton, 2018).

The term 'solifluction sheet' refers to the areas of mobile (or formerly mobile) regolith, often terminated in the foothills, forming step-like ridges or ribs that extend transversely to the slope. In places, where the marginal part of the solifluction sheets takes a more curved shape (solifluction lobe), this indicates locally accelerated mass movement (Harrison *et al.*, 2010). Such forms were described from contemporary areas of polar deserts (Matsumoto and Ishikawa, 2002; Verpaelst *et al.*, 2017) and many locations in the British Isles (Ballantyne and Harris, 1994; Harrison, 2002; Mitchell, 2008). Solifluction sheets are relatively smooth and continuous debris mantles that cover areas of up to several square kilometres (Washburn, 1980; Ballantyne and Harris, 1994). They deposited sediment in repeated cycles, at the foot of the hills, on the valley floor or at other similar topographical locations, where the slope gradient decreases, and they can form systems of terrace-like landforms. As a consequence, they are often termed solifluction terraces (Ballantyne and Harris, 1994).

In all of the studied sites in the Chełm Hills, the structures analysed have a record of lithofacies succession, typical of the periglacial environment (Murton and Ballantyne, 2017). At the foot of a chalk hill, they form a distinctive, ordered pattern of landforms, composed of repeated solifluction sheets (rarely solifluction lobes), subparallel to the edge of the hill, marking successive generations of these landforms. Owing to the mechanical properties of the chalky material, the saturated regolith moved down the slope and caused ductile deformation en masse in the marginal part of the solifluction sheets, forming narrow zones of humps/banks. Their significant number, amounting to several dozen identified structures in each site, points to the long-term, common nature of the depositional processes,(repeatedly continued in similar weather conditions, and also indicates the primary direction of solifluction flow. The intensification of solifluction processes was mainly related to the transition periods between cold and warm episodes of the Late Glacial: Oldest Dryas and Bølling, Older Dryas and Allerød and Younger Dryas termination (Fig. 8; Dobrowolski, 2006). In these periods, a gradual increase in the average annual air temperature occurred, reaching even up to approximately 4.5°C in the study area (Maruszczak, 1974). Rapid temperature changes, especially in summer, resulted in the deepening of the permafrost active layer, initially without a succession of vegetation preserving the slope surfaces (Müller *et al.*, 2020).

“Ghosts” of solifluction sheets, relics of the final phase of solifluction, are still preserved beneath the peats. However, generally they are not visible on the slopes, owing to the transformation by Holocene denudation and extensive agricultural cultivation (Fig. 8). As mass movements took place in host material, dominantly composed of silty deposits, the slow accumulation of new material on the foothill surface led to the syngenetic development of permafrost and to the aggradation of ground ice over the pre-existing surface. The movement of saturated regolith on the slope, owing to the inflow of meltwater, resulting from numerous near-surface freeze-thaw cycles, caused vertical and lateral sorting and reshaped the morphology of the slope and its foothill (Verpaelst *et al.*, 2017).

An analogous assemblage of periglacial forms, considered to be the most widespread depositional landforms in chalklands, was described in many English chalkland uplands (Bateman *et al.*, 2014), where they form distinct ‘solifluction terrace steps’ composed of chalky regolith (Murton and Ballantyne, 2017). Their deposition was dated using the OSL method, mainly as the Younger Dryas (Harrison *et al.*, 2010). Verpaelst *et al.* (2017) point to the strong influence of the morphology of solifluction structures (solifluction sheets and lobes) on the ice content of the permafrost. According to these authors, ice-poor zones existed in general under the peripheral ridges, whereas ice-rich zones were formed under the central depression of the sheets/lobes. Active layer deepening in solifluction sheets and lobes would be temporarily buffered by the high ice content of the ice-rich zone formed in the central depressions, while the thawing of the relatively ice-poor ridges should in general be faster. Hence, the ridges of solifluction sheets/lobes are more susceptible to permafrost degradation than the central depressions (Verpaelst *et al.*, 2017).

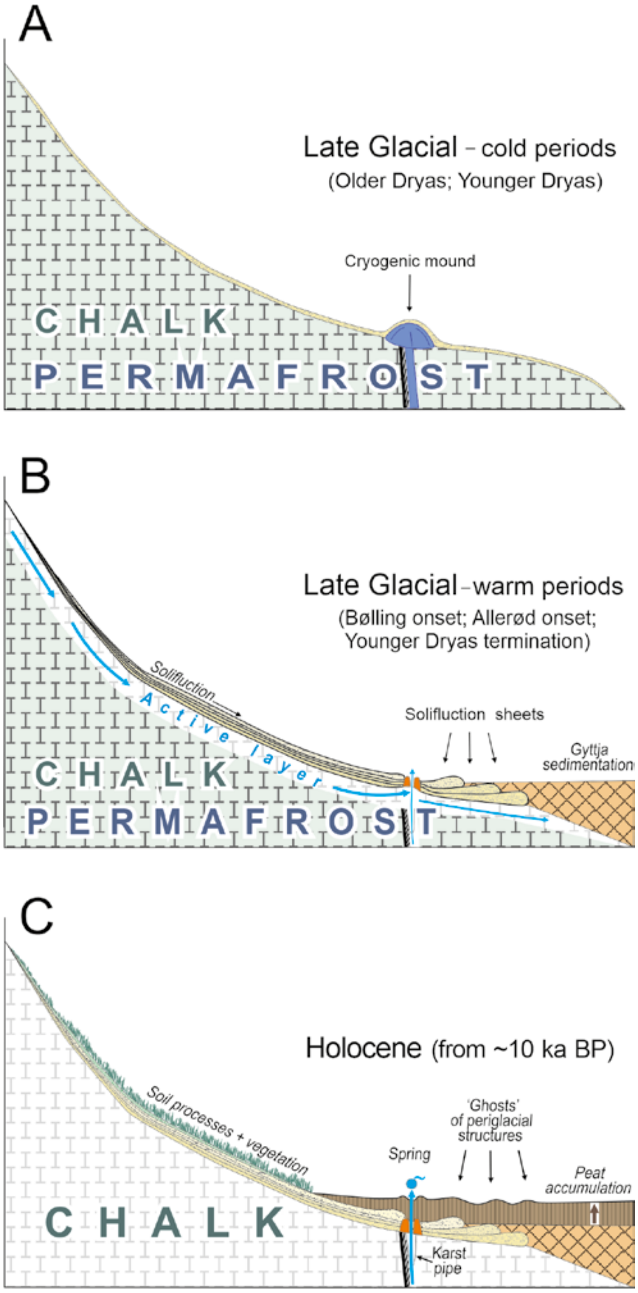

Fig. 8. Model of the development of ghost structures in the Chełm Hills; detailed description in the text.

Relict cryogenic mounds

In two cases, at the Strupin and Zawadówka sites, apart from the solifluction structures on the border between the chalk hills and the peatland basin, ring structures were identified as small closed palaeodepressions with readable ramparts. The geological and geomorphological contexts show that they are relict frost mounds, marking the sites of former pingos or related forms – lithalsas or mounds, transitional between palsa and frost blisters (Wolfe *et al.*, 2014; Murton and Ballantyne, 2017). Their size, including their horizontal orientation, axis length and rampart width, however, is clearly differentiated, indicating a separate mechanism for their development. Similar morphological variations of such forms have been described from many other chalklands (Walmsley, 2008; Clay, 2015; West, 2015). Four types of relict ground-ice depressions in the English chalklands were distinguished by West (2015): (1) clusters of fresh ramparted depressions, related to active springs at the heads of low valleys, (2) isolated ramparted depressions, close to springs in valleys, (3) oblong forms on the slopes of shallow valleys, and (4) degraded forms with little surface expression that are widespread in higher locations, related to the limit of former glacial lakes.

The features of ring structures in the Strupin site indicate the type-1 palaeodepression, proposed by West (2015). All ramparted depressions occurring here are associated with artesian springs, active today and in the past (Dobrowolski, 1998). French (2007) described such forms as the remnants of frost mounds, transitional between palsas and frost blisters, which may result from a combination of ice segregation and ice injection. Fault-guided groundwater seepage to the freezing front at this site could have favoured both ice segregation and intrusive ice formation (Ross *et al.*, 2011). Thus, they should be interpreted as former frost mounds that developed as a result of seasonal or perennial freezing of the active layer, where groundwater under increased hydrostatic pressure (artesian springs) caused doming of the ground through the development of intrusive ice (Pollard and French, 1984). The growth of cryogenic mounds in the study area occurred mainly in the ascending phases of cold periods, especially during the first part of the Younger Dryas (Dobrowolski, 2006). The water was subjected to increased hydrostatic pressure as a result of repeated solifluction flows in the relatively warmer periods (summer half-year) of the Late Glacial. High water pressures were produced by the confined downslope flow of groundwater beneath frozen ground and by the occurrence of clayey layers of solifluction covers. Repeated groundwater injections into the cracked rock massif yielded complex intrusions, finally forming ice cores of open pingos and frost mounds (Liestøl, 1996). According to Mackay (1978, 1988), Washburn (1980), and Huijzer and Isarin (1997), open pingo systems can form under consolidated ground conditions, when the average annual air temperature is between –4°C and –1°C. Thus, in the study area, permafrost may have formed during aggradation in the cool climatic phases of the Late Glacial.

On the other hand, at the Zawadówka site there are only palaeodepressions of type 2 *sensu* West (2015), which are interpreted as former open-system pingos. However, considering the fact that the peats covering the form are younger than the identified structure and that their development was not related to mound formation, it would be more appropriate to refer to these structures as former lithalsas (*sensu* Pissart, 2002), developed through ice segregation in mineral ground. Ice segregation resulted in the cracking of porous chalk and the formation of an ice-rich, brecciated layer in the upper segments of the permafrost. This layer was prone to melting and thawing, which in the absence of drainage resulted in an increase in pore water pressure and deformation of the sediment. The height and width of the embankments in all identified lithalsas are a consequence of the primary morphology of each mound, the thickness of mineral cover and its lithological features, and the course of local slope processes during the melting of the ice core. Since the state of preservation of both types of ring palaeostructures in the study sites is relatively fresh, and the age of the biogenic cover deposits is considered to be early Holocene (Dobrowolski *et al.*, 2005), it should be assumed that all relict frost mounds, like the analogous English sites (Clay, 2015; West, 2015), developed in conditions of discontinuous permafrost at the end of the Younger Dryas and their degradation took place at the beginning of the Preboreal period, along with the progressive warming of the climate (Dobrowolski, 2006). The analysis of stable oxygen isotopes for the study sites shows that it was supplied only by isotope-light groundwater during the entire Late Glacial period. This fact indicates explicitly the melting origin of groundwater (Dobrowolski et al., 2002).

Periglacial structures vs. organic succession of the fen

The presence of "ghost structures" in the micromorphology of contemporary alkaline fens raises the question of the influence of the solifluction structures occurring in the chalk basement on the nature of the Holocene peat succession. The results of the biolithofacies analysis of the basal peats within various parts of fossil solifluction sheets/terraces (in central depressions and above ridges/ribs) indicate significant differences, determining the development of the peatlands. This is particularly clear in relation to the ramparted structures, where there is a distinctly different organic succession in the bottoms of the depressions and over the ramparts/embankments (Fig. 9). In the bottoms of these forms, the succession begins with the detritus-calcareous or calcareous gyttja passing upward into moss, sedge and/or reed peat. Significant lithogenetic importance to the deposition of carbonates, forming the lower sections of the mineral-organic sediments of the alkaline fens, should be attributed to the cryogenic precipitation of $CaCO_3$, associated with the formation and subsequent degradation of cryogenic mounds (Dobrowolski, 2006). Within the embankments, the organic succession begins with sedge peats, and calcareous tufa inserts occurring in the whole profile. Moreover, taking into account the record of sedimentary succession within the identified relict cryogenic mounds (the presence of calcareous tufa in the whole ramparts' profile), it can be assumed that they continued to be fed with artesian groundwater during the Holocene (development of local spring-fed fens).

The differences in the succession of Holocene organic deposits are also marked in the depressions and ridges of solifluction sheets (Fig. 9). A different type of organic succession in different parts of the basement had a significant impact on the reflection of fossil structures in the micromorphology of the mire. Due to high resolution of the LiDAR image (height differences of ca. 15 cm), they are visible even under a peat cover about 3 m thick. Thus, the primary style of organic deposition had a key influence on the nature of the entire Holocene sedimentary succession.

The relationships between the morphology of the mire substratum, determinants of their origin, and the nature of the organic succession are rarely the subject of detailed investigations. In the context of the results presented, such an analysis seems to be an extremely important direction for palaeoecological research, necessary for an understanding of the function of wetlands (Dobrowolski *et al.*, 2019) and their proper management (Osadowski *et al.*, 2019).

SUMMARY AND CONCLUSIONS

A detailed survey of LiDAR data for the Chełm Hills (Lublin chalkland) revealed a remarkable and clearly visible set of structures in the micromorphology of alkaline fens, not related directly to paludification processes. Field verification in the form of a set of geological core drillholes revealed the presence of twin structures in the chalk substratum of the peatlands. The structures at the fen surface were termed "ghost structures". The analysis of the internal structure of the chalk bedrock and the organic cover allowed recognition of the depositional sequence and the origin and

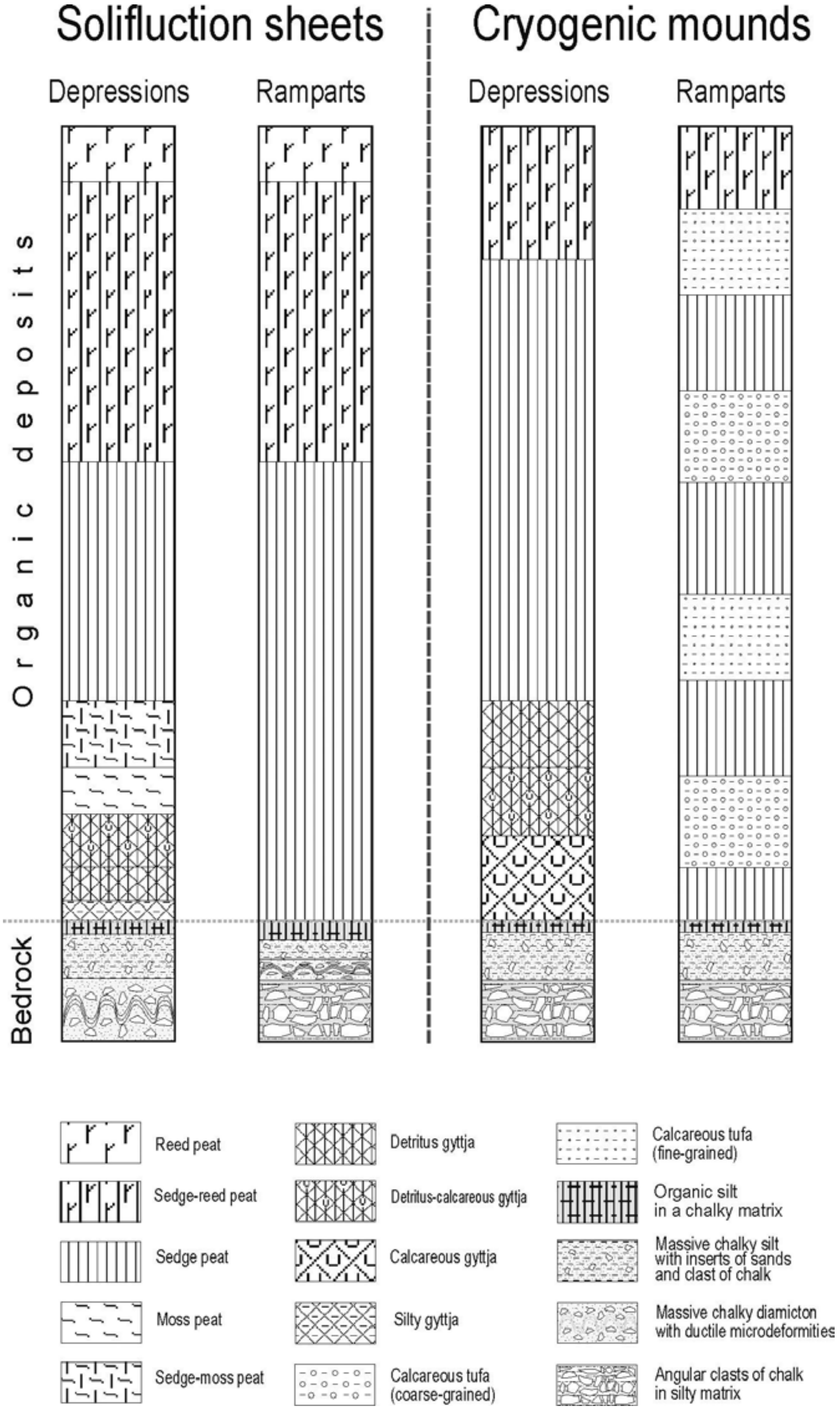

Fig. 9. Synthetic profiles of biogenic sedimentary succession over "ghost structures".

approximate age of the deposits. A conceptual model is proposed for landscape development during the transition between the Late Glacial and the Holocene. The main conclusions resulting from the research are:

1. Periglacial activity was widespread in the Chełm Hills during the Late Glacial.
2. The main morphogenetic process in this area was solifluction/slopewash, which was responsible for intense transformation of the relief. It was supported by the processes of permafrost degradation, i.e., degradation of segregated and/or intrusive ice.
3. Both types of periglacial process contributed to the development in relation to the climatic cycles of a set of forms, including:
   a. solifluction sheets, lobes and terraces,
   b. pingo-type structures (ramparted depressions, lithasas) and
   c. relict cryogenic mounds, i.e., frost mounds, transitional between palsas and frost blisters.
4. The occurrence of the non-sorted solifluction terraces was strictly controlled by local topography in the study area.

5. Both types of mound structure were developed at the foot of chalk hills. They are varied in terms of their size, internal structure, origin and geological context:
   a. lithalsas, located in the head deposits forming solifluction terraces/sheets; and
   b. frost mounds, fed by artesian springs and related to the trend of tectonic mesofaults in the Cretaceous rock complex.
6. The recharge of artesian waters within the relict cryogenic mounds (after the degradation of intrusive ice) continued in the Holocene, leading to the development of local spring-fed fens.
7. Post-depositional paludic activity in the bottoms of large depressions (alkaline fen development) during the Holocene contributed to the good preservation of periglacial structures in the substratum and their revitalization within peat covers, i.e., the development of spring-fed fen mounds at the locations of relict, cryogenic mounds.
8. The results of the research indicate the extremely important role of a sound geological recognition of the substratum of fens, especially in chalklands, for a good understanding of the functioning of wetlands and their proper management.

Acknowledgements

I wish to thank reviewers Ab Grootjans and Mirosław Błaszkiewicz and editor Michał Gradziński for their helpful comments, which greatly improved the manuscript. Special thanks go to Piotr Zagórski and Piotr Demczuk for support and assistance in spatial analysis. I would also like to thank Magdalena Suchora and Jarosław Pietruczuk for assistance in the field work and sediment sampling.

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